Overview of a Project to Determine the Surface Temperatures of Insulated Glazing Units: Thermographic Measurement and Two-Dimensional Simulation

Harry F. Sullivan, Ph.D., P.E.
Member ASHRAE

John L. Wright, Ph.D., P.E.
Member ASHRAE

Roydon A. Fraser, Ph.D., P.E.

ABSTRACT

A collaborative research project was undertaken to generate surface temperature profiles for the indoor side of seven different double- and triple-glazed insulated glazing units exposed to the ASHRAE winter design condition. Four research groups produced four sets of results in a blind study. Two sets were measured by means of thermography and two were generated using two-dimensional numerical simulation. In addition, each simulation group produced results using simplified methods. Companion papers each present results from the individual studies along with some observations and commentary. This paper, an overview, presents a compilation of results and provides the opportunity for a variety of comparisons. Good agreement was found among all four sets of data. Simplified simulation models also show promise. The reassurance offered by these accomplishments is important because both the measurement and simulation methods are in the early stages of development. In addition, details found in individual temperature profiles provide valuable insights regarding the mechanisms of window heat transfer.

INTRODUCTION

A collaborative research study related to determination of surface temperatures for a series of insulated glazing units (IGUs) has been completed. The research groups included two simulation laboratories and two thermographic measurement laboratories. Duplicate sets of glazing units were provided to the measurement laboratories and their construction details were given to the simulation laboratories. The contributions from these researchers have been described in detail in a set of companion papers (Griffith et al. 1996; Elmahdy 1996; Zhao et al. 1996; deAbreu et al. 1996) and the reader looking for more information about either the measurement techniques or the modeling details is referred to these papers. The purpose of this paper is to provide the overall viewpoint of this study.

The objective of the research was to perform a blind, quasi-round-robin series of surface temperature determinations to answer the following questions:

- Knowing that different laboratories were given almost identical units, how well do different laboratories compare in terms of measured absolute temperature profiles?
- Similarly, how well do different simulators and simulation programs compare in terms of predicted temperature profiles?
- Do simulations agree well with experimental measurements?

Both methods involved are at an early stage of development (in terms of the analysis of windows) and benefit from this cross-comparison. It should be noted that the comparison of local parameters is a much more stringent test than the more traditional approach in which global performance characteristics (e.g., U-factor) are compared. In addition, the details found in individual temperature profiles provide valuable insights regarding the mechanisms of window heat transfer.

PROCEDURE

A manufacturer of commercial edge-seal products assembled multiple sets of glazing units having the characteristics listed in Table 1. Two laboratories with the capability of making thermographic measurements were supplied with sample sets. One laboratory (Lab 1) has constructed an apparatus consisting of two environmental chambers; the cold chamber is a modified commercial food freezer and the warm chamber incorporates an adjustable bellows to permit the infrared (IR) thermography (Griffith et al. 1996). The second laboratory (Lab 2) uses a guarded hot box with its usual procedure modified to facilitate the IR camera (Elmahdy 1996). Each laboratory was required to

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Harry F. Sullivan is a professor, John L. Wright is an adjunct professor, and Roydon A. Fraser is an associate professor in the Department of Mechanical Engineering at the University of Waterloo, Waterloo, Ont., Canada.

TABLE 1 Description of Glazing Units

IGU#	Glass Description	Pane Spacing(s), d (air filled)	Spacer(s)
1	Clear double-glazed	12.7 mm (0.50 in.)	Foam
2	Clear double-glazed	12.7 mm (0.50 in.)	Aluminum
3	Clear double-glazed	6.4 mm (0.25 in.)	Foam
4	Clear double-glazed	19.1 mm (0.75 in.)	Foam
5	Low-e double-glazed	12.7 mm (0.50 in.)	Foam
6	Clear triple-glazed	12.7 mm (0.50 in.)	Foam
7	Clear triple-glazed	6.4 mm (0.25 in.)	Foam

report cold-side and warm-side heat transfer coefficients corresponding to each of the surface temperature profiles produced.

