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Using Infrared Thermography for the Creation of a Window Surface Temperature Database to Validate Computer Heat Transfer Models

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INTRODUCTION

Infrared thermography is a non-invasive, non-destructive technique for measuring surface temperatures of an object. These surface temperatures can be used to understand the thermal performance of window components and complete window systems. Infrared (IR) thermography has long been used for qualitative field assessment of window thermal performance, and is now being used in the laboratory for quantitative assessments of window thermal performance [1,2]. As windows become better and better, more refined test methods and/or simulation tools are required to accurately detect performance changes and make comparisons between products. While hot box calorimetery has worked well to characterize the thermal performance of conventional insulating products, differences in the thermal performance of new highly insulating systems are often less than the resolution of conventional hot box calorimeters. Infrared imaging techniques offer the opportunity to resolve small differences in the thermal performance of components of highly insulating window systems that hot box measurements are not able to identify.

Lawrence Berkeley Laboratory (LBL), a U.S. national research laboratory, is currently using infrared thermography to develop a database of measured surface temperature profiles for a number of different fenestration products for use in validating both basic and advanced two- and three-dimensional finite element method (FEM) and finite difference method (FDM) fenestration heat transfer simulation programs. IR surface temperature data, when taken under controlled laboratory conditions, can be used to direct the development of these simulation codes, identify their strengths and weaknesses, set research priorities, and validate finished modeling tools. Simulation of fenestration heat transfer is faster and less expensive than hot box testing of fenestration products, and forms the basis of window energy codes being implemented, developed, or considered in the US, Canada, the Former Soviet Union, Europe, and Australia. The National Fenestration Rating Council (U.S.) has developed a simulation-based standard [3] which is used to rate and label window U-values for a published directory of over 10,000 different window products [4].

THE INFRARED THERMOGRAPHY FACILITY

At the Infrared Thermography Facility at Lawrence Berkeley Laboratory, an infrared imaging radiometer is used to measure long-wave infrared radiation reflected, transmitted, and emitted from the surface of a test specimen that is subject to a temperature differential in an environmental chamber. A computer-based processing card converts the measured radiosity to surface temperature data by comparison to a known reference surface using known surface emissivity and IR background radiosity in conjunction with a lookup table. This data is represented in the form of a pixel-based, two-dimensional, spatial surface temperature map, or *thermogram*, of the specimen. The thermogram is stored in electronic form for post-processing and data analysis. Surface temperature profiles may be generated from the thermogram for any cross section of the test specimen. These profiles form the basis for the surface temperature database discussed in this paper.

In order to obtain quantitative results for the database, the IR facility is set up to maintain steady-state, characterized, repeatable environmental conditions before and during the test. Techniques to reduce errors and quantify environmental conditions are employed. A thorough error analysis is performed to determine the accuracy of the measurements. In this section we give a discussion of our test method, techniques employed to reduce error and improve the accuracy and repeatability of laboratory-based IR thermographic measurements, and basic sources of errors encountered in IR thermography. Issues affecting IR measurement accuracy are addressed in further detail in a separate paper by the authors [5].

1. Test Method

The IR environmental chamber consists of a cold chamber, a test specimen mounting jig (*mask wall*), a warm chamber with a flexible bellows, an air dehumidification system, control electronics, and a data acquisition system (see Figure 1). Additional components of the chamber include an extended-area black body reference emitter and a calibration transfer standard, as discussed below. For an infrared test, a window specimen up to 1 m^2 is mounted in a polystyrene foam mask wall (see Figure 2) and secured between the cold chamber and the warm chamber. The cold side chamber is chilled to a specified setpoint and employs a forced convective air flow parallel to the test specimen. The warm side chamber maintains natural convective air flow at a controlled ambient temperature. The environmental chambers are run overnight and allowed to come to thermal equilibrium with the test specimen before imaging with

