Thermal Performance of Complex Fenestration Systems: Skylights, Greenhouse Windows and Curtainwalls

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EXECUTIVE SUMMARY

A recently developed standard, CSA A440.2, provides a method to rate regular windows and sliding glass doors for energy performance. In addition to other doors, which are being addressed in another standard, CSA A453, there are a few additional fenestration products found in Canadian buildings. This report specifically addresses problems of obtaining U-values for some complex window systems: skylights, greenhouse windows and curtainwalls.

Examples of these products are examined for energy performance using guarded-hot-box testing and detailed computer simulation.

Considerable difficulty was found both in testing and simulating these products. However reasonably good agreement was found between testing and simulation for a flat skylight and for a curtainwall, less with a domed skylight and a greenhouse. Film coeffi\cients and thermal bridging caused concern.

Noteworthy was the fact that all products tested had substantially higher U-vales than even standard vertical windows, let alone high-performance windows. Recommendations are made for further development of test procedures, further testing and extension of CSA standards to cover these products.

RÉSUMÉ

La norme CAS A440.2, récemment établie, fournit une méthode d'évaluation de la performance énergétique des fenêtre ordinaires et des portes coulissantes. En plus des autres portes, régis par la norme CSA A453, il existe d'autres produits de fenestration que l'on retrouve dans le bâtiment canadien. La rapport porte sur les difficultés posées par l'évaluation de la valeur U sur certains systèmes de fenêtres complexes: puits de lumière, fenêtres de serre et murs-rideaux.

On étudie la performance énergétique de certains produits à titre d'exemples à l'aide de boîtes d'essais thermique et de simulation par ordinateur.

ON a rencontré de nombreux obstacles en voulant mettre à l'essai ou simuler ces produits. Les puits de lumières plats ainsi que les murs-rideaux ne présentèrent pas trop de difficultés comparativement aux serres et aux puits de lumière en coupole. Les coefficients de film et les ponts thermiques suscitèrent particulièrement l'attention.

Il faut noter que tous les produits étudiés comportaient des valeurs U pius élevées que dans le cas des fenêtres ordinaires verticales, sans mentionner les fenêtres haute performance. Des recommandations sont faites pour élaborer des procédures d'essais, faire plus d'essais et élaborer les normes CSA afin d'englober ces produits.

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1.0 INTRODUCTION

The thermal performance of standard residential windows systems has been the subject of many research projects [Enermodal, 1992; Elmahdy, 1990; Elmahdy, 1992]. These projects used research-class guarded-hot-box testing and finite-difference/finite-element modelling to develop total-window U-factors. The results from these studies have been used to validate computer models, provide information on the performance of window systems and contribute to the development of standards for rating products.

There are several major groups of fenestration products for which very little research-class thermal performance evaluation has been conducted. These products include skylights, garden or greenhouse windows and curtainwalls. The building designer needs accurate information on the performance of these products to accurately size HVAC equipment and determine annual energy use.

This report examines the performance of these fenestration systems using guarded-hot-box testing and detailed computer simulation. The physical testing was performed at the National Research Council of Canada and the simulations were performed using the FRAME and VISION3 computer programs.

2.0 METHODOLOGY

2.1 Evaluation Procedures

There are two approaches that have been used to evaluate the thermal performance of fenestration systems: guarded-hot-box testing and detailed computer simulation. Guarded hot-box testing, if performed in a research-class facility, has the advantage of providing an accurate assessment of the total product heat loss. Computer simulation has the advantages of low cost, speed and providing component heat loss.

Nevertheless, there are some difficulties in using these procedures to evaluate skylights, greenhouse windows and curtainwalls. With regard to testing, the ASTM C1199 test procedure requires that the inside and outside film coefficients be determined so that standardized film coefficients can be applied [ASTM, 1991]. There is, however, uncertainty in the film coefficient for skylights and garden windows because the three-dimensional nature of these products makes it difficult to accurately area-weight temperature readings. Most test chambers can only evaluate windows in the vertical position for horizontal heat flow, whereas skylights are by definition mounted at an angle. A horizontal U-factor may not be representative of how a product performs in a tilted orientation.

There are also some concerns with using computer simulation to evaluate complex windows. Domed skylights have the complication that the glazing analysis programs (VISION3 and WINDOW) are not designed to evaluate domed surfaces. Curtainwalls with spandrel panels are complex systems that usually have minimal thermal breaks and regions of high heat transfer around assembly screws. Windows with non-planar surfaces are difficult to evaluate because of three-dimensional heat transfer effects and uncertainty in how the window shape might affect the inside and outside film coefficients.

Despite these concerns, it was felt that a combination of testing and computer simulation could be used to assess complex fenestration systems. If both methods gave similar results, there would be some confidence that the results are a reasonable representation of product performance and that either method could be used to rate products.

Guarded-hot-box testing was performed at the National Research Council of Canada in accordance with their procedures for testing windows [NRC, 1985]. This method is similar to ASTM C1199. In the NRC method, temperature-dependent equations for inside and outside film coefficients are developed using measurements on a calibration panel. These equations are assumed to apply to the fenestration system being tested, thereby eliminating the need for direct measurement of window surface temperatures. Nevertheless, window surface temperature measurements were made on the greenhouse window to determine whether this is a reasonable assumption for fenestration products that project out from the wall. Computer simulation was performed using the FRAME [Enermodal, 1992] and VISION3 [UofW, 1992] computer programs. These test and simulation procedures have been successfully used in previous window evaluation studies (see references given in Introduction).

The complexity of the product configurations necessitated modifications to the standard procedures for simulation and testing. These changes are discussed in Sections 2.3 and 2.4.

2.2 Products Selected for Evaluation

Four products were analyzed as a part of this project: a flat skylight, a domed skylight, a greenhouse window and a curtainwall system.

Flat Skylight

The flat skylight is double-glazed with an aluminum-clad wood frame and is manufactured by Velux Inc. The glazing unit has a 9.6-mm cavity filled with 95% argon. Each of the glazing lites is 3 mm thick. The inboard lite has a PPG Sungate coating, e=0.085. The spacer is dual-seal aluminum.

The skylight is operable, opening like an awning window. The skylight has an integral curb and was mounted on the outside of the mask wall for testing. The mounting detail and head and sill cross-sections are shown in Figure 2.1 and the jamb cross-sections are shown in Figure 2.2. The inside of skylight curb lined up with the mask wall opening. The outside skylight and mask wall dimensions and areas are summarized in Table 2.1. The skylight projects 102 mm out from the mask wall.

Table 2.1: Flat Skylight Dimensions

Configuration	Height (mm)	Width (mm)	Area (m^2)
Rough Opening	1104	480	0.530
Outside Skylight	1181	546	0.645

Figure 2.1: Head and Sill Cross-Sections of Flat Skylight

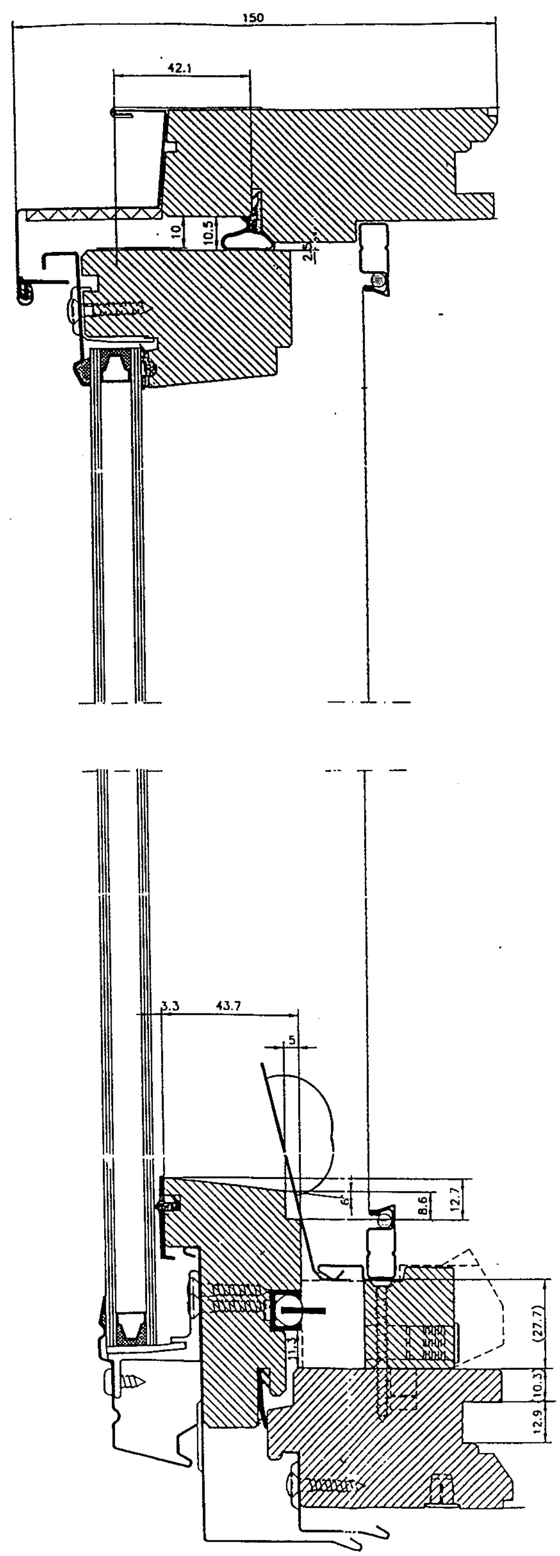
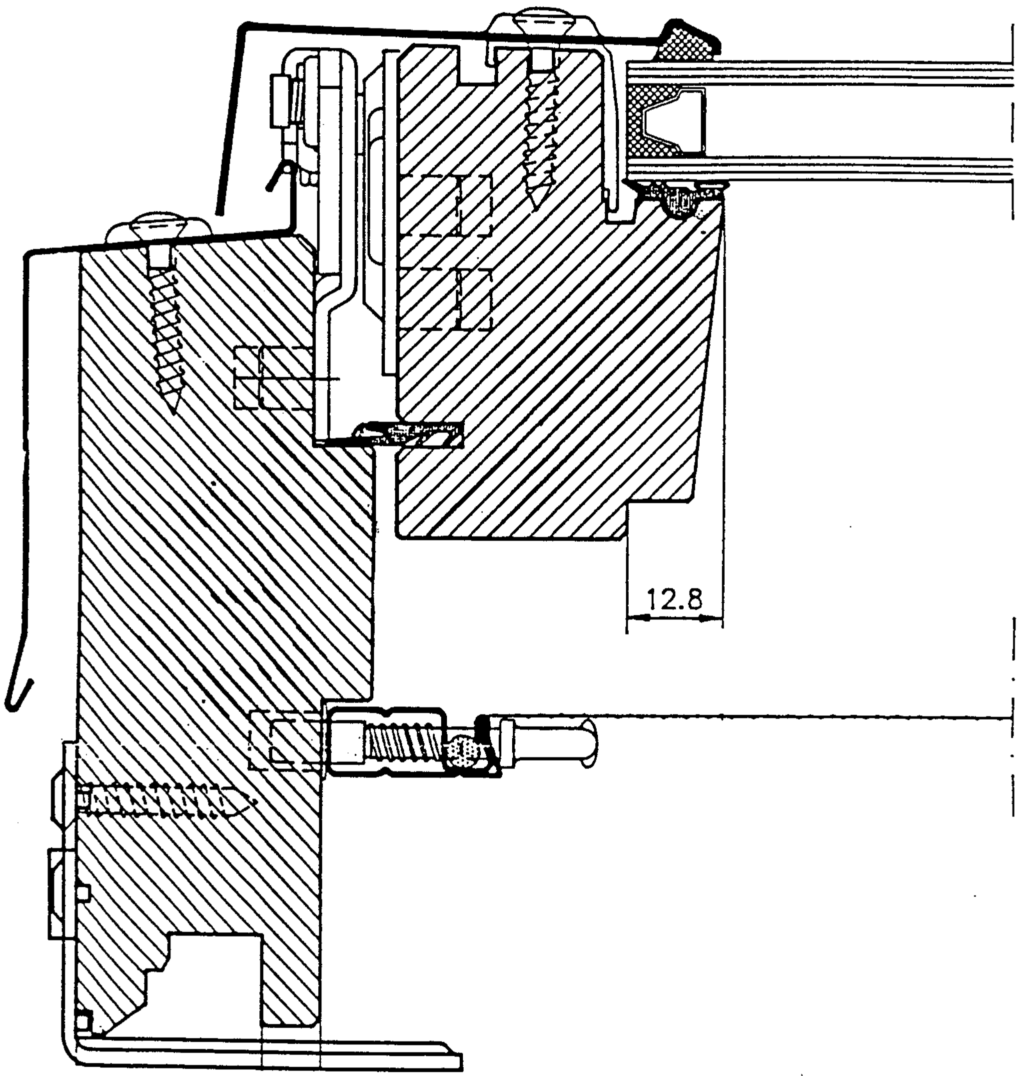