Details regarding the construction (e.g., pane spacing, edge-seal geometry and materials) of each glazing unit were provided to the two simulation laboratories. One simulation laboratory (SIMUL 1) used an in-house, two-dimensional, finite-volume simulation code (de Abreu et al. 1996). The second simulation laboratory (SIMUL 2) used an available finite-element code to complete two-dimensional simulations (Zhao et al. 1996). Both simulation groups also generated results using more simplified techniques, and samples of the results from these methods are presented in this overview paper.

Each group was required to obtain its data without knowledge of the results of the other groups. This paper fulfills the functions of gathering and comparing the four sets of data.

TEST AND SIMULATION CONDITIONS

The test laboratories were asked to impose test conditions similar to the ASHRAE winter design condition (i.e., 15-mph wind on the cold side and natural convection on the warm side). Since the actual laboratory warm- and cold-side heat transfer coefficients were not known a priori, the simulation laboratories used the conditions shown in Table 2. When the test results were available, it was found that Lab 1 reported an average indoor-side heat transfer coefficient of 7.6 W/m^2·°C (1.34 Btu/h·ft^2·°F) and an outdoor-side coefficient of 28.9 W/m^2·°C (5.1 Btu/h·ft^2·°F). The corresponding values from Lab 2 were 7.3 W/m^2·°C (1.29 Btu/h·ft^2·°F) and 30.0 W/m^2·°C (5.29 Btu/h·ft^2·°F). A sensitivity study dealing with changes in these heat transfer coefficients can be found in deAbreu et al. (1996). Note that the heat transfer coefficients (film coefficients) mentioned above account for both convective and radiative heat transfer.

TABLE 2 Glazing Unit Boundary Conditions

Indoor Temp.,T_i	Indoor Heat Transfer Coefficient, h_i	Outdoor Temp.,T_o	Outdoor Heat Transfer Coefficient, h_o
21.1°C	8.3 W/m^2·°C	–17.8 °C	30 W/m^2·°C
70 °F	1.46 Btu/h·ft^2·°F	0 °F	5.29 Btu/h·ft^2·°F

RESULTS

Figures 1 through 7 represent a compilation of the results for each of the seven IGUs, respectively. Each figure shows four vertical profiles of surface temperature—one from each of the research groups. In each figure, two curves represent simulation results and two curves represent measured data. The vertical axis corresponds to vertical distance, ranging from zero at the bottom edge of the IGU to 508 mm (20 in.) at the top of the IGU. The horizontal axis shows the temperature scale, which ranges from –6°C (21.2°F) to 16°C (60.8°F) except where results are shown for IGU 2 (the only unit with an aluminum spacer bar), where the scale is shifted down by 2°C (3.6°F).

It should be noted that the surface temperature curves are plotted without adjustment even though each one corresponds to a specific film coefficient, as discussed earlier. Differences caused by the differences in film coefficients are not large (estimated to be on the order of 1°C [1.8°F]). A discussion of film coefficients is presented in a later section.

In addition to the detailed two-dimensional modeling, each of the simulation laboratories generated results using simplified codes. SIMUL 1 used VISION4/FRAME 4.0 (Wright and Sullivan 1995; de Abreu et al. 1996) and SIMUL 2 used THERM-CR (Zhao et al. 1996). In the studies referenced above, comparisons are made between surface temperature profiles produced using both simplified and detailed models. To provide a comparison with measured data, Figures 8 and 9 are included as samples to show results of the simplified models for IGUs 1 and 2, respectively. IGU 1 is the reference glazing (clear, 12.7-mm [1/2-in.] foam spacer) and IGU 2 is a comparable unit with an aluminum spacer bar. Additional results and details can be found in de Abreu et al. (1996) and Zhao et al. (1996).