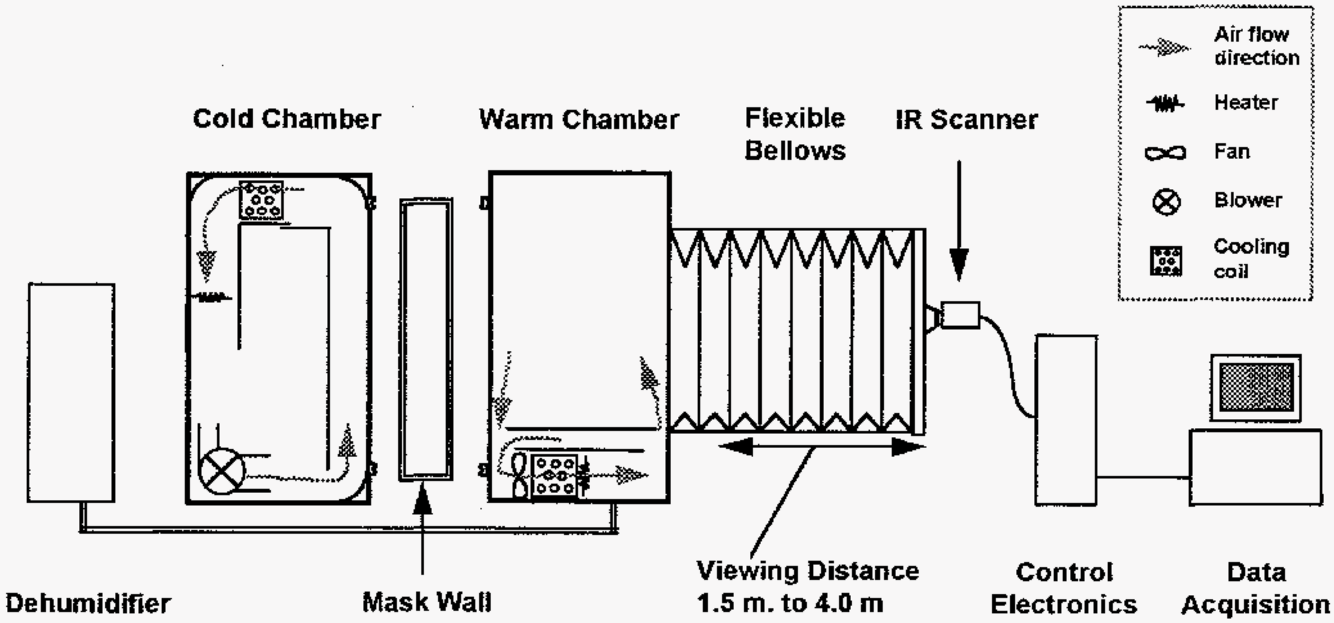
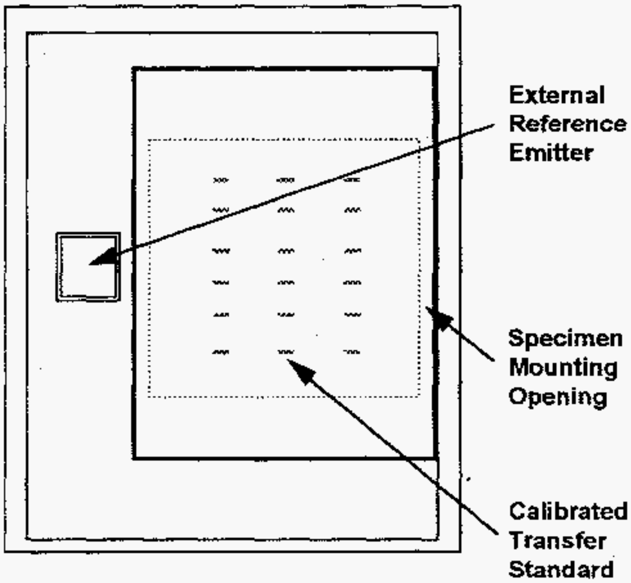


Figure 1 Schematic representation of the LBL Infrared Thermography Facility environmental chamber showing air circulation systems in the warm and cold chambers.

Figure 2 Schematic representation of the mask wall, showing the location of the external reference emitter and the position of the calibrated transfer standard used for measuring heat transfer coefficients on the warm and cold side surfaces. The mask wall measures 1.3 m. x 1.6 m. and the specimen mounting opening measures 0.9 m. x1.2 m.



the IR scanner, as steady-state heat transfer through the window test specimen is required for thermal performance characteristics to be inferred from surface temperature data. It should be noted that IR thermography is limited to conditions were infrared radiation can pass though the medium between the sample and the detector. Furthermore, overall thermal conductance values cannot be accurately calculated from infrared surface temperature measurements because of the difficulty in obtaining accurate film coefficients.