Figure 2.2: Jamb Cross-Sections of Flat Skylight



Domed Skylight

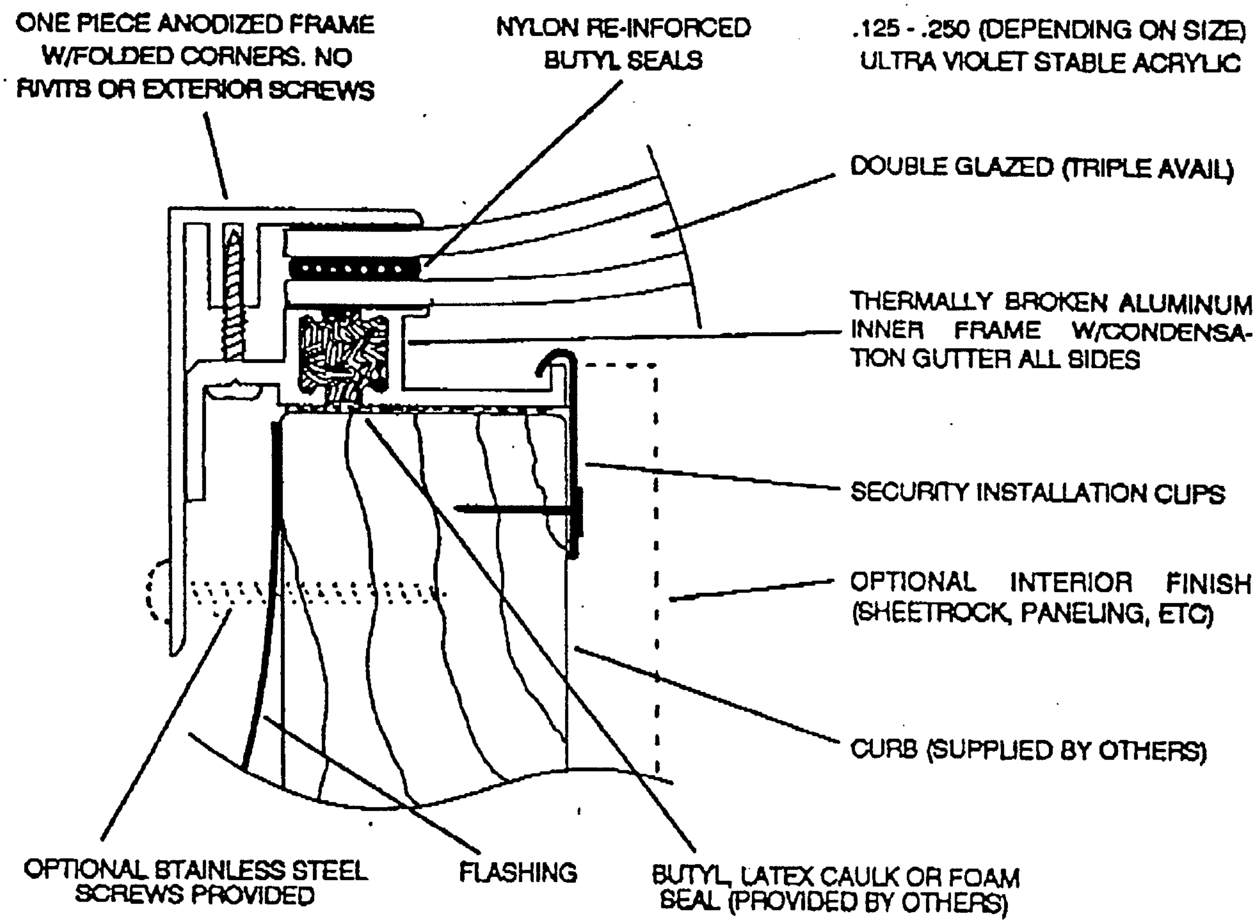
The domed skylight is a non-operable thermally broken aluminum unit as manufactured by Crystalite. It features a double-layered domed acrylic IG unit. The outer dome is larger than the inner dome so that the air gap between the acrylic panes is not constant. At the edges the panes are only 3 mm apart, whereas at the centre the gap increases to 26 mm. The edge spacer consists of butyl rubber 12.6 mm high and 3 mm thick.

The domed skylight does not have its own curb, but is usually mounted on a wooden curb in the field. The skylight was tested and simulated as mounted on a wooden curb. Figure 2.3 shows the frame cross-section and mounting detail.

Table 2.2: Domed Skylight Dimensions

Configuration	Height (mm)	Width (mm)	Area (m^2)
Rough Opening	1160	550	0.638
Outside Skylight	1240	630	0.786

Figure 2.3: Cross-Section of Domed Skylight



Greenhouse Window

The greenhouse window has five surfaces: top, front, two sides and a bottom (see Figure 2.4). Figures 2.5 and 2.6 show vertical cross-sections through the front and sides of the greenhouse window. The top is a fixed glazed unit which measures 420 mm by 1501 mm and is sloped at 25 degrees from the horizontal. The front face, measuring 771 mm by 1501 mm, is also fixed. The sides of the greenhouse window are similar to a single-hung operable window. The height of the sides varies in order to match the slope of the top face. The average height of the sides is 860 mm with a width of 381 mm. The base of the unit is wood and measures 1501 mm by 381 mm.

Table 2.3: Greenhouse Window Dimensions

Configuration	Height (mm)	Width (mm)	Area (m^2)
Standard Rough Opening	1602	911	1.459
Tested Rough Opening	1656	916	1.517
Outside Dimensions	1740	1000	1.740

The frame and sashes of the greenhouse window are aluminum with no thermal break. The IG unit used in all the glass faces of the greenhouse window is 3-mm clear double glazing with a 6.7-mm air-filled cavity. The spacer is Swiggle Strip, 6.7 mm wide by 5.7 mm high.

The window tested is 1740 mm (68.5") wide by 1000 mm (39") high including the nailing flange. The unit is made for a rough window opening of 1602 mm (63") by 911 mm (36").

