ALTERNATIVE METHOD FOR ASSESSING CONDENSATION POTENTIAL OF WINDOWS

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Abstract

The objective of this study was to compare condensation resistance data obtained by simulation, using the computer programs FRAME and VISION, with measured data. Further, if practical, recommendations would be made for a replacement of the condensation resistance determination of CSA A440.2 with a less expensive estimate based on computer simulation, rather than physical testing.

At first poor agreement was obtained with measured data, and efforts were made to refine the computational procedure. Later it was concluded that the measured data were suspect unless obtained under carefully calibrated research conditions, and as a result recommendations are made for improving testing.

Air leakage and even wind-washing may affect condensation potential in some windows, but for many others simulation is a viable alternative to more expensive physical testing.

Sommaire

Le but de cette étude était de comparer les données de résistance à la condensation de fenêtres, obtenues par mesure expérimentale et par simulation sur l'ordinateur à l'aide des logiciels FRAME et VISION. En outre, on a voulu dans la mesure du possible, dégager les bases d'une méthode alternative par simulation sur ordinateur pour calculer la résistance à la condensation: l'avantage de cette méthode serait d'être moins onéreuse et techniquement équivalente à la méthode expérimentale actuelle stipulée par la norme CSA A440.2.

Initialement, il y a eu faible concordance entre les données expérimentales et les données simulées, et le travail a donc porté sur l'amélioration des procédures de modélisation. Cependant, on s'est finalement aperçu que c'était plutôt les données expérimentales qui étaient suspectes, sauf pour celles obtenues sur bancs d'essai rigoureusement calibrés et sous conditions d'essai soigneusement contrôlées. Ainsi, l'étude a permis l'élaboration de recommendations pour améliorer la méthodologie des essais.

Bien que l'infiltration de l'air et l'effet de balayage du vent puissent influencer la capacité de résistance à la condensation de certaines fenêtres, la méthode d'évaluation par simulation sur ordinateur représente une alternative viable pour la plupart des fenêtres au essais en laboratoire plus coûteux.

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1.0 INTRODUCTION

Condensation on windows is a major concern in many buildings. The condensation obscures the view to the outdoors, can cause window and building damage and may lead to mold growth and poor indoor air quality. CSA A440 [CSA, 1990] has a test procedure for determining a condensation resistance temperature index (I). At present this test is optional. As a result, most window manufacturers do not have I numbers -- and even those that do probably have not had all their glazing options evaluated. The principle reason I evaluations have not been done is cost: a single test can cost between $1500 and $3000.

In commercial building construction, the fenestration system is often designed specifically for a particular building. The architect will often require that the fenestration system be tested for condensation resistance. This testing can represent a significant portion of the cost to supply fenestration products to the project.

The most recent versions of the FRAME and VISION computer programs analyze the convective motion in the glazing cavity to be able to predict the inside surface temperature of the window. Initial comparison of surface temperatures with test results has shown good agreement [McGowan, 1995]. The cost of performing computer simulations is typically an order of magnitude less than physical testing. The simulation technique does, however, have two important limitations. First, the FRAME computer program is two-dimensional and cannot account for three dimensional effects on temperature in the corners or at local cold spots (e.g., due to hardware or assembly screws). Second, it does not address the effects of air leakage on surface temperature.
The purpose of this study is fourfold:

- to assess the strengths and weaknesses of the test and simulation methods;
- to identify the effect of various conditions and window design features that affect the condensation potential of the product (with the intent of developing a test procedure that addresses these effects);
- to evaluate whether computer simulation can be used in conjunction with or as an alternative to physical testing; and
- to recommend a new procedure that is an accurate indicator of window condensation potential, but at lower cost than the current CSA A440 procedure.

This examination is performed based on a combination of previous research and testing and computer analysis done as a part of this project. This report is a preliminary examination; further work is required to validate the recommended procedure and to prepare the standards language for inclusion in CSA A440.

2.0 PHYSICAL TESTING TO ASSESS WINDOW SURFACE TEMPERATURE

2.1 The CSA A440 Test Method

The 1990 version of CSA A440 included a revised procedure for assessing the condensation potential of windows. The standard calls for windows to be placed in a test chamber and subjected to a 50-degree temperature difference (20 C inside, -30 C outside). An artificial wind is blown perpendicular to the window at approximately 6.7 m/s to achieve an outside film coefficient of 22 W/m^2K. Air moves by natural convection on the inside. The window is unsealed but pressure balanced to minimize air leakage.

Thermocouples are mounted on the room-side surface of the window to attempt to locate the coldest temperature (first location of condensation). CSA A440 does not define the number and location of the thermocouples, although some guidance is given. Three thermocouples must be placed along the bottom of the glazing 50 mm above the sightline: one at each corner and one at the centre. Frame thermocouples may be placed no closer than 10 mm from the glass surface. The Canadian testing industry has collaborated to better define thermocouple placements. Figure 2.1 shows the typical thermocouple placement for a casement window.

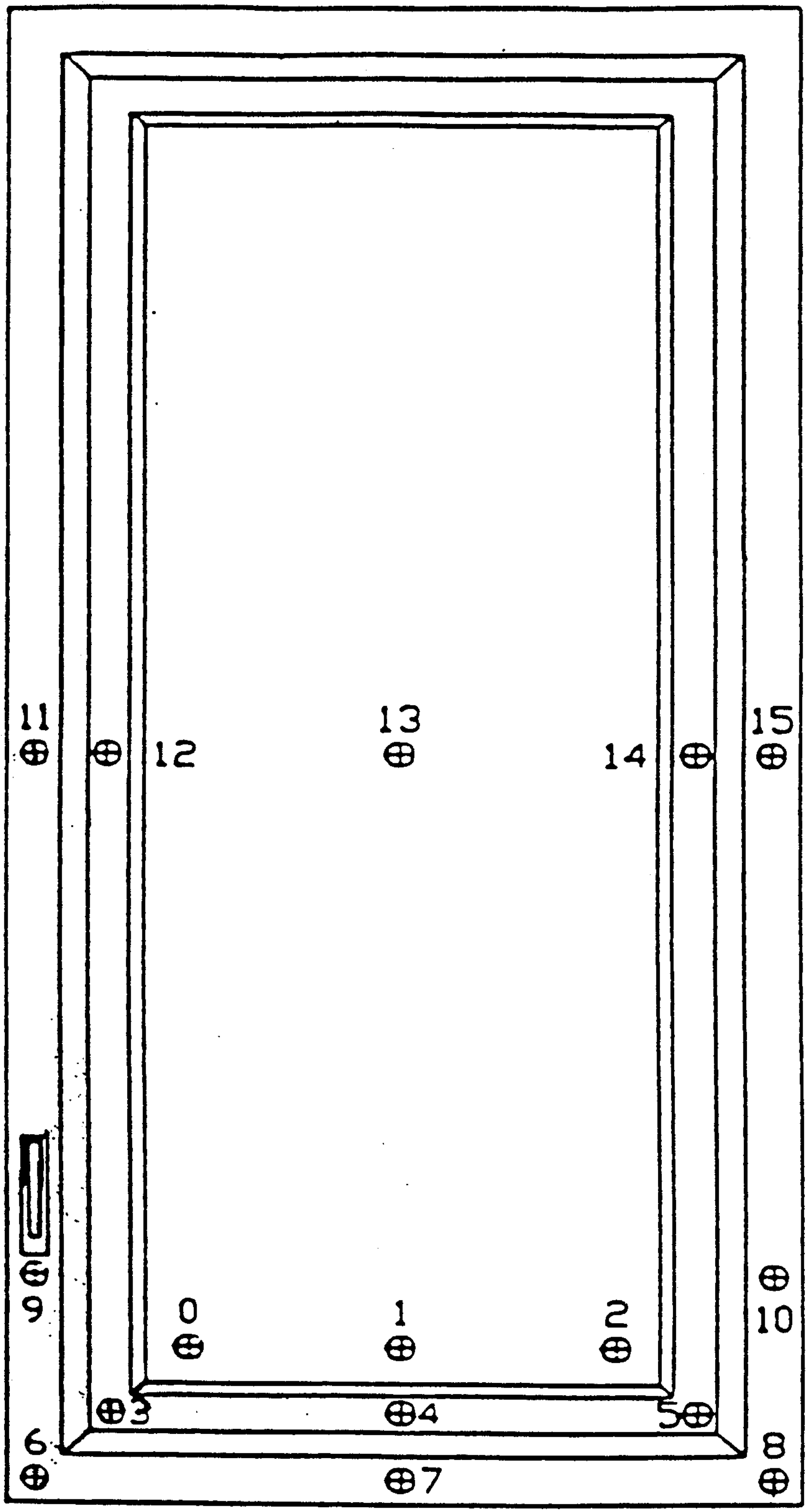
The A440 uses the term "Temperature Index" to define the condensation resistance of a window. The Temperature Index (I) is equal to

$$I = (T - T_c)/(T_h - T_c) \times 100$$

where T is the frame or glass surface temperature
T_h is the hot side air temperature (20 C)
T_c is the cold side air temperature (-30 C)

In effect, the I value is the percentage difference between the inside and outside temperatures. The I value is calculated for the glass (using an average of the three coldest temperatures) and for the frame (using the single coldest frame temperature). Both values are usually reported, but the lower of the two defines the I value for the window.

Figure 2.1 Thermocouple locations for a casement window, per CSA A440



To comply with CSA A440, the window must have an I value of 40 or greater. For standard double-glazed windows with aluminum spacers the coldest point is typically on the glazing. These windows have an I value of approximately 50 to 55. Adding a low-e coating, inert-gas fill and (most importantly) an insulated spacer can raise the I value to between 60 and 65. However, as the glazing system is improved, the frame becomes the coldest location and further improvements in the glazing system have no impact on the window I value.

In the U.S., a similar procedure is used to determine the CRF in accordance with AAMA 1502.7 [AAMA, 1981]. The CRF is calculated using the same equation as for the I value, but a different procedure is used to get the glass and frame surface temperatures. The AAMA method has defined frame thermocouple locations but also allows the test laboratory to use four "roving" thermocouples, placed at the discretion of the operator, to locate the coldest frame temperatures. The CRF is calculated using the average of all the glass thermocouples and the six coldest frame temperatures. The NFRC is also developing a condensation resistance procedure, but it has yet to be finalized.

The CSA A440 committee has agreed to modify the current condensation resistance procedure to reduce variability between laboratories and to better harmonize with the U.S. procedures. The changes which will come into effect with the next release of the standard are:

- test conditions of 21 C inside and -18 C outside,
- defined locations for thermocouples,
- test specimens to be same size as A440.2 sizes (Energy Standard),
- four roving thermocouples to locate coldest frame temperature,
- frame I value is calculated using the average of the three coldest frame temperature measurements, and
- additional glazing thermocouples are to be located 12.5 mm up from the sightline (but they are not used in calculation of I value).

It is expected that these changes will come into effect in 1997.

2.2 Advantages and Limitations of the Test Method

The CSA A440 condensation resistance test procedure is a reasonable technique for assessing the potential for condensation on windows. Several laboratories are set up to do the test and the results are accepted by the industry. The I value concept is useful, because when used in conjunction with the modified psychometric chart in the Users Guide, it can identify the maximum allowable relative humidity before condensation occurs.

There are, however, some flaws in the test method. First, temperatures are measured only at selected points. This presents two problems: uncertainty in the measurement and uncertainty in the amount of condensation. Discrepancies can result if laboratories choose different locations in an attempt to locate the coldest temperature. Furthermore, differences can result from variability between laboratories in positioning of the thermocouples. In some areas of the window (e.g., the bottom of the glazing), a variation of a few millimetres may cause significant temperature differences (as much as 1°C; see Section 4.3 on location of thermocouples).