DISCUSSION

All of the data sets presented in Figures 1 through 7 show good agreement. It can be seen, even without adjustment, that each set of curves falls within a band typically no wider than 1°C (1.8°F). Exceptions occur in the vicinity of steep temperature gradients as seen near the top and bottom of the glazings where the observed temperature band can be as large as 3°C (5.4°F). However, these discrepancies are misleading, knowing that some spatial uncertainty exists regarding the location of measured profiles—a topic that is discussed in more detail in a subsequent section.

Although the sample sets include units with a wide variety of parameter variations (e.g., pane spacing, edge-seal type) all of the surface temperature profiles have a common characteristic shape. Differences in detail can be seen from one curve to the next, depending primarily upon differences in the mechanisms of conductive and convective heat transfer.

In all seven IGUs the thermal resistance of the edge-seal is less than the corresponding resistance of the center-glass area. This thermal bridge causes higher heat flux and colder warm-side surface temperatures5 at the perimeter of the IGU. Each curve shows a local minimum at or near the top and bottom of the glazing.
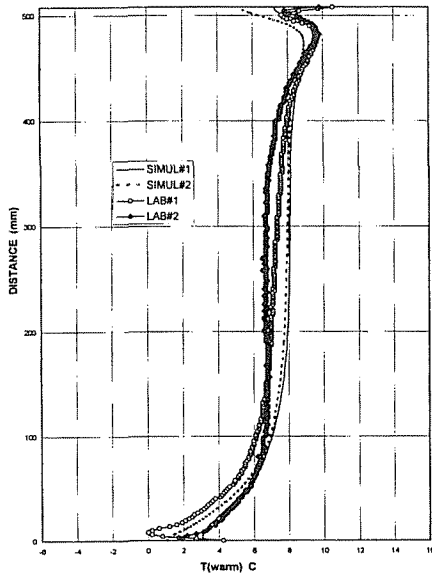
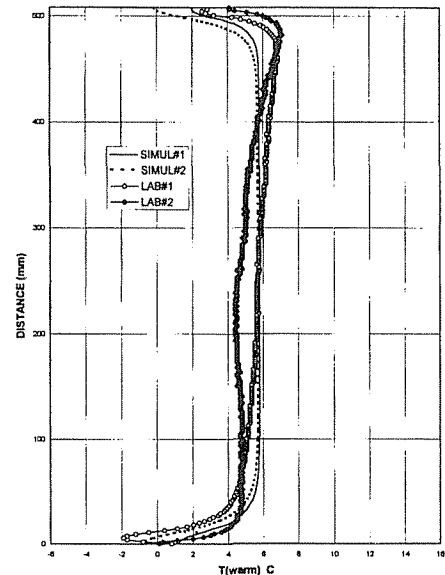**Figure 1** *Temperature profiles, IGU 1, clear double 12.7 mm foam spacer.*

Figure 3 *Temperature profiles, IGU 3, clear double 6.4 mm foam spacer.*
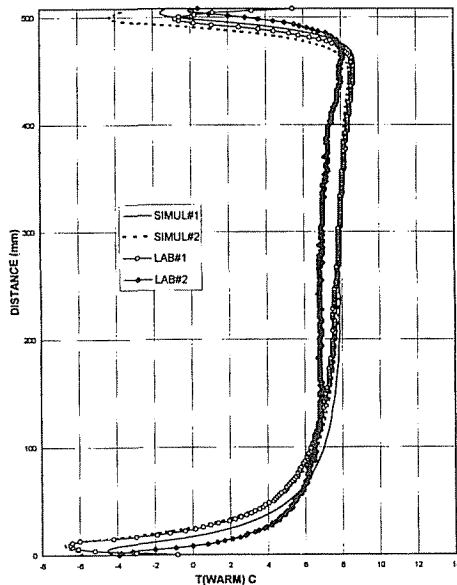

