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ASSESSMENT OF THE THERMAL PERFORMANCE OF THE NVLAP ROUND ROBIN WALL SPECIMEN IN IRC'S GUARDED HOT BOX FACILITIES

1.0 SUMMARY

The NVLAP (National Voluntary Laboratory Accreditation Program)/C-236 Round Robin has two purposes. It serves as an accreditation test for NVLAP Laboratories and provides more data for a precision and bias statement for the C-236 standard. The thermal performance of a standard test specimen was determined in the two guarded hot box facilities at the Institute for Research in Construction, National Research Council Canada (IRC/NRCC). The tests were performed under ASTM designation C-236 set by the American Society for Testing and Materials.

The thermal resistance of the test specimen was measured at four different temperature conditions in the guarded hot box that is generally used to test walls (South box). The specimen was then tested in the guarded hot box generally used to test windows (North box) where three of the South box test conditions were repeated.

2.0 TEST SPECIMEN

The test specimen (Figure 1) was constructed to the guidelines set by Rollin Inc., the NVLAP round robin coordinator. The test specimen was a 38 mm by 89 mm wood stud construction containing unfaced RSI-2.3 glass fibre insulation. This was finished on the hot and cold surfaces with controlled density (CD) gypsum ceiling board.

The framing members were comprised of carefully selected knot free California redwood. The studs and single top and bottom plates were milled to 37 mm by 87 mm and the half stud widths, located at both ends of the specimen, were milled to 19 mm by 87 mm. The moisture content of the framing material was measured using a "Protimeter: Diagnostic" model D179TS. These readings indicated a moisture content between 7 and 8 percent. This value was obtained from four observations on each piece of wood and is well below the 12 percent limit set by Rollin Inc. The average density of the framing members was determined to be 440 kg/m^3. The framing material was fastened together using 89 mm common nails. Pilot holes were drilled to ensure that the material did not split.

The glass fibre insulation used to fill the stud cavities was manufactured by Manville and had nominal physical dimensions of 92 mm by 381 mm by 2.44 m. The relaxed thickness of this material was found to be 89 mm. The insulation was type B 328, unfaced RSI-2.3. This insulation was carefully installed in the stud cavities to ensure minimum air gaps between the insulation and the framing material and the gypsum board. The average density of the glass fibre insulation was determined to be 14.0 kg/m^3.

Controlled density (CD) gypsum ceiling board, 13 mm thick, was used to cover the specimen. The board was secured using #8 by 32 mm bugle head drywall screws. These were located every 204 mm along the studs and the top and bottom plates. A vertical seam, located at the center stud, was finished with one layer of drywall tape and two coats of joint compound. Two coats of white latex paint were applied to both sides of the specimen. The same construction techniques were used on both sides of the specimen. The moisture content of the gypsum board was measured by taking weight measurements before and after drying in an oven. The moisture content was found to be 0.5 percent. The average density of the gypsum board was determined to be 628 kg/m^3.