The various spot measurements of temperature may adequately identify whether condensation will occur, but it does not provide information on the total area covered by condensation. Homeowners may be willing to accept the odd spot of condensation but not a continuous band, especially on the glass where the view may be obscured. The current test does not provide information on the amount of condensation, nor on the area covered by condensation.

The room-side surface temperature depends on the magnitude of the warm-side film coefficient. There could be variability between laboratory results because of different test chamber layouts or operation, which can affect the room-side film coefficient. Unfortunately, the current test procedure does not require reporting (or even measurement) of the room-side film coefficient. It has also been shown that the type of tape used can affect the surface temperature by 1°C [McGowan, 1995]: again, the tape is not specified in the test procedure, and is not reported by most testing laboratories.

2.3 Accuracy of the Test Method

The National Research Council and Canada Mortgage and Housing Corporation undertook a round-robin investigation of test laboratories in 1990 [Elmahdy, 1990]. In this study four windows were tested for condensation resistance at four test laboratories.

The four windows were a fixed, casement, vertical slider and horizontal slider, all with clear double glazing in thermally broken aluminum frames. The glass and frame results are summarized in Table 2.1.

Table 2.1 Physical Condensation Resistance Test Results (from [Elmahdy, 1990])

Window	Lab #1			Lab # 2			Lab # 3			Lab #4		
	T_g	T_f	I	T_g	T_f	I	T_g	T_f	I	T_g	T_f	I
Vertical slider	0.1	-0.3	54	-2.7	-0.3	54	-2.7	-5.6	49	-3.1	-0.4	52
Casement	0.5	-1.5	57	-2.9	5.8	54	-2.1	-0.6	56	-3.7	-0.1	53
Horizontal Slider	0.5	-1.5	57	0.0	-3.4	53	-2.2	-4.6	51	-1.9	-4.6	51
Fixed	-0.5	-0.5	59	-0.4	0.3	52	--	--	--	-4.2	-1.8	52

As Table 2.1 shows, there was a wide range of variability between labs in the results for any given specimen. No one laboratory appears to be consistently low, although Lab #1 is consistently high, and no particular specimen is consistently the best or worst performer of all those tested. The inter-laboratory variability in I rating ranged from 4 points (for the casement) to 7 points (for the fixed window). Surface temperatures varied by up to 5.1°C on the glass and up to 7.3°C on the frame. This is similar to more recent experience, in which the same specimen (a commercial fixed window with a thermally broken aluminum frame) was tested at two different facilities, resulting in a difference in the I rating of 0.9 for the glazing and 4.6 for the frame [Kawneer, 1996].

As a part of this project, two identical samples of a commercial thermally broken aluminum fixed window were built and sent to two different laboratories. Lab # 1 tested the window sample twice and Lab # 2 tested it four times. All tests were done in accordance with accepted procedures for measuring condensation resistance, but with slightly different temperatures, methods of controlling the indoor side temperature and techniques for attaching the thermocouples. These six sets of results provide a measure of the repeatability of the test procedure at the same laboratory and the comparability between two laboratories.

Figure 2.2 shows the surface temperature measurements normalized to the indoor-to-outdoor temperature difference (in other words, a local I-value) from the six tests. The values were normalized to remove any temperature variation due to test temperatures. The location of the thermocouples is shown in Figure 2.3. Not all thermocouple locations were used in all the tests.

There were some spurious data (e.g., thermocouple 20 in Lab 2 #1 test) possibly caused by poor thermocouple attachment or incorrect placement, but in most cases the I-values agree to within 4 I-value points or 2°C. Unfortunately, some of the largest differences are with the glass temperatures at the bottom of the window (thermocouples 15, 29 and 30): the locations that define the product I-value. In this case the spread in I-value is approximately 8 I-value points or 4 Celsius degrees. Part of the reason for the differences in test results is the variation in room-side film coefficient which ranges from 7 to 8.3 W/m^2-°C. The higher value was measured when a fan was used to control the room-side film coefficient (see Section 4.2 for a further investigation of the effect of film coefficients on I values). A second reason for the differences could be minor variations in placement of the thermocouples at the bottom of the glass between tests.

An interesting result from this set of condensation resistance testing is the temperature stratification of the frame temperatures. The average sill I-value (thermocouples 1 - 3) is approximately 68, whereas the average head temperature (thermocouples 4 - 6) is approximately 78, or a difference of about 5 Celsius degrees. The jamb I-values (thermocouples 7 - 14) are arrayed vertically down the jamb frames and show the increase in frame temperature with height.

Fig 2.2 Measured Local I Values
Specimen K7

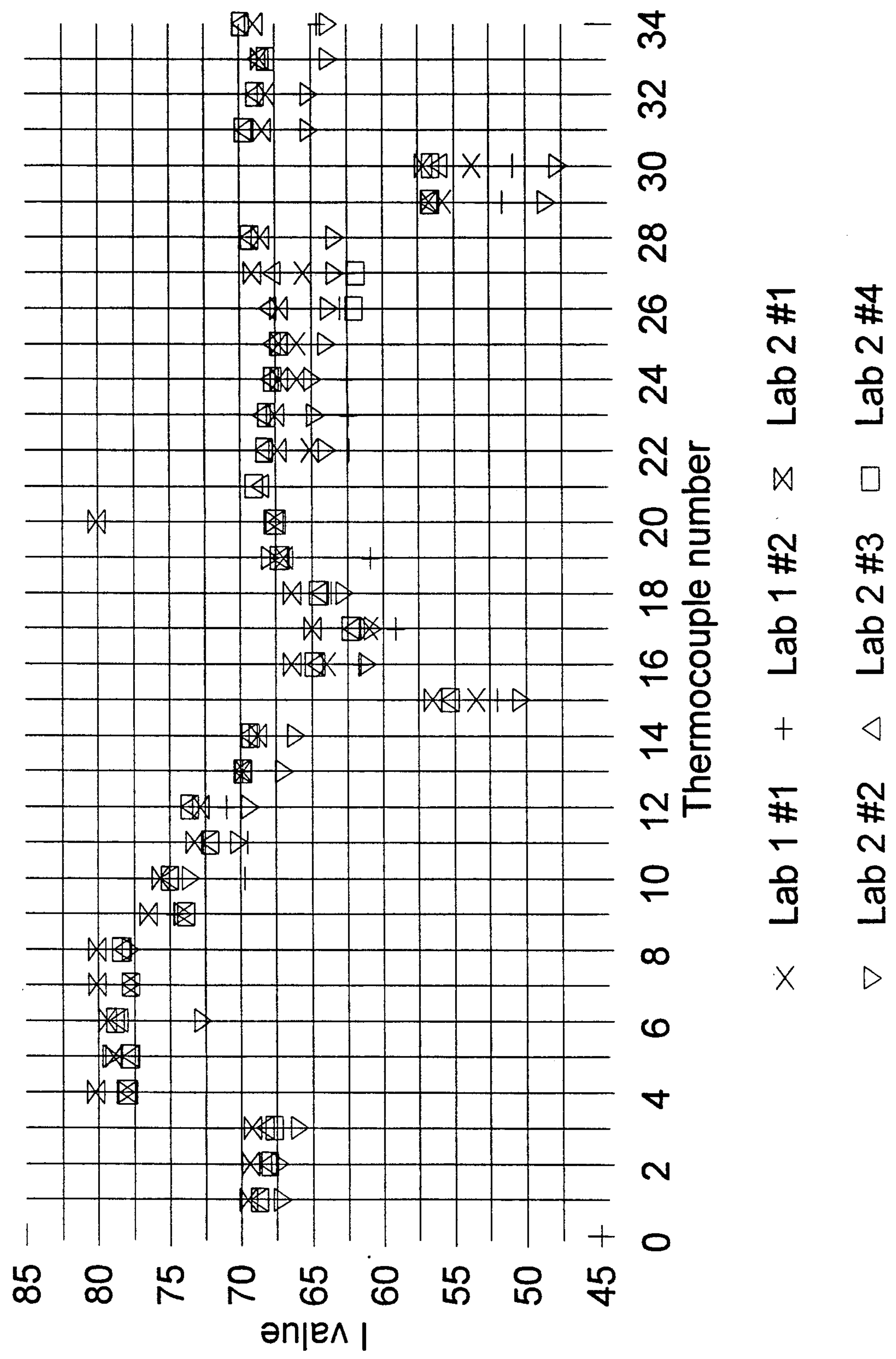
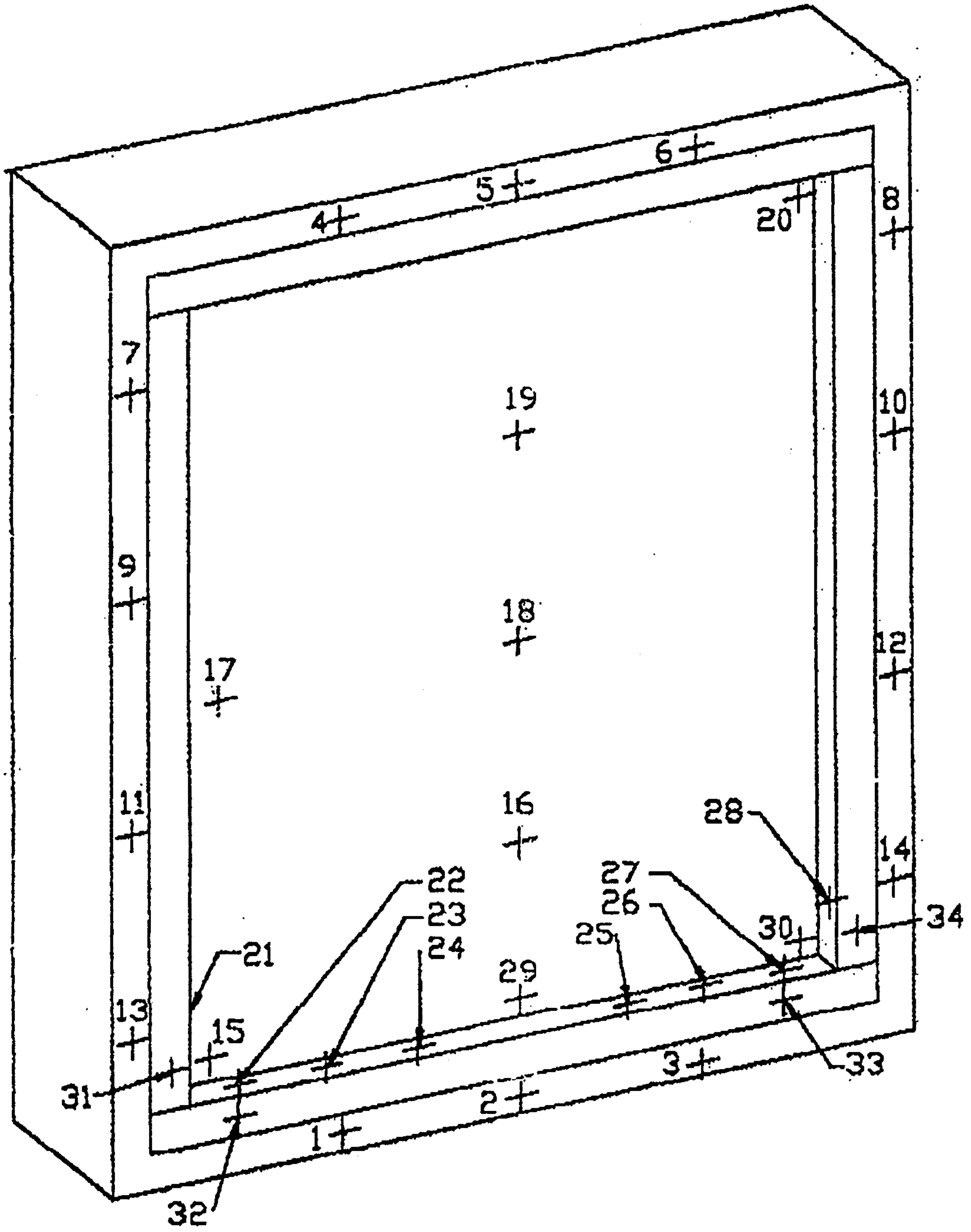


Figure 2.3 Thermocouple Locations for Specimen K7



3.0 COMPUTER SIMULATION TO ASSESS WINDOW SURFACE TEMPERATURE

3.1 The FRAME/VISION Simulation Method

The FRAME and VISION computer programs are an integral part of the CSA A440.2 standard for calculating the U-value and solar heat gain coefficient of windows. The accuracy of these programs in determining heat transfer properties has been demonstrated in many studies [Enermodal, 1993; Elmahdy and Frank, 1993]. In calculating the U-value of windows, the assumption is made that the radiant exchange and the convective motion between the glazing layers can be modelled by an "effective conductivity". That is, the thermal conductivity of the gas in the glazing cavity is increased to account for the other modes of heat transfer. This approach under-estimates the heat transfer at the bottom of the window and over-estimates heat transfer at the top of the window. These two effects tend to cancel each other out and the total calculated heat transfer is very close to that measured in a physical test (for U-value calculation).