2. Environmental Chamber Details

Test conditions in the LBL environmental chamber are similar to the ASHRAE/NFRC [3] Winter U-value test conditions for windows: The chamber (see Figure 1) uses forced convection and a temperature setpoint of -17.8°C on the cold side, and natural convection and a temperature setpoint of 21.1°C on the warm side. Wind speed is variable between 1 and 7 m/s, parallel upwards to the test surface. As it is critical that the cold side surface have constant air temperature and velocity, the cold box compressor runs continually, with resistance strip heaters to reheat the air to the desired setpoint and a tangential blower which circulates the conditioned air along a plenum parallel to the test sample. Once thermal equilibrium has been achieved, the cold chamber air temperature is stable and uniform to within ± 0.1°C. The warm-side chamber maintains constant air temperature and velocity, and minimizes extraneous IR background radiation. A 1 meter deep rigid box holds a fan rack and strip heater assembly used to drive a natural convective flow and reheat the air in the warm side shroud to the desired setpoint. A cooling coil is incorporated to stabilize the effects of heating. A flexible bellows is attached to the rigid box, allowing the IR scanner viewing distance to be adjusted from a minimum of 1 m. to a maximum of 4 m. from the test sample. The bellows is opaque to infrared radiation and provides a uniform IR background by shielding the test sample from extraneous infrared radiation. The uniformity of background IR radiation is assessed by imaging a low-emissivity specularly reflecting surface placed in the plane of the sample. This surface mirrors the background radiation to the scanner, allowing quantification of the thermal background levels present. The rigid box and flexible bellows allow a stable warm-side convective flow to be maintained by isolating the sample from random room air currents. The warm side air temperature is stable and uniform to within ± 0.2 °C once thermal equilibrium has been established. As condensation on the imaged surface can affect test results, a dehumidification system is employed to allow testing at low temperatures without generating condensation.

3. IR Scanner Details

The IR scanner used is a high-speed scanning infrared imaging radiometer with a mercury/cadmium/ telluride photon detector. The scan rate is 8 kHz horizontal and 60 Hz vertical. The detector measures IR radiation in the 8-12 μm range, where room-temperature black-body radiation peaks and an atmospheric window for IR radiation of these wavelengths exists. The radiometer has an internal emitter referenced at 60 Hz. The factory specification measurement accuracy is ± 2.0°C or 2% of the temperature span for absolute temperature measurements, and a noise equivalent temperature difference of ± 0.05°C. Our goal is to reduce the absolute accuracy of the IR system from the factory specification to within ± 0.5°C through use of an external reference emitter and careful error analysis. We locate a NIST-traceable reference emitter near the test object to aid in removing bias in absolute temperature measurements [5]. The reference emitter is an extended area black body consisting of a temperature-controlled flat aluminum plate with a high emissivity coating across its surface, has a long-term temperature stability of ± 0.04°C, and is recalibrated annually. Thermal noise associated with the random nature of photon emissions from the object surface is reduced to ± 0.05°C by averaging a number of images. The images are typically averaged in one of two ways; 50 frames taken over a period of 16 seconds, or 60 frames taken over a period of 10 minutes. Other sources of measurement error are variations over the field-of-view of the scanner and variations across the temperature span. We have experimentally determined each of these errors to be ± 0.20°C [5]. Summing the absolute and relative errors, we find that our referenced IR measurements are accurate to within ± 0.5°C for low thermal contrast regions for a 5 °C span [5]. This figure assumes no operator or procedural errors with respect to emissivity, background radiosity, and distance/resolution issues. Accuracy may be less for regions of high thermal contrast.

4. Characterization of Environmental Conditions

Air temperatures, air velocity, and relative humidity are measured with thermocouples and/or thermistors, hot wire anemometers, and humidity transducers, respectively. Warm and cold side heat transfer coefficients for the test sample are measured using a 1 m^2 calibrated reference standard (CTS). The CTS consists of a matrix of eighteen special limits type-T thermocouple pairs on either side of a well-characterized reference insulation, sandwiched between two layers of glass and sealed against air and vapor infiltration. The CTS and the air-temperature junctions for each of the eighteen thermocouple pairs are subject to the steady-state test conditions and temperature data taken over an extended time period. The values of the heat transfer coefficients are then calculated in a manner consistent with the procedures outlined in the ASTM C-1199 Standard [6]. These heat transfer coefficients may be input as the boundary conditions for simulation of heat transfer through a window tested in the chamber under the same environmental conditions. It should be noted that experimental characterization of heat transfer coefficients for complex (i.e. projecting) surfaces subject to natural convection is extremely difficult due to the temperature gradients present and three-dimensional nature of the surface. Further research is required to be able to determine accurate heat transfer coefficients for complex projecting products such as skylights and greenhouse windows.

