Simulation and Testing of Curtain Wall/ Sloped Glazing Systems

Alexander G. McGowan, P.Eng.
Member ASHRAE

André O. Desjarlais

ABSTRACT

U-factor losses in commercial fenestration can have a significant effect on building loads, yet there is little information on the performance of these products. With this in mind, ASHRAE TC 4.5, Fenestration, sponsored a research project involving test and computational analysis of commercial fenestration systems. The objectives of the project were to evaluate the thermal performance (U-factors) of commonly used commercial glazed roof and wall assemblies; to obtain a better fundamental understanding of the heat transfer processes that occur in these specialty fenestration products; to develop general correlations for laminar natural convection flow in complex glazing cavities; to develop a methodology for evaluating complex fenestration products, suitable for inclusion in ASHRAE proposed standard 142P; and to generate U-factors for common commercial fenestration products, suitable for inclusion in the ASHRAE Handbook —Fundamentals.

This paper describes actual and computer-simulated hot box testing of a curtain wall/sloped glazing specimen for various conditions and slopes and provides guidelines for modeling commercial glazed wall systems based on the validated results.

INTRODUCTION

ASHRAE Research Project 877, sponsored by TC 4.5, Fenestration, was designed to address the lack of understanding surrounding commercial fenestration systems. The project entailed hot box and computer-simulated hot box testing of several commercial fenestration products (a barrel-vault skylight, a pyramidal skylight, and a curtain wall/sloped glazing specimen) under several different conditions. Assuming that comparison of test and simulation validated the computer model, the simulation procedure was then used to generate component and total-product U-factors to extend the design data in the fenestration chapter of the *ASHRAE Handbook—Fundamentals* (1997). The project and its findings are described in detail in the final report (EE 1998) from which the information in this paper is taken.

The portion of the research project related to glazed walls entailed the successful completion of four main activities:

- two-dimensional simulation of a glazed-wall specimen,
- physical testing of the same system under winter and summer conditions at various slopes,
- synthesis of simulated and test results to develop an improved procedure for calculating U-factors of curtain walls and sloped glazing systems, and
- development of a set of representative U-factors for specialty fenestration products to improve and expand the table of U-factors in the fenestration chapter of *Fundamentals* to cover a wider range of commercial wall and roof glazing systems.

This paper describes the first three of these activities, comprising the testing and simulation of the U-factors of a curtain wall/sloped glazing specimen (Figure 1) at several slopes for summer (heat flow down) and winter (heat flow up) conditions. The portion of the project that dealt with the skylight specimens is addressed in another paper (McGowan et al. 1998), and the development of representative U-factors for *Fundamentals* was presented at an ASHRAE meeting (McCabe 1998).

DESCRIPTION OF TEST SPECIMEN

Simulation and guarded hot box tests were performed on a specimen comprising a thermally broken frame, with extruded aluminum framing separated by a 6 mm (0.24 in.)

Alex McGowan is vice-president of Enermodal Engineering Limited in Kitchener, Ontario, Canada. **André Desjarlais** is a staff engineer at Oak Ridge National Laboratory, Oak Ridge, Tenn.