The "effective conductivity" technique is not suitable for calculating local window surface temperatures. Comparison with test results has shown that using the effective conductivity model will over-predict the lower glazing surface temperature by 5 to 6 Celsius degrees and under-predict the upper glazing by 2 to 3 Celsius degrees [McGowan, 1995]. These errors would result in an unacceptable 10-point over-prediction of the condensation index.

Version 4 of the VISION program calculates the velocity field in the glazing cavity (assuming isothermal plates and laminar flow as described in Wright [1994]) for the region with 63.5 mm of the sightline. Version 4 of the FRAME program uses the velocity field to determine the convective relationship between the two-dimensional array of nodes in the glazing cavity. Radiative heat transfer across the glazing cavity is modelled by adding an energy source term equal to the radiative heat transfer calculated by VISION to the nodes on the cold side of the glazing and subtracting the same amount of energy from the nodes on the warm side of the glazing. Initial comparisons with physical tests shows that this new algorithm corrects most of the discrepancy between test and simulation, compared to the previous version of the simulation programs [McGowan, 1995].

3.2 Advantages and Limitations of the Simulation Method

Computer simulation offers several advantages over physical testing. Most importantly, computer simulation can generate surface temperatures at much lower cost and in a much shorter time period than physical testing can. Because most window manufacturers have had their windows rated for U-value using the FRAME and VISION programs, the incremental cost of generating surface temperatures is minimal. Furthermore, computer simulation generates continuous surface temperatures over the edge-of-glass and frame regions, as opposed to point temperatures with testing. Therefore, by not being limited to a few point temperatures, computer simulation can more easily locate the coldest surface temperature.

The final advantage of computer simulation is repeatability. With proper training, simulators can produce the same ratings. Computer simulation overcomes test laboratory problems of accurate thermocouple placement and variability between laboratory test chambers and operation.

There are still some limitations to the simulation technique that mean it cannot be a direct replacement for the current CSA A440 condensation resistance test. First, the FRAME program performs a two-dimensional analysis: a cross-section through the centre of each framing component (e.g., head, sill, jamb). Three-dimensional effects due to corners and point thermal bridges (e.g., assembly screws and hardware) are ignored. Although guarded hot box testing has shown that these 3-D effects have little impact on the total-window heat transfer, these effects can reduce the local inside surface temperature. It is possible to analyse the window in three dimensions including convective and radiative exchange; however, the time and effort to do so would mean that computer simulation would not offer any cost savings over physical testing.

As the CSA A440 condensation resistance test is voluntary, few test data were available to assess the cooling impact at the corners. Corner glass temperatures can be compared to centreline glass temperatures for the testing conducted as part of this project (see Figure 2.2, thermocouples 29 and 30 versus 15). For these six tests, the glass corner temperatures are only marginally cooler than the centreline. These results are consistent with the three other sets of test results examined for this project. Two sets showed no corner cooling (i.e., the temperatures measured 50 mm from either corner was the same as that measured 50 mm above the sill at the centreline), and one showed a slight effect (the corner temperatures were 1 °C cooler). Nevertheless, additional tests results are required before a correlation between centreline and corner glass temperatures can be made.

The inside surface temperature depends on the inside film coefficient. Recently the VISION program was updated to include the film coefficient correlations recommended in ASHRAE SPC 142 [ASHRAE, 1996]. These correlations should provide accurate values for most of the glazed areas. The window frame and sash can cause local disturbances in convective air flow and reduce the radiative coupling to the room. Previous research has shown high film coefficients on the window head and lower film coefficients on the sill [Curcija and Goss, 1993]. Recognizing the complexity in predicting local film coefficients, ASHRAE SPC 142 recommends using the same film coefficients on the frame as on the glazing. This is probably reasonable as an average value, but could result in an under-estimation of the sill surface temperature. The effect of film coefficient on surface temperatures is discussed in Section 4.2.

As discussed in Section 3.1, Versions 4 of the VISION and FRAME computer programs can model the convective motion and radiative exchange in the glazing cavity. The cavities in vinyl, aluminum or fibreglass frames are, however, still modelled using the effective conductivity approach. Of particular concern are the cavities in the jamb sections of tall commercial windows. If the cavities are not sealed, they could act as a chimney to increase heat transfer. The impact of this heat transfer mechanism is under investigation in a current ASHRAE research project [ASHRAE, 1995], but results to date are inconclusive on this issue.

The most significant limitation of the simulation method is the inability to account for the effects of air leakage. As discussed in Section 2.1, windows are unsealed during the condensation resistance test. Although the window is pressure balanced, velocity pressure will cause some cold-side air to leak into frame openings and through to the warm side. This air movement will result in cooler frame temperatures, especially at the frame/sash junction.

3.3 Accuracy of Simulation Method

Previous work by Enermodal [McGowan, 1995] compared simulation using a convective model for the glazing cavity against physical test results from the National Research Council. These comparisons were made for five specimens chosen specifically to have a pronounced edge effect, so that they would constitute worst-case comparisons. For the specimens in that study, simulation and test agreed to within 2°C for nonmetal frames and within 5°C for metal frames (when comparing frame surface temperatures). When comparing glass surface temperatures (as measured at 50mm from the sill sightline), the agreement was slightly better: simulation was within 1°C for nonmetal frames and 4.5°C for metal-framed windows. It was noted that the type of tape used to attach thermocouples in a physical test can cause a variation of at least 1°C, and differences between test labs can be as much as 5°C, therefore the simulation results for that study were within the variation seen between physical laboratories.

In the 1995 study, it was suggested that part of the reason for differences between test and simulation were related to local variation in the room-side film coefficient, but this variation was beyond the scope of that study. The effect of local variation in film coefficient is addressed in this report, however (see Section 4.3).

A collaborative research project was undertaken by the University of Waterloo, Lawrence Berkeley National Laboratory, the National Research Council Canada, and the University of Massachusetts to compare thermographic testing and various simulation techniques [Sullivan et al., 1996]. Although the test specimens were only insulated glass units, this study comprised the first full-scale comparison of testing and simulation among several laboratories. FRAME/VISION results were compared to infra-red thermographic results for seven specimens covering a range in spacer materials, pane spacings and low-e coatings. The simulated interior surface temperatures were typically within 2 Celsius degrees of the tested values.

One of the participants in the study varied the average (uniform) film coefficients for the room side and weather side, however, so that the average effect of film coefficient on surface temperatures was examined with computer simulation [de Abreu et al., 1996]. The weather-side film coefficient had relatively little effect on room-side surface temperatures (unless the weather-side condition approached natural convection), but the room-side film coefficient had a strong influence on the surface temperatures.

It was proposed for this project to compare the existing body of test data against computer simulations of the specimens associated with those data, using the convective model [McGowan, 1995] or some variation of it. Unfortunately, however, almost none of the existing data are useful for comparison: in the AAMA and NFRC testing, the thermocouple placement does not allow a direct comparison (thermocouples must be located along the centreline of the glass to match the model), whereas the CSA test method does not measure or record film coefficients (so that the test conditions cannot be replicated in the simulation). The limited amount of existing test data available was compared to simulation for this project; the results are discussed in Sections 4.3. The comparison between test and simulation for the specimen specifically tested for this project is also included in Section 4.3 (see Figures 4.6 and 4.7).

3.4 Comparison of Test and Simulation Methods

Physical testing and computer simulation are different approaches to assessing the condensation resistance of windows. Each method has its disadvantages and advantages. These differences are summarized in Table 3.1. The primary advantage of physical testing is the ability to account for localized effects on the framing members of film coefficient variations and air leakage. The primary advantages of computer simulation are lower cost and repeatability.

Table 3.1 A Comparison of Physical Testing and Simulation of Condensation Resistance

Physical Testing of Condensation Resistance (I value)	
Advantages	Disadvantages
can account for three-dimensional and localized effects (corners, hardware, etc.)	expensive and time-consuming
	no permanent record of test procedure
can account for air leakage	results may be affected by condensation on specimen, thermocouple placement, tape
	wide variation seen in results from different testing facilities

Computer Simulation of Condensation Resistance	
Advantages	Disadvantages
low cost, short time to get results	model requires an experienced operator
repeatability of results	accuracy compared to test is not known
gives continuous temperature profiles, not just values at certain discrete points	physical phenomena affecting performance (e.g., air leakage, wind-washing) are not fully understood, so cannot be accurately modelled

4.0 EFFECT OF WINDOW CHARACTERISTICS ON SURFACE TEMPERATURE

4.1 Effect of Glazing, Spacer and Frame Type

Several different windows were simulated under controlled conditions to evaluate the effect of various design features on the room-side surface temperatures of the windows. These products were evaluated with the new (proposed) CSA standard conditions of T_o = -18°C, T_i = 21°C, and h_o = 25 W/m^2°C. To minimize the number of variables in this part of the study, the room-side film coefficient was held constant at h_i = 7 W/m^2°C for all specimens in this part of the study.

Three specimens (a fixed window with an improved thermally broken aluminum frame, a wood-framed casement window, and a horizontal slider with a pour-and-debridge thermally broken aluminum frame) were simulated, each with two different glazing systems and three different spacers. The combinations of glazing systems (clear double-glazed and double-glazed with 0.2 low-e/argon) and spacer assemblies (dual-seal aluminum, thermally broken aluminum and silicone foam) in the three frames produced a total of 18 different products, and allowed examination of the sensitivity of the surface temperatures to each design option.

The results of the analyses of these windows with various glazings and spacer assemblies are shown in Tables 4.1a through 4.1c. Glass surface temperatures at 13 mm and 50 mm from the sightline were recorded for possible comparison against physical testing (or against other simulations which were comparable to physical tests). Frame surface temperatures at 13 mm from the sightline and at the midpoint of the frame were also recorded, as these are also typical locations for test thermocouples. The temperatures and resulting local I-values are shown in Tables 4.1a through 4.1c.