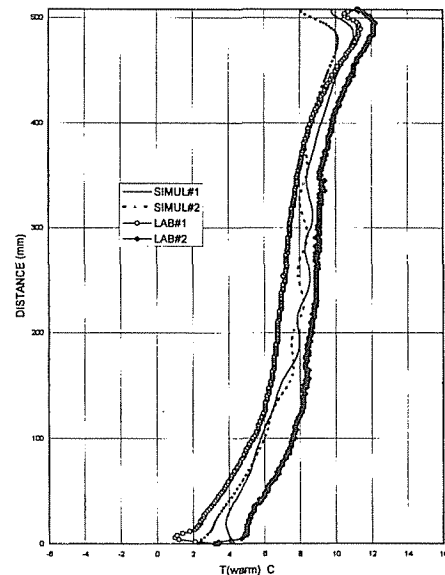**Figure 2** *Temperature profiles, IGU 2, clear double 12.7 mm aluminum spacer.*

Figure 4 *Temperature profiles, IGU 4, clear double 19.1 mm foam spacer.*

In the absence of convection each, temperature profile would exhibit a top-to-bottom symmetry. Fill-gas motion has the effect of skewing the temperature profiles. Fill gas flows upward near the warm glazing and downward near the cold glazing. The descending gas becomes progressively colder. At the bottom of the cavity, this cold fill gas turns and flows close to the bottom of the warm glazing, where it starts its ascent. Thus, the bottom edge of the warm glass is cooled by the coldest fill gas. A similar situation occurs at the top of the cavity, where the fill gas heats the top of the cold glazing.

The effect of edge-seal conduction is seen at both the top and bottom. Fill-gas motion provides additional cooling at the bottom edge and reduced cooling at the upper edge. Therefore, the combined effect of the edge-seal conduction and the fill-gas convection consistently places the coldest temperature near the bottom edge. For this reason, condensation resistance studies focus on this region of the window.

If one focuses on the center-glass portion of the profiles, a change in slope can be seen as a function of pane spacing. This characteristic is a result of the different aspect ratios of the glazing cavities. Glazing systems with narrow pane spacings (IGUs
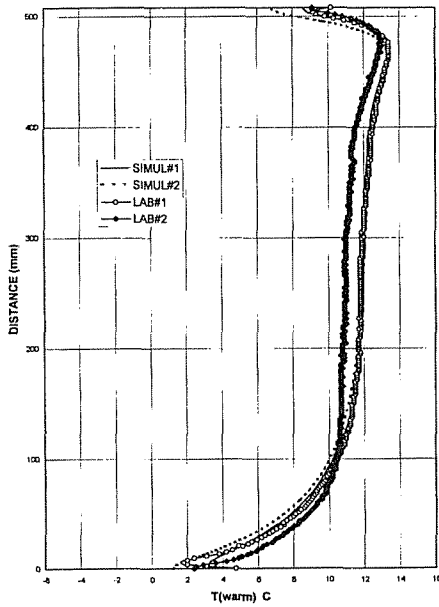
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Figure 5 *Temperature profiles, IGU 5, low-e double 12.7 mm foam spacer.*

3 and 7) have the flattest temperature profiles through the center-glass area and the narrowest region where edge-glass effects can be seen. Wider pane spacings are accompanied by a more pronounced slope in the center-glass temperature profile and edge effects that extend farther from the sightline.

In addition, at the widest pane spacing (IGU 4) the simulations show evidence of secondary cells in the fill-gas flow, resulting in ripples on the surface temperature profile. The laboratory data do not show these ripples. This discrepancy is likely caused by the fact that the Rayleigh number of the cavity (Ra ≈ 22,000) is high enough (i.e., pane spacing and temperature difference are

high enough) not only to exceed the critical value of Ra for secondary cells to form (Ra$_c$ ≈ 6,850) but also for a time-unsteady fill-gas flow to exist (Wright and Sullivan 1989, 1994). Consequently, the local effect of individual cells would not be apparent in the glass temperature as the cell locations constantly change. In contrast, the numerical calculation generates a steady solution with stationary cells, and their effect is then seen in the temperature of the glass.

