Highly Insulating Glazing Systems using Non-Structural Center Glazing Layers

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ABSTRACT

Three layer insulating glass units with two low-e coatings and an effective gas fill are known to be highly insulating, with center-of-glass U-factors as low as 0.57 W/m^2*-K (0.10 Btu/h-ft*^{2}*-°F). Such units have historically been built with center layers of glass or plastic which extend all the way through the spacer system.*

This paper shows that triple glazing systems with non-structural center layers which do not create a hermetic seal at the edge have the potential to be as thermally efficient as standard designs, while potentially removing some of the production and product integration issues that have discouraged the use of triples.

INTRODUCTION

Windows in the building stock in the United States are estimated to use 2 EJ (2 Quads) a year in heating energy. Even if all existing windows were replaced with available energy-efficient low-e products (U values < 2.0 W/m^2-K (0.35 Btu/h-ft^2-°F), windows related heating would still be over 1 EJ (1 Quad) (Arasteh et al. 2006).

Because heating loads are strongly tied to conductive losses, technologies which lead to lower window U-factors are the key to reducing heating energy. A 0.57 W/m^2-K (0.10 Btu/h-ft^2-°F) window is targeted as a product, which will meet the requirements of zero-energy homes. Dynamic control of solar gains, which will further reduce heating needs by allowing winter solar heat gains to be effectively utilized, are also key to the next generation of high performance windows (Apte et al. 2003, Arasteh et al. 2006). (Dynamic control of solar gains is the subject of other research efforts and is not covered in this paper.) Significant cooling load savings can also be expected from lower U-factor windows in certain climates and from dynamic windows in all climates.

Current strategies used to reduce heat loss through windows are triple or quadruple glazing, which adds significant weight, or suspended films, which are costly. Because of these weight and cost disadvantages, very highly efficient multi-layer, low-emissivity (low-E) gas-fill window products account for less than one percent of today's window sales.

BACKGROUND

This project's focus is on developing insulating glass units with center-of-glass U-factors of 0.57 W/m^2-K (0.10 Btu/h-ft^2-°F) while maintaining appropriate solar heat gain characteristics to meet the requirements of zero-energy homes. This project researches the potentials and practicality of using non-structural, insulating, central glazing layers in order to meet industry's cost, durability, and weight criteria (Arasteh et al. 1989, Selkowitz et al 1990). Lightweight, thin, non-structural central glazing layers allow the development of highly insulating glazing systems that do not significantly increase manufacturing and installation costs relative to other high-performance windows. Specific designs to be investigated are described in Figure 1 and Table 1a, 1b, below. While there are multi-layer low-E/gas-fill technologies on the market today, such products account for less than one percent of all sales, due in part to high manufacturing costs and structural issues. This project focuses on high performance glazing systems; other R&D efforts are needed to focus on reductions in frame/edge heat transfer.

The development of highly insulating windows has been the subject of research efforts around the world for several decades. Three technological routes have emerged:
- Aerogel is a micro-porous insulating material currently under R&D worldwide. An excellent insulator, manufacturing techniques aimed at minimizing cost and haze has been funded under a DOE-NETL grant.
- Vacuum glazings offer theoretically high center-glass performance but total window performance is compromised by structural spacers used in a grid to keep the glass layers apart, edge short circuiting, and the need to use low-e coatings which can sustain high temperatures during the edge welding process. Structural issues (glazing implosion) are of great concern. Nevertheless, development of manufacturing processes for commercial products is underway in the UK, Australia/Japan, Germany, and recently in the U.S. through a DOE-NETL grant. Vacuum glazing is now commercially available in Japan from Nippon Sheet Glass with a U-factor of 1.5 W/m^2-K (0.26 Btu/h-ft^2-°F) however, it falls short of our performance goal.
- Multiple (three or more) glazing layers with one low-e coating per gap and low-conductivity gas fills are the current state-of-the-art technology for low U-factor windows. The use of a second (or multiple) gap(s) minimizes convective/conductive heat transfer; ensuring that there is one low-e coating per gap minimizes radiative heat transfer across the gap (Arasteh et al. 1985). Such products are sold, in limited numbers, throughout heating dominated climates of the world. Significantly increased labor costs and/or added weight and structural issues are the main technological reasons why the sales fraction of such products is less than one percent in the United States.

The focus of this proposal is the development of alternative center glazing layers for multiple low-e/gas-filled units, which will overcome the labor, weight, and structural issues associated with current products. Currently, technological options fall into 2 categories:
- Heat Mirror^{TM} units where one or two thin low-e coated polyester films are stretched between two pieces of glass, then heat shrunk. The care with which the film must be handled and the heat shrinking process adds significant labor costs to this product. The use of a dual spacer system (one spacer on each side of the film) also increases costs and adds to concerns about gas-leakage. The low-e coated films are more expensive than coated glass. When complete, however, this product weighs no more than the average double glazed product.
- Triple Glazed units (with multiple low-e coatings and gas-fills) are an extension of current insulating glass manufacturing technologies. These units use an extra layer of glass, making them 50% heavier. The added weight has consequences for manufacturing, operating hardware, and for product installation. Two spacer systems are required as well (Figure 1b), inviting the complication of twice the seal length and the different temperatures and pressures in adjacent sealed air spaces inducing deflection of the glazing layers.

The proposed designs aim to increase the number of technological options available to industry for center glazing layers. The two technologies in use today (noted above) have been in use for over two decades. However by using light-weight, thin, non-structural layers (Figure 1c,f,k), the focus of this proposal, there can be manufacturing and performance advantages:

- no secondary spacer system (less costly, less gas leakage)
- no significant weight changes and thus minimal or no changes in operating hardware
- thinner layers mean overall insulating glass widths do not increase as much, making the products more likely to fit in existing cross-sections
- pressure equalization between the internal gaps is possible.

Specific designs to be examined under this project are detailed in Figures 1a-k. Technical questions addressed include:

- Is there any deterioration in thermal performance when there are small gaps (< 3 mm (0.12 in.)) around a center glazing layer (Figures 1h,i,j)?
- How well do triangular gaps perform (Figure 1d)?
- What are the potentials for IR transparent layers, such as polytetrafluoroethylene (PTFE)? Do they eliminate the need for a second low-e surface (Figures 1e,f)?
- How much of a convection baffle is a semi-pervious layer such as a screen (Figure 1f)?