From these tables, it is evident that the mid-frame temperature is relatively independent of the type of glazing system, unless both the frame and spacer assembly are highly conductive. Also, the frame surface temperatures for low-conductance frames are

Table 4.1a Thermally Broken Aluminum Fixed Window: various glazings and spacers

Glazing	Spacer	glass temp, °C		local glass I-value		frame temp, °C		local frame I-value	
		@ ½"	@ 2"	@ ½"	@ 2"	@ ½"	mid	@ ½"	mid
DG: 0.2 low-e on surface #3 95% argon	DS al	6.0	8.5	61.5	67.9	10.8	11.3	73.8	75.1
	TB al	7.4	9.1	65.1	69.5	12.1	12.5	77.2	78.2
	foam	8.5	9.4	67.9	70.3	13.0	13.3	79.5	80.3
double-glazed clear glass with air fill	DS al	3.3	4.4	54.6	57.4	10.5	11.0	73.1	74.4
	TB al	4.5	4.9	57.6	58.7	11.6	12.0	75.9	76.9
	foam	5.5	5.2	60.3	59.5	12.5	12.8	78.2	79.0

All cases are for T_o = -18/C, h_o = 25.0 W/m^2/C; T_i = 21/C, h_i = 7.0 W/m^2/C

Table 4.1b Wood Casement Window: various glazings and spacers

Glazing	Spacer	glass temp, °C		local glass I-value		frame temp, °C		local frame I-value	
		@ ½"	@ 2"	@ ½"	@ 2"	@ ½"	mid	@ ½"	mid
DG: 0.2 low-e on surface #3 95% argon	DS al	1.9	6.8	51.0	63.6	10.3	16.6	72.6	88.7
	TB al	3.3	7.4	54.6	65.1	11.3	16.7	75.1	89.0
	foam	4.7	7.8	58.2	66.2	12.2	17.0	77.4	89.7
double-glazed clear glass with air fill	DS al	-0.7	2.7	44.4	53.1	10.0	16.8	71.8	89.2
	TB al	0.4	3.1	47.2	54.1	10.7	16.9	73.6	89.5
	foam	1.5	3.5	50.0	55.1	11.5	16.9	75.6	89.5

All cases are for T_o = -18/C, h_o = 25.0 W/m^2/C; T_i = 21/C, h_i = 7.0 W/m^2/C

Table 4.1c Thermally Broken Aluminum Sliding Window: various glazings and spacers

Glazing	Spacer	glass temp, °C		local glass I-value		frame temp, °C		local frame I-value	
		@ ½"	@ 2"	@ ½"	@ 2"	@ ½"	mid	@ ½"	mid
DG: 0.2 low-e	DS al	1.3	6.6	49.5	63.1	-1.7	4.1	41.8	56.7
on surface #3	TB al	2.0	6.9	51.3	63.8	-2.7	2.9	39.2	53.6
95% argon	foam	2.5	7.1	52.6	64.4	-2.3	3.0	40.3	53.8
double-glazed	DS al	-1.4	2.4	42.6	52.3	-3.7	2.6	36.7	52.8
clear glass	TB al	-0.9	2.6	43.8	52.8	-3.3	2.7	37.7	53.1
with air fill	foam	-0.5	2.8	44.9	53.3	-2.9	2.8	38.7	53.3

All cases are for T_o = -18/C, h_o = 25.0 W/m^2/C; T_i = 21/C, h_i = 7.0 W/m^2/C

independent of both glazing and spacer type. As might be expected, the low conductance of the wood frame tended to isolate the effect of the spacer assembly to the glass region near the spacer.

It also appears that the glass surface temperature at 50 mm from the sightline is relatively independent of spacer type: therefore, measuring the condensation potential at 50 mm would provide very little information about the performance of the spacer with regard to reducing condensation potential. The glass temperatures at 13 mm above the sightline, and the frame temperatures at 13 mm from the sightline (for highly conductive frames) clearly indicate the effect of the spacer assembly.

4.2 Effect of Film Coefficient

The three different framing systems were also simulated with a low-e argon glazing system and two different spacers at two different room-side film coefficients and two different climatic conditions. The film coefficients chosen (7 and 8 W/m^2-°C) are representative of a reasonable range of expected values for a typical testing situation, and the air temperatures chosen reflect the current CSA A440 conditions for condensation testing (+20°C and -30°C) and those proposed in the latest revision to the

Standard (+21°C and -18°C). The results of these simulations are shown in Tables 4.2a through 4.4b. The glass and surface temperatures and temperature indices are for the same locations as those in Table 4.1. As with Table 4.1, the "temperature indices" here are just the surface temperatures non-dimensionalized to the indoor-outdoor air temperature difference.

The results show that temperature indices for these film coefficients are quite independent of the air temperatures used in the simulations. Therefore, the idea that non-dimensionalizing the surface temperature by the indoor-outdoor air temperature difference seems to be accurate. Holding air temperatures constant and varying the film coefficient between $h_i = 7$ and $h_i = 8$ shows that the temperature indices are strongly dependent on the room-side film coefficient, except for the frame temperatures of the low-conductance frame. This could be expected: the higher the conductivity of the frame is, the more sensitive to the film coefficient the thermal performance of the frame (and, therefore, the frame temperature) will be.

Comparing the results of Tables 4.2a and 4.2b (or 4.3a and 4.3b, etc.), however, shows that the room-side surface temperatures are strongly dependent on the exterior air temperature. The room-side film coefficient (which reflects natural convection) is dependent on the surface temperature. Thus, a colder exterior air temperature could result in a lower room-side film coefficient and a lower I-value. This hypothesis was tested by allowing the room-side film coefficient to "float" to its natural value, as required by the analytical procedure outlined in the ASHRAE SPC 142 draft procedure [ASHRAE, 1996].

For a constant exterior film coefficient of 25 W/m^2-°C, an exterior air temperature of -18°C gives a room-side film coefficient of 6.74 W/m^2-°C, and an exterior air temperature of -30°C gives a value of h_i = 6.79 W/m^2-°C. Thus, we see that the room-side film coefficient is not strongly dependent on the exterior temperature, and the statement that a non-dimensional temperature index is independent of the temperature conditions is still valid.

The sensitivity of surface temperatures (and temperature indices) to the room-side film coefficient points out serious concern in the testing procedure, however; as film coefficients are not measured, comparing test results from two different laboratories is quite problematic. Indeed, it was not possible to directly compare test results to simulation for this study, as the only available data were either from CSA A440 condensation resistance tests (wherein the film coefficients are not available) or from

AAMA or NFRC thermal tests (wherein film coefficients are reported, but the thermocouples are placed in the corners of the specimens, and so cannot be directly compared to simulation, which applies to the centreline of the product).

Table 4.2a Simulation of Thermally Broken Aluminum Fixed Window: various spacers and h_i

spacer	h_i,	glass temp, °C		local glass I-value		frame temp, °C		local frame I-value	
type	W/m^{2}°C	@ ½"	@ 2"	@ ½"	@ 2"	@ ½"	mid	@ ½"	mid
TB alum	7.0	7.4	9.1	65.1	69.5	12.1	12.5	77.2	78.2
TB alum	8.0	8.4	10.1	67.7	72.0	13.0	13.3	79.5	80.3
DS alum	7.0	6.0	8.5	61.5	67.9	10.8	10.8	73.8	75.1
DS alum	8.0	7.0	9.6	64.1	70.8	11.8	11.8	76.4	77.7

All cases are for .2 low-e on#3, 95% argon fill; **T_i = 21°C, T_o = -18°C**, h_o = 25.0 W/m^{2}°C

Table 4.2b Simulation of Thermally Broken Aluminum Fixed Window: various spacers and h_i

spacer	h_i,	glass temp, °C		local glass I-value		frame temp, °C		local frame I-value	
type	W/m^{2}°C	@ ½"	@ 2"	@ ½"	@ 2"	@ ½"	mid	@ ½"	mid
TB alum	7.0	2.0	3.7	64.0	67.4	8.4	8.9	76.8	77.8
TB alum	8.0	3.2	5.1	66.4	70.2	9.6	10.0	79.2	80.0
DS alum	7.0	0.2	3.1	60.4	66.2	6.9	7.4	73.8	74.8
DS alum	8.0	1.5	4.5	63.0	69.0	8.1	8.7	76.2	77.4

All cases are for .2 low-e on#3, 95% argon fill; **T_i = 20°C, T_o = -30°C**, h_o = 25.0 W/m^{2}°C

Table 4.3a Simulation of Wood Casement Window: various spacers and h_i

spacer	h_i,	glass temp, °C		local glass I-value		frame temp, °C		local frame I-value	
type	W/m²°C	@ ½"	@ 2"	@ ½"	@ 2"	@ ½"	mid	@ ½"	mid
TB alum	7.0	3.3	7.4	54.6	65.1	11.3	16.7	75.1	89.0
TB alum	8.0	4.4	8.5	57.4	67.9	12.4	17.2	77.9	90.3
DS alum	7.0	1.9	6.8	51.0	63.6	10.3	16.6	72.6	88.7
DS alum	8.0	3.0	8.1	53.8	66.9	11.5	17.3	75.6	90.5

All cases are for .2 low-e on #3, 95% argon fill; **T_i = 21°C, T_o = -18°C**, h_o = 25.0 W/m²°C

Table 4.3b Simulation of Wood Casement Window: various spacers and h_i

spacer	h_i,	glass temp, °C		local glass I-value		frame temp, °C		local frame I-value	
type	W/m²°C	@ ½"	@ 2"	@ ½"	@ 2"	@ ½"	mid	@ ½"	mid
TB alum	7.0	-3.3	1.6	53.4	63.6	7.4	14.5	74.8	89.0
TB alum	8.0	-1.9	3.1	56.2	66.2	8.8	15.1	77.6	90.2
DS alum	7.0	-5.0	1.0	50.0	62.0	6.2	14.4	72.4	88.8
DS alum	8.0	-3.6	2.6	52.8	65.2	7.6	15.0	75.2	90.0

All cases are for .2 low-e on #3, 95% argon fill; **T_i = 20°C, T_o = -30°C**, h_o = 25.0 W/m²°C

Table 4.4a Simulation of Thermally Broken Alum. Sliding Window: various spacers and h_i

spacer	h_i,	glass temp, °C		local glass I-value		frame temp, °C		local frame I-value	
type	W/m^2°C	@ ½"	@ 2"	@ ½"	@ 2"	@ ½"	mid	@ ½"	mid
TB alum	7.0	2.0	6.9	51.3	63.8	-2.7	2.9	39.2	53.6
TB alum	8.0	3.2	8.2	54.3	67.2	-1.7	4.1	41.8	56.7
DS alum	7.0	1.3	6.6	49.5	63.1	-3.3	2.7	37.7	53.1
DS alum	8.0	2.5	7.9	52.6	66.4	-2.2	4.0	40.5	56.4

All cases are for .2 low-e on#3, 95% argon fill; **T_i = 21°C, T_o = -18°C**, h_o = 25.0 W/m^2°C

Table 4.4b Simulation of Thermally Broken Alum. Sliding Window: various spacers and h_i

spacer	h_i,	glass temp, °C		local glass I-value		frame temp, °C		local frame I-value	
type	W/m^2°C	@ ½"	@ 2"	@ ½"	@ 2"	@ ½"	mid	@ ½"	mid
TB alum	7.0	-5.0	1.0	50.0	62.0	-10.6	-3.9	38.8	52.2
TB alum	8.0	-3.4	2.7	53.2	65.4	-9.3	-2.3	41.4	55.4
DS alum	7.0	-5.8	0.7	48.4	61.4	-11.3	-4.1	37.4	51.8
DS alum	8.0	-4.2	2.4	51.6	64.8	-10.0	-2.4	40.0	55.2

All cases are for .2 low-e on#3, 95% argon fill; **T_i = 20°C, T_o = -30°C**, h_o = 25.0 W/m^2°C

4.3 Local Variation in Film Coefficient

One of the issues raised in previous research [Curcija and Goss, 1993; McGowan, 1995] is that the assumption of a uniform room-side film coefficient is incorrect, and may result in errors in the numerical prediction of surface temperatures. With this in mind, simulations were performed for several different specimens, using a uniform film coefficient for the entire room-side surface, as well as modelling local variation of the film coefficient.