5. Basic Issues in Quantitative IR Thermography

Thermal Stability: An IR environmental chamber is designed to maintain an environment that is both thermally stable over the course of an IR test, and repeatable between tests. For steady-state heat transfer the air temperature on each side of the sample, as measured using thermistors or thermocouples, must be constant prior to and during the test. Surface temperatures are affected by convective heat transfer, which is a strong function of air velocity, the temperature difference between the surface and the air, and surface emittance. Wind speeds must remain constant on the cold side, and must not be disrupted during the test in the case of natural convection on the warm side. The warm-side chamber eliminates thermal transients that can be induced by changes in air conditioning or heating output, turning on (or off) heat producing equipment such as lights, computers, or office machinery during the test, and by changes in the weather if the surrounding building shell is poorly insulated. As the heat from the IR control electronics may change the air temperature, and the bulk of the hardware may affect the air flow characteristics in the warm-side chamber, the control electronics and data acquisition system are located outside of the test chamber. The warm-side shroud also eliminates disruptions in natural convective flows that may be caused by air handling equipment, fans, and motion in the test area. The IR scanner is located such that it does not disrupt the required test conditions, while allowing imaging of the sample at normal or near-normal incidence angles.

IR Background Radiation: There are often sources of non-homogeneous background radiation arising from surfaces that are at a temperature different than the ambient test temperature. This radiation will reflect off the test sample, giving erroneous surface temperature readings. The IR imaging system corrects for background radiation levels using one average background temperature value for the whole image. Background radiation shielding must be used to ensure that the test sample sees only a uniform IR background. In the cold chamber the chiller coil is shielded from the test specimen by a radiant barrier. Common sources of warm-side non-uniform background radiation include lighting, heaters or chillers, office equipment, electrical junction boxes, and personnel (including the system operator). As previously mentioned, an IR-opaque construction is employed to shield the test specimen from warm side non-homogeneous radiation. In a closed space such as the warm-side shroud, the air may stagnate and create a vertical temperature gradient in the enclosed space, which can lead to non-uniform wall temperatures and non-homogeneous IR background radiation. In the LBL warm chamber the natural convective flow is driven slightly by a fan system to avoid these stacking effects within the warm box.

Imaging Distance: The thermal resolution of an IR image is a function of the distance from the IR detector to the imaged object. As a scanner is moved closer to an object, a greater number of pixels per unit area are obtained, thereby increasing measurement resolution. This distance is limited by the focal length of the scanner lens (0.15 m. in our case), and by increasing reflections of the scanner lens off of the imaged object as the scanner is moved closer. However, to include an external reference emitter in the image, or to obtain a single image of a complete window system, the distance between the scanner and the object must be increased. The tradeoff inherent in IR imaging is that thermal and spatial resolution decrease as imaged area increases. In cases where accurate measurements of a small feature in a region of high thermal contrast (such as the coldest sightline temperature on a window) are desired, we find that differences in the measured surface temperature of a small region deviate by as much as 3.5°C when moving the scanner from a distance of 4.0 m to 1.5 m from the object [5].

Surface Emissivity: In taking IR measurements, one must be sure that one is measuring the infrared radiation emitted from the object, and not that of other objects reflected from the imaged surface. Low emissivity (highly reflective) surfaces, such as chromed or mirrored light fixtures, will simply reflect the background radiation. The surface of such objects must be coated with a low thermal resistance substance of known, high emissivity (such as masking tape) to measure their surface temperatures accurately. The emissivity of imaged surfaces must be known as accurately as possible, as an error in the emissivity input into the IR scanner software will lead to errors in the surface temperatures calculated from the measured radiosity. Errors in emissivity are compounded by the fact that the measurement error varies with the magnitude of the temperature difference between the imaged surface and the ambient temperature. Emissivity values must be specified for the wavelength range being measured, 8-12 μm in our case. Differences in emissivity must be taken into account when imaging an object with more than one surface emissivity value. The IR processing software used can assign different emissivities to different regions when necessary.