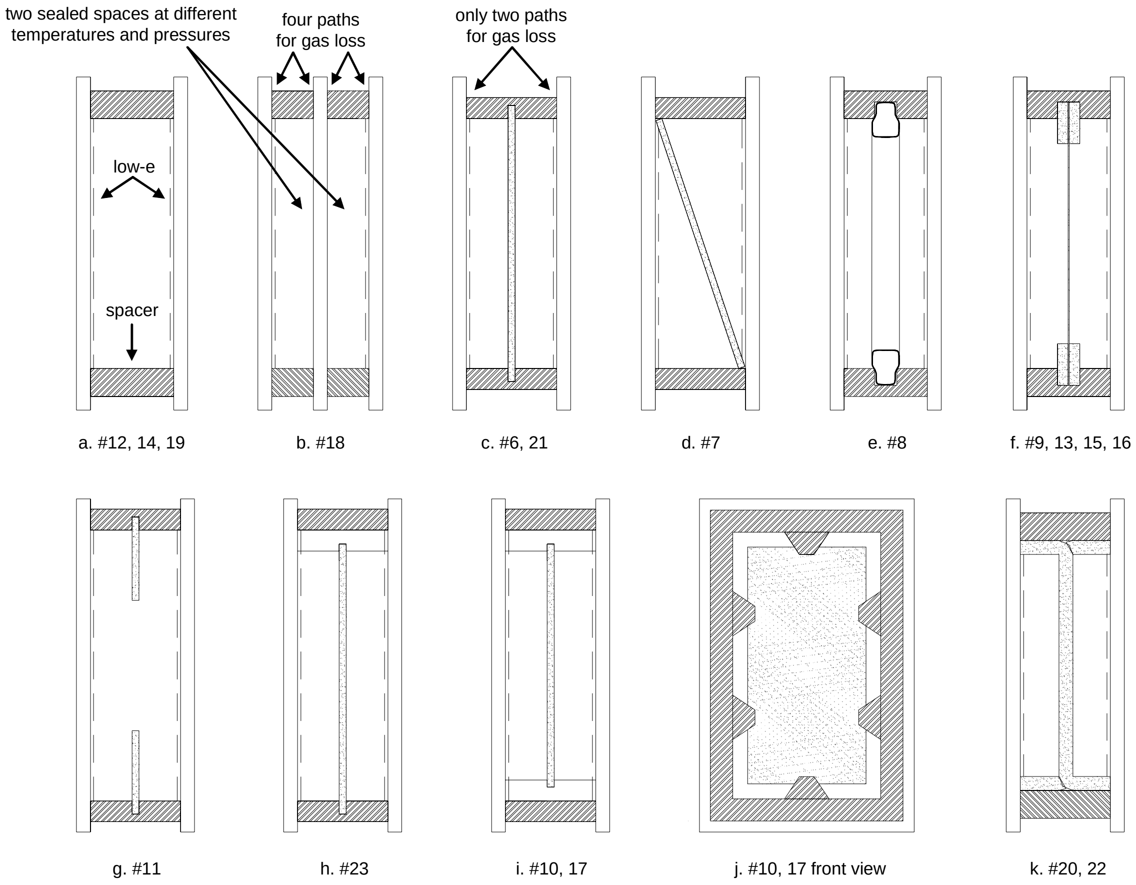


Figure 1(a-k) – Cross-sectional geometry of the prototype insulated glazing units tested. Drawings are not to scale. Refer to Table 1 for dimensions. Specimens 16 and 19 have one low-e despite the two pictured typical of other specimens. Specimen 21 has a commercial vacuum panel center layer, but is otherwise similar to specimen 6 in construction. Specimens 9 and 15 utilized screen materials in the center layer position, while 13 and 16 were continuous PTFE sheets.

EVALUATING PERFORMANCE

Performance potentials for the products designed under this project were evaluated using IR Thermography in the LBNL IR Thermography Facility (Figure 2, also http://windows.lbl.gov/facilities/irlab). IR Thermography testing allows for the visual observation of localized and whole prototype thermal performance through the high-resolution measurement of surface temperatures. This detailed data can indicate whether specific aspects of the design are improving or diminishing total performance. The typical result of a window tested in this facility is a temperature map of the room side surface of the window. Data is either presented visually (with false-color images, thermograms, of the window, where the color scale corresponds to surface temperature) or can be numerically processed and presented graphically. For the purposes of this study, we evaluate performance potentials by graphing the top to bottom surface temperatures of each IGU tested, along the centerline.

The full height window temperature data are composed by combining an image of the upper and lower half of each specimen. These images are collected at slightly different times and conditions. Discontinuities at half glazing height can be observed in the thermograms and vertical center line data.

Target environmental conditions for the experiments are in accordance with NFRC 100 (-18 °C (0 °F) exterior condition side with 30 W/m^2-K (5.3 Btu/h-ft^2-F)average surface heat transfer coefficient, and 21 °C (70 °F) on the room condition side with ~7 W/m^2-K (1.2 Btu/h-ft^2-°F) average surface heat transfer coefficient). Preceding the window specimen measurements, a calibration run was performed on the chambers to match these parameters as closely as possible, using a calibrated transfer standard (CTS). The CTS is constructed with 25 mm (1 in.) of foam between the temperature sensor pairs used to derive heat flux at 18 locations over a 914 mm (36 in.) by 914 mm (36 in.) area. This highly insulating CTS is a good match with the target insulating values for the prototype highly insulating windows presented. However, it should be mentioned that geometry differences between the CTS (flush mounted) and the prototype insulated glazing units (tested recessed about 25 mm (1 in.) in a foam mask wall on the warm side) make the exact surface heat transfer coefficients indeterminate during the following tests of IGUs. The measured surface heat transfer coefficients with the CTS for the center zone were 27.4 W/m^2-K (4.8 Btu/h-ft^2-°F) on the cold side and 7.8 W/m^2-K (1.4 Btu/h-ft^2-°F) on the warm side. The IR thermography data are collected in tightly controlled environmental chambers. Reflection of background radiation is removed and an external reference emitter provides correction for absolute temperature. Qualitative accuracy of IR measurements is +/- 0.5 °C (0.9 °F). Further details of the facility and the methodology of the referencing and corrections necessary to obtain accurate quantitative surface temperatures from infrared thermography are discussed in reports of previous work (Griffith et al. 2002, 1999, 1996).

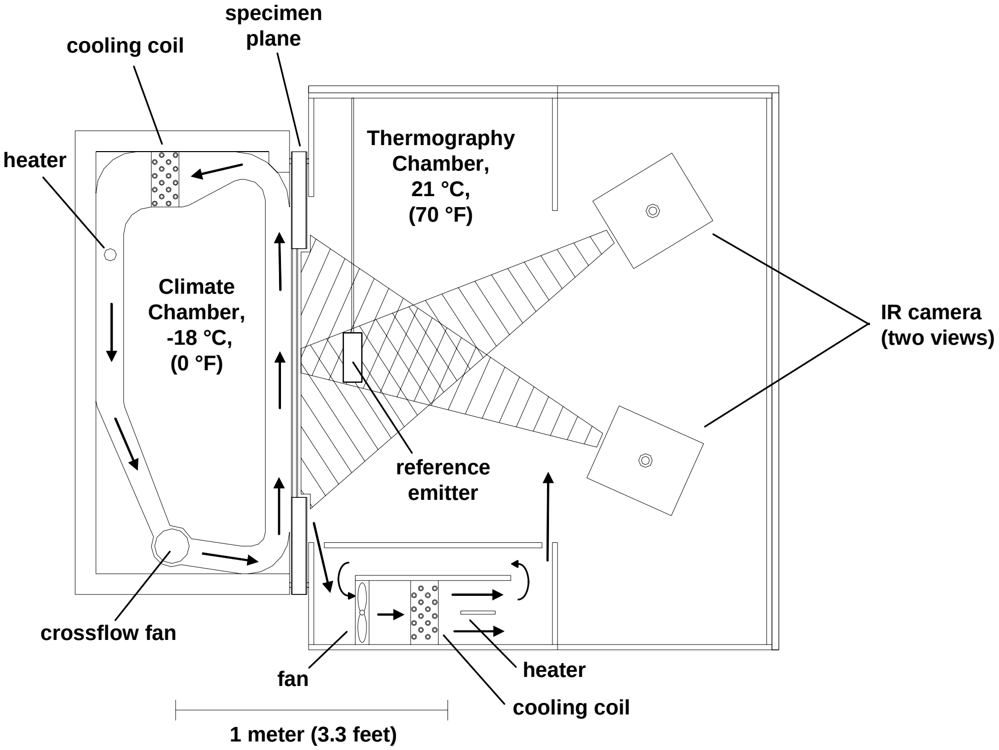


Figure 2 – Infrared Thermography Facility (side view cross-section)