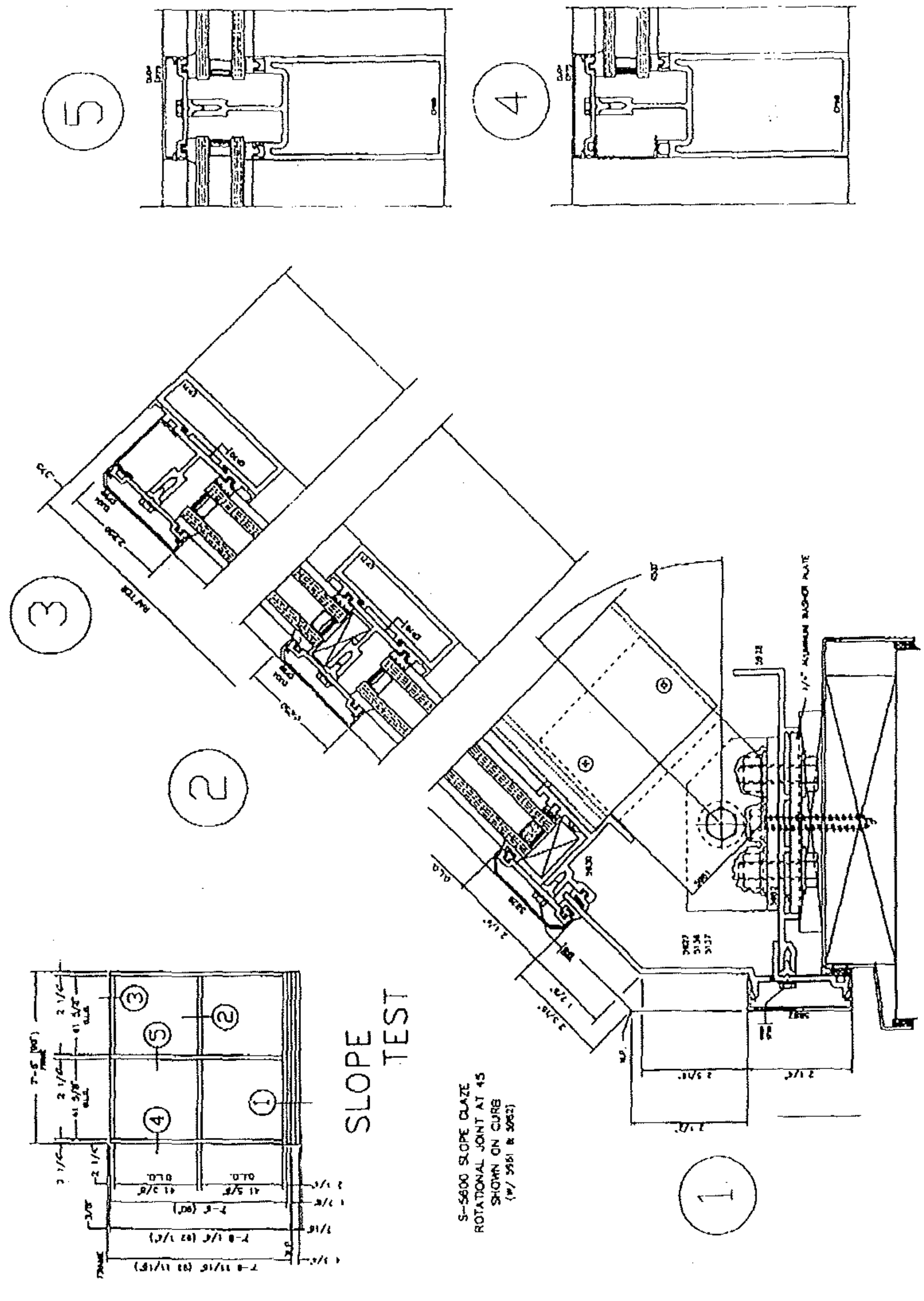

Figure 1 Section and elevation of the curtain wall specimen.

thermal break. The thermal break was a continuous vinyl strip gasket bridged with stainless steel bolts spaced at 229 mm (9 in.) on center. The specimen was glazed with a 25 mm (1 in.) insulated glazing unit composed of two 6 mm (1/4 in.) clear glass layers separated by a 13 mm (1/2 in.) air space and a conventional dual-seal aluminum spacer assembly. The overall specimen was 2286 mm (90 in.) wide and 2343 mm (92 1/4 in.) high.

The base of the specimen was constructed with a pivoting joint to allow installation at various slope angles, although the pivot joint was fixed at a 45° angle and the specimen was set into a wood frame made of two layers of nominal 38 mm × 241 mm (2 in. × 10 in.) pine. Except for the pivot joint, this framing system in the vertical orientation is typical of curtain wall assemblies used in commercial buildings. Assuming validation of the simulation against the test results for this specimen, it would then be a simple matter to extend the results to typical curtain wall systems by removing the pivoted sill and using the head section in place of the sill for the computer model (see Figure 1).

This specimen was tested at several different slopes (achieved by rotating the specimen and wood frame together) and for several different test conditions.

COMPUTER SIMULATION OF THE SPECIMEN

The glazing system of this specimen was simulated using a one-dimensional calculation program (UW 1996) that conforms to proposed ASHRAE standard 142P (1996). The framing systems and the edge-glass portion of the glazing for each component of the specimen (e.g., head, mullion, sill) were modeled using a two-dimensional finite-volume heat transfer program (EE 1996a). Simulations are performed by drawing a cross section of the specimen or assembly to be analyzed (using a simple CAD interface), applying the as-tested boundary conditions to the structure, and refining the finite-volume grid as required to provide increased accuracy in areas of interest. The program uses a finite-volume conduction model to determine temperature distribution and heat transfer within the structure and thermal transmittance/resistance through areas of interest. Convection and radiation within the specimen are included by increasing the effective thermal conductivity of the components involved. This model has been shown to be quite accurate in simulating a hot box test of complex fenestration systems, such as pyramid and barrel-vault skylights (McGowan et al.1998), curtain-wall and flat-glazed skylight systems (Carpenter and Elmahdy 1994), and residential window systems. In fact, it forms the basis for evaluating frame and edge-glass heat transfer in window rating systems in North America (CSA 1998; NFRC 1997).

Internal details of all components were taken from engineering drawings supplied by the manufacturers (which appear in Figures 1 through 6). All models included 63.5 mm (2 1/2 in.) of the glazing system to ensure that heat transfer in the center-glass region of the product was not affected by thermal bridging in the frame and spacer assembly. The thermal conductivities given to the components were those recommended in ASHRAE 142P. Typical framing cross sections and their models are shown in Figures 2 through 6. These figures are given to show similarity between the model and the actual

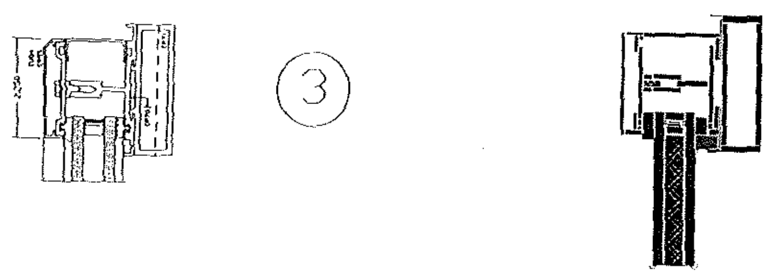

Figure 2 Detail and FRAME model of the curtain wall head section.