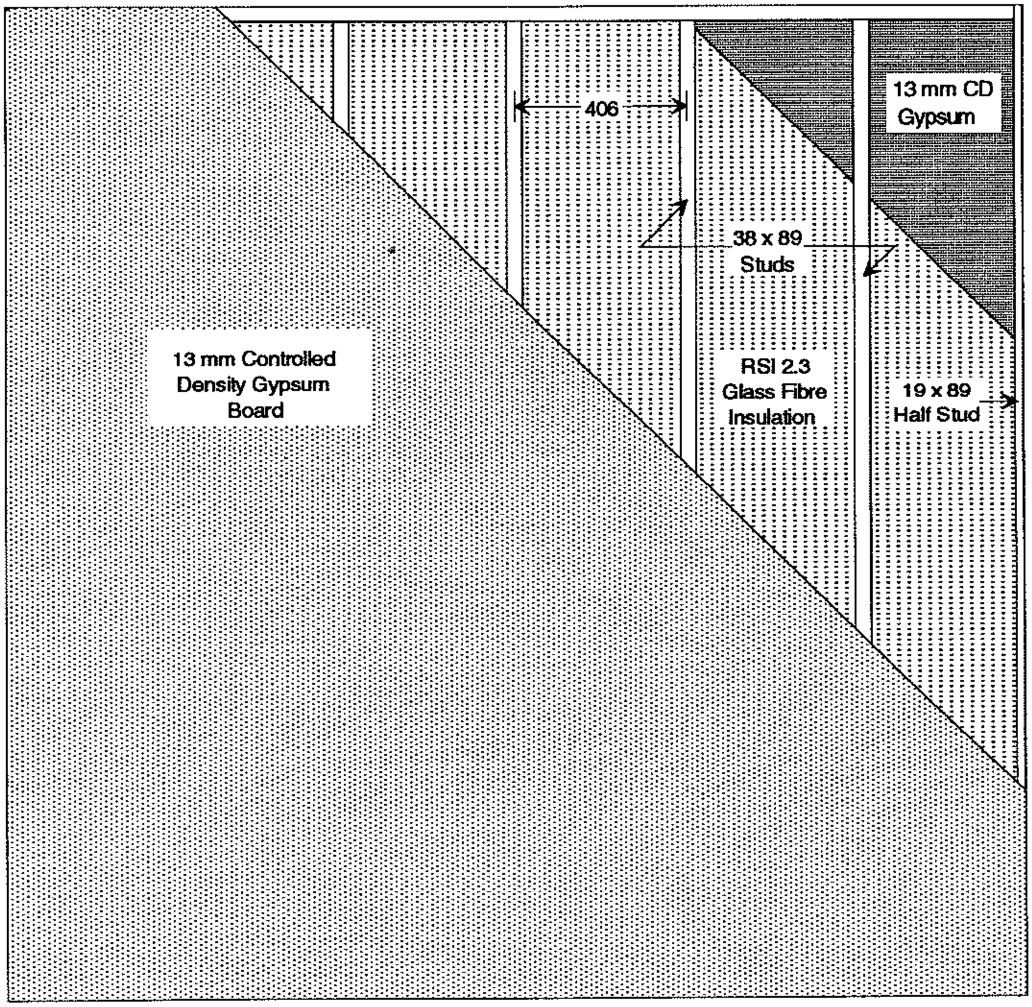
3.0 PROCEDURE

Type T thermocouples were attached to the hot and cold surfaces to measure the respective surface temperatures of the test specimen (Figure 2). Thermocouples to measure the temperature gradient through the specimen (Figure 2) were consistently located at the material interfaces shown in Figure 3.

The heat transfer through the specimen and the thermal resistance of the specimen were determined using the procedures outlined in Appendix A and Appendix B.

Test 1 was conducted with nominal temperatures of 34°C on the hot side and -2°C on the cold side. This test provides the highest mean temperature. Tests 2, 3 and 4 are performed with a hot air temperature of 20°C while the cold air temperatures were nominally -5°C, -20°C and -35°C respectively. Tests 1, 2 and 4 were repeated, with approximately the same temperature conditions, in the North box.