PROTOTYPES BUILT AND TESTED

Five groups of prototypes were built and tested. Details are given in Table 1a, 1b and Figure 1a-k. Unless otherwise noted, all units have an overall IG width of about 26 mm (1 in.) and are Krypton filled, using foam spacers. Argon is a commonly used in gas-filled windows, but Krypton gas is chosen for this project because of its higher thermal resistance which enables us to reach our target U-factor of 0.57 W/m^2-K (0.10 Btu/h-ft^2-°F) while allowing an acceptable glazing thickness. Foam spacers provided both excellent thermal performance and easy machining for custom groove configurations. WINDOW5 simulations were performed for a triple glazed window with two low-e coatings and a 95% krypton gas fill to determine the optimal gap width. A gap width of 9.5 mm (0.37 in.) was determined to be the optimal and this dimension was used for all specimens unless otherwise noted. All units are 914 mm (36 in.) high. For all three layers units, low-e coatings are on the #2 and #5 surfaces, unless otherwise noted. For the four layer units, low-e coatings are on the #2 and #7 surfaces. Many of the units utilize plastic center layers. For the rigid plastics, both acrylic and polycarbonate materials were used, however the optimal plastic material choice remains for further research. Measuring the thermal performance of different geometries was the primary thrust of the work to date. Bent edge inserts were easier to prototype from polycarbonate, but there is no reason that the same part couldn't be fabricated from other materials, with the proper fabrication technique.

Group 1 includes several products designed to serve as references. These are either conventional products, or products using conventional technologies designed to help us evaluate alternative designs:

- #19 represents the best possible double glazed low-e, krypton-filled unit, with a single low-e layer.
- #18 represents a traditional 3 layer, highly insulating glass unit, with low-e coatings on surfaces 2 and 5, with 9.5 mm (0.37 in.) Krypton filled gaps, a near optimum. Calculated (according to NFRC100) center-of-glass U-factor is 0.60 W/m^2-K (0.11 Btu/h-ft^2-°F).
- #12 is intended to represent a three layer high-performance unit, but without the center layer. It has two low-e surfaces and a wide gap (19 mm (0.75 in.)). By comparing other units to this one, we can see the impact of a center layer in reducing convection and radiation.
- #14 is double layer reference similar to #12, except that the gap is reduced to 9.5 mm (0.37 in.), as opposed to the atypical 19 mm (0.75 in.) double, in order to minimize convection.
- #21 uses a vacuum IG as the center "layer", commercially available from Japan, turning this into a unit with four pieces of glass. The slightly smaller gaps (6.4 mm (0.25 in.)) were filled with xenon to maximize performance. This unit is intended to represent the best possible performance in a 4 layer, 26 mm (1 in.) glazing system.

Group 2 products were designed to see if there is any degradation in thermal performance when there are small gaps around a center layer. Specific designs and prototypes include:

- #6 has a 1.6 mm (0.06 in.) thick acrylic center layer retained in a grooved spacer. Because of the snug fit of the sheet in the groove for the entire perimeter, there is no avenue for direct convection between the two gas spaces, although the two sides are not hermetically separated.
- #10 has an acrylic center layer held on standoffs which maintain a 3 mm (0.12 in.) gap between the entire perimeter edge of the center layer and the spacer.
- #17 is similar to #10 but with a 1.6 mm (0.06 in.) gap between center layer and spacer
- #20 utilizes a 1.6 mm (0.06 in.) thick polycarbonate layer, with the 150 mm (5.9 in.) long edge tabs folded, in alternating directions, so as to keep the center layer equidistant between the two glass layers without the use of a grooved spacer.
- #22 is similar to #20 but with a 3.2 mm (0.13 in.) thick polycarbonate (for a more rigid center layer)
- #23 is similar to #10 except the 3 (0.12 in.) mm gap is only along the top or bottom edge (depending on test orientation), the other three edges sit in a grooved spacer.

Group 3 products were designed to understand the effects of triangular gaps, which could be easily constructed by "wedging" in the appropriate sized insert.

- #7a has a 1.6 mm (0.06 in.) acrylic center layer, wedged in the gap, slanted so that the top points toward the warm side.
- #7b is similar to #7a except that the top points towards the cold side.

Group 4 products were designed to evaluate the potentials of long-wave infrared transparent layers. In theory, if a layer is completely IR transparent, only one low-e coating is needed for both gaps (Wright, 1987). A completely IR transparent layer functions as a convective baffle in large gas gap, without any impacts on radiation heat transfer. Unfortunately, even the exceptionally thin IR transparent layer we tested (0.01 mm (3.9 * 10^{-4} in.) thick PTFE) was only partially IR transparent (Tir=0.64); the corresponding partial IR absorptance decreases its effectiveness as a convective-only baffle.

- #8 has two IR baffles, creating three thin gaps, with two low-e coatings on the gap facing glass surfaces. The two PTFE layers were wrapped around, and tensioned by, a central 6 mm (0.24 in.) wide aluminum spacer frame retained in the center of the unit by a groove in the foam spacer.

- #13 has one layer of PTFE film held in the middle of the gap by a simple frame of plastic which holds the film in the foam spacer groove. There is a low-E coating on both pieces of glass.
- #16 is similar to #13 with one PTFE center layer, however, only one low-E coating is present (surface #2). The performance of this unit relative to #13 indicates the degree to which the IR transparency of the center film layer can eliminate the need for one low-e surface in each gas space, as is typical for optimal triple glazing performance.

Group 5 products were alternative designs intended to see if effective convection baffles could be developed from air permeable materials.

- #9 is a three layer unit where the center layer is a standard window screen with a 70% open area.
- #15 is similar to #9 except that the solar shade screen used has only about 20% open area.
- #11 does not have a full center layer but rather utilizes horizontal baffles running across the bottom 150 mm (5.9 in.) and the top 150 mm (5.9 in.) of the unit, made from 1.6 mm (0.06 in.) thick acrylic and held in place by a partially grooved foam spacer.