Figure 2.4: Isometric of Greenhouse Window

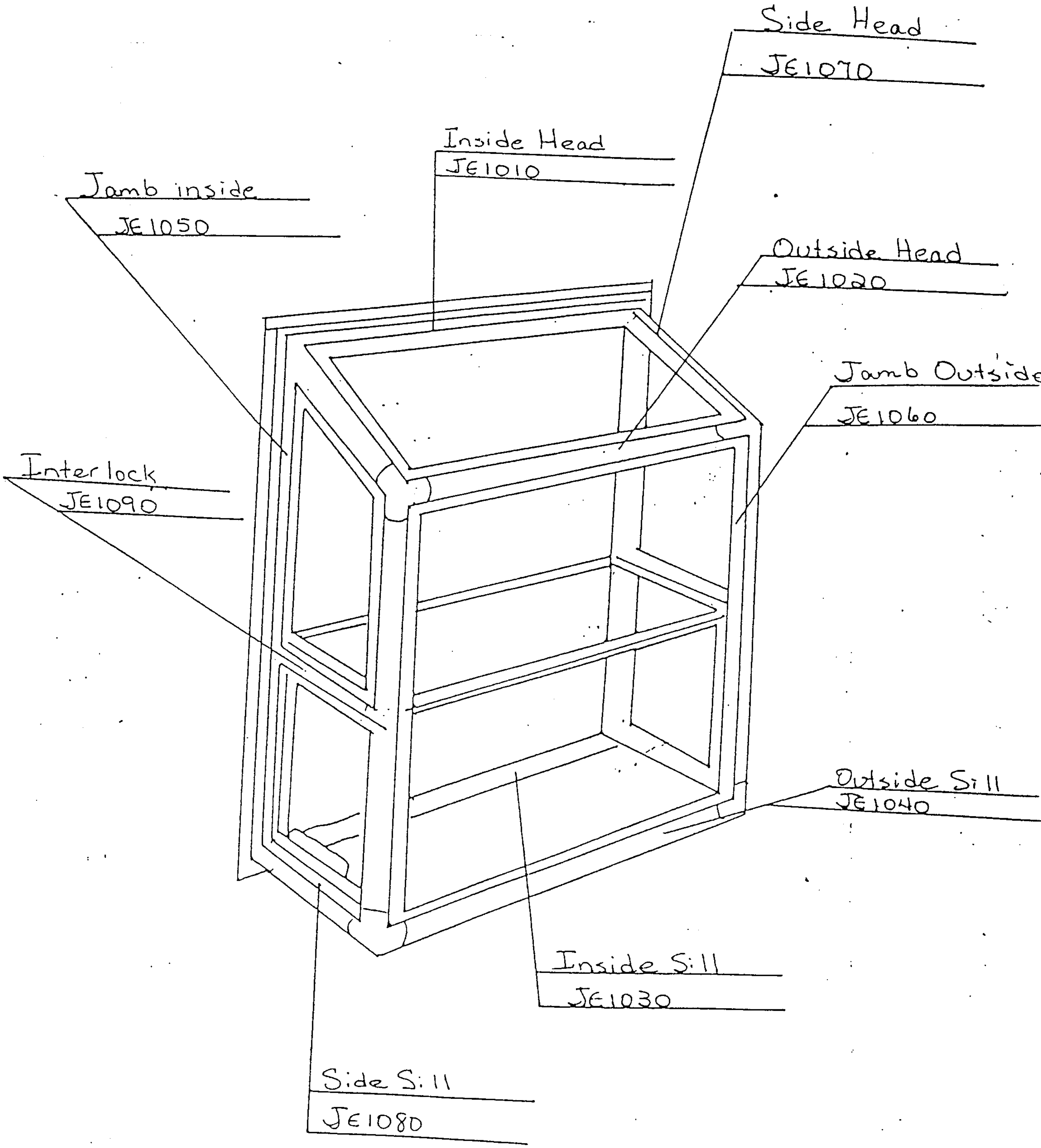


Figure 2.5: Vertical Cross-Section of Greenhouse Window

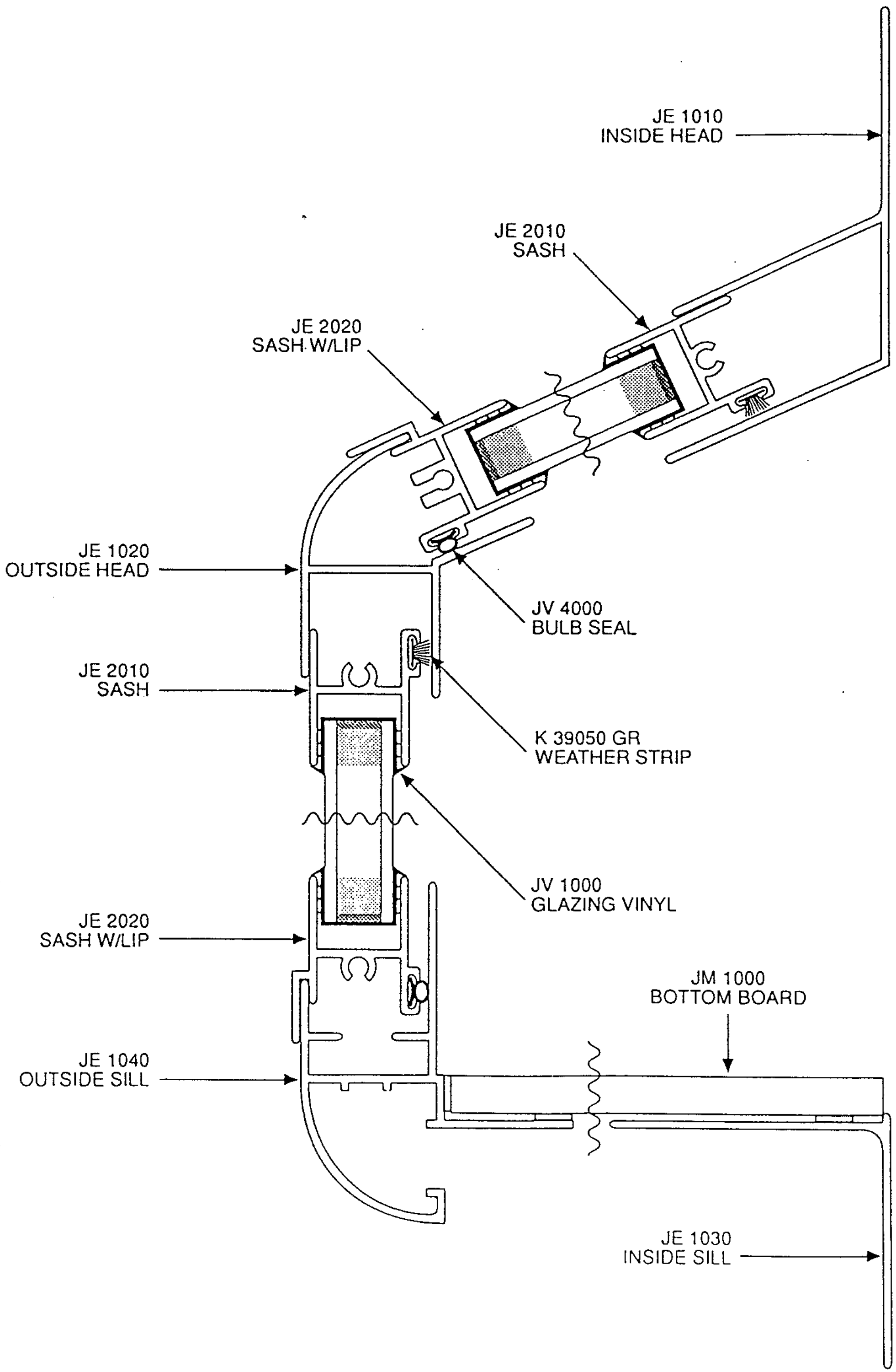
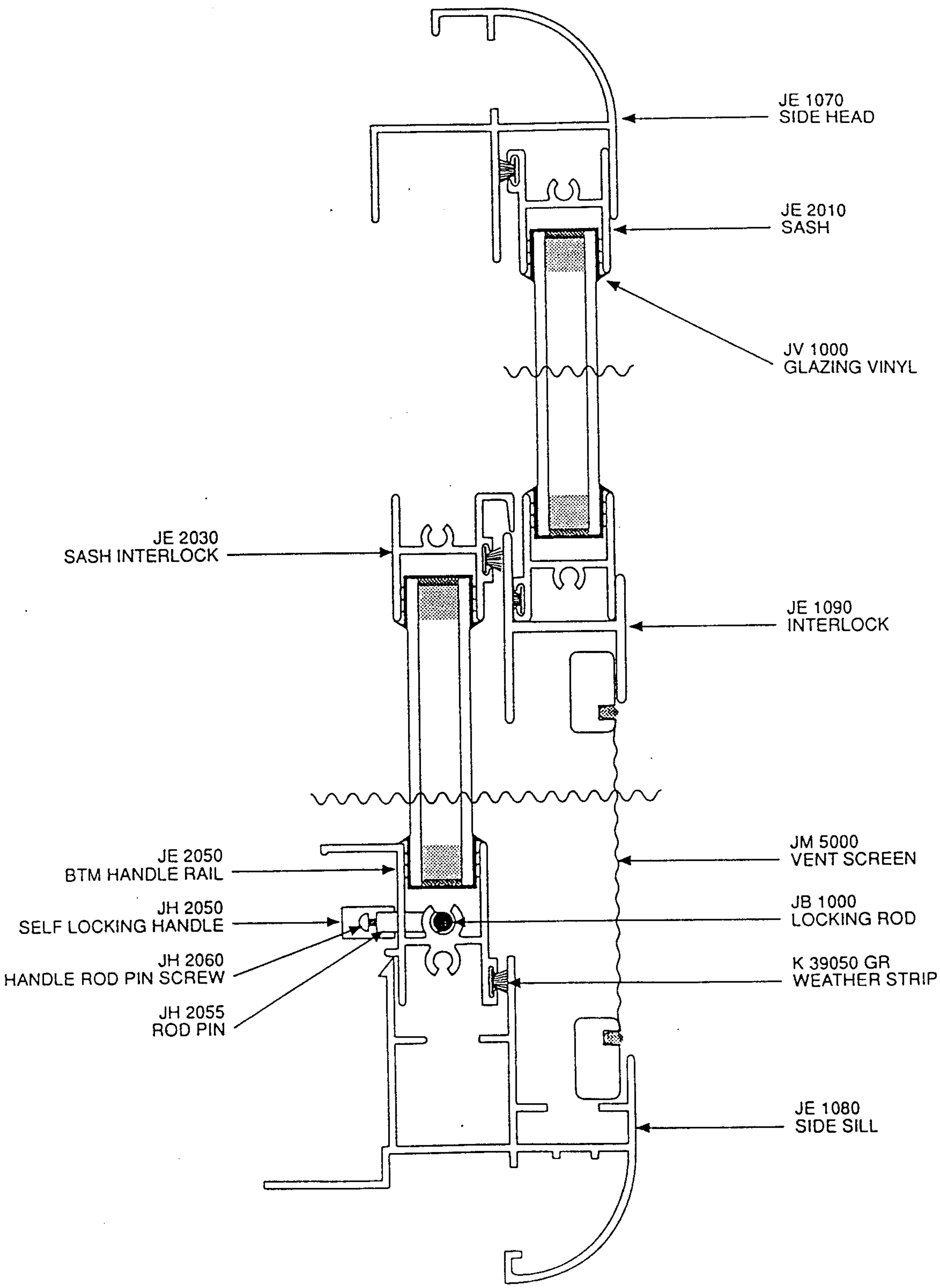


Figure 2.6: Vertical Cross-Section of Greenhouse Window



Curtainwall

The curtainwall consists of four sections: two vision panels and two spandrel panels, all separated by thermally broken aluminum mullions. The vision section is made up of 2 lites of 6-mm glass with a 13.4-mm air-filled cavity fixed into a thermally broken aluminum frame. A standard dual-seal aluminum spacer is used. The spandrel section is 113.4 mm thick consisting of 6 mm glass, 21.6 mm air cavity, 85.8 mm of fibreglass insulation and a 0.9 mm steel pan. The spandrel panels are also fixed into the thermally broken aluminum frame. Steel bolts placed on 152mm (6") centres hold the frame together. The overall size of the unit evaluated was 1816mm (71.5") wide by 2070mm (81.5") high. Figures 2.7 through 2.10 shows cross-sections of the curtainwall.

Table 2.4: Curtainwall Dimensions

Configuration	Height (mm)	Width (mm)	Area (m^2)
Rough Opening	2070	1816	3.76
Outside Dimensions	2070	1816	3.76