The room-side film coefficient was varied by first determining its free-stream value (i.e., the value at the centre-of-glass, as determined by VISION) and the relative proportion of radiative and convective heat transfer, as given by h_r and h_c. It is suggested [Curcija and Goss, 1993] that the convective coefficient, h_c, be linearly interpolated between the sightline and 50mm from the sightline on the glass: this interpolation technique was used for all vertical surfaces, with the vertical surfaces split into smaller segments of approximately 12.5 mm in length. The radiative coefficient, h_r, was also modified by accounting for self-viewing. Figure 4.1 shows an example of the modified film coefficients used for the vertical surfaces in a fixed window with a thermally broken aluminum frame. The first term shows the modification to the convective coefficient, and the second shows the modification to the radiative term (the modifier for the radiative term is the view factor from the surface to the room-side chamber).

For the horizontal surfaces, separate correlations are given for the convective coefficient near the edge (i.e., the last 6 mm) of the surface and along the remainder [Curcija and Goss, 1993]. The radiative component is also modified, to account for the reduced view factor from the surface to the room-side chamber.

Five windows were simulated to examine the impact of local variation in film coefficients. The results of the simulations with test results where available are given in Figures 4.2 through 4.7. The average change in surface temperatures resulting from allowing a locally varying room-side film coefficient (as opposed to using a uniform value for h_i) is shown in Table 4.5.