Table 1a – Prototype construction details – SI units

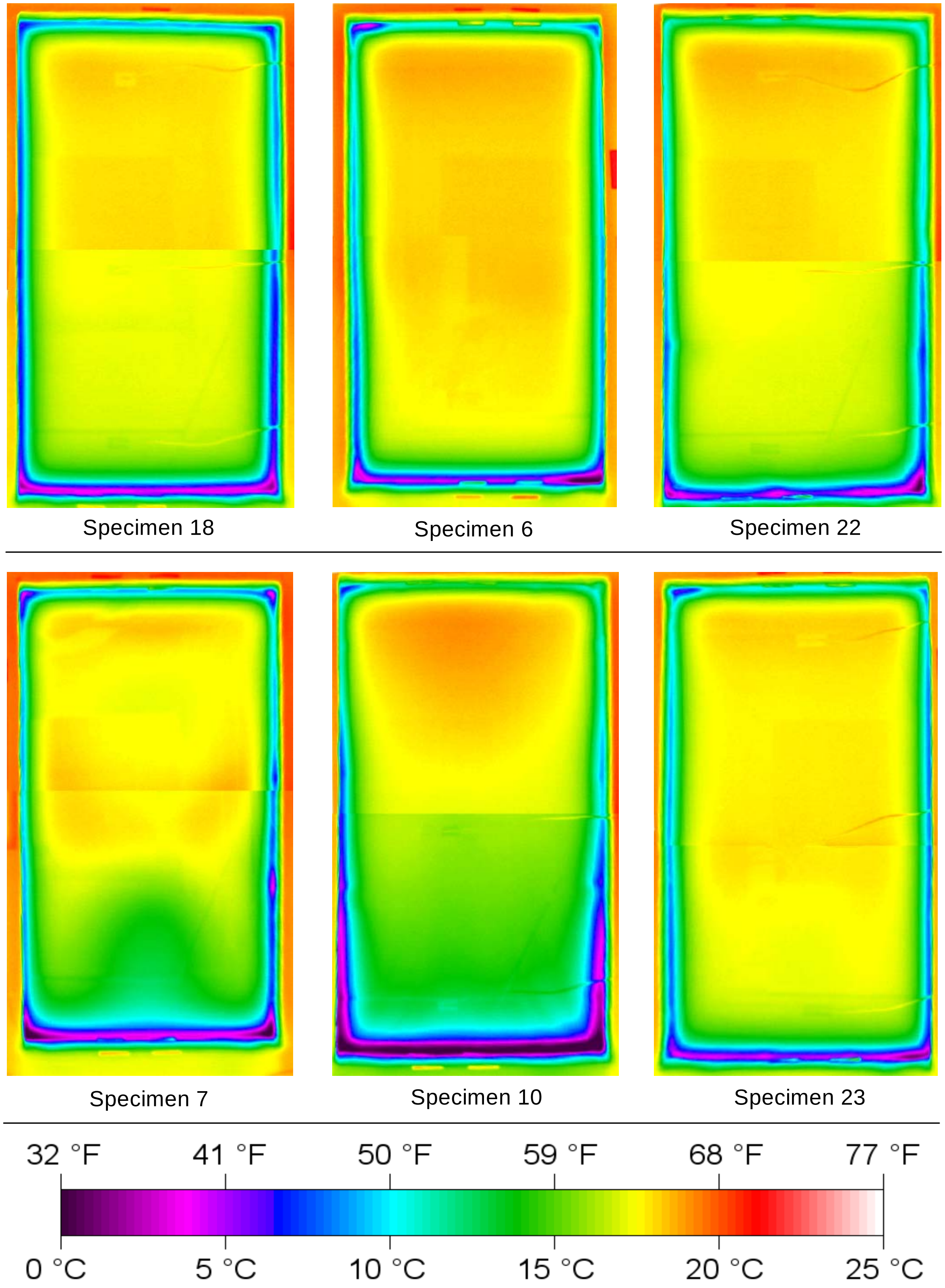
Group-#	Prototype Description	Gas	Layer 1	Layer 2	Layer 3	Center layer (mm)	Gap (mm)	Overall thickness (mm)
1-19	9.5 mm double convection standard for screens and gaps (one low-e)	Kr	3 mm e = 0.04	None	3 mm e = 0.84	none	9.5	15.5
1-18	traditional glass center layer in broken spacer	Kr	3 mm e = 0.04	3 mm clear glass e = 0.84	3 mm e = 0.04	3	9.5	28
1-12	19 mm double convection standard for screens and gaps	Kr	3 mm e = 0.04	None	3 mm e = 0.04	none	19	25
1-14	9.5 mm double convection standard for screens and gaps (two low-e)	Kr	3 mm e = 0.04	None	3 mm e = 0.04	none	9.5	15.5
1-21	quad, low-e vacuum panel center layer, Xe	Xe	3 mm e = 0.04	6.4 mm vacuum panel	3 mm e = 0.04	6.4	7.1	26.6
2-6	parallel acrylic center layer in grooved spacer	Kr	3 mm e = 0.04	1.6 mm acrylic	3 mm e = 0.04	1.6	9.5	26.6
2-10	acrylic center layer with 3.2 mm perimeter gap	Kr	3 mm e = 0.04	1.6 mm acrylic	3 mm e = 0.04	1.6	9.5	26.6
2-17	acrylic center layer with 1.6 mm perimeter gap	Kr	3 mm e = 0.04	1.6 mm acrylic	3 mm e = 0.04	1.6	9.5	26.6
2-20	folded edge 1.6 mm polycarbonate center layer	Kr	3 mm e = 0.04	1.6 mm polycarbonate	3 mm e = 0.04	1.6	9.5	26.6
2-22	folded edge 3.2 mm polycarbonate center layer	Kr	3 mm e = 0.04	3.2 mm polycarbonate	3 mm e = 0.04	3.2	8.7	26.6
2-23	acrylic center layer with a 3mm gap on only one edge (top or bottom)	Kr	3 mm e = 0.04	1.6 mm acrylic	3 mm e = 0.04	1.6	9.5	26.6
3-7	angled acrylic center layer in grooved spacer	Kr	3 mm e = 0.04	1.6 mm acrylic	3 mm e = 0.04	1.6	variable	26.6
4-8	two layer PTFE center insert (clinging in center)	Kr	3 mm e = 0.04	two 0.01 mm PTFE	3 mm e = 0.04	0.01	variable	25
4-13	PTFE center insert (two low-e)	Kr	3 mm e = 0.04	0.01 mm PTFE	3 mm e = 0.04	0.01	9.5	25
4-16	PTFE center insert (one low-e)	Kr	3 mm e = 0.04	0.01 mm PTFE	3 mm e = 0.84	0.01	9.5	25
5-9	70% open fiberglass insect screen center layer	Kr	3 mm e = 0.04	72% insect screen	3 mm e = 0.04	0.3	9.5	25
5-15	20% open screen center layer (similar aperture size to insect screen)	Kr	3 mm e = 0.04	30% solar screen	3 mm e = 0.04	0.5	9.5	25
5-11	150 mm acrylic fins top and bottom (partial center layer)	Kr	3 mm e = 0.04	1.6 mm acrylic (partial)	3 mm e = 0.04	1.6	9.5	26.6