Figure 2.7: Frontal View of Curtainwall

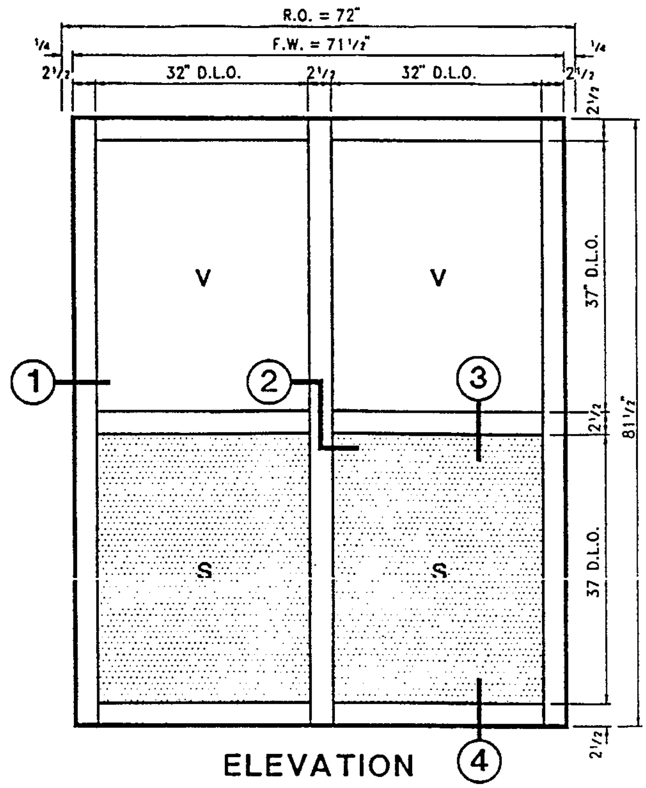


Figure 2.8: Vertical Jamb Mullion Cross-Section

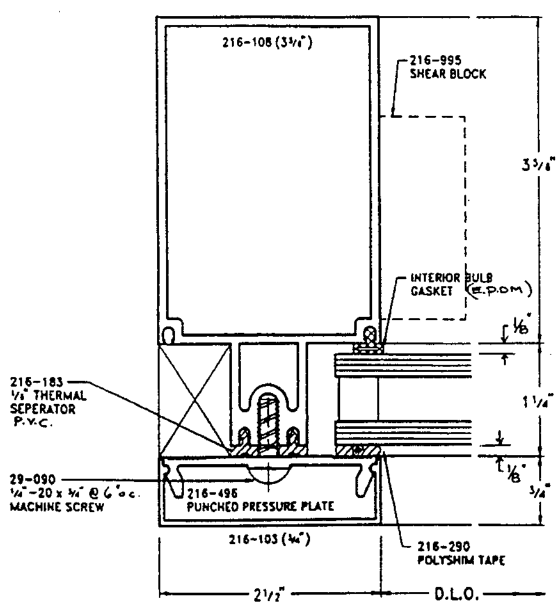


Figure 2.9: Spandrel Sill / Vision Head Cross-Section

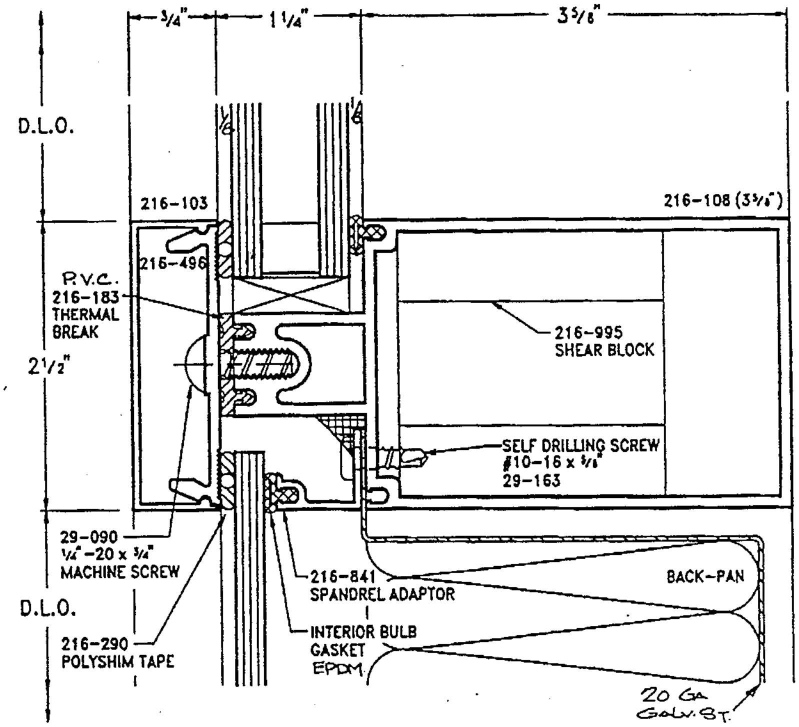
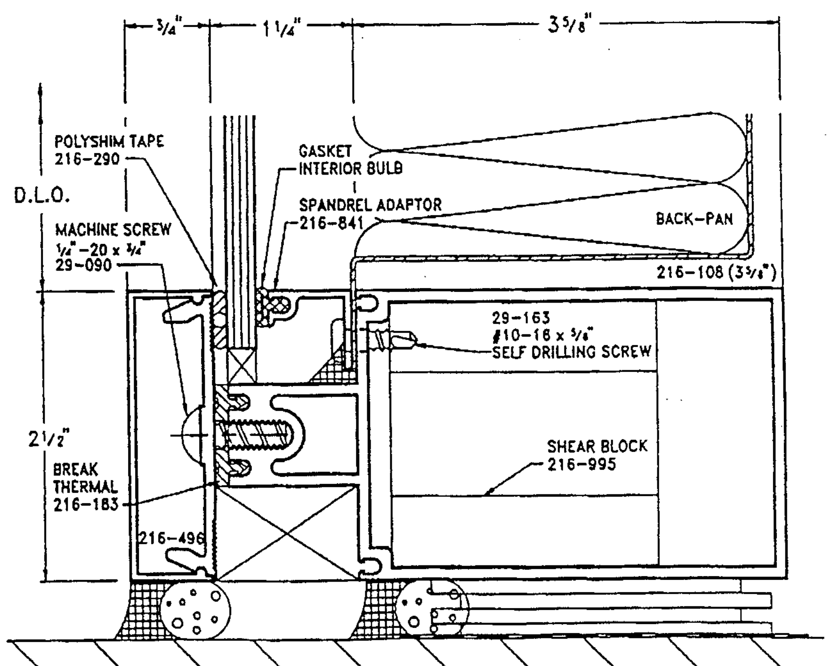


Figure 2.10: Spandrel Panel at Sill Cross-Section



2.3 Test Procedure

Some adjustments had to be made to NRC's standard test procedure to evaluate two of the fenestration products. Because the domed skylight and greenhouse window extend significantly beyond the mask wall, it was necessary to devise a method of supporting these products without damaging the mask wall. The domed skylight was mounted on a 2X6 wooden curb. The wooden curb was inserted 50 mm (2 inches) into the mask wall to permit attachment while leaving 87.5 mm (3.5 inches) exposed beyond the mask wall to represent a 2X4 curb. For the greenhouse window a 2X4 curb was mounted inside the mask wall opening and flush to the exterior mask wall skin. The outside flanges of the greenhouse window were screwed to the wood curb. Because of the mounting arrangement, slightly more area of the skylight was visible from the inside (warm side) than in a typical installation. The flat skylight was light enough that it could be screwed to the exterior mask wall skin without causing damage to the mask wall. The curtainwall was installed in a manner similar to that for windows.

The initial test of the greenhouse window gave unrealistic results. The problem was attributed to the extra interior surface area (due to the projection out from the mask wall) and the low thermal resistance of unit. Both of these factors made the value of the interior film coefficient extremely important in determining window performance. To obtain better estimates of the interior and exterior film coefficient, 44 thermocouples were installed on the window and the window was retested. The location of these thermocouples and the method of data reduction is given in Appendix A. The second test provided more realistic results which are presented in Section 3. The other three window systems were tested using the standard NRC procedure, that is, without measurement of the surface temperatures.

2.4 Simulation Procedure

Simulation procedures also had to be modified to evaluate three of the four window products. No modifications were required for the flat skylight.

Three issues had to be addressed to simulate the performance of the domed skylight: thermal-optical properties of acrylic, intra-glazing convective heat transfer, and the effect of increased surface area due to dome. Thermal-optical properties for acrylic are not listed in the VISION3 program. The thermal conductivity for acrylic was assumed to be 0.200 W/mC (as listed in the FRAME program). The long-wave emissivity of the acrylic was measured at the University of Waterloo to be 0.86.

The shape of the dome means that the interior and exterior glazed surface areas are greater than for a flat surface and the width of the air cavity between the sheets of acrylic is not constant. It was felt, however, that the geometry is similar enough to two parallel plates that the convective heat transfer correlations used in VISION3 could be used with the gap spacing set to the average value of the unit. The increased surface area could be handled by increasing the centre-glazing heat transfer coefficient by the increase in interior surface area over a flat plate. (The interior surface area was chosen because it more adequately represents the resistance effect of the interior film coefficient and radiative heat transfer.)

Several measurements were made to determine the areas and dimensions of the domed skylight. By measuring the volume of the interior dome, the total surface area was calculated assuming that the dome could be represented by the shape of a pyramid. The volume of the interior cavity was measured by drilling a hole in the outer dome and filling the cavity with a measured quantity of water. The average width of the cavity was determined by dividing the cavity volume by the interior surface area. The average cavity width was determined to be 18.2mm and the interior glazed surface area was 0.670 m^2 , 2 % larger than a flat surface.

The centre-of-glazing U-value was determined by running the VISION3 program with an 18.2mm air cavity. The convective heat transfer is fairly constant in this region of cavity spacings, so that a minor variation in the cavity spacing would have little impact on the centre-of-glazing U-value. For the edge-of-glazing U-value, the FRAME program was run with a 3-mm air cavity for the 63.5 mm (2.5 inches) of edge glazing in order to accurately model the frame/edge interface heat transfer.

To determine the U-value of the greenhouse window, separate component U-values were determined for each of the five faces. The total window U-value was determined by summing the product of the U-value and the surface area of each of the five separate windows and dividing by the total area of the rough opening.

The simulation of the greenhouse window was complicated by two factors: heat transfer through the spandrel panel and thermal bridging due to bolts. The spandrel panel cross-section was modelled in FRAME with the thermal conductivity of the insulation set to 0.034 W/mC. The thermal resistance of the air cavity between the insulation and the cover glass was determined using the glazing analysis program.

The steel bolts represent a significant thermal bridge because there is no thermal isolation. A two-step model was developed to determine the three-dimensional impact of the steel bolts. First, a cross-section through the bolts parallel to the mullion was made showing the bolts every 150 mm (6 inches). An effective conductivity was determined that represented the average heat transfer across the air/bolt cavity. The value, 2.028 W/mC, is a weighted average of the heat transfer through the bolt and through the air cavity. This conductivity value was used to represent a continuous strip of bolt/air cavity in each of the cross-section models perpendicular to the mullions where the bolt would be found.

To determine the overall U-value, the curtainwall was treated as two separate windows: vision panel and spandrel panel. The total curtainwall U-value was determined by summing the product of the vision-panel U-value and the surface area with the product of the spandrel-panel U-value and the surface area and dividing the total UA by the total window test size.

Two sets of simulations were performed for each of the windows: test conditions and standard conditions. In the test-condition simulations of the interior film coefficients for the glass and frame were calculated based on the temperature dependent equation used in VISION and Chapter 27 of the ASHRAE Handbook of Fundamentals. It was felt that these values should be reasonably close to the average values obtained during the test. The simulations were then repeated with the interior and exterior film coefficients fixed at 8.3 and 30 W/m^{2}C, the standard conditions used in NRC testing.

For the test-condition simulations, it was necessary to adjust the interior radiative coefficient to account the reduced view factor of some portions of the window. In standard flat windows, essentially all of the heat radiated from the interior-side of the window ends up in the room. For windows that project out from the wall (e.g., skylights and greenhouse windows), the portions of the window that are perpindicular to the wall have a view factor to the room of approximately 0.5. Thus, the radiative heat transfer coefficient is half the value used for conventional flat windows. In addition, the vertical glazing (especially in the greenhouse window) has a reduced view factor because some of the radiation is to the side panels. For the size of greenhouse window tested, the vertical glazing view factor is 0.54.

3.0 TEST AND SIMULATION RESULTS

The results of the tests and simulations on the four fenestration systems are summarized in Table 3.1. The test report is included in Appendix A. The values listed are for two sets of conditions: test-conditions and NRC standard conditions. The simulated component U-values for the four windows are given in Table 3.2. Given the difficulties in testing and simulating these products, there is reasonable agreement between test and simulation for three of the four windows. The only significant discrepancy was with the domed skylight.

Table 3.1: Comparison of Tested and Simulated U-values[1]

Window	Test-Conditions[2] (W/m^2C)			Adjusted to NRC Standard Conditions[3] (W/m^2C)		
	Test	Simulation	% Diff.	Test	Simulation	% Diff.
Flat Skylight	3.32	3.03	-8.7	3.57	3.22	-9.8
Domed Skylight	4.35	5.05	16.1	4.59	5.34	16.4
Greenhouse	7.65	9.38	22.6	9.91	11.15	12.5
Curtainwall	2.89	2.94	1.7	3.03	3.08	1.7

[1] All U-values are based on area of rough window opening.

[2] The film coefficient for the test and simulation are not necessarily equal.

[3] The test and simulation results adjusted to equal film coefficients of 8.3 W/m^2C (inside) and 30 W/m^2C (outside)

Table 3.2: Simulated Component U-Values (In W/m² °C)

Flat Skylight	U-Value Centre Glazing	U-Value Edge Glazing	U-Value Frame	U-total (Rough Opening)
as tested	1.59	2.37	5.65	3.03
standard conditions	1.59	2.40	6.27	3.22

Domed Skylight	U-Value Centre Glazing	U-Value Edge Glazing	U-Value Frame	U-total (Outside Dimensions)	U-total (Rough Opening)
as tested	2.78	3.65	10.81	4.07	5.05
standard conditions	2.78	3.67	12.40	4.31	5.34

Green-house Window	Section	U-Value Centre Glazing	U-Value Edge Glazing	U-Value Frame	U-Value Section	U-Total (Outside Dimensions)	U-total (Rough Opening)
as tested	front	2.80	3.19	9.73	3.74	7.93	9.38
	top	2.76	3.10	4.79	3.52		
	bottom	3.72	3.72	3.76	3.74		
	sides	2.76	3.06	8.22	5.52		
NRC standard condition	front	3.19	3.78	11.75	4.38	9.41	11.15
	top	3.19	3.73	5.49	4.10		
	bottom	4.75	4.76	4.56	4.68		
	sides	3.19	3.67	9.6	6.47		

Curtainwall	U-Value Centre Glazing	U-Value Edge Glazing	U-Value Frame	U-Value Panel	U-Total
as tested - vision panel	2.76	3.27	8.84	4.01	
as tested - spandrel panel	0.34	2.58	5.83	1.86	2.94
NRC std. conditions - vision panel	2.76	3.27	9.90	4.21	
NRC std. conditions - spandrel panel	0.34	2.57	6.26	1.94	3.08

The difference between test and simulation for the curtainwall was less than 2%. This excellent agreement is consistent with previous studies comparing simulation and test results for standard (flat) windows. Had the effect of the bolts been ignored, the total simulated product U-value would have been 2.64, 13 % lower than the tested U-value. Perhaps somewhat surprising is the relatively low U-value of the total assembly, considering that half of the assembly is made up of RSI 2.9 (R 16.7) insulated panels. A simplistic calculation of total product U-value ignoring thermal bridging effects of the frame, bolts and edge spacers would give a value of 1.55 W/m^2C, half the true value of the assembly.