Figure 4.1 Local Variation in Room-side Film Coefficient

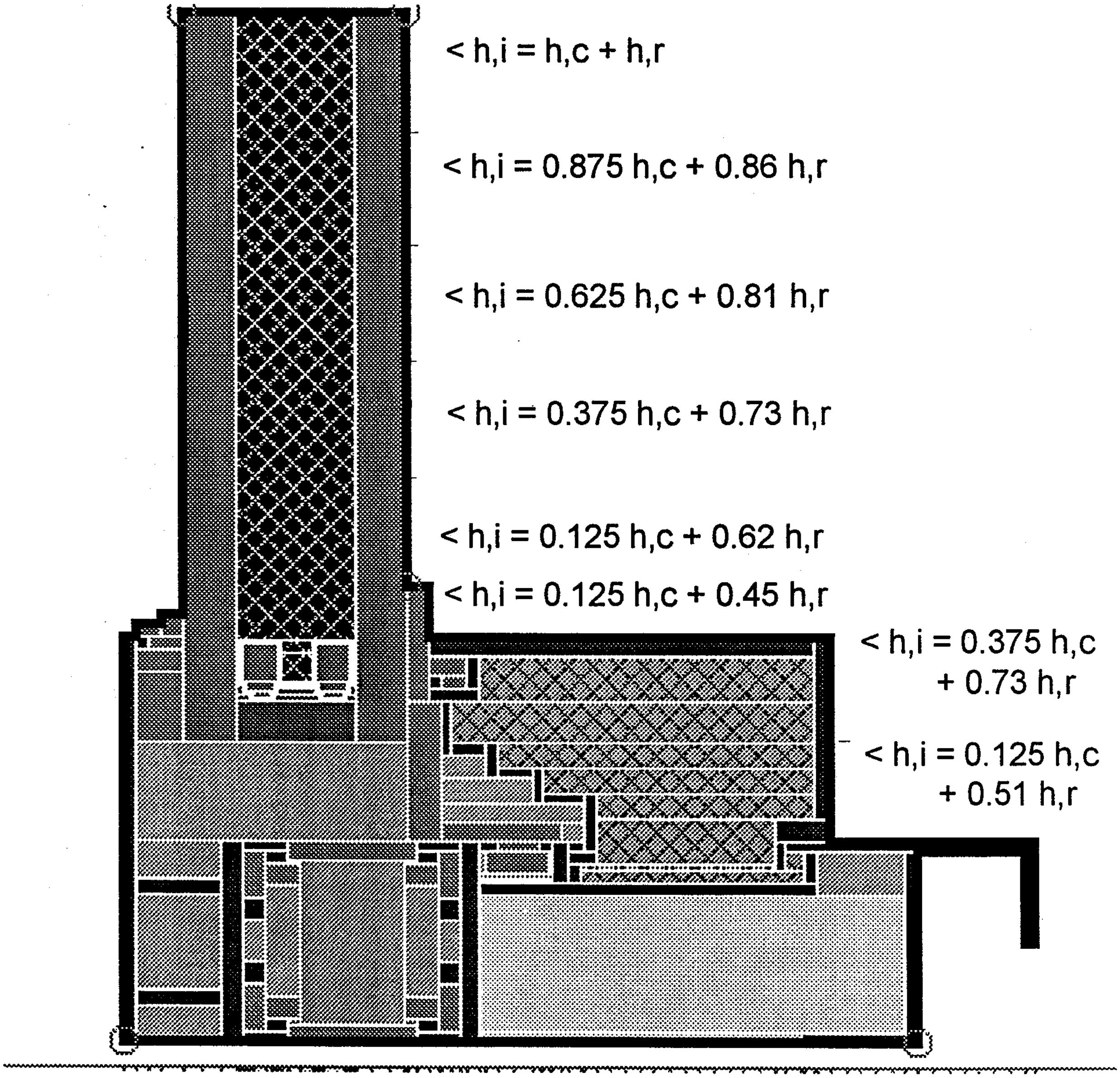


Fig 4.2 Specimen M1 sill temperatures
wood frame, DS alum spacer

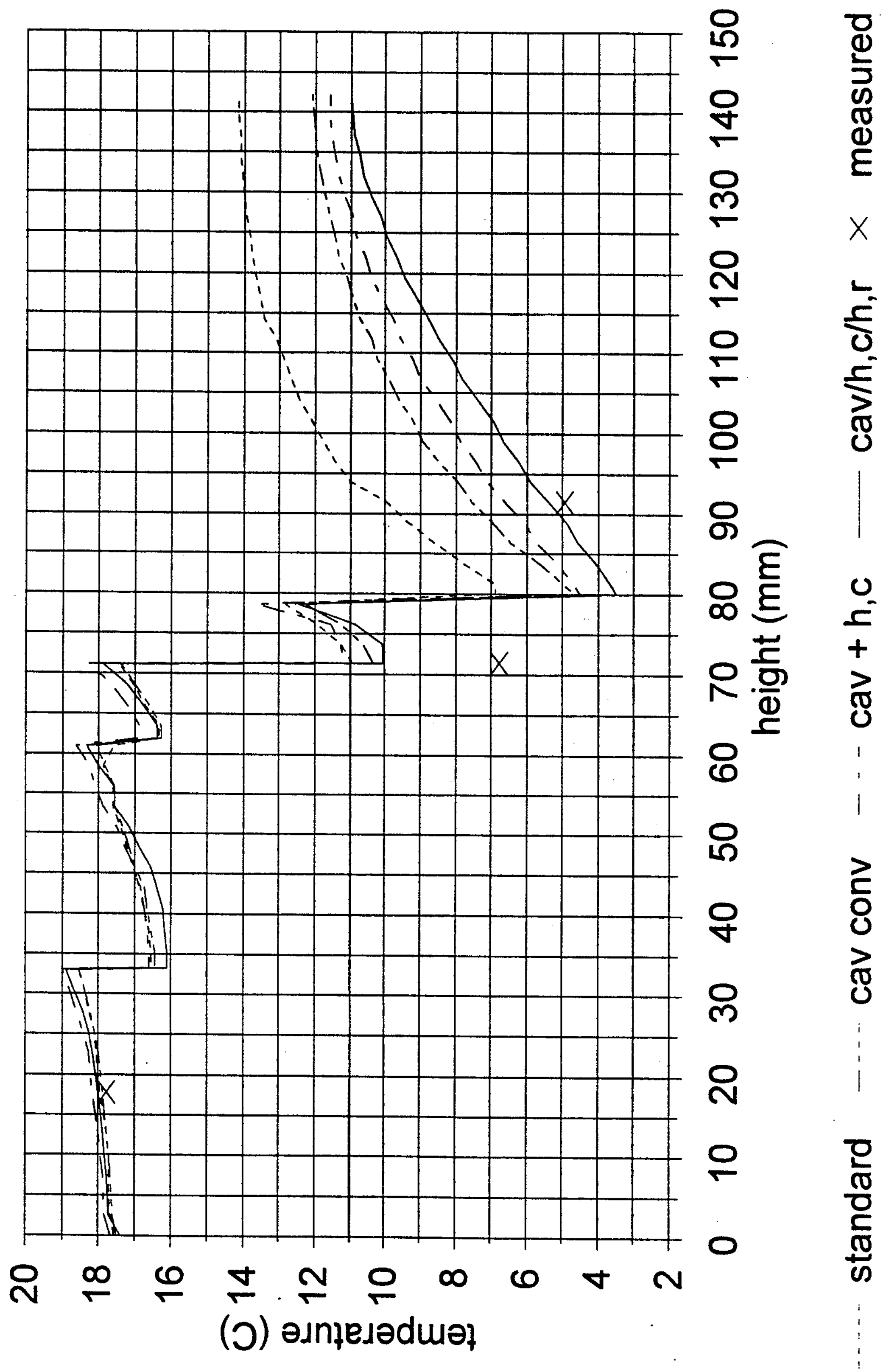


Fig 4.3 Specimen M6 sill temperatures

Al-clad wood frame, foam spacer

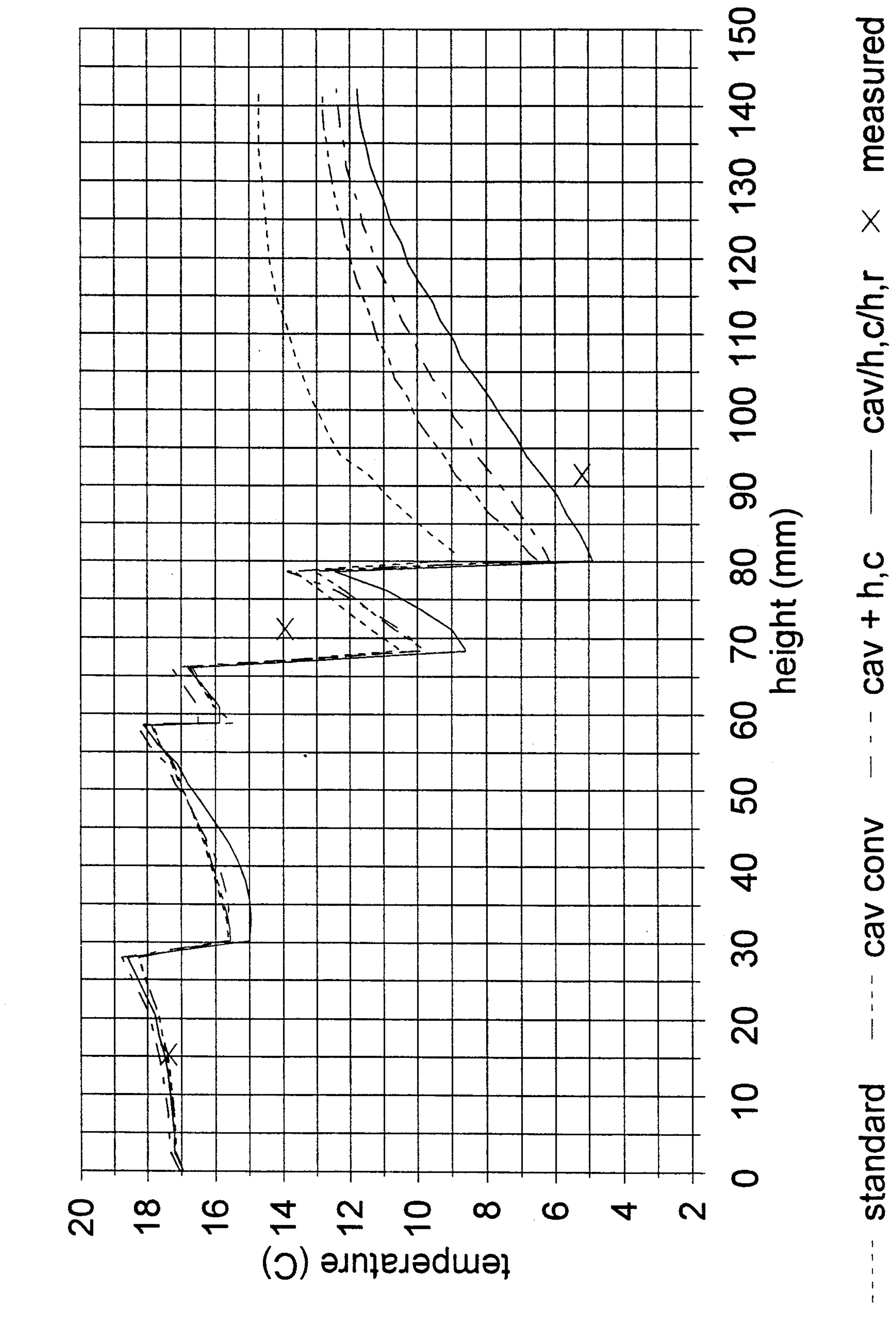


Fig 4.4 Specimen K5 sill temperatures

TB alum fixed frame - TB alum spacer

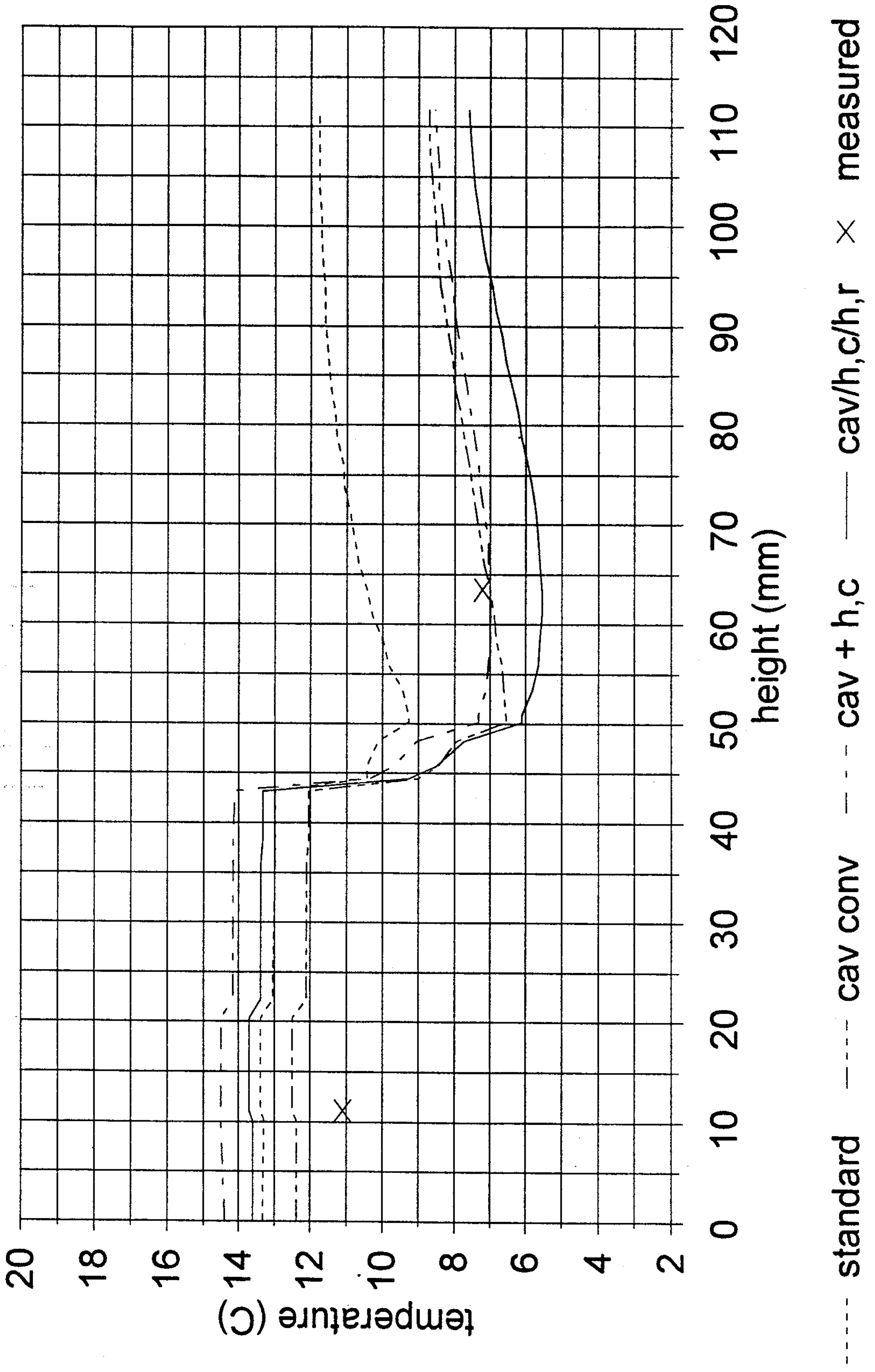


Fig 4.5 Specimen K6 sill temperatures
TB alum oper frame - TB alum spacer

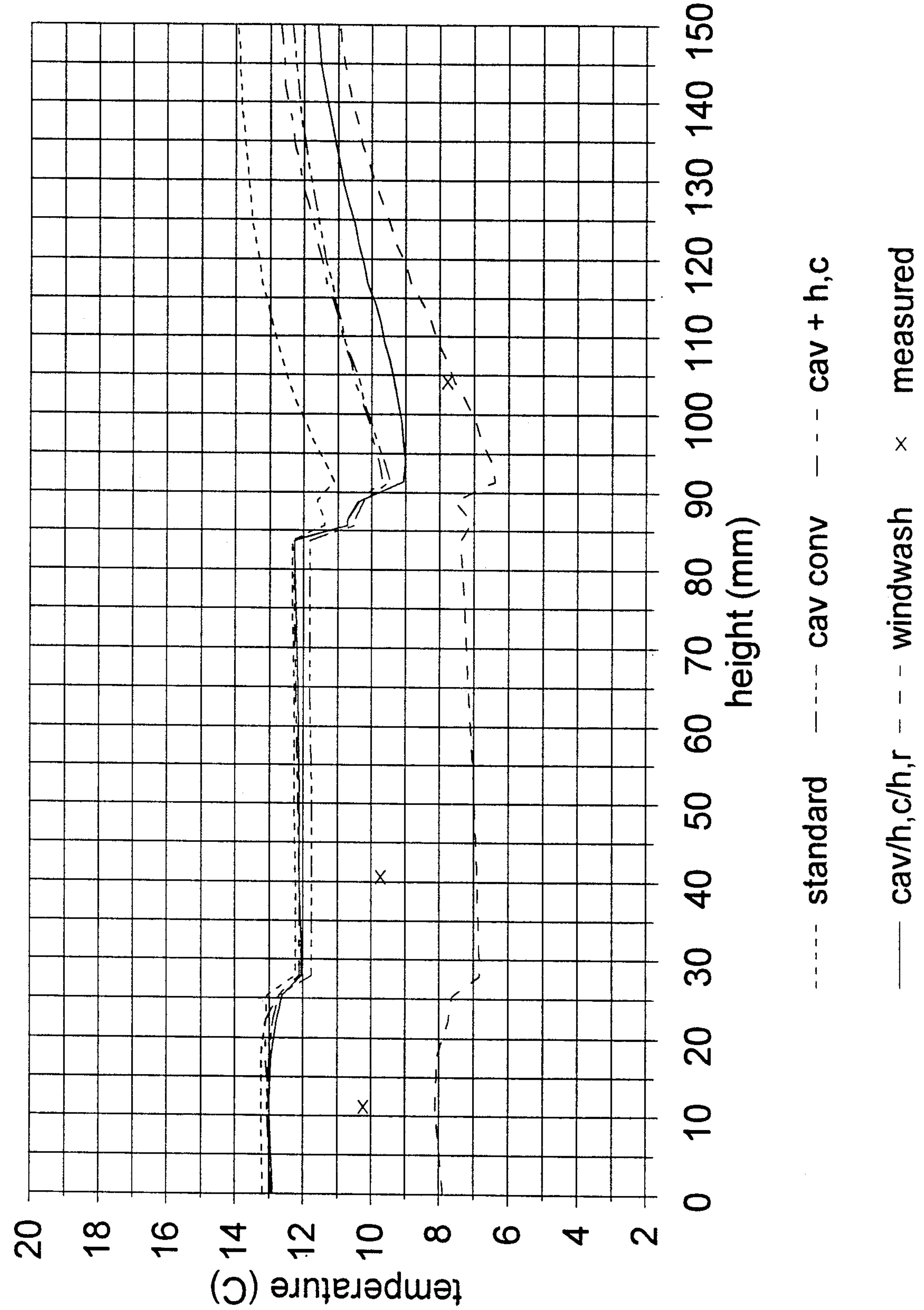


Fig 4.6 Specimen K7a sill temperature
TB alum fixed frame - foam spacer

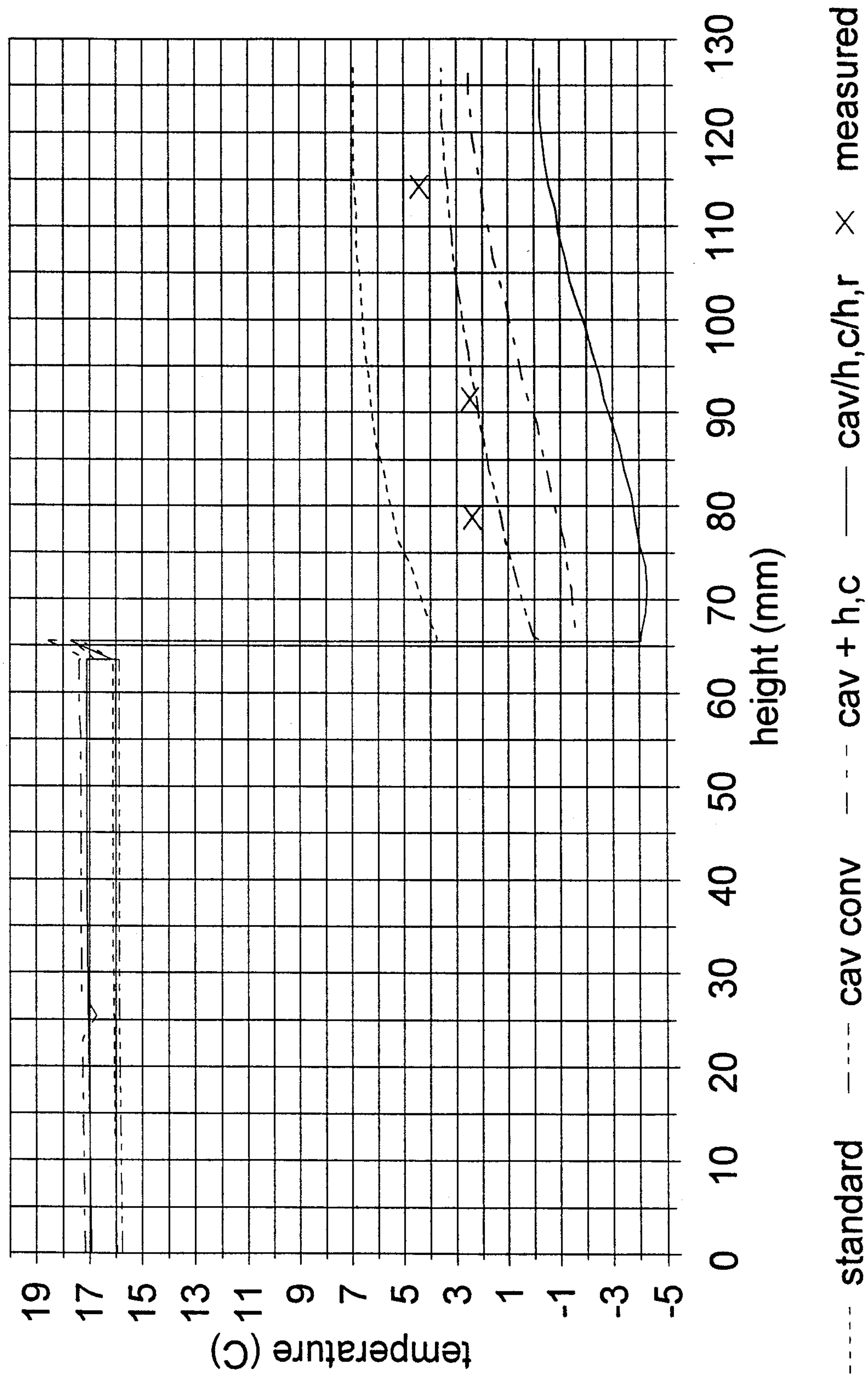


Fig 4.7 Specimen K7b sill temperatures

TB alum fixed frame - foam spacer

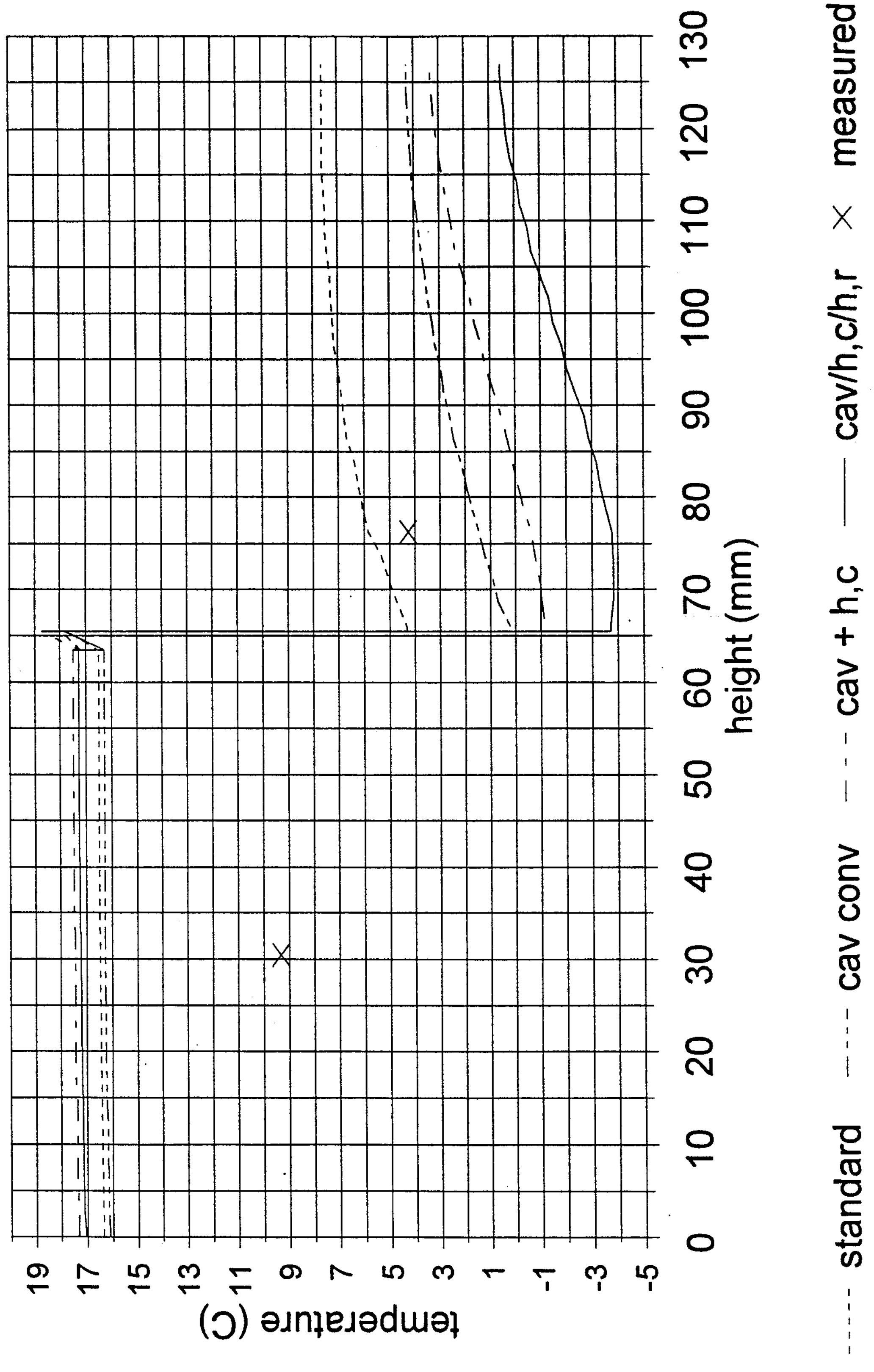


Table 4.5 Average change in surface temperature due to local variation in h_i, °C (°F)

ID	Description of Specimen	frame	glass
M1	wood casement frame, DS aluminum spacer	-0.02 (-0.04)	-1.7 (-3.1)
M4	alum-clad wood casement frame, DS aluminum spacer	-0.5 (-0.8)	-2.2 (-4.0)
M5	wood casement frame, silicone foam spacer	-0.3 (-0.5)	-1.7 (-3.0)
M6	alum-clad wood casement frame, silicone foam spacer	-0.3 (-0.6)	-1.8 (-3.3)
M7	wood casement frame, TB aluminum spacer	-0.3 (-0.6)	-1.8 (-3.2)
M8	alum-clad wood casement frame, TB aluminum spacer	-0.4 (-0.7)	-1.9 (-3.4)
M9	wood casement frame, vinyl spacer	-0.2 (-0.4)	-1.6 (-2.9)
K5	TB aluminum fixed frame, TB aluminum spacer	+0.9 (+1.6)	-1.3 (-2.4)
K6	TB aluminum operable frame, TB aluminum spacer	+0.2 (+0.3)	-0.9 (-1.6)
K7	TB aluminum fixed frame, silicone foam spacer	+1.2 (+2.2)	-4.2 (-7.5)

In all figures, the specimens were simulated with the conventional CSA A440.2 method for determining U-values, in which convective motion in the glazing cavity is applied uniformly over the entire cavity and the average room-side film coefficient is distributed uniformly over the surface of the specimen (labelled "standard" in all figures). Convective motion in the glazing cavity is then simulated explicitly (see Section 3.1), as shown in the figures ("cav conv"). The convective component of the room-side film coefficient is then allowed to vary locally ("cav + h,c"); and, finally, the radiative component is also allowed to vary locally ("cav/h,c/h,r"). Where available, measured values from physical tests are provided for comparison ("measured").

In all cases shown in Figures 4.2 through 4.7, an explicit model of the convective motion in the cavity produces colder surface temperatures on the sill sections, and including local variation of the room-side film coefficient produces colder temperatures still. In most cases, these modifications result in more accurate results (relative to measured temperatures). It also appears that the magnitude of the changes is roughly equally attributable to the effects of convection in the glazing cavity and local variation in the room-side film coefficient.

The measured values should be viewed with some caution, however: thermocouple placement on the frames is not specified in the test reports, so their vertical location is uncertain. For example, the thermocouple on the sash in Figure 4.2 was assumed to have been placed on the vertical surface of the sash (at y = 71 mm). If it was in fact placed on the horizontal surface of the sash (at y = 79.5 mm), then the simulation would be as accurate in its prediction of the sash temperature as it is for the frame temperature (at y = 18 mm).

Also, the measured glass temperatures shown in Figures 4.2 through 4.5 were recorded at 50 mm from the corner of the window, whereas simulation applies to the centreline of the window. As discussed in Section 3.2, the measured temperature at the centreline could be anywhere from zero to two Celsius degrees warmer. (The measured glass values in Figures 4.6 and 4.7 are at the centreline.) Still, it appears that the changes resulting from including cavity convection and local variation in room-side film coefficient produce results closer to the test results.

In Figure 4.5, the modified simulation procedure produces temperatures which are closer to the measured values, but are still 2 - 3°C warmer than the thermocouple readings. It was suggested that this specimen, which is an operable casement window, might experience "wind-washing" during the testing. In other words, some of the wind impinging on the weather-side surface may find its way past weatherstripping and into weepholes, thus bringing cold air into the interior cavities of the specimen, possibly bypassing the thermal break in the frame. This effect was investigated by introducing the weather-side conditions into the interior of the specimen during a simulation, bypassing the thermal break (shown by the line labelled "windwash" in Figure 4.5). This represents a worst-case situation: as Figure 4.5 shows, the measured values are between the case of no wind-washing and maximum wind-washing.