Table 1b – Prototype construction details – IP units

Group-#	Prototype Description	Gas	Layer 1	Layer 2	Layer 3	Center layer (in.)	Gap (in.)	Overall thickness (in.)
1-19	0.37 in. double convection standard for screens and gaps (one low-e)	Kr	0.12 in. e = 0.04	None	0.12 in. e = 0.84	none	0.37	0.61
1-18	traditional glass center layer in broken spacer	Kr	0.12 in. e = 0.04	0.12 in. clear glass e = 0.84	0.12 in. e = 0.04	0.12	0.37	1.10
1-12	0.75 in. double convection standard for screens and gaps	Kr	0.12 in. e = 0.04	None	0.12 in. e = 0.04	None	0.75	0.98
1-14	0.37 in. double convection standard for screens and gaps (two low-e)	Kr	0.12 in. e = 0.04	None	0.12 in. e = 0.04	None	0.37	0.61
1-21	quad, low-e vacuum panel center layer, Xe	Xe	0.12 in. e = 0.04	0.25 in. vacuum panel	0.12 in. e = 0.04	0.25	7.1	1.05
2-6	parallel acrylic center layer in grooved spacer	Kr	0.12 in. e = 0.04	0.06 in. acrylic	0.12 in. e = 0.04	0.06	0.37	1.05
2-10	acrylic center layer with 0.13 in. perimeter gap	Kr	0.12 in. e = 0.04	0.06 in. acrylic	0.12 in. e = 0.04	0.06	0.37	1.05
2-17	acrylic center layer with 0.06 in. perimeter gap	Kr	0.12 in. e = 0.04	0.06 in. acrylic	0.12 in. e = 0.04	0.06	0.37	1.05
2-20	folded edge 0.06 in. polycarbonate center layer	Kr	0.12 in. e = 0.04	0.06 in. polycarbonate	0.12 in. e = 0.04	0.06	0.37	1.05
2-22	folded edge 0.13 in. polycarbonate center layer	Kr	0.12 in. e = 0.04	0.13 in, polycarbonate	0.12 in. e = 0.04	0.13	8.7	1.05
2-23	acrylic center layer with a 0.12 in. gap on only one edge (top or bottom)	Kr	0.12 in. e = 0.04	0.06 in. acrylic	0.12 in. e = 0.04	0.06	0.37	1.05
3-7	angled acrylic center layer in grooved spacer	Kr	0.12 in. e = 0.04	0.06 in. acrylic	0.12 in. e = 0.04	0.06	variable	1.05
4-8	two layer PTFE center insert (clinging in center)	Kr	0.12 in. e = 0.04	two 3.9 * 10^{-4} in. PTFE	0.12 in. e = 0.04	0.01	variable	0.98
4-13	PTFE center insert (two low-e)	Kr	0.12 in. e = 0.04	3.9 * 10^{-4} in. PTFE	0.12 in. e = 0.04	0.01	0.37	0.98
4-16	PTFE center insert (one low-e)	Kr	0.12 in. e = 0.04	3.9 * 10^{-4} in. PTFE	0.12 in. e = 0.84	0.01	0.37	0.98
5-9	70% open fiberglass insect screen center layer	Kr	0.12 in. e = 0.04	72% insect screen	0.12 in. e = 0.04	0.3	0.37	0.98
5-15	20% open screen center layer (similar aperture size to insect screen)	Kr	0.12 in. e = 0.04	30% solar screen	0.12 in. e = 0.04	0.5	0.37	0.98
5-11	5.9 in. acrylic fins top and bottom (partial center layer)	Kr	0.12 in. e = 0.04	0.06 in. acrylic (partial)	0.12 in. e = 0.04	0.06	0.37	1.05

RESULTS

Each of the specimens described above was tested in our IR thermography chamber, as described in the section titled Evaluating Performance, above. Experiments typically involved side-by-side testing of two prototypes. Warm side surface temperature maps were generated for each image, with typical examples shown below in Figure 3. The data was also processed in order to obtain quantitative surface temperature data for a vertical line segment (sightline to sightline) in the middle of each unit. Contact thermocouple (TC) temperature measurements were taken at the center of glass and 100 mm (3.9 in.) from the head and sill. The IR data is presented graphically, in Figures 4-7, and IR and TC data is summarized in Table 2a, 2b, below. The full data set is also available on the following website, http://windows.lbl.gov/irlab/hirtesting/


Specimen 18

Specimen 6

Specimen 22

Specimen 7

Specimen 10

Specimen 23

Figure 3 – Examples of false color plots showing warm side surface temperature maps from infrared thermography (not accurate in black and white)

Table 2a – Summary of warm side surface temperature results – SI units (under -18°C, 21°C test conditions)

Group-#	Prototype Description	Modeled* U-factor W/(m^2-K)	Modeled* Center of glass temp. (°C)	Center of Glass TC temp. (°C)	100 mm from sill TC temp. (°C)	IR line average temp. (°C)
1-19	double Kr, one low-e, 9.5 mm gap, Kr	1.27	15.0	15.53	14.97	14.13
1-18	triple Kr, two low-e, uncoated glass center layer in traditional broken spacer	0.60	18.4	18.38	17.67	17.37
1-12	double Kr, two low-e, large gap reference for screens and perimeter gaps	1.31	14.8	15.24	14.26	14.18
1-14	double Kr, two low-e, 9.5 mm gap reference for screens and perimeter gaps	1.23	15.3	15.76	14.71	14.55
1-21	quad Xe, two low-e glass layers, low-e vacuum panel center layer	0.41	19.4	19.33	18.72	18.69
2-6	triple Kr, two low-e, acrylic center layer in grooved spacer	0.60	18.4	17.92	17.76	17.35
2-10	triple Kr, two low-e, acrylic center layer with 3.2 mm perimeter gap	n/a	n/a	17.08	14.15	16.17
2-17	triple Kr, two low-e, acrylic center layer with 1.6mm perimeter gap	n/a	n/a	16.14	16.08	16.15
2-20	triple Kr, two low-e, 1.6 mm folded edge polycarbonate center layer	0.60	18.4	17.24	16.06	16.67
2-22	triple, Kr, two low-e, 3.2 mm folded edge polycarbonate center layer	0.60	18.4	17.87	16.90	17.12
2-23a	triple, Kr, two low-e, acrylic center layer with one edge gap (top)	n/a	n/a	17.74	17.53	17.00
2-23b	triple, Kr, two low-e, acrylic center layer with one edge gap (bottom)	n/a	n/a	18.07	17.38	17.27
3-7a	triple Kr, two low-e, angled acrylic center layer, top toward warm side	n/a	n/a	17.12	16.09	16.01
3-7b	triple Kr, two low-e, angled acrylic center layer, top toward cold side	n/a	n/a	17.80	13.74	15.77
4-8	quad Kr, two low-e, two layer PTFE center insert (clinging in center)	n/a	n/a	18.14	17.67	17.56
4-13	triple Kr, two low-e, one layer PTFE center insert	0.60	18.4	18.03	17.49	17.57
4-16	triple, one low-e, one layer PTFE center insert	0.89	16.9	16.48	15.94	15.58
5-9	triple Kr, two low-e, 70% open insect screen center layer	n/a	n/a	17.12	13.05	15.91
5-15	triple Kr, two low-e, 20% open solar screen center layer	n/a	n/a	17.07	13.77	16.26
5-11	triple Kr (partial), two low-e, 150mm acrylic fins top and bottom	n/a	n/a	15.05	16.59	15.13

*Boundary conditions for the simulation were based on experimental conditions at the center of the glazing: 21.4 °C and 7.8 W/m^2K on the warm side and -17.76 °C and 27.4 W/m^2K on the cold side

Table 2b – Summary of warm side surface temperature results - IP units (under -0.4 °F, 69.8 °F) test conditions)