There is also good agreement between test and simulation for the flat skylight: the simulated value is within 10% of the tested value. The adjustment from "tested" to "NRC standard" conditions is approximately the same for test and simulation, indicating that similar film coefficients are being used. Despite having a well-insulated centre glazing (low-e argon gas filled), the unit has a total U-value (based on rough opening area) greater than for a standard double-glazed casement window. The value is consistent with the value listed in the 1993 ASHRAE Handbook of Fundamentals (3.58 W/m^2C) for skylights of similar design.

When corrected to standard film coefficients, there is reasonable agreement between test and simulation for the greenhouse window. Although the 12.5 % difference is slightly greater than the 10% difference required in the NFRC 100-91 procedure, a larger discrepancy is not unexpected given the uncertainties in the inside and outside air flow patterns over the window. The simulations were performed assuming a uniform wind over the exterior and unrestricted natural convection over the interior. The lower test U-value may be a result of some wind shielding on the exterior and/or dead air pockets on the inside caused by the projecting shape of the window. The magnitude of the film coefficients is extremely important in this case because of the low thermal resistance of the window system. Had the window been constructed with a thermally broken frame, a wider air cavity or other insulating features (e.g., low-e coating), discrepancies caused by differences in film coefficients would have been much less noticeable.

The greenhouse window has a U-value two to three times that of a standard flat window for the same rough opening. This is a result of the greenhouse window having a surface area that is 2.4 times greater than the rough opening.

The domed skylight has the poorest agreement between test and simulation. There are several possible reasons for this 16% difference. The tests show a 30% increase in U-value of the domed skylight over the flat skylight. This small increase is somewhat surprising given that the flat skylight has low-e coated glass, argon gas fill and a wood frame. The surface temperatures of the domed skylight were not measured during the test. It is possible that some of the difference between test and simulation is due to uncertainty in the film coefficients. A second possible source of error is differences in the predicted and tested convective heat transfer. The curved interior air cavity may have a lower convective heat transfer than predicted by the model. Finally, as with the greenhouse window, the projecting shape of the skylight may reduce warm-side air flow over the window. This would result in a lower warm-side temperature adjacent to the skylight and therefore lower heat loss.

4.0 CONCLUSIONS and RECOMMENDATIONS

4.1 Conclusions

Several conclusions can be drawn from this study on complex window systems:

- extra care must be taken in the simulation and testing of complex windows. Surface temperatures and film coefficients must be carefully measured during testing and simulations must account for the thermal bridging, including bolts in curtainwalls and curbs in skylights.

- for two of the four complex window systems guarded-hot-box testing and detailed computer simulation gave results within 10% for total-window U-value. The poorer agreement between testing and simulation for the domed skylight and greenhouse window may be due to differences in the interior and exterior film coefficients and/or the inter-glazing convective heat transfer.

- despite having half its area in spandrel panel, the curtainwall total U-value is slightly higher than a standard double-glazed window. The high U-value is due to high heat transfer through the mullions and steel bolts.

- the greenhouse window has a total U-value two to three times the value of a standard non-projecting double-glazed window based on the area of the rough opening. This increase is due to the extra surface area of the side, top and bottom panels. The total U-value based on NRC standard film coefficients is much higher than the as-tested U-value. It would appear that the interior radiative and convective film coefficients are lower with a greenhouse window than with a standard window.

4.2 Recommendations

Based on this study the following recommendations are made:

- further testing and simulation is required to reduce the differences between the two values for the domed skylights, specifically guarded hot box with surface temperatures measured, infra-red thermography, and three-dimensional modelling of fluid flow between the glazings and over the inner and outer glazings;

- it would appear that computer simulation and guarded hot box testing give similar U-values for curtainwalls, greenhouse windows and flat skylights. The CSA A440.2 standard should be extend to cover these windows;

- the evaluation of complex window systems should incorporate the additional testing and simulation procedures used in this report;

- extend NRC test procedure to handle projecting products and modify test apparatus to allow testing of skylights at tilt angles; and

- in developing standards for performance assessment of projecting windows, consideration should be given to basing U-value ratings on typical interior film coefficients instead of the standard film coefficients used for flat windows.

5.0 REFERENCES

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APPENDIX A:

National Research Council Canada
Conseil national de recherches Canada

Institute for Research in Construction
Institut de recherche en construction

CLIENT REPORT

for

Enermodal Engineering Ltd.
368 Philip Street
Waterloo, Ontario N2L 5J1
Attention: Mr. Stephen Carpenter

To determine the thermal resistance and heat transmission values of two skylights, one curtainwall section, and one "greenhouse window".

This appendix describes work which was carried out at the National Research Council, Institute for Research in Construction.

Permission was granted for its reproduction.

Report No.	A3076.1
Report Date:	December 10, 1993
Contract No.	A3076
Reference:	Application for test dated 7 June, 1993
Laboratory:	Building Performance

8 Pages
Copy No. 1 of 4 copies

Canada

To Determine the Thermal Resistance and Heat Transmission Values of Two Skylights, One Curtain Wall Section, and One "Greenhouse Window"

1. Summary:

The thermal resistance and heat transmission values for four test specimens were determined by tests conducted in the Environmental Test Facility of the Institute for Research in Construction.

2. Test Specimens:

The applicant supplied four test specimens consisting of one domed skylight, one ventilating skylight, one curtain wall section, and one "greenhouse window". The dimensions were measured at IRC prior to testing.

#1. A domed skylight with frame dimensions of 0.063m wide by 1.240m high by 0.063m deep containing a double-walled polycarbonate dome that protrudes 0.05m outside of the aluminum frame.

#2. A ventilating skylight with frame dimensions of 0.548m wide by 1.178m high by 0.102m deep containing a sealed double glazed unit with low emissivity coating on surfaces #2 and #4 and argon gas filled.

#3. A four bay section of a curtain wall with frame dimensions of 1.813m wide by 2.070m high by 0.143m deep containing two sealed double glazed units of clear glass and two steel spandrel pans in an aluminum frame.

#4. A "green house window" with overall dimensions of 1.740m wide by 1.000m high by 0.435m deep containing four fixed and two operable sealed double glazed units of various sizes totaling nearly 2m^2 of glass surface plus 0.6m^2 of wood surface and 0.7m^2 of aluminum framing.

3. Test Procedures:

The test procedures are described in the Appendix. These procedures were developed for conventional geometry windows with most of the area as vertical glazing. This allows the proper profiling of the wind machine tubes to insure that the outside film coefficient is correct and that the room-side conduction/convection characteristics are similar to those determined during calibration. The geometry of all four test specimens fail to meet these requirements. Consequently, the uncertainty in calculating the R- and U-values listed in this report may exceed the limits established for conventional windows.

4. Test Conditions:

Prior to testing each specimen, the calorimeter was purged with dry air and the room-side chamber was dehumidified to avoid condensation on the glazing. During all tests, the calorimeter air temperature was maintained at 21.0°C ± 0.1°C. Each test specimen was tested with the weather-side air temperature held at -18.0°C ± 0.1°C. The static pressure difference across each test specimen was held to less than 3 Pa. The weather-side air movement was established through the use of a wind machine that directs the air perpendicular to the vertical surfaces of the test assembly and provides a film coefficient of 25.2 ±3 $W/(m^2 \cdot K)$ on a flat vertical surface. No efforts were made to determine the film coefficient on the domed skylight or the "greenhouse window".

5. Test Specimen Mounting:

Each specimen was mounted vertically in a custom-sized opening that was centered in the 183mm thick surround panel (Mask). The applicant requested that the specimens were to be inserted into or onto the surround panel as follows:

#1. The specimen was attached and sealed to a wood buck made of 41mm by 138mm pine. The buck was inserted from the weather-side to a depth of 49mm, i.e., 89mm of the buck protruding into the weather-side chamber.

#2. The specimen was attached to the exterior (weather-side) of the surround panel with screws through the six brackets supplied. This allowed the specimen to protrude 0.102m into the weather-side chamber.

#3. The specimen was mounted from the room-side and flush with the room-side of the surround panel.

#4. The specimen was mounted from the weather-side onto a wood buck of 42mm by 88mm pine that was wedged in the surround panel opening flush at the weather-side. The specimen protruded 0.435m into the weather-side chamber.

NOTE: The mounting of the skylights according to the above instructions caused portions of the wood buck or wood frame to be exposed to the warm and cold sides. This means that the portion of the heat loss through the skylights is transferred through the mounting buck.

6. Test Specimen Preparation:

The full perimeter of each test specimen was sealed with tape at the room-side and weather-side. The operable gaps in Test Specimen #2 were sealed on the room-side and the operable gaps of Test Specimen #4 were sealed at the weather-side using 3M #471 PVC tape.

7. Test Results:

Table 1 lists the measured data and gives the values of the Design Thermal Resistance and the Design Coefficient of Heat Transmission for Test Specimens #1, #2, and #3. The estimated maximum uncertainty in determining the Design Thermal Resistance is about ± 6% for *conventional vertical* windows. No effort was made to estimate the uncertainty level for the current set of tests due to the unconventional design of the assemblies.

Test Specimen #4 could not be tested using the IRC procedure because of the extreme geometry of the specimen. Therefore, for Test Specimen #4, a total of 88 temperature sensors (30 ga thermocouples) were mounted on the room-side and weather-side of the various glazing, aluminum frame, wood floor, and wood buck/specimen mounting flange surfaces to determine the area-weighted average specimen surface temperatures T_1 and T_2. The test results of Test Specimen #4 are shown on Table 2. Some of the measured and derived values for Test Specimen #4 are also shown on Table 1.

The overall conductance of specimen #4 was calculated as follows:

$$C = Q_s/(A * (T_1 - T_2))$$

where:

A average developed area of the window, (wood buck face area + (inside area + outside area)/2), m^2

T_1&T_2 area weighted average warm and cold surface temperatures, °C
(other quantities are defined in the attached tables).

Special Note: The U- and R-values quoted for Test Specimens #1 and #2 may have high level of uncertainty because of testing these skylights in a vertical position. The values for Test Specimen #3 may also have high level of uncertainty because the glazing area is only about 40% of the total area. None of the above conditions were accounted for in the development of the IRC test procedure for conventional windows.

Table 1: R- and U-Value Results Using IRC Standard Test Procedures

	Units	Symbol	# 1	# 2	# 3	# 4
Mean Weather-side Air Temperature	°C	T_c	-18.0	-18.0	-18.0	-18.0
Mean Room-side Air Temperature	°C	T_h	21.0	21.0	21.0	21.0
Mean Baffle Temperature	°C	T_b	21.6	21.6	22.8	23.0
Mean Room-side Surface Temperature of Specimen	°C	T_1	3.7	4.6	6.8	N/A
Mean Weather-side Surface Temperature of Specimen	°C	T_2	-12.6	-12.9	-13.5	N/A
Total Heat Flow Through the Test Assembly	W	Q_t	150.2	113.3	441.0	471.9
Heat Flow Through the Surround panel (Mask)	W	Q_m	42.6	44.6	18.0	33.5
Heat Flow Through the Test Specimen	W	Q_s	107.6	68.7	423.0	438.4
Heat Flow Through Unit Area of Test Specimen*	W/m^2	q_s	136.9	129.6	112.9	N/A
Temperature Difference (Surface to Surface)	K	T_1-T_2	16.3	17.5	20.3	N/A
Test Specimen Conductance	$W/(m^2 \cdot K)$	C	8.40	7.41	5.56	N/A
Resistance of the Test Specimen	$m^2 \cdot K/W$	R	0.12	0.13	0.18	N/A
Room Side Air Film	$W/(m^2 \cdot K)$	f_i	7.8	7.7	7.4	N/A
Weather Side Air Film	$W/(m^2 \cdot K)$	f_o	25.2	25.2	25.2	N/A
Design Resistance of the Test Specimen	$m^2 \cdot K/W$	R_D	0.27	0.28	0.33	N/A
Design Coefficient of Heat Transmission Through the Test Specimen	$W/(m^2 \cdot K)$	U_D	3.70	3.57	3.03	N/A
Area of the Mask Opening	m^2	A_1	0.786	0.530	3.747	1.740

NOTE: The Area of Test Specimen is equal to the Area of the Mask Opening.