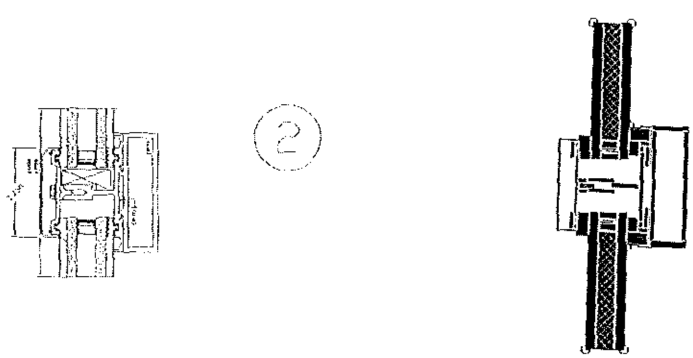

Figure 3 Detail and FRAME model of the curtain wall horizontal mullion.

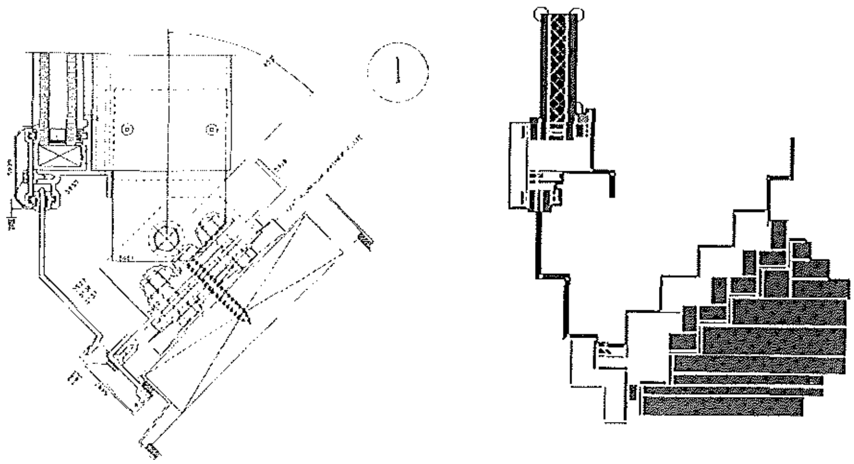

Figure 4 *Detail and FRAME model of the curtain wall sill section.*

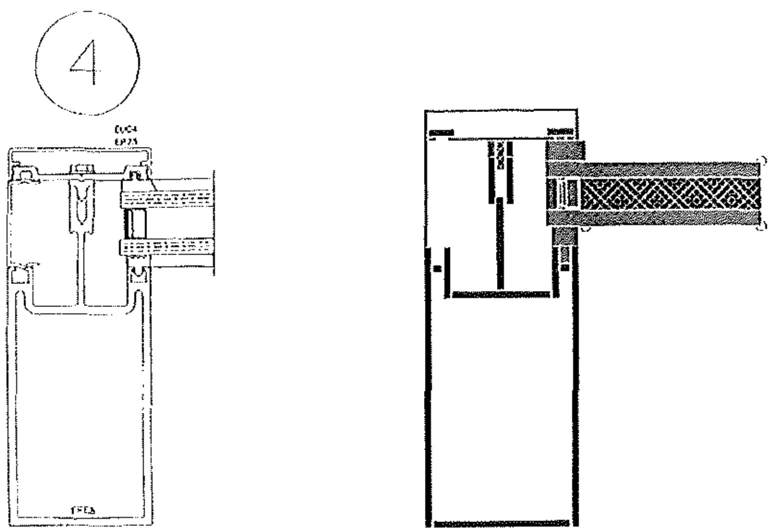

Figure 5 *Detail and FRAME model of the curtain wall jamb section.*

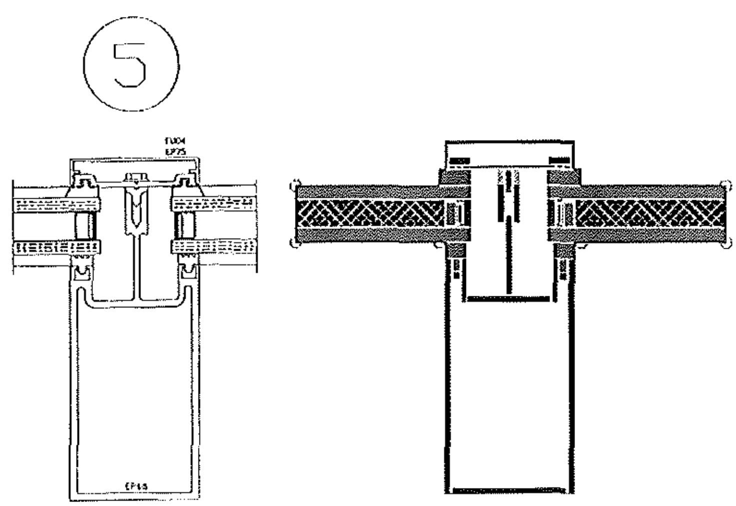

Figure 6 *Detail and FRAME model of the curtain wall vertical mullion.*

cross sections provided by the manufacturer; for detailed dimensional drawings, the reader should refer to the 877-RP final report (EE 1998). The large circled numbers in Figures 2 through 6 refer to the section numbers in Figure 1. The computer model chosen for this analysis represents all cross sections as a series of rectangular elements in a finite-volume mesh; as the figures show, this approach produces a very good representation of the actual specimen cross sections, except in the case of the sloped sill section in Figure 4. The oblique surfaces in the sill section were represented by a series of stepped rectangles, with corresponding adjustments in the local film coefficient (also called the *surface heat transfer coefficient*) to account for the increased surface area.