Figure 1. NVLAP Specimen

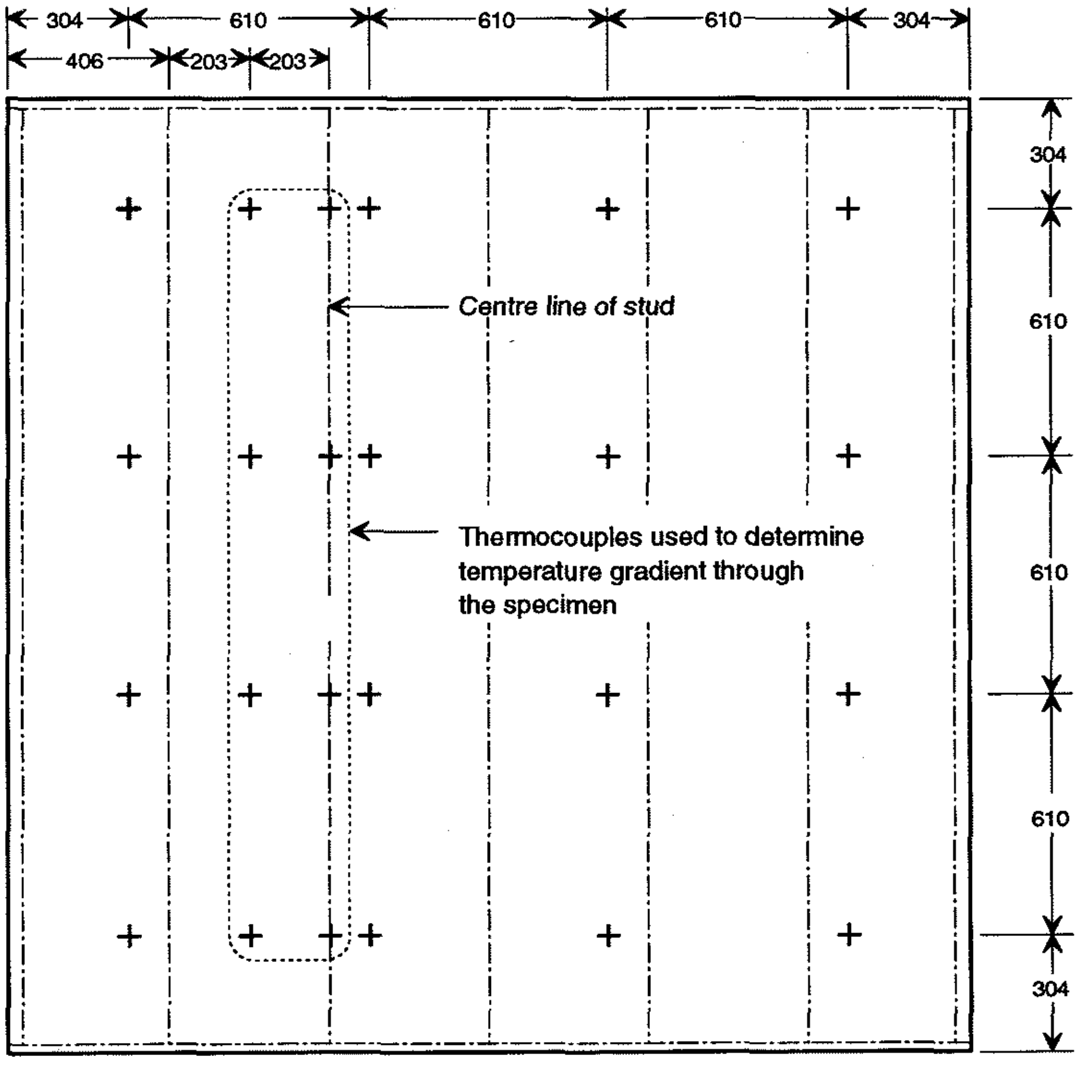


NOTE: Dimensions in millimetres.
Overall dimensions of specimen 2438 mm x 2438 mm.

4.0 RESULTS

The results of the heat transmission tests are listed in Tables 1 and 2. The hot air temperature (T_h), baffle temperature (T_b), cold surface temperature (T_2), cold air temperature (T_c), and the heat flux (q_t) were determined from measurement. The equivalent hot air temperature (T_e), the average warm surface (T_1), the average specimen temperature (T_{ave}), the total resistance (R_t), the specimen resistance (R_w), the hot surface film resistance (R_{fh}) and the cold side film resistance (R_{fc}) were calculated using the procedures outlined in Appendix A and Appendix B.

Figure 2. Location of thermocouples



Viewed from the room side.
All dimensions in millimetres.

Table 1. Measured and calculated results - South box.

Value	Test S1	Test S2	Test S3	Test S4
T_h(°C)	34.2	20.2	19.9	19.8
T_b(°C)	32.6	18.9	18.3	17.7
T_2(°C)	-1.4	-4.7	-19.4	-34.0
T_c(°C)	-2.0	-5.1	-20.1	-34.9
q_t(W/m^2)	16.80	11.04	17.43	23.48
T_e(°C)	33.2	19.3	18.9	18.6
T_1(°C)	31.6	18.1	17.1	16.2
T_{ave}(°C)	15.1	6.7	-1.2	-8.9
R_t(m^2·K/W)	2.10	2.21	2.23	2.28
R_w(m^2·K/W)	1.96	2.06	2.09	2.14
R_{fh}(m^2·K/W)	0.10	0.11	0.10	0.10
R_{fc}(m^2·K/W)	0.04	0.04	0.04	0.04

Table 2. Measured and calculated results - North box.

Value	Test N1	Test N2	Test N3	Test N4
T_h(°C)	35.2	20.1	N	20.0
T_b(°C)	35.3	20.2	O	20.2
T_2(°C)	-0.2	-4.6	T	-34.2
T_c(°C)	-0.9	-5.0		-35.0
q_t(W/m^2)	17.20	11.44	P	24.12
			E	
T_e(°C)	35.3	20.2	R	20.2
T_1(°C)	33.6	18.9	F	17.5
T_{ave}(°C)	16.7	7.2	O	-8.4
R_t(m^2·K/W)	2.10	2.19	R	2.28
R_w(m^2·K/W)	1.96	2.05	M	2.14
R_{fh}(m^2·K/W)	0.10	0.11	E	0.11
R_{fc}(m^2·K/W)	0.04	0.03	D	0.03

Additional thermocouples were affixed to the interior of the test specimen (see Figure 3). They were consistently located in order to produce temperature profiles along the stud line and the center of the insulating cavity. The average temperatures, shown in Tables 3 and 4, were calculated by averaging the four thermocouple readings along either the stud line or cavity.