Table 2: R- and U-Value Results Using Measured T_1 and T_2

Area-Weighted Room-Side Surface Temperature of Specimen #4	°C	T_1	2.7
Area-Weighted Weather-Side Surface Temperature of Specimen #4	°C	T_2	-8.9
Total Heat Flow Through the Test Assembly	W	Q_t	471.9
Heat Flow Through the Surround panel (Mask)	W	Q_m	33.5
Heat Flow Through Test Specimen #4	W	Q_s	438.4
Heat Flow Through Unit Area of Test Specimen #4	W/m^2	q_s	123.5
Temperature Difference (Surface to Surface)	K	T_1-T_2	11.6
Test Specimen Conductance	$W/(m^2 \cdot K)$	C	10.64
Resistance of the Test Specimen	$m^2 \cdot K/W$	R	0.09
Design Resistance of the Test Specimen #4	$m^2 \cdot K/W$	R_D	0.24
Design Coefficient of Heat Transmission Through Test Specimen	$W/(m^2 \cdot K)$	U_D	4.10

Total Surface Area of Test Specimen #4= $3.551 m^2$

APPENDIX FOR A-3076.1

TEST PROCEDURE AND CALORIMETER HEAT TRANSFER CHARACTERISTICS FOR THE NORTH BOX

CALORIMETER HEAT TRANSFER CHARACTERISTICS

The general approach used to determine the heat transmission characteristics of the test specimen is outlined in the paper *DBR's Approach for Determining the Heat Transmission Characteristics of Windows*, by R.P. Bowen, BRN 234, IRC, Nov. 1985 (copy attached). In summary, the approach involves measuring the total power supplied to the calorimeter and deducting the heat transfer through the mask to arrive at the heat transfer through the specimen. From the specimen heat transfer, using the relationships for the radiation and convective heat transfer from the calorimeter to the specimen, the equivalent room-side surface temperature of the specimen is calculated. The equivalent weather-side surface temperature is also calculated from the specimen heat transfer and the air film provided by the wind machine. The thermal conductance, resistance, design thermal resistance and design coefficient of heat transmission are calculated.

The following is a summary of the equations used for the calculations

$$Q_T = Q_S + Q_m$$

where Q_T = total measured power supplied to the calorimeter
Q_s = the heat transfer through the test specimen
Q_m = the heat transfer through the mask

In turn Q_s is given by

$$Q_s = Q_c + Q_r$$

and

$$Q_c = A_1 C (T_h - T_1)^B$$

$$Q_r = A_1 \sigma \sum_{i=3}^{5} F_{1i}(T_i^4 - T_1^4)$$

where Q_c = convective component of the heat transfer from the calorimeter to the specimen
Q_r = radiative component of the heat transfer from the calorimeter to the specimen
T_h = the calorimeter air temperature
A_1 = area of specimen
T_1 = the room-side specimen surface temperature
Ti = the temperature of surface i with radiation interchange with surface 1
F_{1i} = the interchange factor for radiation from surface 1 to the other surfaces

	Spec. #1	#2	#3	#4
i=3 for mask	F_{13} = 0.046	0.049	0.017	0.040
i=4 for baffle	F_{14} = 0.688	0.690	0.625	0.674
i=5 for calorimeter	F_{15} = 0.093	0.089	0.161	0.116

σ = the Stefan-Boltzmann constant = 5.6703×10^{-8} W / ($m^2 \cdot K^4$)
B & C are constants for the convective heat transfer to the specimen

The constants B and C were established from the results of a series of tests using the same mask as used for the test specimen but with specially constructed calibration specimens 1.0 x 1.6 m and 0.8 x 1.0 m in place of the test specimen. The calibration test conditions were nominally the same as those for the test specimen; that is, 22 °C room-side and -7 °C, -21°C, and -35 °C weather-side temperatures. From the measurements with the calibration specimen and the conductance which was determined in the Thermal Conductivity Laboratory of IRC, Q_r was calculated and Q_c established for each set of conditions. A linear fit of the data yields values of

$$B = 1.266 \quad \text{and} \quad C = 1.581\ W/(m^2 \cdot K^{1.266}).$$

$$\text{Thus } \frac{Q_s}{A_1} = q_s = q_r + q_c = 1.581(T_h - T_1)^{1.266} + \sigma\sum_{i=3}^{5} F_{1i}(T_i^4 - T_1^4)\ W/m^2$$

Once the mean surface temperature of the test specimen is established, coefficients for the convective and radiative exchange, h_c and h_r, can be calculated:

$$h_c = 1.581\ (T_h - T_1)^{0.266} = q_c / (T_h - T_1)\ W/(m^2 \cdot K)$$

$$h_r = q_r / (T_b - T_1)\ W/(m^2 \cdot K)$$

The room-side surface film coefficient, f_i, or inside film resistance R_{fi} is then

$$f_i = h_c + h_r \quad W/(m^2 \cdot K)$$

$$R_{fi} = \frac{1}{f_i}\ m^2 \cdot K/W$$

The equivalent weather-side surface temperature, T_2, is calculated by

$$T_2 = \frac{q_s}{f_o} + T_c$$

where T_c = the weather-side air temperature
f_o = weather-side surface film coefficient established during calibration tests was 25.2 W / ($m^2 \cdot K$) (weather-side film resistance R_{fo} is then 0.04 $m^2 \cdot K/W$)

Expressions to Calculate Specimen R-value and U-value

The test specimen conductance, C, W/(m^2·K) and resistance, R, m^2·K/W are calculated by:

$$C = q_s / (T_1 - T_2)\ W/(m^2 \cdot K); \qquad R = 1 / C\ m^2 \cdot K/W$$

The values assigned to R_{fi} and R_{fo} in window design resistance values, R_D, are usually:

$$R_{fi} = 0.12\ m^2 \cdot K/W \quad \text{and} \quad R_{fo} = 0.03\ m^2 \cdot K/W.$$

The total specimen design resistance then becomes:

$$R_D = R + 0.12 + 0.03 \ m^2 \cdot K/W$$

The design U-value; U_D is then:

$$U_D = 1 / R_D \ W/(m^2 \cdot K)$$

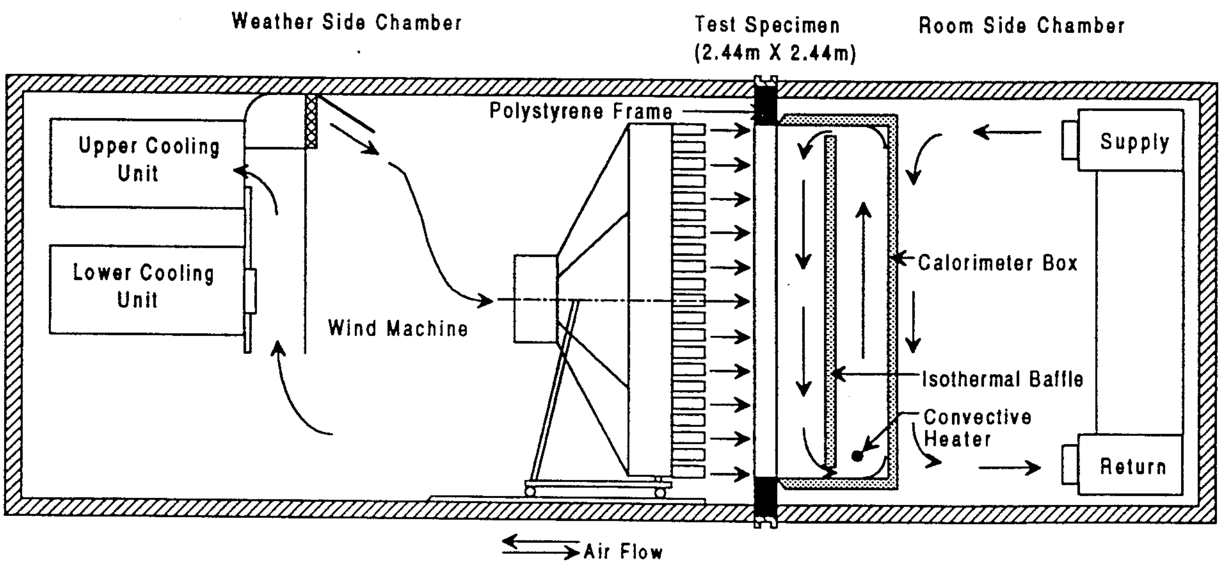
TEST PROCEDURE

A steel frame was used to hold the test assembly consisting of a surround panel, referred to as the mask, and the test specimen. The mask was constructed of 150 mm extruded polystyrene insulation with 17 mm of plywood covering on the room-side and weather-side surfaces. The thermal resistance of the mask was determined in the Environmental Test Facility prior to making an opening for the test specimen. The mask, with a calibration specimen in the opening made for the test specimen, was calibrated using the same room-side and weather-side conditions as those to be used for the test specimen.

Subsequently, the test specimen was installed into the surround panel (mask). The specimen was centered in the opening and sealed to minimize air leakage through the opening. Thermocouples were used to measure the room-side and weather-side surface temperatures on the surround panel (mask).

The test assembly was mounted on the weather-side chamber of the Environmental Test Facility. The calorimeter used to measure the heat flow through the test assembly was mounted over the room-side surface of the test assembly. The room-side chamber was joined to the weather-side chamber.