In general, however, the differences between the manufacturer's drawings and the computer models were of little consequence when compared with the differences between the manufacturer's drawings and the actual specimen. A great deal of time was involved in resolving initial differences between test and simulation results; these were found to be due to differences between the specimen as it was shown in the drawings (from which the original models were developed) and as it really was. These differences were resolved via detailed measurement of the specimen and corresponding adjustments in the computer model. Some of the more important areas that required accurate description of the model included:

- the width of the thermal break (shown as 3 mm or 1/8 in. in the drawings, it was actually 1/10 in. or 2.5 mm, a difference of 25% in the main resistance to heat transfer in the specimen);
- the actual overall dimensions of the specimen, which affect, among other things, the split between glass and framing components of the specimen; and
- the way in which the specimen was mounted into the hot box apparatus

It has been shown (Carpenter and McGowan 1998) that the presence of bolts bridging the thermal break has a significant effect on the thermal performance of the specimen. In this case, the bolts were modeled by assigning an effective conductivity to the region of the model representing the bolt. This can be considered a rectangular solid (extending into the third dimension of the two-dimensional model) comprising steel bolts every 229 mm (9 in.) and the thermal break material between the bolts, as described elsewhere (McGowan et al. 1998).

As-tested boundary conditions (average air temperatures and film coefficient values) were also used in the simulations, so that the comparison of simulation results to test is done for the same conditions. The film coefficients along parts of the sill section were reduced to account for the fact that there is no radiant heat transfer between the specimen and the warm side of the test chamber in this region (see Figure 4).

Total-product U-factors of the specimen were determined by area weighting the component U-factors from the simulation results for the glazing and for the five frame models (one each for the head, sill, jambs, and vertical and horizontal mullions). It is interesting to note that, although the specimen has approximately 21% framing by area, the simulation suggests that the framing UA is 51% of the total (i.e., over half of the heat loss occurs through the frame).

PHYSICAL TESTING

The specimen was tested in a rotatable guarded hot box apparatus (EE 1998) to provide accurate experimental results to compare against numerical analyses. Six tests were performed on this specimen:

C.1—0° slope (horizontal), winter conditions (21°C and −18°C, 6.7 m/s exterior wind) (70°F and 0°F, 15 mph exterior wind)

C.2—same as C.1, but 20° from horizontal

C.3—same as C.1, but 90° from horizontal (i.e., vertical)

C.4—same as C.1, but 45° from horizontal, C.5—same as C.4, but with minimal exterior wind

C.6—same as C.4, but with summer conditions (24°C and 35°C [75°F and 95°F]) and minimal exterior wind

The tests provided data for use in characterizing glazed wall and roof areas, including roof sections at various slopes and test conditions. The specimen was tested in accordance with ASTM Standard C1199 (ASTM 1991); thermocouples were installed at key points on the interior and exterior surfaces and critical internal locations of the specimens to allow calculation of component U-factors. Preliminary computer models of each specimen were used to provide guidance for installation of additional thermocouples wherever the simulation indicated significant temperature gradients (due to thermal bridging). Some additional thermocouples were used to characterize the temperature profile of the air around the specimens. The instrumentation of all specimens used in the research project is more completely described in the 877-RP final report (EE 1998).

COMPARISON OF TEST AND SIMULATION

The test and simulation results for all conditions and configurations are shown in Table 1. Based on previous calibration results for a homogeneous wall assembly (EE 1996b), the bias of the apparatus for these results is estimated to be on the order of 4% to 6%. Simulated U-factors are shown for the specimen without and with bolts.

Table 1 generally shows excellent agreement between test and simulation. Test results show a larger difference between summer and winter U-factors than simulation predicts, probably because of temperature stratification in the room-side air during the summer test rather than changes in the behavior of the specimen itself. This stratification would likely reduce conductive/convective gains near the top of the fenestration, as indicated by the lower U-factors for the specimen under summer (cooling) conditions.

TABLE 1
Test and Simulation Results for Curtain Wall/Sloped Glazing Specimen

Specimen and conditions	Test U-factor W/m²·°C (Btu/h·ft²·°F)	Simulated U-factor, W/m2-EC (BTU/h-ft2-EF)		
		No Bolts	With Bolts[1]	With Bolts % diff. to test
Winter (vertical)	3.74 (0.66)	3.78 (0.67)	3.86 (0.68)	2.4
Winter (horizontal)	4.07 (0.72)	4.21 (0.74)	4.29 (0.76)	4.3
Winter (20° from horizontal)	3.88 (0.68)	4.07 (0.72)	4.15 (0.73)	5.8
Winter (45° from horizontal)	3.98 (0.70)	4.11 (0.72)	4.20 (0.74)	4.4
Winter (45°, no wind)	3.56 (0.63)	3.60 (0.63)	3.67 (0.65)	2.1
Summer (vertical)	3.05 (0.54)	3.29 (0.58)	3.35 (0.59)	8.5
Summer (45° from horizontal)	3.04 (0.54)	3.23 (0.57)	3.28 (0.58)	6.9

[1] Effect of bolts minimized by thermal bridging in this specimen only, not typical of curtain walls in general.