There is no way of predicting how much wind-washing will occur in a given test (and no way of determining the response of the specimen to wind-washing). Separate from the effects of air leakage (see Section 4.4), then, wind-washing poses some difficulty for the simulation procedure. It should be noted, however, that the specimen shown in Figure 4.5 has a relatively large thermal break, and could be more sensitive to the effects of wind-washing than most thermally broken metal-frame windows. Given that this constitutes something close to a worst-case situation, the difference between simulation and measured temperatures (2 - 3°C) may not be too serious. Moreover, the effect of wind-washing on the glass temperature (which is the colder temperature, and would therefore define the I value) is less than that of the frame, and the simulation is only 1 - 2°C off of the measured value in this region.

The results of the commercial thermally broken aluminum window are shown in Figures 4.6 and 4.7. The glass temperature prediction for the "cavity convection model" is very close to the measured result and overpredicted by 3.3 Celsius degrees for the "cavity convection and hc adjusted model" when compared to the National Research Council test (Figure 4.6). This a larger difference than with the other windows but probably still acceptable. There is, however, a larger temperature difference for the frame: 5 Celsius degrees (see Figure 4.7). Referring back to the test results in Figure 2.2, there was approximately a 5 Celsius degree temperature difference between the sill and the head. Thus, the FRAME program temperature predictions are close for the head (and upper jamb) portions of the window, but high for the sill and lower jamb portions. This discrepancy may be due to air leakage or convection within the large aluminum channels.

As Table 4.5 indicates, the effect of improving the simulation procedure have very little effect on frame surface temperatures (which are already reasonably accurate relative to tested values). The improvements have a substantial effect on glass temperatures, however, and appear to be bringing those values much closer to the measured glass surface temperatures.

The simulations with no local variation in the radiative component of the film coefficient (labelled "cav + h,c" in Figures 4.2 through 4.7) are also reasonably close to the measured values for the metal-frame specimens. These simulations were done partly to determine the magnitude of the radiative-component effect, but also because it was hypothesized that this might be a more accurate model of the room-side film coefficient. The basis of this hypothesis is that, although the direct view factor from the surface of the specimen to the room is reduced, the radiative heat transfer between the room-side air and the room-side surface of the specimen might not be substantially reduced due to reflections off the frame surfaces. At the sightline, for example, the glass surface has a view factor of 0.5 to the room and 0.5 to the frame, but at such a low angle of incidence to the frame, most of the view factor to the frame is actually a reflection of the room, so that the view factor to the room is not significantly reduced.

Given that the hypothesis appears to have been borne out by the results shown in Figures 4.4 - 4.7 (i.e., the metal-frame specimens), and that the modifications to the radiative component of the film coefficient are somewhat involved, it is reasonable to suggest that the modifications to the radiative component are not justifiable in terms of the increase in accuracy for the amount of additional effort required.

4.4 Effect of Air Leakage

Some concern has been expressed that air leakage can affect the condensation potential in a given window design. Air leakage (in which air from the cold side of the specimen leaks completely through the specimen and enters the room side of the specimen) can reduce room-side surface temperatures much in the same way as wind-washing (in which cold air enters the specimen, but does not penetrate to the room side). In some case, the introduction of cold, dry weather-side air may reduce the tendency for condensation to form, but this is difficult to predict as it depends on several variables.