Figure 3. Material Interfaces and Surface Numbers

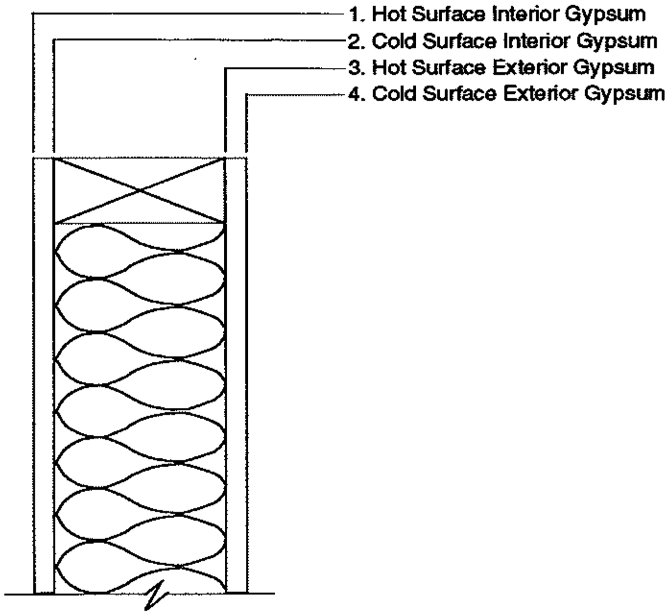


Table 3. Average Temperatures(°C) - South box

Surface	Location	Test S1	Test S2	Test S3	Test S4
1	stud	30.5	17.3	15.8	14.3
	cavity	31.7	18.3	17.3	16.4
2	stud	28.4	15.9	13.5	11.1
	cavity	30.6	17.4	16.1	14.8
3	stud	1.2	-2.9	-16.7	-30.5
	cavity	-0.5	-4.1	-18.4	-32.8
4	stud	-0.6	-4.1	-18.6	-33.0
	cavity	-1.3	-4.7	-19.5	-34.1

Table 4. Average Temperatures(°C) - North box

Surface	Location	Test N1	Test N2	Test N3	Test N4
1	stud	32.5	18.0	-	15.5
	cavity	33.7	19.0	-	17.7
2	stud	30.3	16.6	-	12.4
	cavity	32.4	18.2	-	16.1
3	stud	2.5	-2.9	-	-30.4
	cavity	0.9	-4.0	-	-32.6
4	stud	-0.5	-4.2	-	-33.1
	cavity	-0.2	-4.6	-	-34.2

5.0 COMMENTS

As can be seen in Tables 1 and 2, thermal resistance measured by the two guarded hot boxes are in close agreement. It should be noted that the two guarded hot boxes are not identical, in that the methods of heat delivery are different. The South box uses free convection (see Figure A2, Appendix A), while the North box utilizes a powered isothermal baffle/radiative surface.

The NVLAP round robin has reinforced the confidence in measurements obtained from the two guarded hot box facilities. The results from the three different tests at nominally the same temperature conditions produced results that were close to identical. The values obtained at IRC may vary from values obtained from other sources due to the fact that test specimens that will be produced at other facilities will be similar, but not identical to the one used in the tests in the North and South boxes.

It was noted that the thickness of the insulation batts varied significantly from piece to piece. It is suggested that more consistent insulation and simplified construction be used in any further round robins.

APPENDIX A

TEST PROCEDURE AND CALORIMETER HEAT TRANSFER CCHARACTERISTICS FOR THE SOUTH BOX

CALORIMETER HEAT TRANSFER CHARACTERISTICS

The calorimeter (Figures A1 and A2) is constructed of 76 mm isocyanurate foam covered inside and outside with fiberglass and polyester resin. The inside dimensions of the box are 2490 mm high by 2490 mm wide by 675 mm deep. The box has one 2490 mm square side open. A baffle of 40 mm fiberglass resin covered isocyanurate foam is installed 230 mm from the back wall. The baffle is the full calorimeter width and 2015 mm high leaving a gap of 238 mm across the top and bottom. A row of electric heaters are installed between the baffle and the back wall just above the bottom of the baffle so that the baffle shields the test specimen from direct radiation from the heaters. Air heated by these heaters flows up between the baffle and the back wall, through the gap at the top, down the 405 mm space between the baffle and the test wall and back through the gap at the bottom.