Film Coefficients

Both simulation laboratories completed their calculations using a cold-side (outdoor-side) film coefficient of $h_o = 30$ W/m^2·°C (5.29 Btu/h·ft^2·°F). The same figure was reported by Lab 2, while Lab 1 reported $h_o = 28.9$ W/m^2·°C (5.1 Btu/h·ft^2·°F). De Abreu et al. (1996) show that changing h_o from 20 to 40 W/m^2·°C (3.53 to 7.05 Btu/h·ft^2·°F) will decrease the warm-side surface temperature by only about 1°C (1.8°F). Therefore, no alteration of the surface temperature profiles was made to account for the small differences in h_o.

A warm-side (indoor-side) film coefficient of $h_i = 8.3$ W/m^2·°C (1.46 Btu/h·ft^2·°F) was used for all simulations. Lab 1 reported $h_i = 7.6$ W/m^2·°C (1.34 Btu/h·ft^2·°F) and Lab 2 reported $h_i = 7.3$ W/m^2·°C (1.29 Btu/h·ft^2·°F). Sensitivity calculations presented by de Abreu et al. (1996) show that changing h_i from 7.0 to 8.0 W/m^2·°C (1.23 to 1.41 Btu/h·ft^2·°F) will increase the warm-side surface temperature of IGU 1 (clear, double-glazed) by about 1.1°C (2°F). The surface temperature of a unit with higher thermal resistance (say, double-glazed with low-e or triple-glazed) would be less sensitive to h_i. These figures indicate that adjustments might have been made to account for differences in h_i but these adjustments would have been of the same order of magnitude as the uncertainty in the measured laboratory
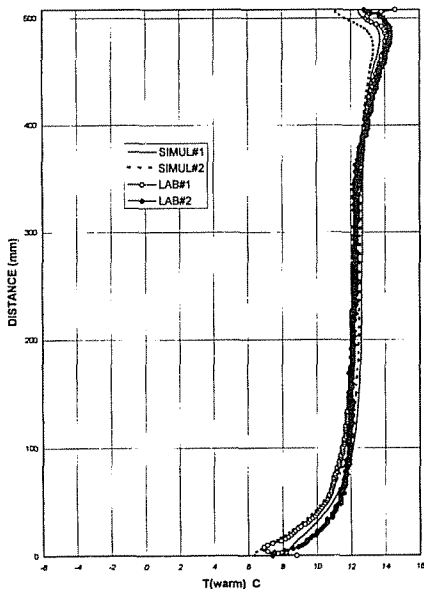

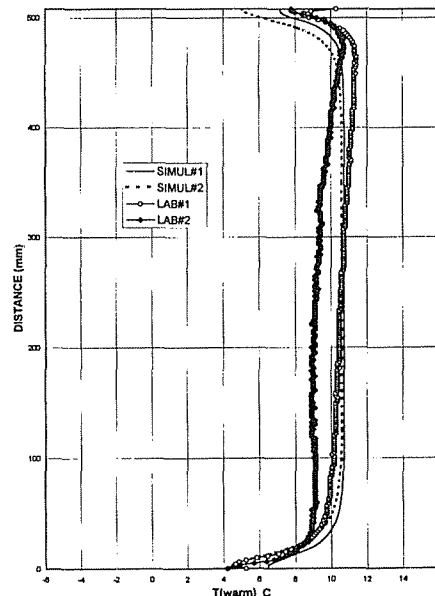**Figure 6** *Temperature profiles, IGU 6, clear triple 12.7 mm foam spacer.*