Figure B1: NRC/IRC Environmental Test Facility (North Box)



A3076WGT.XLS

1993

Specimen #4: Garden ("Greenhouse") Window

SENSOR ID #	AREA	# of AREAS	R.S. TEMP	W.S. TEMP	For RS Temp
SLOPED IG UNIT					
T100/T200	0.0120	2	6.0	-8.5	2*0.0120*(6.0+4.0)
T103/T203	0.0120	2	4.0	-11.1	
T101/T201	0.0220	2	7.4	-6.5	2*0.0220*(7.4+3.3)
T104/T204	0.0220	2	3.3	-12.4	
T102/T202	0.0441	1	7.0	-7.5	0.0441*(7.0+3.2)
T105/T205	0.0441	1	3.2	-12.9	
T106/T206	0.0458	2	6.7	-8.0	2*0.04585*(6.7+6.7+5.1+5.0)
T107/T207	0.0459	2	6.7	-7.5	
T108/T208	0.0458	2	5.1	-10.4	
T109/T209	0.0459	2	5.0	-10.6	
	AREA WGT'D AVG:		5.61	-9.39	AREA: 0.5910
VERT. IG UNIT					
T110/T210	0.0192	2	2.1	-14.1	2*0.0192*(2.1+1.2)
T113/T213	0.0192	2	1.2	-14.3	
T111/T211	0.0220	2	2.0	-14.1	2*0.0220*(2.0+0.7)
T114/T214	0.0220	2	0.7	-14.2	
T112/T212	0.0441	1	1.8	-14.2	0.0441*(1.8+1.0)
T115/T215	0.0441	1	1.0	-14.2	
T116/T216	0.0864	2	2.8	-13.1	2*0.0864*(2.8+2.4+1.6+2.1)
T117/T217	0.0864	2	2.4	-13.3	
T118/T218	0.0864	2	1.6	-12.7	
T119/T219	0.0864	2	2.1	-13.6	
	AREA WGT'D AVG:		2.02	-13.44	AREA: 0.9442
EDGE GLAZING					
1300/1400	0.0123	4	7.3	-4.7	4*0.0123*(7.3+0.8)
1301/1401	0.0123	4	0.8	-10.8	
1302/1402	0.0157	2	4.1	-9.6	2*0.0157*(4.1)
1303/1403	0.0158	2	6.7	-6.0	2*0.0158*(6.7+3.7)
1304/1404	0.0158	2	3.7	-7.9	
1305/1405	0.0165	2	3.0	-9.0	2*0.0165*(3.0)
1306/1406	0.0195	2	1.9	-9.9	2*0.0195*(1.9)
1307/1407	0.0219	2	6.8	-6.3	2*0.0219*(6.8)
1308/1408	0.0247	2	4.0	-6.9	2*0.0247*(4.0+3.4)
1309/1409	0.0247	2	3.4	-8.1	
	AREA WGT'D AVG:		4.15	-7.86	AREA: 0.4076

A3076WGT.XLS

1993
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Specimen #4: Garden ("Greenhouse") Window

SENSOR ID #	AREA	# of AREAS	R.S. TEMP	W.S. TEMP	For RS Temp.	
FLOOR						
1316/1416	0.0412	2	-0.1	-8.9	2*0.0412*[(-0.1)+(0.7)]	
1317/1417	0.1559	1	1.9	-6.4		
1318/1418	0.1559	2	0.9	-7.0	0.1559*(1.9+0.9+0.9)	
1319/1419	0.0412	2	0.7	-6.4		
	AREA	WGT'D AVG:	0.99	-7.02	AREA:	0.6325
FRAME						
TX119/TX219	0.1269	1	2.2	-2.0		
1310/1410	0.1269	1	-7.5	-12.3	0.1269*[(2.2)+(-7.5)+(-9.7)]	
1311/1411	0.1269	1	-9.7	-13.6		
1312/1412	0.0338	2	-2.0	-4.9		
1313/1413	0.0338	2	2.5	-8.6	2*0.0338*[(-2.0)+(2.5)+(-8.5)]	
1314/1414	0.0338	2	-8.5	-10.8		
1315/1415	0.0846	2	3.7	-0.3	2*0.0846*(3.7)	
	AREA	WGT'D AVG:	-2.42	-6.95	AREA:	0.7527
WOOD BUCK						
TX116/TX216	0.0696	1	13.5	-7.3	0.0696*(13.5+18.1)	
TX117/TX217	0.0421	2	19.0	0.2	2*0.0421*(19.0)	
TX118/TX218	0.0696	1	18.1	-2.6		
	AREA	WGT'D AVG:	17.01	-3.01	AREA:	0.2234
AREA WGT'D	AVERAGE	SURF. TEMP:	2.68	-8.95	AREA:	3.551

Q Spec.=	438.4
q Spec=	123.5
Measured T1=	2.7
Measured T2=	-8.9
C=	10.64
R Test=	0.09
R Design=	0.24
U Design=	4.10

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NOTES OF / NOTES DE J. Keatley
SUBJECTS / SUJET Garden or Greenhouse Window DATE

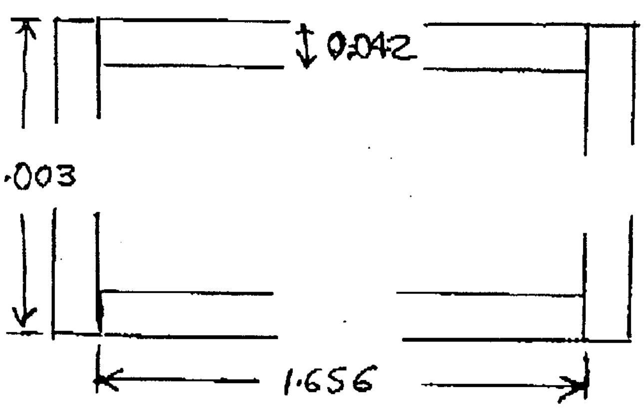
AREA WGT'D AVG

TOTAL EXT. SURFACE AREA OF SPECIMEN : 3.448
TOTAL INT. SURFACE AREA OF SPECIMEN: 3.208 } +

6.656 ÷ 2

EFFECTIVE SURFACE AREA OF SPECIMEN = 3.328 m^2

WOOD BUCK



0.042 * 1.656

0.042 * 1.003

AREAS

for TX118 & TX116 : 0.042 * 1.656 = 0.069552

for Sensor TX117 : 2 * 0.042 * 1.003 = 2 * 0.042126

Wood Buck Total Area = 0.223356

∴ TOTAL SPECIMEN AREA = 3.328 + 0.223 = 3.551 m^2

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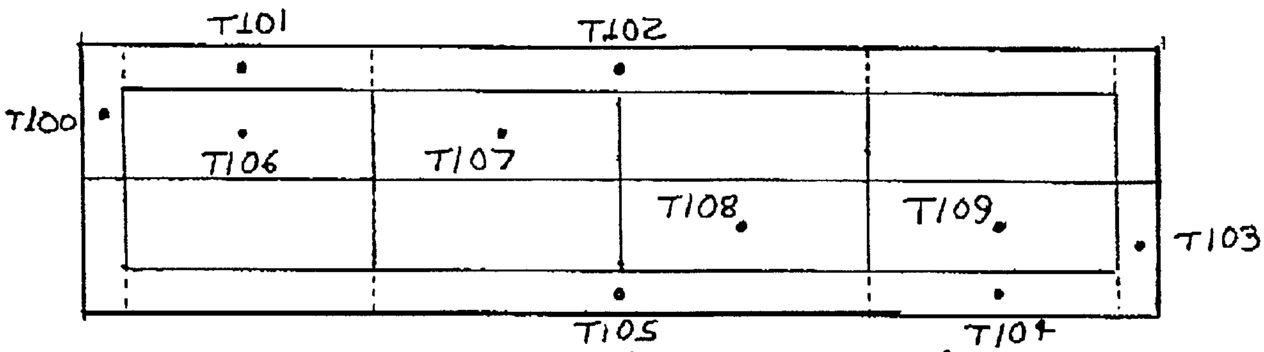
NOTES OF / NOTES DE JG Keatley

SUBJECTS / SUJET Garden & Greenhouse Window DATE

AREA WGT'D AVG

SLOPED IG : "Daylight" is 1.535 * 0.385 = 0.590975 m² (0.591)



"Edge" of glass = 0.0625 (1.535-(2*0.0625))/4 = 0.3525

(0.385-(2*0.0625))/2 = 0.1300

Areas

for T100 & T103 : 2*(0.0625*0.385/2) = 2*0.01203125

for T101 & T104 : 2*(0.0625*0.3525) = 2*0.02203125

for T102 & T105 : 0.0625*2*0.3525 = 0.0440625

for T106 to T109 : 2*0.3525*0.1300 = 2*0.045825

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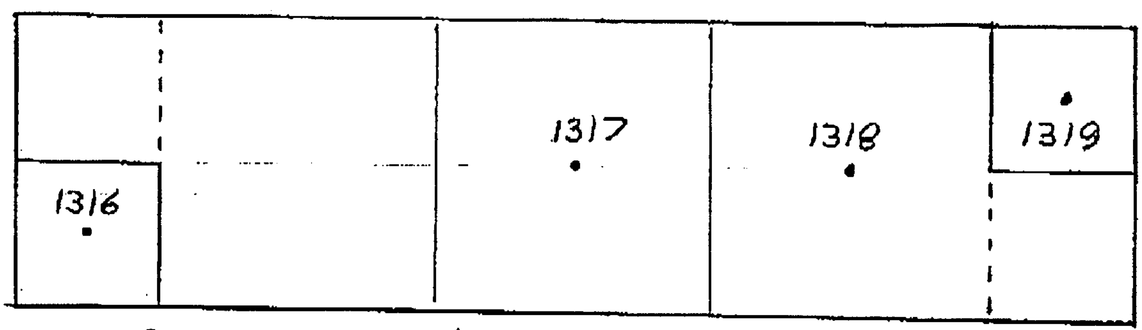
NOTES OF / NOTES DE J. Keatley
SUBJECTS / SUJET Garden or Greenhouse Window DATE

AREA WGT'D AVG

FLOOR : 1·558 * 0·406 = 0·632 5480 m² (0·633)



(1·558 − (2 * 0·203)) / 3 = 0·3840

AREAS

SENSOR 1316 + 1319 : 2 * 0·203 * 0·203 = 2 * 0·041209

SENSOR 1318 : 2 * 0·384 * 0·406 = 2 * 0·155904

SENSOR 1317 : 0·384 * 0·406 = 0·155904

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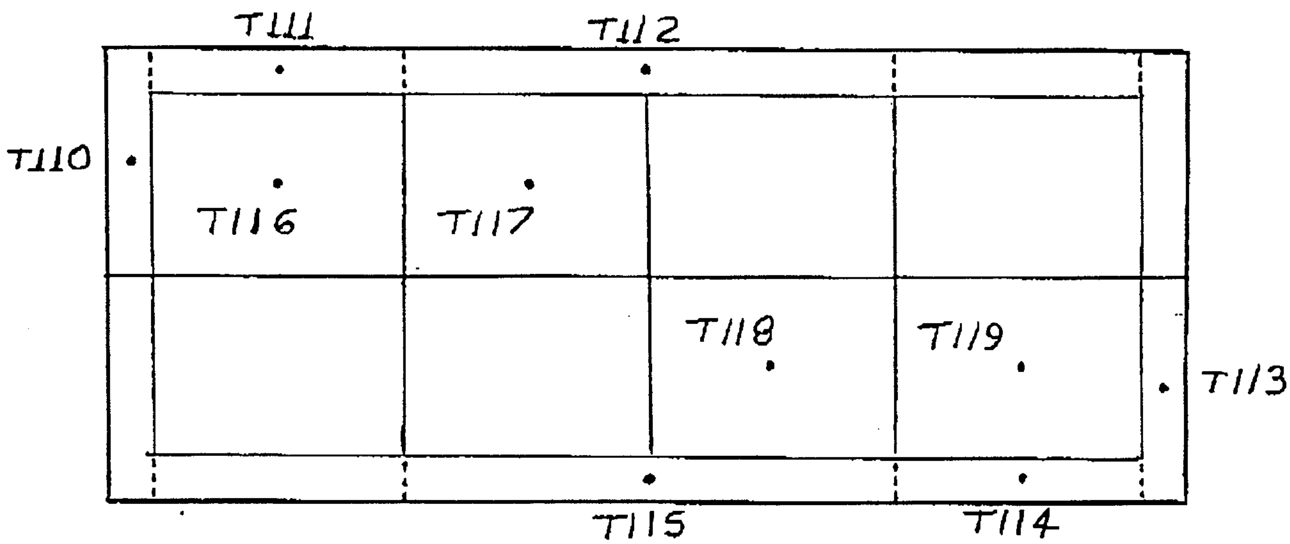
NOTES OF / NOTES DE J G Keatley