WINDOW SURFACE TEMPERATURE PROFILE DATABASE

Computer simulation programs for analyzing heat transfer through window systems or components can be used to calculate window U-values and condensation resistance factors. These models need to be validated to verify their accuracy and define their limitations. A database of window surface temperature profiles for the validation of these models is being created through the use of infrared thermographic imaging. A number of windows varying in size, thermal performance, and complexity, are undergoing testing in a characterized and controlled IR thermography laboratory as described above. Surface temperature profiles generated by simulation programs, run under the same boundary conditions as in the thermographic test, can then be compared to the thermographic surface temperature profiles of the window physically tested, affording a clear indication of whether the simulation program is able to accurately predict the surface temperatures of the window. Agreement between the surface temperature profiles generated by the simulation programs with those measured using infrared thermography will indicate accurate modeling of heat transfer through the window system. Disagreements will help define and prioritize areas for software improvements.

The database is being developed over time in a phased manner, beginning with simple glazing configurations and later incorporating window configurations of increasing complexity. Phase I of the IR window surface temperature profile database will test the accuracy of insulated glazing radiative, convective, and conductive modeling using multiple glazing types with different gap widths, gas fills, and low-E coatings. The first Phase I tests were run on two sets of simple glazing configurations, as described below.

Condensation Resistance Test Glazings: The first set of glazings tested is intended to examine the effect of convection and spacer materials on edge-of-glass surface temperatures. This data will provide a strong test for models which seek to determine window condensation resistance factors. The glazings selected were air-filled double- and triple-glazed units, see Table 1. For this test the glazing units were mounted flush to both the warm and cold side of the mask wall. These glazings measure 35.5 cm x 50.8 cm. Data was taken along the vertical center line of the window.

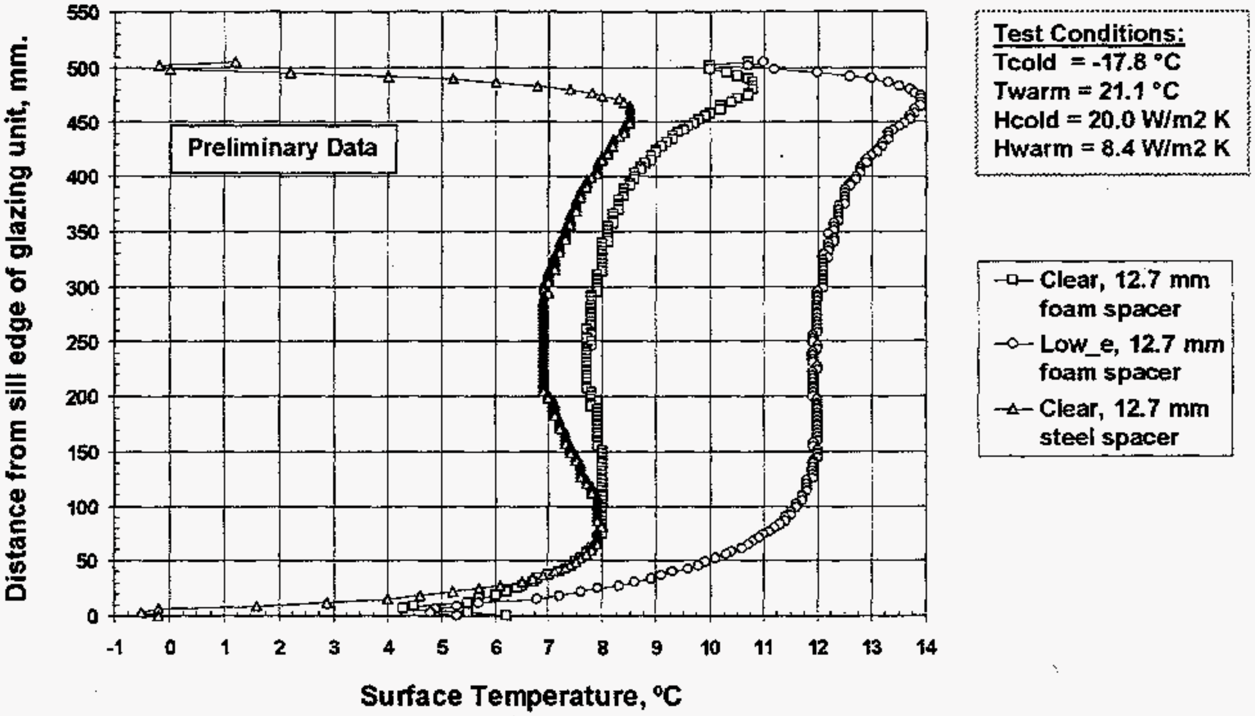


Figure 3 Vertical surface temperature profiles of air-filled double glazing units as measured by the IR scanner at the centerline of the glazing. Depressed center-of-glass temperatures on two of the units indicate glazing deflection.