Figure 7 *Temperature profiles, IGU 7, clear triple 6.4 mm foam spacer.*
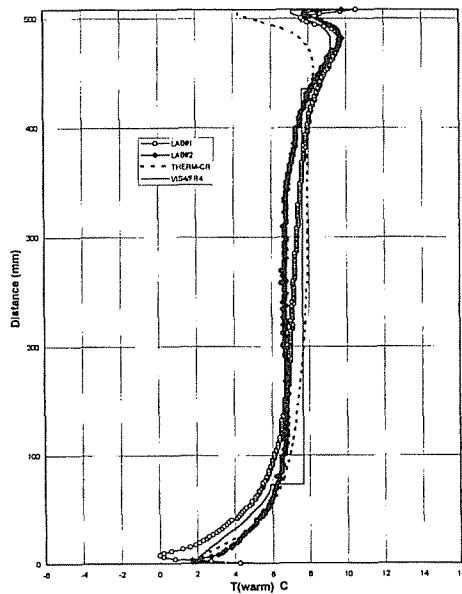
Figure 8 *Simplified models vs. measured temperature profiles, IGU 1.*
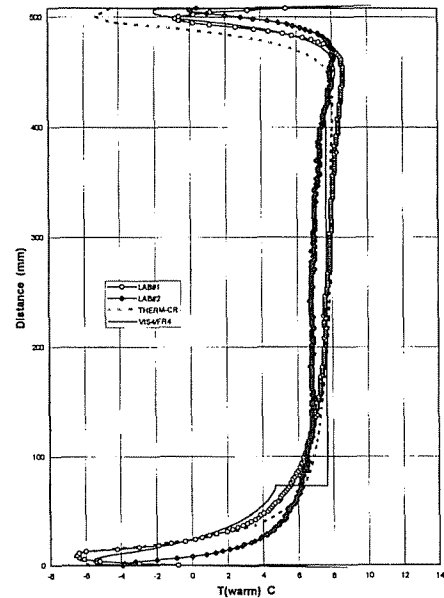

Figure 9 *Simplified models vs. measured temperature profiles, IGU 2.*

data, so no alterations of the reported surface temperature profiles were made.

It is important to recognize that simulations were performed using a uniform warm-side film coefficient. In other words, a constant value of h_i was applied at each location over the surface of the IGU. In contrast, h_i is not expected to have been constant over the height of the glazing units that were tested. Indoor air moves downward over the face of the IGU and mask wall, forming thermal and velocity boundary layers. As a result, the local value of h_i is expected to be higher near the top of the IGU, decreasing as it moves downward. This trend in h_i would in itself have caused warmer surface temperatures near the top of the IGU. Since the fill-gas motion causes a similar trend, it is difficult to distinguish between the two effects. However, some portion of the difference between simulation and measurement can be explained by the modeling assumption of constant h_i. It should be pointed out that the mounting configuration selected for this study (i.e., IGU mounted flush with mask wall on the warm side) was intended to minimize local variations in h_i. The more usual situation of an IGU recessed in a sash and frame is known to have local pockets of flow recirculation/stagnation in the corners where detailed information is of interest but also where h_i is expected to be at a minimum. It will be important to extend this study to examine more realistic geometries.

Spatial Uncertainty

Both sets of thermography data have an uncertainty in locating the edges of the IGU. Lab 1 expresses the uncertainty as 3.7 mm in the y-axis of their temperature profiles. Lab 2 has also commented on this difficulty. In preparing the composite plots, the data supplied by Lab 2 were handled in the following way. The minimum values in the temperature profiles for the bottom and top temperature profile segments were fixed at zero and 508

mm (20 in.), respectively, corresponding to the bottom and top edges of the glazing unit. It was then relatively easy to splice the center temperature profile segment between the other fixed segments. It was felt that this procedure, although somewhat arbitrary, gave the greatest confidence in the uncertainty regarding the vertical spatial dimension. Note, however, that this procedure precludes significant observations regarding the degree of agreement between simulation and measurement precisely where the greatest interest lies.

Bottom Edge

The bottom edge of each IGU, where the minimum temperature is located, is the area of greatest interest because of concerns regarding both condensation resistance and thermal stresses.

Preceding sections have shown that difficulties can arise when comparing surface temperatures near the edges of an IGU because of local variation in h_i and spatial uncertainty. In addition, the measured temperatures have an uncertainty of approximately 0.5°C (0.9°F). All of these effects are present in the most critical region—at or near the bottom edge. These and other effects are discussed in the following paragraphs. In addition, it was discovered that the two simulation laboratories had used slightly different geometries to represent edge-seals. The dimensions used for the foam spacer were identical, but a small difference in total seal height (i.e., spacer plus sealant) was used. The difference was 1.59 mm (1/16-in.) less sealant used in the model of SIMUL 1. This difference at least partially explains the lower minimum surface temperatures consistently reported by SIMUL 2 relative to the results of SIMUL 1.