Studies looking at the effects of pressure cycling [Air-Ins, 1993] and operation cycling [Air-Ins, 1991] showed a general increase in air leakage in windows after 2000 pressure cycles or 2000 motion cycles. The studies also showed a reduction in I values for many of these same specimens, but there was no clear correlation between the amount of increased air leakage and the reduction in I value for the specimens evaluated. In some cases, although the air leakage of the windows generally increased after pressure cycling, the I values also increased.

The results of both these studies showed that the effect of increased condensation potential is largely limited to the frame, and that I values for the glazing are not affected by the increase in air leakage. In the current study, varying the frame type in simulations had little effect on the glass I values (compare Tables 4.1b and 4.1c), unless the glazing-in system was substantially different (compare Tables 4.1a and 4.1c: the specimen in Table 4.1a was glazed in using a foam glazing tape which extended above the sightline and affected the glass results).

Therefore, although air leakage may affect condensation potential to some degree, it does not appear to substantially change the I values for the glass. As the glass values define the I values for the window in the case of most windows with non-metal frames, air leakage may not have a substantial effect on condensation potential for these types of products. Further research would be required, however, before categorically stating that air leakage is only important for metal-framed windows.

5.0 DEVELOPMENT OF A NEW PROCEDURE

An effective simulation procedure for condensation potential must be both simple and accurate. A simple method will reduce the cost of simulation, and will be less likely to introduce errors, relative to a complicated method which might be slightly more accurate. Based on the assessment of the current testing procedures, it may also be more desirable to achieve consistency, rather than attempting to achieve more accuracy with simulation than is currently the case in physical testing. Unfortunately, there is a very small amount of useful physical data upon which to base a robust simulation methodology.

First, it is important to recognize the limitations of simulation. If air leakage has a significant effect on condensation potential, then products which are found to have a significant amount of air leakage should be required to undergo physical testing for condensation potential. Further study is needed to determine the exact level of leakiness at which this effect becomes important.

Also, two-dimensional simulation reflects temperature profiles at or near the centreline of the product. It is difficult to assess the magnitude of corner effects, or to attempt to develop a correlation between centreline and corner temperatures, as there are insufficient data to do so. Thermographic testing would be useful in this regard, but only in cases where the room-side film coefficient could be measured, to allow accurate comparison between simulation and thermographic results.

When these issues have been resolved, however, the procedure for simulating condensation potential should be relatively simple:

1. Only sill sections need be analyzed. The other sections of a window do not contribute to the condensation potential;
2. The convective cavity model in VISION4 and FRAME4 should be used to properly characterize the contribution of the glazing cavity to condensation potential;
3. Although local variation of the room-side film coefficient on the glass is important in accurately assessing surface temperatures, it does not make as great a difference on the frame and sash assembly, and is not worth the additional effort to modify the film coefficient in this region. Therefore, the nominal centre-glass film coefficient can be used, if modified to account for the linear reduction in the convective film coefficient near the sightline, as well as the reduced view factor between the glass and the room-side chamber in that region. The method outlined in Section 4.3 is

recommended for modifying the convective component of the room-side film coefficient. The radiative component can be modified (see Section 4.3), but the effort required does not produce an appreciable increase in the accuracy of the result, so this modification is unnecessary and not recommended.

4. The temperature locations recommended in the test procedure should be used to determine frame and glass surface temperatures, and non-dimensionalized as described in Section 2.1 to define separate I values for the glass and frame. The I rating for the frame may only be achievable via physical testing, if the window exhibits significant air leakage, but the I rating for the glass can always be obtained via simulation.
5. If simulation is to be compared against testing, the average room-side film coefficient must be known (and used in place of the nominal centre-glass value in Step 3), and the thermocouple locations must be known for precise comparison. Room-side and weather-side air temperatures are also important inputs to the simulation procedure, and the test values must also be known prior to simulation.

6.0 CONCLUSIONS

The temperature index is a useful concept, but it appears that physical testing is not done consistently, and certain key variables (room-side film coefficient, thermocouple location) are not being reported.

A comparison of physical testing results showed a variation in surface temperature measurements of up to 5.1°C on the glass and 7.3°C on the frame, resulting in a variation of 4 to 7 points in the I rating [Elmahdy, 1990]. Surface temperature is strongly dependent on the room-side film coefficient: different testing facilities may have different layouts which affect the room-side film, which may account for the variability seen in test results.

Computer simulation of condensation resistance offers low cost, repeatability, and a permanent record of the evaluation procedure, and appears to be reasonably accurate compared to test results, although there are not sufficient data to make a categorical statement regarding the accuracy of simulation.

A two-dimensional simulation model does not include corner effects, although local effects of hardware can be considered. A three-dimensional model would address this problem, but would be as expensive as testing in some cases, and the complexity of the data input required would likely introduce more errors, so that the simulation would ultimately be less accurate. It may be possible to assess the magnitude of corner effects, or to attempt to develop a correlation between centreline and corner temperatures, but there are insufficient physical test data to do so. Thermographic testing would be useful in this regard, but only in cases where the room-side film coefficient could be measured, to allow accurate comparison between simulation and thermographic results.

A comparison of simulation with test results shows that differences between test and simulation are equal to or less than the variability seen between laboratories (for the same specimen). The difference between test and simulation for the lower glass temperature is typically in the order of 1 to 2 Celsius degrees with a worst case of 3.3 C° when compared to results from the National Research Council Canada. There appears to be slightly poorer agreement between test and simulation for the frame and sill temperatures. Typically simulation is 3 C° higher than the test and in the worst case 5 C° for thermally broken aluminum windows.

The larger difference for the framing system may be due to wind-washing, air leakage or convection in large aluminum channels. Simulation does not currently address the influence of air leakage on condensation resistance: indeed, this effect has not been quantified (although it may be significant). Also, wind-washing (partial air leakage) may contribute to a reduced I value: this effect is also not quantified, and may depend in part on the specific design of the frame and weatherstripping. Wind-washing is not specifically addressed by the simulation procedure.

Frame temperature is relatively independent of the glazing system, and sash temperature is relatively independent of the glazing system for low-conductance (i.e., nonmetal) frames. Also, the sash temperature is affected by the spacer type, but the frame temperature is not (in the case of low-conductance frames, or where the sash is insulated from the frame).

The glass temperature at 50 mm above the sightline is relatively independent of spacer type, but the glass temperature at 13 mm above the sightline is not. Also, the glass temperature is generally not affected by the frame type, but is somewhat dependent on the glazing-in system (i.e., the weatherstripping and sealants used to secure the glazing system into the sash).

Room-side surface temperatures are strongly dependent on the magnitude and local variation of the room-side film coefficient. Room-side temperatures are also dependent on the exterior and interior temperatures, but the non-dimensionalized temperature index (I value) is not.

Local variation in the room-side film coefficient to account for reduced convective effects in corners and reduced radiative view factors between the room-side surface and the room produces a change in the room-side surface temperatures roughly equal to the change resulting from an explicit model of convection within the glazing cavity. Together, these effects result in a reduction of approximately 2°C for the glass temperature and 0.3°C for the frame temperature (although metal frame temperatures tended to increase by about 1°C when local h_i variation was modelled).

7.0 RECOMMENDATIONS

The condensation test procedure should be modified to either standardize the room-side film coefficient, or allow it to be measured during the test and reported. Also, thermocouple locations should be specified as part of the test report. Condensation tests in which the room-side film coefficient has not been properly addressed should be considered suspect.

The effects of wind-washing and air leakage on condensation resistance should be further investigated. This would require physical testing of several specimens, both sealed and unsealed to permit partial or complete air leakage, with thermography used to assess room-side temperature distribution. Also, measurement of room-side film coefficients would be required for comparison to simulation (with the intent of developing a computer model that would account for these effects).

In the absence of a clear understanding of the effects of air leakage on condensation, simulation should not be used to assess condensation potential in the case of specimens which exhibit air leakage above a certain threshold (yet to be determined). Such products would require condensation evaluation to be done by physical testing.

Thermographic testing should also be used to assess the magnitude of corner effects, or to attempt to develop a correlation between centreline and corner temperatures, as there are insufficient data to do so. Again, the room-side film coefficient should be measured, to allow accurate comparison between simulation and thermographic results.

A method for simulating condensation resistance is proposed, to predict condensation resistance in sill sections for reasonable airtight windows (see Section 5). This procedure should be validated against physical tests, partly to assess its accuracy and fine-tune the simulation method, but also to determine the point at which air leakage effects become so predominant that the specimen cannot be simulated for condensation resistance, and must be tested.

8.0 REFERENCES

AAMA, 1981. "Voluntary Test Method for Condensation Resistance of Windows, Doors and Glazed Wall Sections", publication no. AAMA 1502.7-1981. American Architectural Manufacturers Association.

Air-Ins, 1991. "A Study of the Long Term Performance of Operating and Fixed Windows Subjected to Pressure Cycling", report prepared for the Energy and Alternative Energy Technology Branch of CANMET Division of Natural Resources Canada, December, 1991.

Air-Ins, 1993. "Long Term Performance of Operating Windows Subjected to Motion Cycling", report prepared for the Energy and Alternative Energy Technology Branch of CANMET Division of Natural Resources Canada, March, 1993.

ASHRAE, 1995. "ASHRAE Research Project 877-RP: Determination of Glazed Wall/Roof Fenestration U-Factors for the ASHRAE Handbook of Fundamentals", project currently under way by Enermodal Engineering Limited (results pending completion of project).

ASHRAE, 1996. "ASHRAE Standard 142: Standard Method for Determining and Expressing the Heat Transfer and Total Optical Properties of Fenestration Products, Public Review 1.0", American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc. October, 1996.

CSA, 1990. "CAN/CSA-A440-M90. Windows: A National Standard of Canada", Canadian Standards Association.

Curcija, D., and W.P. Goss, 1993. "Two-dimensional Natural Convection over the Isothermal Indoor Fenestration Surface - Finite-Element Numerical Solution". ASHRAE Transactions 1993 vol. 99, Part 1. American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc. January, 1993.

De Abreu, P.F., R.A. Fraser, H.F. Sullivan, and J.L. Wright, 1996. "A Study of Insulated Glazing Unit Surface Temperature Profiles Using Two-Dimensional Computer Simulation", ASHRAE Transactions 1996, vol. 102, Part 2. American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc. June, 1996.

Elmahdy, A.H. 1990. "A Universal Approach to Laboratory Assessment of the Condensation Potential of Windows", Transactions of the 16th Annual Conference of the Solar Energy Society of Canada, June 18-20, 1990.

Elmahdy, A.H., and Th. Frank, 1993. "Heat Transfer at the Edge of Sealed Insulating Glass Units: Comparison of Hot Box Measurements with Finite-Difference Modeling". ASHRAE Transactions 1993 vol. 99, Part 1. American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc. January, 1993.

Kawneer, 1996. John Spadaro, personal communication, including confidential test report documentation. Kawneer Company Canada Limited, August, 1996.

McGowan, A.G. 1995. "Numerical Prediction of Window Condensation Potential", ASHRAE Transactions 1995 vol. 101, Part 1. American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc. January, 1995.

H.F. Sullivan, J.L. Wright, and R.A. Fraser, 1996. "Overview of a Project to Determine the Temperatures of Insulated Glazing Units: Thermographic Measurement and Two-Dimensional Simulation", ASHRAE Transactions 1996, vol. 102, Part 2. American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc. June, 1996.

Wright, J.L. 1994. "A 2-D Numerical Model for Natural Convection in a Vertical Rectangular Window Cavity", ASHRAE Transactions 1994, vol. 100, Part 2. American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc. June, 1994.