Preliminary test results for three of the double-glazed units are shown in Figure 3. Data is plotted for vertical temperature profiles taken along the centerline of the glazings. Heat transfer coefficients for the test were measured using the CTS to be 8.4 W/m^2 K and 20.0 W/m^2 K on the warm and cold sides, respectively. Non-uniform temperatures in the center-of-glass region indicate glazing deflection on both of the clear glazing units. Breather tubes will be installed to eliminate the deflection in future tests, but the current data can be used to test a program's ability to model convection in deflected glazings. As one would expect, the steel spaced unit has sightline temperatures well below the foam-spaced units. The addition of the low-E coating raises the warm-side surface temperature (and thus the thermal performance) of the center-of-glass region greatly in comparison to the clear foam-spaced unit, but the sightline temperatures increase only slightly due to the dominant effect of thermal short-circuiting though the spacer in the edge-of-glass region.

Table 1: Condensation Resistance Test Glazings

glazing	gas fill	spacer	low-E coating	gap width (mm.)	Ucog (W/m^2 K)
double	air	foam	clear	6.35	3.24
double	air	metal	clear	12.7	2.78
double	air	foam	clear	12.7	2.78
double	air	foam	sputtered	12.7	1.99
double	air	foam	clear	19.1	3.24
triple	air	foam	clear	6.35, 6.35	2.16
triple	air	foam	clear	12.7, 12.7	1.82

Edge Convection Test Glazings: The second set of glazings tested is intended to examine the range of edge conditions found in units with the same center-of-glass U-values. This data will provide a strong test of the accuracy of simulation codes incorporating 2-D and 3-D convective modeling. The glazings selected were air- and argon-filled, double- and triple-glazed units, see Table 2. For this test the glazing units were mounted in a mask wall flush on the cold side of the test chamber and flush on the warm side with an insulating strip covering the spacer to the sightline. The trim strips were used so that thermal short circuiting effects from the spacer would better be seen at the glazing edge, thus mimicking a glazing installed in a frame, and to give better definition for the temperature profile at the sightline. These glazings measured 40.6 cm. x 61.0 cm. Data was taken along the horizontal center line of the jamb and along the vertical center line of the sill.

Preliminary test results for two of the glazings, a triple-glazed, air-filled unit and a double-glazed argon-filled unit, are shown in Figures 4 and 5. Heat transfer coefficients were not measured at the time of this test. Both glazings are 25.4 mm.-thick with identical insulating spacers and simulated center-of-glass U-values of 1.42 W/m^2 K. Figure 4 compares a plot of jamb surface temperatures between the two glazings. The measured sightline temperatures are equal, as would be expected given almost identical edges, and the measured center-of-glass temperatures agree to within experimental uncertainty, as would be expected given identical center-of-glass U-values. The fact that these two profiles are identical within experimental error supports the assumption that jamb heat transfer in the edge-of-glass region is decoupled from convective flow in the center-of-glass region. Window heat transfer simulation programs that do not explicitly model convection are expected to predict profiles similar to these jamb profiles.

Figure 5 compares sill surface temperatures for the same two glazing units. While the center-of-glass and edge-of-glass sightline temperatures are the same, the edge-of-glass region of the air-filled triple-glazed unit is warmer than that of the argon-filled double-glazed unit by up to almost 2°C in some places. We believe that this effect is a result of reduced convection at the edge of glass due to the two thinner glazing cavities in the triple-glazed unit as compared to the single larger cavity of the double-glazed unit. An analysis of the Nusselt numbers seems to confirm this. Nusselt numbers for the gaps of the triple glazing were calculated to be 1.01 and 1.00, while that for the gap of the double glazing was calculated to be 1.98. Temperatures for calculating the Nusselt numbers were from FRAME [7] simulations of the glazing edge, taken at 1 inch above the sightline. Temperatures measured closer to the sightline give similar trends in the Nusselt numbers. A window heat transfer simulation program that does not explicitly model convection will not predict this measured difference in surface temperatures, but one that does should, and can be validated with this data.