In this case, the effect of bolts has little effect on the simulation result—the difference between the simulations with and without bolts is on the order of 2%. This is likely due to high heat loss in other parts of the specimen (especially in the sill, where a single aluminum plate separates the room side from the climate side, see Figure 4), which reduces the effect of the bolts on the total-product U-factor.

Another aspect of thermal performance (and a measure of the accuracy of the model) is the room-side temperature profile shown in Figure 7. The figure shows an accurate prediction of glass surface temperatures near the sill sightline (at y ~100 mm or 4 in.) but not near the top of the product (y ~ 2200 mm or 86.5 in.). The variation in surface temperatures near the top sightline has been noted previously (McGowan 1995) and was found to be due to local variation in the film coefficient near the top of the specimen, where convective flow is poorly developed. Also, although the model accurately predicts frame surface temperatures at the midpoint of the window (y ~ 1250 mm or 49 in.), it overpredicts frame temperatures at the top and (especially) at the bottom of the specimen. Prior to testing, it had been hypothesized that increased heat loss due to stack effect in the vertical framing members (see Figures 4 and 5) might occur in this product, so the test specimen was instrumented to assess this effect. Thermocouples were attached to the room-side surface of the vertical mullion at one-fourth, one-half, and three-fourths of its height, and additional thermocouples were suspended in the middle of the framing channel of the vertical mullion at the same heights to measure air temperature inside the vertical channel.

Figure 8 shows the temperature profile of the air in the vertical framing member (rafter) of the specimen. There is a 6°C (11°F) temperature gradient over 1100 mm (40 in.), which suggests that the stack effect also occurs in the curtain wall system. The surface temperatures suggest, however, that this effect is masked by the high conductivity of the aluminum framing. Thus, it appears that the large vertical framing members in these commercial products create convective flow, which tends to increase heat loss. Although the computer model does not show this temperature gradient, it does predict surface temperatures to within 4°C (7°F)—more accurate results could be obtained by modeling local variation in the room-side film coefficient. The model appears to capture the effect on overall heat transfer (see Table 1), so the model can be used in further investigation of curtain wall and sloped glazing systems. It is probable that convection in the vertical framing members contributes little to overall heat transfer, as the vertical mullions and jambs do not incorporate the thermal break (so that convection within these components does not bridge the thermal break).

VARIATION OF RESULTS WITH SLOPE

Table 1 also shows the effect of slope on the thermal performance of the specimen. The overall product U-factor ranges from 3.74 W/m^2·°C (0.66 Btu/h·ft^2·°F) for the vertical case to 4.07 W/m^2·°C (0.72 Btu/h·ft^2·°F) for the horizontal case. The temperatures inside the rafters indicate that convection within the vertical framing members is reduced, and even eliminated, as the slope approaches zero (as would be expected, due to reduction in natural convection). The increased heat transfer as the slope decreases is due to the increased room-side film coefficient, which, in turn, arises from air temperature stratification in the enclosed cavity formed by the framing members. In general, heat transfer increases in sloped (or overhead) glazed products, as these (metal) framing systems are placed in an area that sees a large temperature difference between the exterior air and the warmer air due to stratification within the conditioned space. Part of the increase in heat transfer is due to the increased temperature difference, but the change in product slope also produces changes in the room-side convective coefficient and changes in the convective flow inside the glazing cavity. Both of these changes would tend to increase heat loss through the