Group-#	Prototype Description	Modeled* U-factor Btu/H-ft^2-°F	Modeled* Center of glass temp. (°F)	Center of Glass TC temp. (°F)	3.9 in. from sill TC temp. (°F)	IR line average temp. (°F)
1-19	double Kr, one low-e, 0.37 in. gap, Kr	0.22	59	59.95	58.95	57.43
1-18	triple Kr, two low-e, uncoated glass center layer in traditional broken spacer	0.11	65.12	65.08	63.81	63.27
1-12	double Kr, two low-e, large gap reference for screens and perimeter gaps	0.23	58.64	59.43	57.67	57.52
1-14	double Kr, two low-e, 0.37 gap reference for screens and perimeter gaps	0.22	59.54	60.37	58.48	58.19
1-21	quad Xe, two low-e glass layers, low-e vacuum panel center layer	0.07	66.92	66.79	65.7	65.64
2-6	triple Kr, two low-e, acrylic center layer in grooved spacer	0.11	65.12	64.26	63.97	63.23
2-10	triple Kr, two low-e, acrylic center layer with 0.13 in. perimeter gap	n/a	n/a	62.74	57.47	61.11
2-17	triple Kr, two low-e, acrylic center layer with 0.06 in. perimeter gap	n/a	n/a	61.05	60.94	61.07
2-20	triple Kr, two low-e, 0.06 in. folded edge polycarbonate center layer	0.11	65.12	63.03	60.91	62.01
2-22	triple, Kr, two low-e, 0.13 in. folded edge polycarbonate center layer	0.11	65.12	64.17	62.42	62.82
2-23a	triple, Kr, two low-e, acrylic center layer with one edge gap (top)	n/a	n/a	63.93	63.55	62.6
2-23b	triple, Kr, two low-e, acrylic center layer with one edge gap (bottom)	n/a	n/a	64.53	63.28	63.09
3-7a	triple Kr, two low-e, angled acrylic center layer, top toward warm side	n/a	n/a	62.82	60.96	60.82
3-7b	triple Kr, two low-e, angled acrylic center layer, top toward cold side	n/a	n/a	64.04	56.73	60.39
4-8	quad Kr, two low-e, two layer PTFE center insert (clinging in center)	n/a	n/a	64.65	63.81	63.61
4-13	triple Kr, two low-e, one layer PTFE center insert	0.11	65.12	64.45	63.48	63.63
4-16	triple, one low-e, one layer PTFE center insert	0.16	62.42	61.66	60.69	60.04
5-9	triple Kr, two low-e, 70% open insect screen center layer	n/a	n/a	62.82	55.49	60.64
5-15	triple Kr, two low-e, 20% open solar screen center layer	n/a	n/a	62.73	56.79	61.27
5-11	triple Kr (partial), two low-e, 5.9 in. acrylic fins top and bottom	n/a	n/a	59.09	61.86	59.23

*Boundary conditions for the simulation were based on experimental conditions at the center of the glazing: 70.5 °F and 1.4 Btu/h-ft^2-°F on the warm side and 0.0 °F and 4.8 Btu/h-ft^2-°F on the cold side.

More informative than the summary data presented in Table 2a, 2b are graphs which show warm side temperature as a function of vertical distance along the unit’s centerline. Discontinuities in the data at center of glass are the result of combining two separate images as described in “Evaluating Performance”. Four such graphs are presented below, one looking at each of the following effects:

- the impact of the gap at the bottom of a center layer (Group 2, figure 4)
- the impact of triangular gaps (Group 3, figure 5)
- the impacts of IR transparent layers (Group 4, figure 6)
- the impacts of porous convection baffles (Group 5, figure 7)