Table 2: Edge Convection Test Glazings

glazing	gas fill	spacer	low-E coating	gap width (mm.)	Ucog (W/m^2 K)
triple	air	steel, thermally broken	suspended thin film	11.1, 8.0	1.42
triple	argon	steel, thermally broken	suspended thin film	11.1, 8.0	1.19
triple	argon	steel, thermally broken	suspended thin film	8.0, 4.8	1.42
double	argon	steel, thermally broken	sputtered	19.8	1.42
double	argon	steel, thermally broken	sputtered	12.7	1.36
triple	air	steel	suspended thin film	11.1, 8.0	1.42

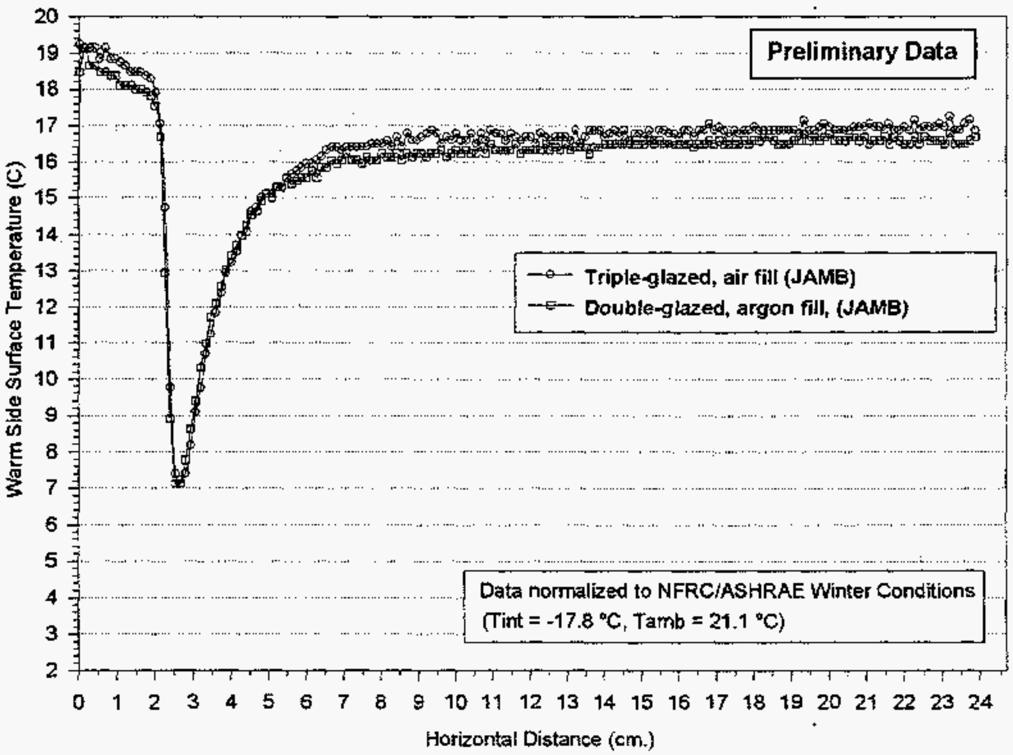


Figure 4 Jamb surface temperature profiles for a triple-glazed, air-filled unit and a double-glazed argon-filled unit. Both glazing units have the same overall width, insulating spacers, and identical center-of-glass U-values.