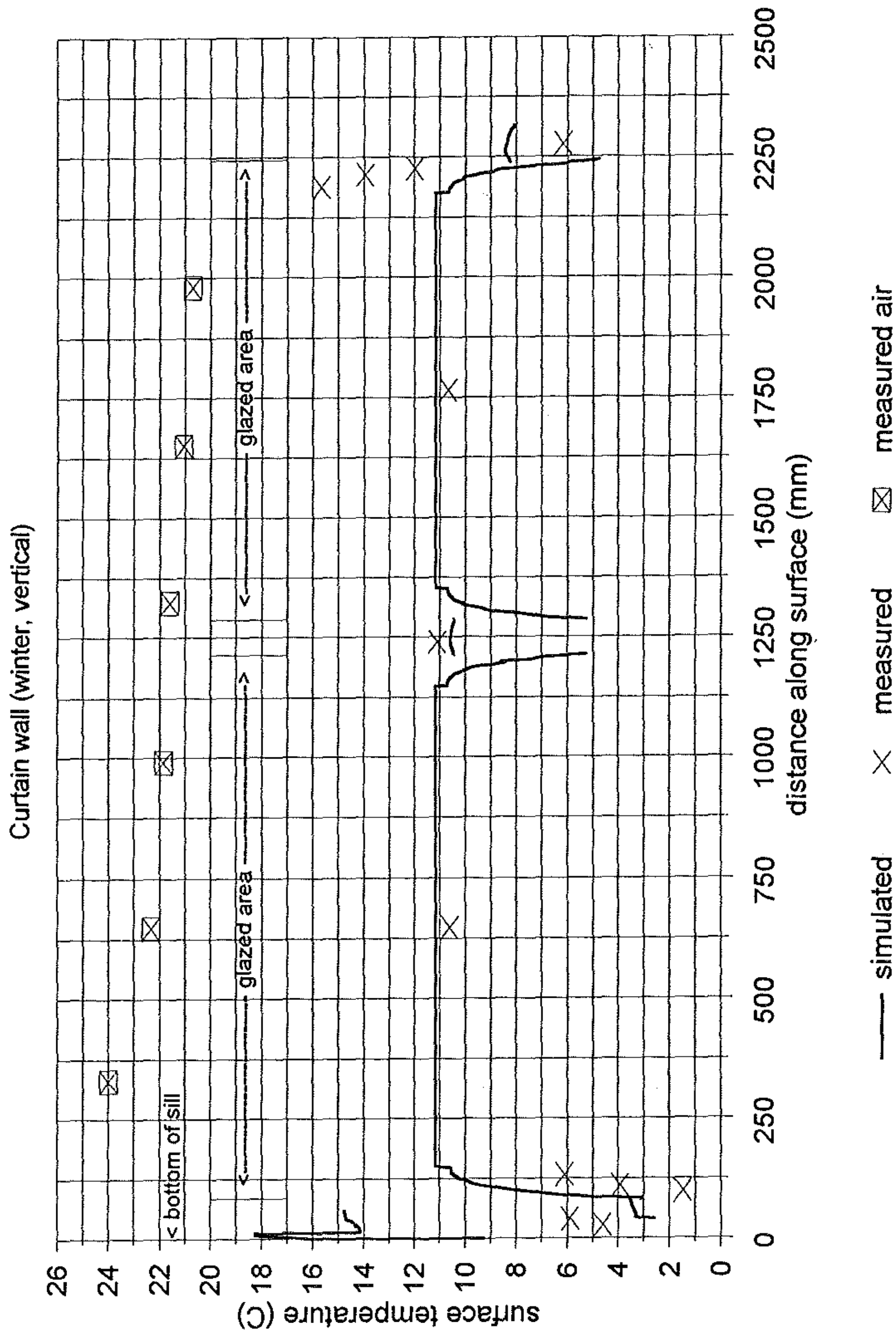

Figure 7 *Interior surface temperature.*

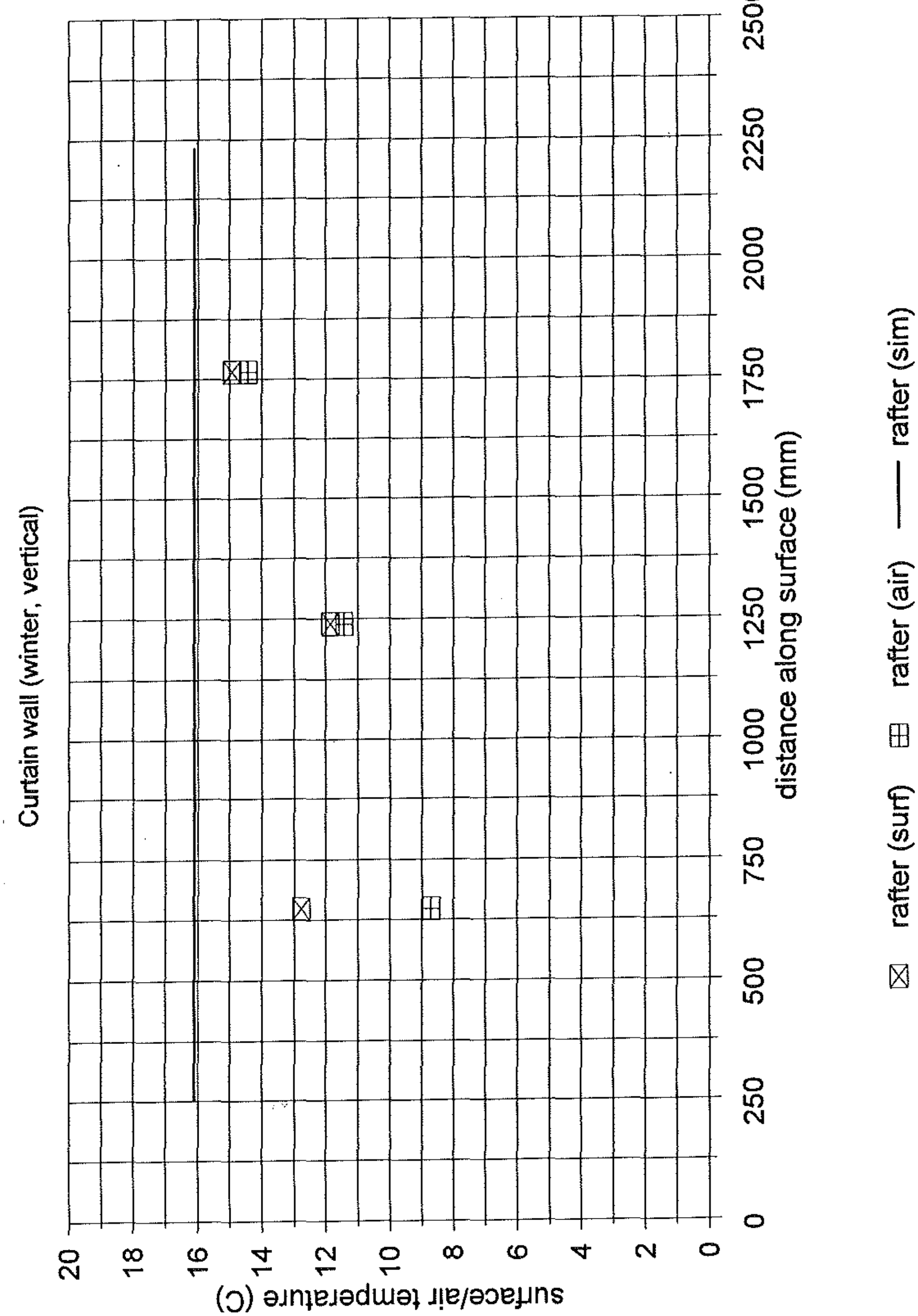

Figure 8 *Rafter temperatures.*

product (in addition to the effects of the larger temperature difference). In general, however, curtain walls use much deeper horizontal mullions than do the sloped glazing systems, so that the overall frame U-factors of curtain walls are higher than sloped glazings. Therefore, U-factors of curtain wall systems should be used with caution to characterize the thermal performance of overhead glazing systems.

EXTENSION TO OTHER DESIGNS

Table 1 shows very good agreement between test and simulation for the total-product U-factor. Given that the computer model of the glazing system has been shown to be quite accurate (e.g., see Sullivan et al. 1996), it is reasonable to infer that the model for the framing system is also accurate. Thus, the validation of the computer model allows the scope of the analysis to be expanded to predict the performance of overhead glazing systems and curtain walls with other framing and glazing systems. Frame designs were chosen to be representative of typical products, so that the frame U-factors for a given product are then only dependent on type of framing material, product type, and spacer and overall thickness of glazing system. The information that is then required to determine a total-product U-factor is the frame height (for the "typical" design), the frame U-factor (tabulated for various material types, spacer assemblies, and glazing widths) and the center-glass U-factor (from which the edge-glass U-factor can be approximated—see Arasteh 1989).

The simulations were done in accordance with ASHRAE 142P and examined several common commercial framing systems. The most common of these is the thermally broken aluminum frame, as characterized by the framing system of the curtain wall specimen. There are several different thermal break designs; the two most common were evaluated in this parametric analysis. The second most common frame is a nonbroken metal frame (similar design to the test specimen but with no thermal separation between the interior and exterior extrusions). All three frame types were evaluated with standard dual-seal aluminum spacer assemblies and for single-, double-, and triple-glazed IG units for both the vertical and sloped cases. It was felt that the 45° slope would be most representative of typical sloped glazing systems.