SUBJECTS / SUJET Garden or Greenhouse Window DATE

AREA WGT'D AVG

VERTICAL IG : "Daylight" is $1.535 * 0.615 = 0.944025\ m^2\ (0.944)$



"Edge" of glass = 0.0625 $(1.535 - (2*0.0625))/4 = 0.3525$

$(0.615 - (2*0.0625))/2 = 0.2450$

AREAS

for T110 & T113: $2*(0.0625*0.615/2) = 2*0.01921875$

for T111 & T113: $2*(0.0625*0.3525) = 2*0.02203125$

for T112 & T115: $0.0625*2*0.3525 = 0.0440625$

for T116 to T119: $2*0.3525*0.245 = 2*0.0863625$

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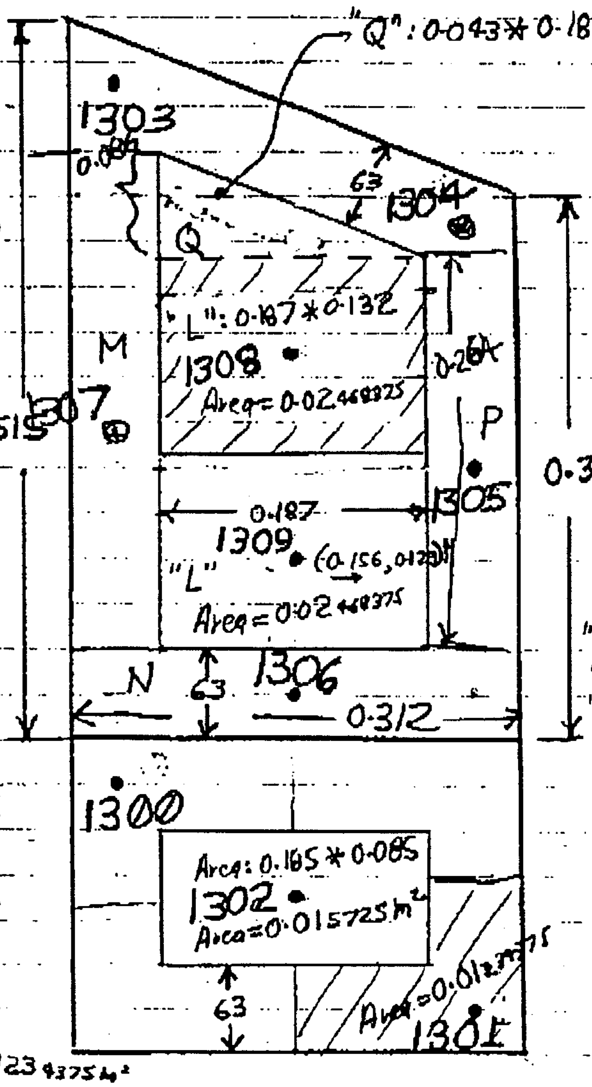
NOTES OF / NOTES DE J.R. Keattey

SUBJECTS / SUJET T/C LOCATIONS DATE :

SCALE: 1=5

FIXED IG
Area: 0.312*0.375
0.356 * (0.515−0.375) [0.140]
AREA = 0.13884



2*"L" = 0.0493675
"Q" = 0.00804100
N+M+P = 0.0578750
0.1152835
Subtract from total

0.3502, 0.2643 .086

8 T/Cs

0.312, 0.125, 0.187 wide

.066, .063, .129

TOTAL 0.138840, 0.115284, 0.023556 ÷ 2 = 0.011778

"N" 0.312*0.0625 = 0.019500
"P" 0.264*0.0625 = 0.016500
"M" 0.350*0.0625 = 0.021875
0.057875

.210, .125, .085

0.310*0.210
Area = 0.0651 m²

0.065100, 0.015725
0.049375 ÷ 4 = 0.01234375 m²

TOTAL T/Cs: 10+10+6+8 = 34 Leaves 10 for frame & wood buck

* Divide Area "Q" between T/C #s

Q÷2 = 0.011778 + 0.004020 = 0.015798

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PROJECT / PROJET A-3076
NOTES OF / NOTES DE [signature]
SUBJECTS / SUJET Garden ov Greenhouse Window DATE

AREA WGT'D AVG

0.944
0.590
0.4078
1.94288

SLOPED IG : 0.591 m² VERTICAL IG : 0.944 m²

TWO SIDE IGU + VERT SLIDING SASHES : 0.408 m²

TOTAL GLAZING = 1.943 m²

FLOOR AREA = 0.632 m²

TOTAL GLAZING + FLOOR AREA = 2.575 m²

EFFECTIVE TOTAL SURFACE AREA = 3.328 m²

∴ FRAME AREA = 0.753 m²

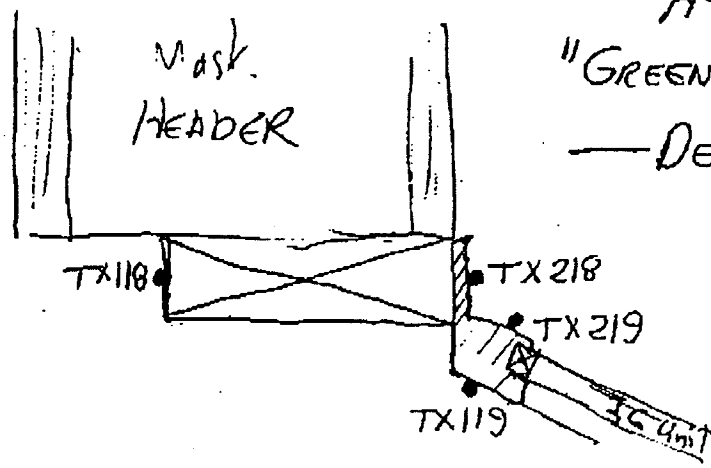
FRAMING LENGTHS = (2*3*0.4) + (3*1.5) + (2*1.0) = ~~5.9m~~ (8.9m)

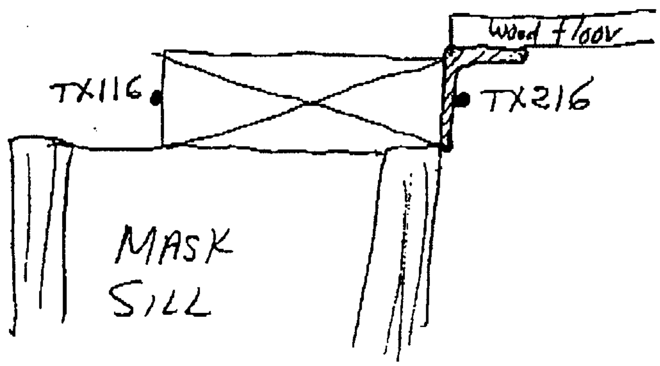
AREA/LENGTH gives 0.084606 m²/m

SENSOR ID	LENGTH	AREA	NUMBER OF AREAS	
TX 119	1.5	0.1269	1	0.3807
1310	1.5	0.1269	1	
1311	1.5	0.1269	1	
1312	0.4	0.0338	2	0.2028
1313	0.4	0.0338	2	
1314	0.4	0.0338	2	
1315	1.0	0.0846	2	→ 0.1692
				0.7527

A-3076
"GREENHOUSE" WINDOW
— DETAILS —

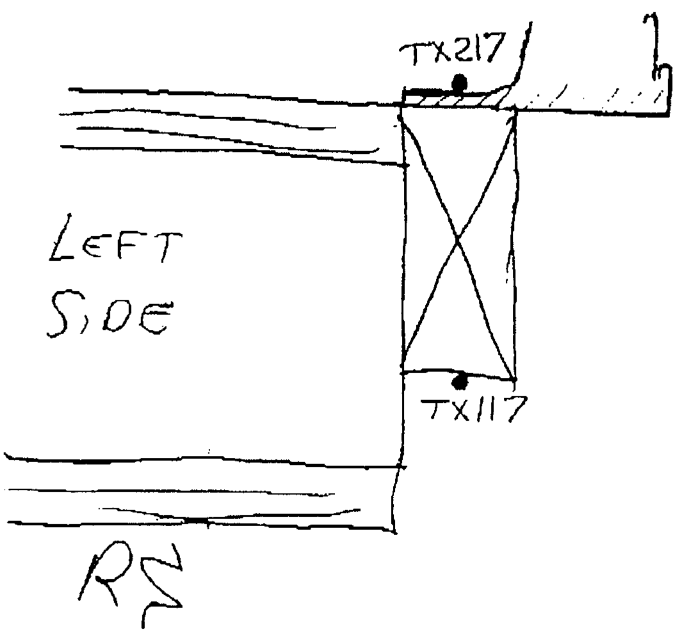
RS





RS

At Vertical Buck Member



RS

T/C NUMBERING

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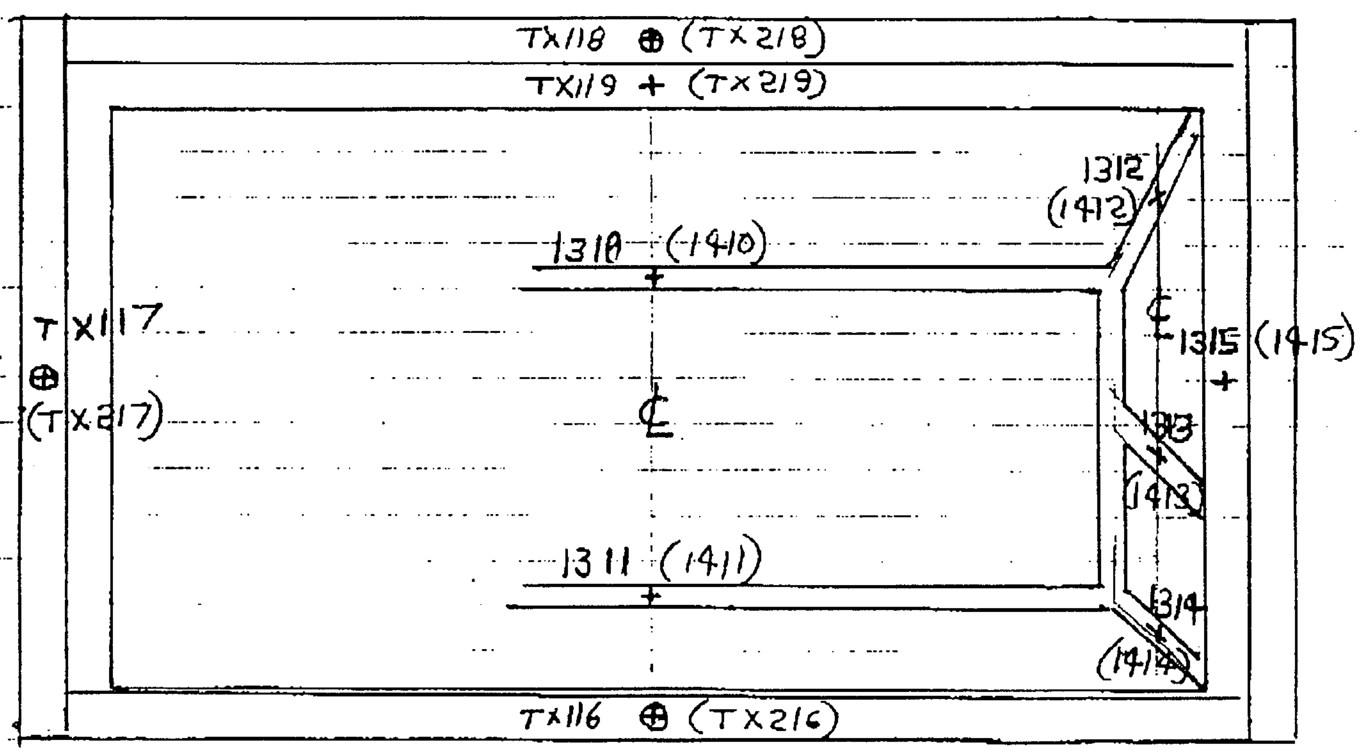
NOTES OF / NOTES DE [signature] Keatley
SUBJECTS / SUJET "Greenhouse" Window DATE 3 Nov 93

10 T/Cs



⊕ T/C locations on RS of Wood Buck (On WS, these locations are on the aluminum flange of the specimen)

\+ T/C locations on RS of aluminum frame of specimen.

SENSOR ID # IN BRACKETS ARE ON WEATHER-SIDE