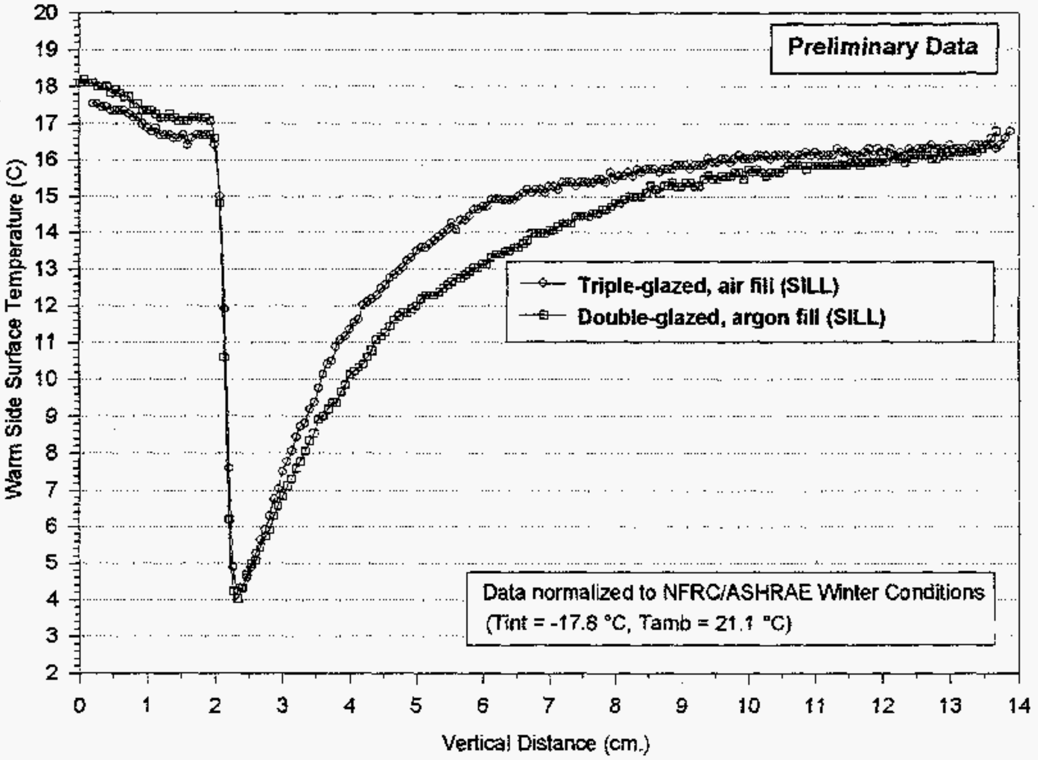


Figure 5 Sill surface temperature profiles for a triple-glazed, air-filled unit and a double-glazed argon-filled unit. Both glazing units have the same overall width, insulating spacers, and identical center-of-glass U-values.

Phase II Configurations: Phase II of the IR window surface temperature database will consist of three levels of complexity of window configurations, as shown in Table 3. It will include a number of window configurations in order to test the limits of the simulation programs under validation analysis. The simple windows will require the least assumptions to model, while the complex windows will require more assumptions and approximations in the modeling. While the single-glazed aluminum picture window may sound simple, its thermal resistance is due almost entirely to the warm-side film coefficient, and is thus very sensitive to the program's treatment of boundary conditions. Additional Phase II testing will include the effect of window aspect ratios for a range of true divided lites, the effects of interior suspended muntin bars, and the sensitivity to variations in heat transfer coefficients by using two different wind speeds on the cold side surface, see Table 4.

The first version of this window surface temperature database will be available to the public in late 1995 [8]. The database will include floppy disks or a CD-ROM with two-dimensional surface temperature maps and selected cross section temperature profiles in a spreadsheet database format; complete technical drawings of the windows tested with specification of all dimensions, materials, thermal conductivities used; and the environmental conditions of the tests along with associated measurement errors.

SUMMARY

- IR thermography is well suited for resolving small differences in the thermal performance of highly insulating window systems. Infrared thermographic measurements made in conjunction with reference emitter techniques in a controlled and characterized laboratory setting can have an absolute accuracy of ± 0.5°C.

Table 3: Proposed Phase II Test Configurations

difficulty	frame	operator type	glazing	gas fill	spacer	low-E coating	gap width (mm.)
Simple	wood	picture	double	air	aluminum	clear	12.7
Intermediate	TB aluminum	slider	double	argon	aluminum	low-E	12.7
	fiberglass or foam-filled vinyl	casement	double	argon	aluminum	low-E	12.7
Complex	aluminum	slider	single	n/a	n/a	clear	n/a
	clad wood	casement	double	krypton	insulating	low-E	19
	wood, sloped sill	double hung	double	air	aluminum	clear	6.35
	vinyl, reinforced, sloped sill	slider	triple	krypton	insulating	low-E	6.35, 6.35

Table 4: Additional Phase II Test Configurations

Aspect ratios of 10, 20, 30, 40, 60, and 80	a) double glazed, 12.7 mm. argon gap, low-E, true divided lites with aluminum spacers b) double glazed, 12.7 mm. argon gap, low-E, true divided lites with insulating spacers
Interior suspended muntin bar	double glazed, clear, air-filled, 3.18 mm-thick aluminum interior suspended muntin bars with gap widths of 6.35, 12.7, and 19.1 mm.
Variation of cold-side heat transfer coefficients	Multiple tests will be run, using two or more different cold-side wind speeds, on the CTS and selected glazings.

- Quantitative infrared thermography requires that a number of sources of error related to measurement accuracy and test environmental conditions be quantified and minimized to the extent possible.
- Laboratory-based infrared thermography can be used to generate window surface temperature profile databases which can be used to direct the development of 2-D and 3-D finite element and finite difference method fenestration heat transfer simulation codes, identify their strengths and weaknesses, set research priorities, and validate finished modeling tools. Development of such a database is under way at Lawrence Berkeley Laboratory, and will be made available for public use.

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