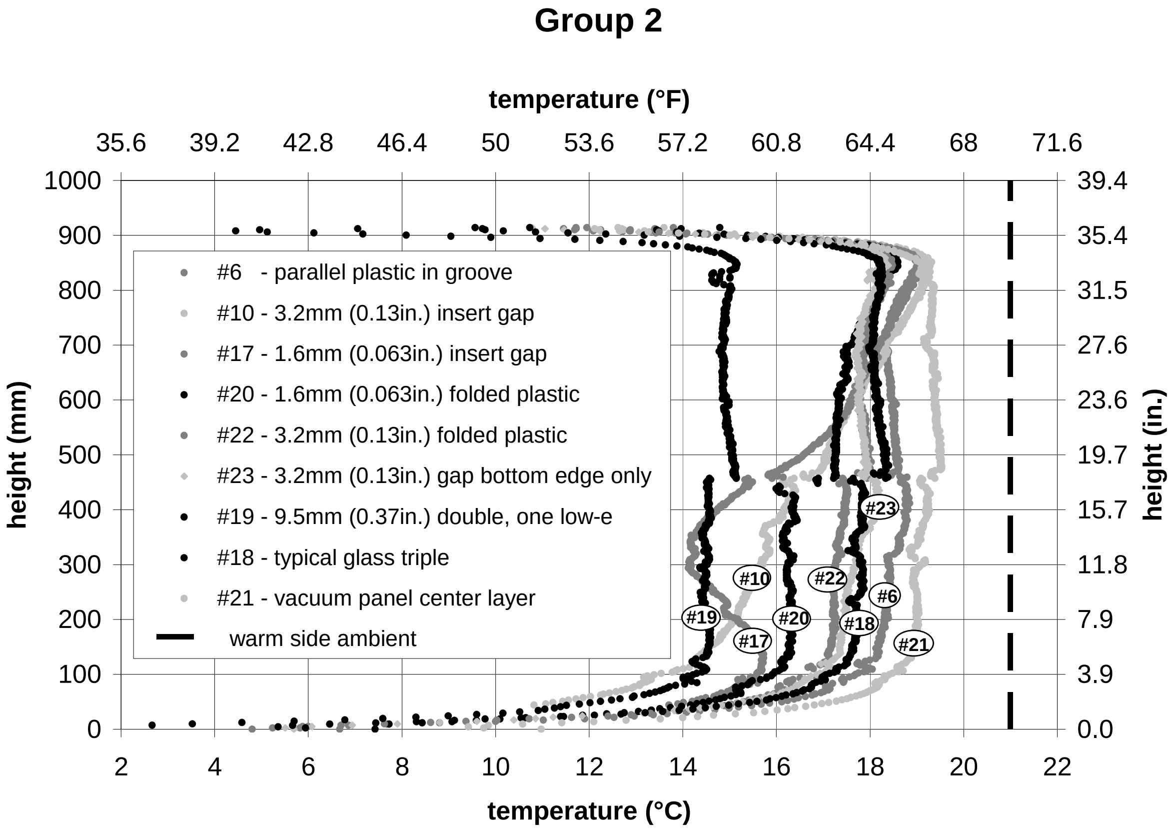


Figure 4 - Group 2 center-line temperature profiles

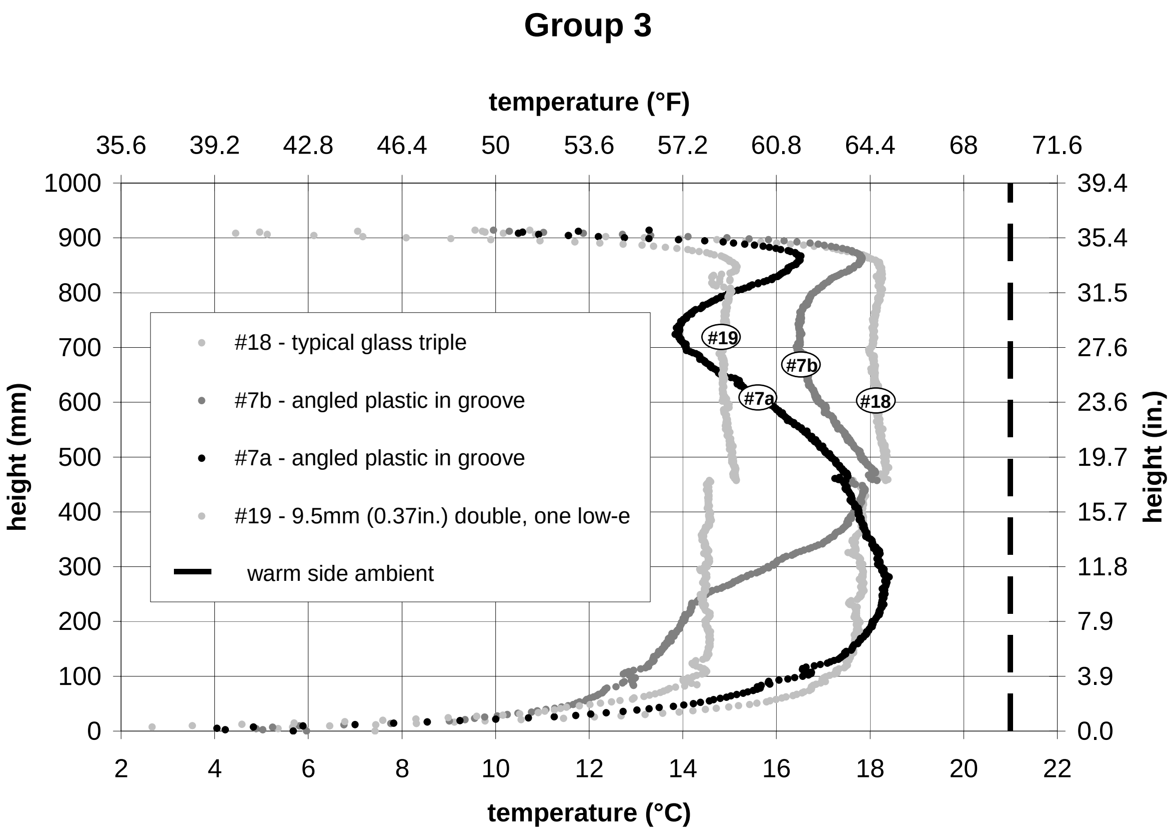


Figure 5 - Group 3 center-line temperature profiles

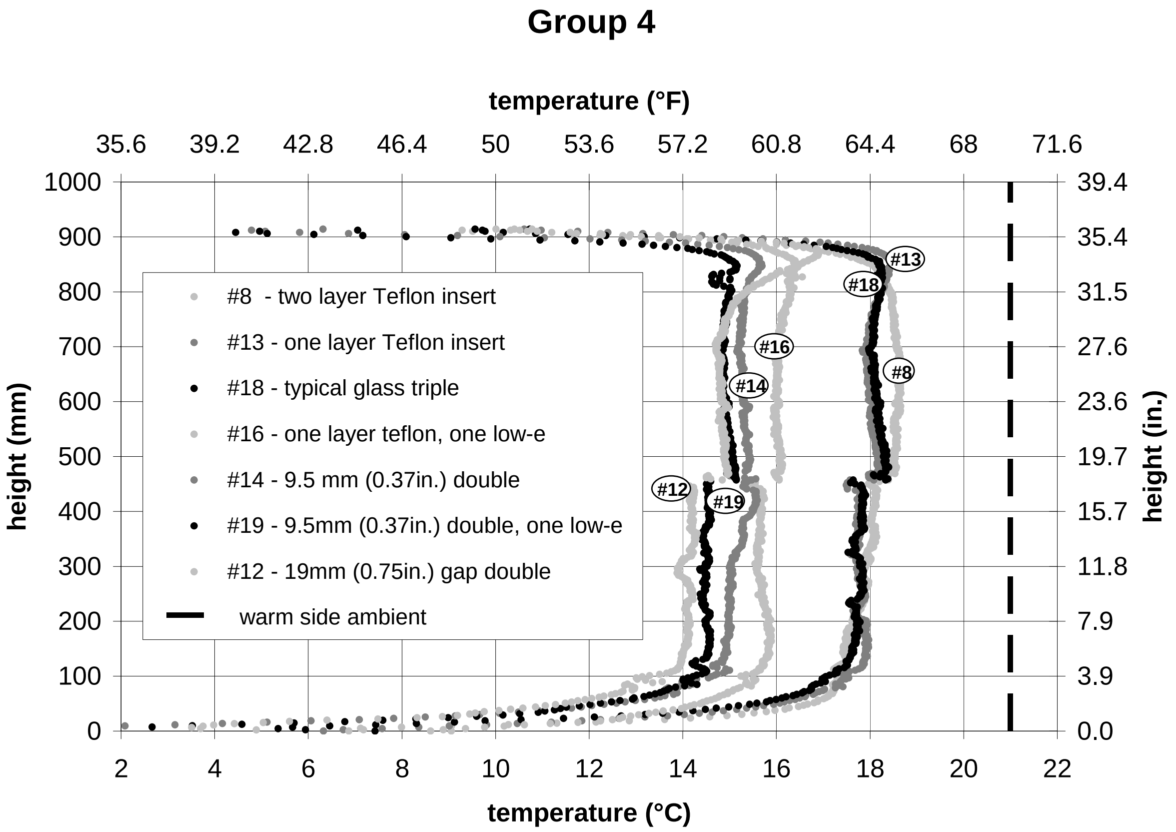


Figure 6 - Group 4 center-line temperature profiles

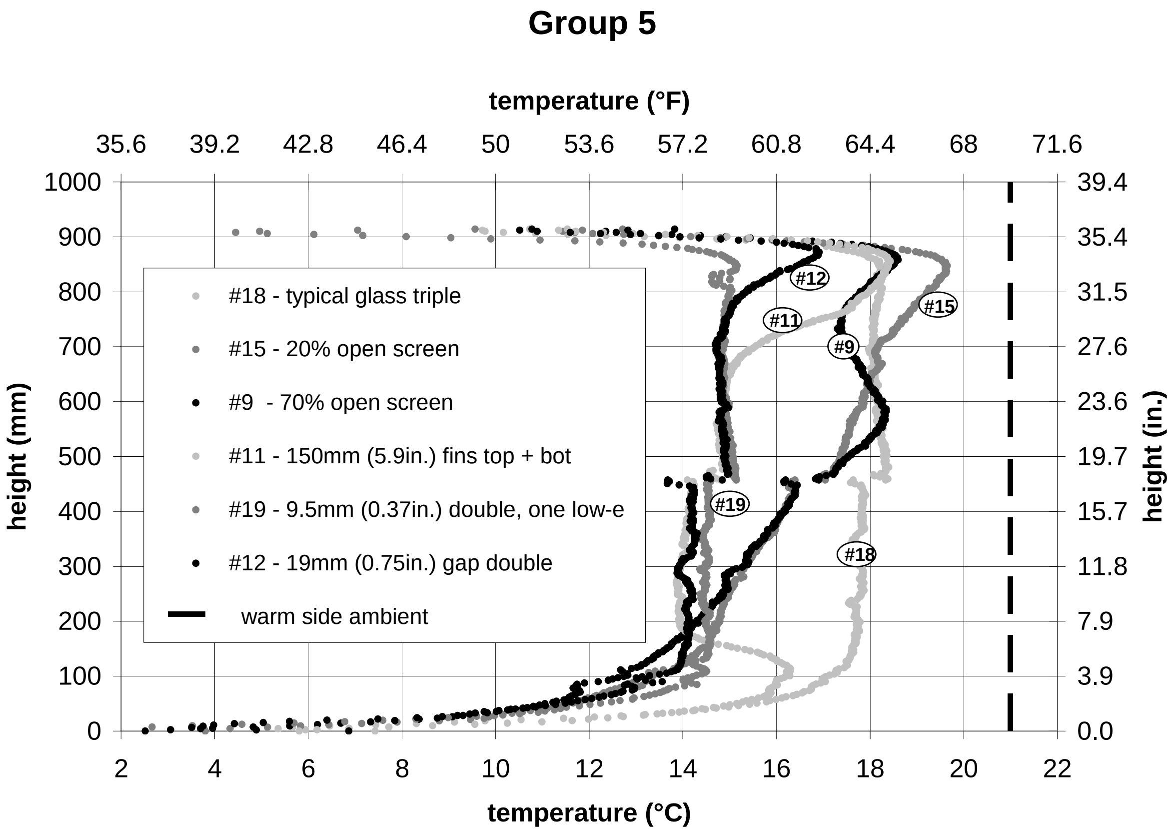


Figure 7 - Group 5 center-line temperature profiles

DISCUSSION

The results presented above provide clear guidance on the thermal performance potentials for non-structural center layers. Looking at figures 4-7, as well as the data in Table 2a, 2b, allows us to answer the questions originally posed:

-Is there any deterioration in thermal performance when there are small gaps (3 mm (0.12 in.)) around a center glazing layer? (Figures 1h,i,j drawings and figure 4 results)
-How well do triangular gaps perform? (Figure 1d drawings and figure 5 results)
- What are the potentials for IR transparent layers, such as PTFE? Do they eliminate the need for a second low-e surface? (Figures 1e,f drawings and figure 6 results)
- How much of a convection baffle is a semi-pervious layer such as a screen? (Figure 1f drawings and figure 7 results)

Center layers with gaps:

Note that we base the following conclusions on the shapes of the IR center-line temperatures and their absolute values, as well as the average values in Table 2a, 2b. As noted in previous work on quantitative thermography (Griffith et al. 2002, 1999, 1996), the accuracy of the IR measurements using our equipment and procedures is +/- 0.5 °C (0.9 °F). In most cases, unless otherwise noted, when comparisons are made, they are made between units of equal gap spaces, gas fills, and low-e coatings.

Looking at Figure 4, we conclude that there are no negative thermal impacts from using a non-structural center layer, tightly inserted into a groove in the spacer. This is seen by comparing #6 to a conventional triple unit (#18) where the center layer is sandwiched between two spacer systems. Unit #6 and unit #18 have essentially the same center of glass average temperature and the same temperature distribution along the vertical center-line. However, there can be deterioration in thermal performance when there are small perimeter gaps (even down to 1.6 mm (0.06 in.) along the edges of a non-structural center layer. This is seen by comparing #10 and #17 (3.2 mm (0.13 in.) and 1.6 mm (0.06 in.) perimeter gaps) vs. #6 or #18. These gaps lead to some convection between the two cavities and thereby reduce performance. The center layer still has a significant effect on the convection pattern, as noted by a comparison to #19. The results of unit #23, similar to #10 but with a center layer edge gap only on the top (or bottom depending on orientation) reveal that convection between the two cavities does not develop as long as either the top or bottom edge is in contact with the spacer.

Perhaps the most significant conclusion from Figure 4 is gained when looking at the performance of center layers with folded edges (#20 and #22). These units were built to fit snugly against the spacer but have gaps on the order of 0.5 mm (0.02 in.) at various spots. In the case of #20, it was noted during the measurements that the center layer was too thin to maintain itself parallel to the two glass layers and this is noticed in the results curve in Figure 4. A thicker layer, #22, remained vertical, with performance essentially identical to the two base triple units (#6 and #18), despite Krypton filled cavities which are slightly smaller than the more optimal dimensions of #6, as a result of using a thicker sheet with the same spacer dimension. Residual mechanical stresses from manufacturing may also influence the tendency of the plastic center layer to rest out of plane or deflect under temperature difference. More research into material properties and processing is necessary.

Angled Center-Layers