The framing system for the sloped glazing system can be represented in the two-dimensional model with two cross sections, one for vertical rafters and one for horizontal mullions. Curtain walls and sloped glazings in buildings are essentially a repeating pattern of individual panels and can be represented by a 1.2 m × 1.2 m (4 ft × 4 ft) vision panel, measured from the center of mullions. The curtain wall system only requires one cross section (which is similar to the vertical rafter section of the sloped glazing system).

Recommended frame U-factors for these products are given in Table 2 for a frame height of 57 mm, or 2.25 in. (typical of these systems). Frame height and U-factor are interrelated and should not be used independently of each other. In general, increasing the frame height decreases the frame U-factor for a given material and product type.

The curtain wall assemblies were also modeled with and without bolts to assess the magnitude of the bolts in a specimen without the metal fascia plate shown in Figure 4. As Table 2 shows, the bolts make a difference of (at most) 0.3% in the frame U-factor for unbroken frames (labeled "AL curtain wall" in Table 2), which translates to a difference of less than 0.1% in the total U-factor of a 1200 mm × 1200 mm (4 ft × 4 ft) panel (measured between mullion centers). Where thermally broken frames are considered, however ("TB curtain wall" in Table 2), this difference increases to as much as 21% for the frame U-factor, which translates to 6.9% for the total-product U-factor. The difference is less important for single-glazed systems (again, any thermal bridging elsewhere in the specimen reduces the effect of the bolts) and more so for systems incorporating an insulating (i.e., low-conductivity) spacer assembly. It is assumed that similar effects would be

TABLE 2

Representative Frame U-Factors for Curtain Wall/Sloped Glazing, W/m^2·°C (Btu//h·ft^2·°F)

		Double-glazed		Triple-glazed	
	Single-glazed	Alum. Spacer	Ins. Spacer	Alum. Spacer	Ins. Spacer
AL curtain wall, bolts	16.58 (2.92)	15.59 (2.74)	15.35 (2.70)	14.87 (2.62)	14.59 (2.57)
AL curtain wall, no bolts	16.55 (2.91)	15.55 (2.74)	15.32 (2.70)	14.83 (2.61)	14.56 (2.56)
TB curtain wall, bolts	9.61 (1.69)	9.12 (1.61)	8.24 (1.45)	8.63 (1.52)	7.66 (1.37)
TB curtain wall, no bolts	7.96 (1.40)	7.49 (1.32)	6.53 (1.15)	7.11 (1.25)	6.11 (1.08)
Struc. curtain wall	9.98 (1.76)	7.11 (1.25)	5.10 (0.90)	5.60 (0.99)	3.44 (0.61)
AL sloped glazing	14.38 (2.53)	13.16 (2.32)	13.00 (2.29)	12.33 (2.17)	12.13 (2.14)
TB sloped glazing	8.43 (1.48)	7.99 (1.41)	7.32 (1.29)	7.48 (1.32)	6.75 (1.19)
Struc. sloped glazing	8.62 (1.52)	6.06 (1.07)	4.49 (0.79)	4.84 (0.85)	3.02 (0.53)

found for sloped glazing systems but not, of course, for structural glazings (labeled "Struc. curtain wall" in Table 2) that do not incorporate bolts.