Another possible source of significant difference between laboratories is the mask wall thickness. Both simulation laboratories and Lab 2 used a mask wall thickness of 101.6 mm (4 in.).

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Because Lab 1 uses a parallel wind direction in the cold-side chamber, they chose to attempt to more closely match the mask wall thickness to the thickness of the glazing unit. One of the curves presented in Griffith et al. (1996) shows temperature profiles of IGU 1 tested with two different mask wall thicknesses. A difference in minimum temperature of about 2°C (3.6°F) was apparent. To check on the significance of the mask wall thickness, a sensitivity study using the VISION4/FRAME 4.0 software package (described by de Abreu et al. [1996]) was used to model the sill and head sections of IGU 1 (the reference unit) and IGU 2 (the unit with the lowest minimum temperature) with four different mask wall thicknesses. The results for the sill are listed in Table 3 and show that the mask wall thickness can account for up to 0.5°C (0.9°F). Similar results were found for the head section.

TABLE 3 Minimum Glazing Surface Temperature vs. Mask Wall Thickness

Mask Wall Thickness		IGU 1		IGU 2	
mm	in.	°C	°F	°C	°F
18.7*	0.74	1.6	34.9	-6.0	21.2
25.4	1	1.8	35.2	-5.7	21.7
50.8	2	2.0	35.6	-5.6	21.9
101.6	4	2.1	35.8	-5.5	22.1

* Equal to thickness of glazing unit

Despite all of the concerns expressed above, the minimum bottom edge surface temperatures observed in each comparison fall within a range of ±1.5°C (2.7°F).

Edge-Glass Demarcation

The current ASHRAE procedure for calculating window U-factors specifies the edge-glass width as 63.5 mm (2.5 in.). Recent research has led to the suggestion that this figure be increased to 100 mm (3.94 in.). Surface temperature profiles for a variety of glazing system designs can be used to demonstrate that neither of these edge-glass widths can be justified on a universal basis. For example, Figures 4 and 5 (IGUs 4 and 5) show that the edge-glass demarcation might be placed somewhere beyond 125 mm (4.9 in.). However, it is generally accepted that the 63.5-mm (2.5-in.) edge-glass width works well for the purpose of calculating total window U-factors (CSA 1993; NFRC 1991). Nonetheless, the edge-glass width could be increased not only because U-factor calculations would benefit from the increased modeling detail, even though the improvement is likely to be marginal, but also (and more likely) for the purpose of harmonization with European procedures.

CONCLUSIONS

The three main goals set out for this project have been met. IGU surface temperature profiles can be generated either through two-dimensional computer simulation or through thermographic measurement, and good agreement has been demon-

strated between simulation results, between measured results, and between simulation and measured results. Simplified simulation models also show promise. These accomplishments represent a significant step forward in our ability to examine and quantify local details regarding the thermal performance of windows. This exercise also offers increased confidence in the ability of thermography to provide absolute temperature measurement as well as more confidence in the use of simulation to better understand the mechanisms of heat transfer at play within the body of the window itself.

ACKNOWLEDGMENTS

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QUESTIONS AND COMMENTS

Roger Henry, Program Manager, CANMET, Ottawa, Ont., Canada: There was extremely good agreement among all results—the greatest variation was probably with one lab's measurement at 3/4-in. gap. Would more work be useful to look at this, as well as different low-e products and different gas fills?

Harry F. Sullivan: I agree with your observation. This was a "blind study." No attempts have yet been made to reconcile any differences but I believe it should be done.

In terms of further work, it would probably be more useful to extend the sample set by putting the insulated glazing units into sashes and frames to determine the effect of these components. In particular, the fact that the glazing surface would no longer be flush with the mask wall would affect the local film coefficient and hence the local temperature.