Angled center layers, while perhaps relatively easy to drop in during the manufacturing process, have a limited performance potential. This is seen by looking at Figure 5, which indicates the presence of strong convection, apparent as a large top to bottom surface temperature gradient. Average center-line temperatures (Table 2a, 2b) are approximately halfway between the no-center layer case of #19 and the baseline triple of #18.

IR – Transparent Layers

Previous research (Wright, 1987) shows the potential for IR transparent layers to serve as convection baffles. With a completely IR transparent layer, one low-e coating could serve to suppress radiation in both gaps, since the IR transparent layer would not exist where radiation heat transfer was concerned. Performance equal to or near that of a double low-e three layer unit could be expected with one low-e and one completely IR transparent layer. However, there are no perfectly IR transparent layers available for window layers. A PTFE film (0.01 mm ($3.9 * 10^{-4}$ in.) thick) was the most likely candidate found (Tir= 0.64). As seen by the data in Figure 6, the performance of unit #16 does not come close to that of the reference #18. Adding a second low-e (#13) remedies this situation, indicating that PTFE would be an excellent candidate as a "standard" center layer. Besides being lightweight and thin, PTFE also has an extremely high solar transmittance (Tsol=0.95).

Unit #8, which utilized two layers of PTFE stretched around an insert, resulting in three 6mm gaps instead of two 9 mm (0.35 in.) gaps, has similar performance to the one layer of PTFE. Whatever (presumably minimal, from theory) reductions in convection gained from smaller gaps was offset by small increases in radiation in the gap between the two PTFE layers. Due to inadequate tension and static attraction, the center portion of #8 was essentially a triple, as the two films of PTFE clung together under static attraction.

Semi-impervious layers

Semi-impervious layers, i.e. shade screens, were researched on the chance that devices which serve as operable solar control devices may also lead to reductions in heat transfer rates. The data from Table 2a, 2b and from Figure 7 indicates that the reductions in heat transfer rates are moderate, at best. It should be noted that the screen with the smallest openings were about 0.5 mm (0.02 in.) by 1 mm (0.04 in.). There is still potential that materials with a much finer opening structure, may exhibit useful convention barrier properties while maintaining an acceptable view.

Another tactic to reduce convection in a gap, that of placing fins at the top and bottom of the gap (#11), is effective at mitigating low temperatures at the sightline but not effective as a means to suppress overall heat transfer rates.

CONCLUSIONS

Three layer insulating glass units with two low-e coatings and an effective gas fill are known to be highly insulating, with center-of-glass U-factors as low as 0.57 W/m^2-K (0.10 Btu/h-ft^2-°F). Such units have historically been built with center layers of glass or plastic which extend all the way through the spacer system.

This study shows that non-structural center layers which do not create a hermetic seal at the edge have the potential to be as thermally efficient as standard designs, while potentially removing some of the production and product integration issues that have discouraged the use of triples. Thus, flexibility exists in how a center layer can be inserted into an IG unit without compromising thermal performance. However, not all designs are effective and care must be taken in the design of such units. While the results of these early prototypes were successful and promise easy to fabricate, lighter weight triple glazings, it should also be noted that our testing revealed potential issues with the mechanical stiffness and residual stresses in plastic center layers as well as their tendency to bow under large temperature gradients. These topics deserve further research, as do the long term durability and materials compatibility of these designs, before their viability for market can be fully determined.

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