CONCLUSIONS AND RECOMMENDATIONS

Correcting a simulation model of a thermally broken aluminum framing system to account for the presence of bolts made a difference of up to 6.9% for the products analyzed in this study, depending on the nature of the glazing system and spacer assembly. When bolts are included in the model, simulation and test agree to within 8.5% for the curtain wall/sloped glazing specimen for all cases. In most cases, differences between test and simulation are within the bias of the test facility.

A simplified two-dimensional heat transfer model can provide a very good simulation of a guarded hot box test for curtain wall and sloped glazing products. The simplified model can be used to investigate the performance of these products under other conditions or of similar products with variations in framing and glazing systems.

Temperature profiles of the test specimens indicate an additional mode of heat transfer in metal-framed products with large hollow profiles. Air is drawn up the hollow tubes by natural convection and exhausted out the top of the tubes, where these tubes are open (either to the inside or the outside). This situation only occurs under winter conditions and is separate from the issue of air leakage, but it does not contribute appreciably to increased heat loss if the convective tube does not incorporate the thermal break.

Temperature stratification increases heat transfer in sloped (or overhead) glazed products, as these products are placed in an area that sees a large temperature difference between the exterior air and the stratified air within the conditioned space.

Recommended frame U-factors are presented for curtain-wall and sloped-glazing specimens.

Frame U-factors for commercial glazed wall/roof products depend on framing materials, overall thickness of the glazing system, and (to some extent) on the nature of the spacer assembly. The performance of a thermally broken frame is primarily dependent on the thickness of the thermal break: 1/8 in.(3 mm) is typical, although wider thermal breaks are gradually becoming more common.

U-factors for curtain wall systems cannot be applied to overhead glazing systems, even though the framing design of both products is somewhat similar (especially with respect to the vertical mullions). The room-side film coefficients are sufficiently different, and the overhead systems often use smaller channels in their horizontal mullions.

Frame U-factors for two-sided curtain-wall or sloped-glazing systems (where either horizontal or vertical framing members are pressure-glazed and the opposite framing members are structural-glazed) can be determined from an area-weighted mean of pressure-glazed and structural-glazed values from Table 2.

REFERENCES

ASHRAE. 1997. *1997 ASHRAE Handbook—Fundamentals.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1996. ASHRAE Draft Standard 142P, Standard method for determining and expressing the heat transfer and total optical properties of fenestration products. Public review draft, October. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASTM. 1991. *ASTM C1199-91, Standard test method for measuring the steady-state thermal transmittance of fenestration systems using hot box methods.* ASTM Standards, vol. 04.06. American Society for Testing and Materials.

Arasteh, D. 1989. An analysis of edge heat transfer in residential windows. *Thermal Performance of the Exterior Envelopes of Buildings IV.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Carpenter, S., and A. McGowan. 1998. Three-dimensional heat transfer effects in building components. *ASHRAE* Transactions, V.104, Pt. 1, SF-98-8-3.

Carpenter, S.C., and A.E. Elmahdy. 1994. Thermal Performance of Complex Fenestration Systems. ASHRAE *Transactions* 100 (2).

CSA. 1998. A440.2-98, Energy performance of windows and other fenestration systems. Toronto: Canadian Standards Association.

EE. 1996a. *FRAME, A computer program to evaluate the thermal performance of window frame systems, Version 4.0.* Developed for CANMET, Division of Natural Resources Canada. Enermodal Engineering Limited.

EE. 1996b. Building insulation system thermal anomalies (RP-785). Final report for ASHRAE TC 4.4, Thermal Insulation and Moisture Retarders, and ASHRAE TC 4.9, Building Envelope Systems. Enermodal Engineering Limited.

EE. 1998. Determination of glazed wall/roof fenestration U-factors for the ASHRAE Handbook of Fundamentals (RP-877). Final report for ASHRAE TC 4.5, Fenestration. Enermodal Engineering Limited.

McCabe, M.E. 1998. U-factor table revisions. Seminar presentation at the 1998 ASHRAE Winter Meeting, San Francisco.

McGowan, A.G., A.O. Desjarlais, and J.L. Wright. 1998. Simulation and testing of pyramid and barrel vault skylights. *ASHRAE Transactions* 104 (1).

McGowan, A.G. 1995. Numerical prediction of window condensation potential. *ASHRAE Transactions* 101 (1).

NFRC. 1997. *NFRC 100, Procedure for determining fenestration product U-factors*. Silver Spring, Md.: National Fenestration Rating Council.

Sullivan, H.F., J.L. Wright, and R.L. Fraser. 1996. Overview of a project to determine the surface temperatures of insulated glazing units: Thermographic measurement and two-dimensional simulation. *ASHRAE Transactions* 102.

UW (University of Waterloo). 1996. *VISION 4.0, glazing system thermal analysis: User's and reference manual.* University of Waterloo Advanced Glazing System Laboratory.