The heat transfer to the test wall is by convection from the air and by radiation from the baffle and the inside calorimeter surfaces in the view of the test specimen. The mean temperature of the baffle and calorimeter surfaces, T_b, is thus lower than the mean hot air temperature, T_h, because of the radiation loss. This presents a problem in calculating the total resistance, R_t, and hot side air film resistance, R_{fh}, from measured values. To cope with this problem, an equivalent temperature, T_e, is calculated such that if T_h and T_b were both equal to T_e, the same heat flow would result as that for the actual air and calorimeter surface temperatures and the same radiation and convection coefficients.

The total heat flow into the hot surface of the test specimen, q_t, will be the sum of the convective component, q_c, and the radiative component, q_r . That is:

$$q_t = q_c + q_r$$

$$q_t = A(T_h - T_1)^B + F_f F_e \sigma(T_b^4 - T_1^4)$$

where: A and B are constants

T_1 is the specimen hot surface temperature

F_f and F_e are form and emmisivity factors which in this case are assumed to be equal to 1.0

σ is the Stefan-Boltzman constant
$\sigma = 5.6703 \times 10^{-8}$ [W/(m²·K⁴)]

The constants A and B were evaluated from the results of a series of tests on a special test specimen. The wall was constructed from very stable and uniform insulating boards with surface coverings of 6 mm plywood. From the tests on this wall, where q_t, T_h, T_1, and T_b were measured, q_r and q_c were calculated. Values of A = 3.025 and B = 1.25 were found to give a good representation of q_c for all heat flows by the equation

$$q_c = A(T_h - T_1)^B$$

Thus $$q_t = 3.025\,(T_h - T_1)^{1.25} + \sigma(T_b^4 - T_1^4)$$

When the test wall has framing or other components that influence the hot surface temperature, the average surface temperature, T_1, is used in the preceeding equation. It is assumed that this approach gives better precision than trying to establish a weighted temperature average from measurements.

Once the average surface temperature of the wall is established, coefficients for the convective and radiative exchange, h_c and h_r, can be calculated.

$$h_c = q_c/(T_h - T_1) = 3.025\,(T_h - T_1)^{0.25}$$

$$h_r = q_r/(T_b - T_1) = \sigma(T_b^4 - T_1^4)/(T_b - T_1)$$

The hot side equivalent temperature, T_e, can be calculated by the following equation.

$$T_e = (h_c T_h + h_r T_b)/(h_c + h_r)$$

The total resistance, R_t, wall resistance, R_w, hot side film resistance, R_{fh}, cold side film resistance, R_{fc}, measured in the test are calculated as follows (T_c is the measured cold air temperature and T_2 is the measured cold surface temperature).

$$R_t = (T_e - T_c)/q_t$$

$$R_w = (T_1 - T_2)/q_t$$

$$R_{fh} = (T_e - T_1)/q_t$$

$$R_{fc} = (T_2 - T_c)/q_t$$

The values assigned to R_{fh} and R_{fc} in wall design resistance values, R_d, are usually 0.12 m^2K/W and 0.03 m^2K/W respectively. The total design resistance then becomes:

$$R_d = R_w + 0.12 + 0.03 = R_w + 0.15$$

The design U-value is then:

$$U_d = 1/R_d$$

TEST PROCEDURE

The test specimen is mounted vertically into a 2.44 m by 2.44 m opening of a polystyrene lined steel test frame. The hot and cold side perimeters of the test specimen are taped to the test frame to eliminate any air leakage around the test specimen.

The test frame, with the specimen installed, is mounted to the cold side chamber of the Environmental Test Facility. The calorimeter (metering box) used to measure heat flow through the specimen is installed over the hot surface of the test specimen. The hot side chamber of the Environmental Test Facility is then joined to the cold side chamber as shown in Figure A2.

During a steady state test, the calorimeter air temperature is maintained constant at the test temperature conditions. Eight equally spaced thermocouples are located in the air on the hot and cold sides of the test specimen as well as six on the baffle in the calorimeter. It is estimated that temperatures are measured by the thermocouples with an accuracy of ±0.1°C.

Power to the calorimeter is measured continuously and 6 hour averages are recorded. A test is assumed to be at steady state conditions when four consecutive 6 hour averages are observed to change by less than 1%. It is estimated that the heat flow is measured by the calorimeter with an accuracy of ±3%

Figure A1. IRC/NRCC Calorimeter.

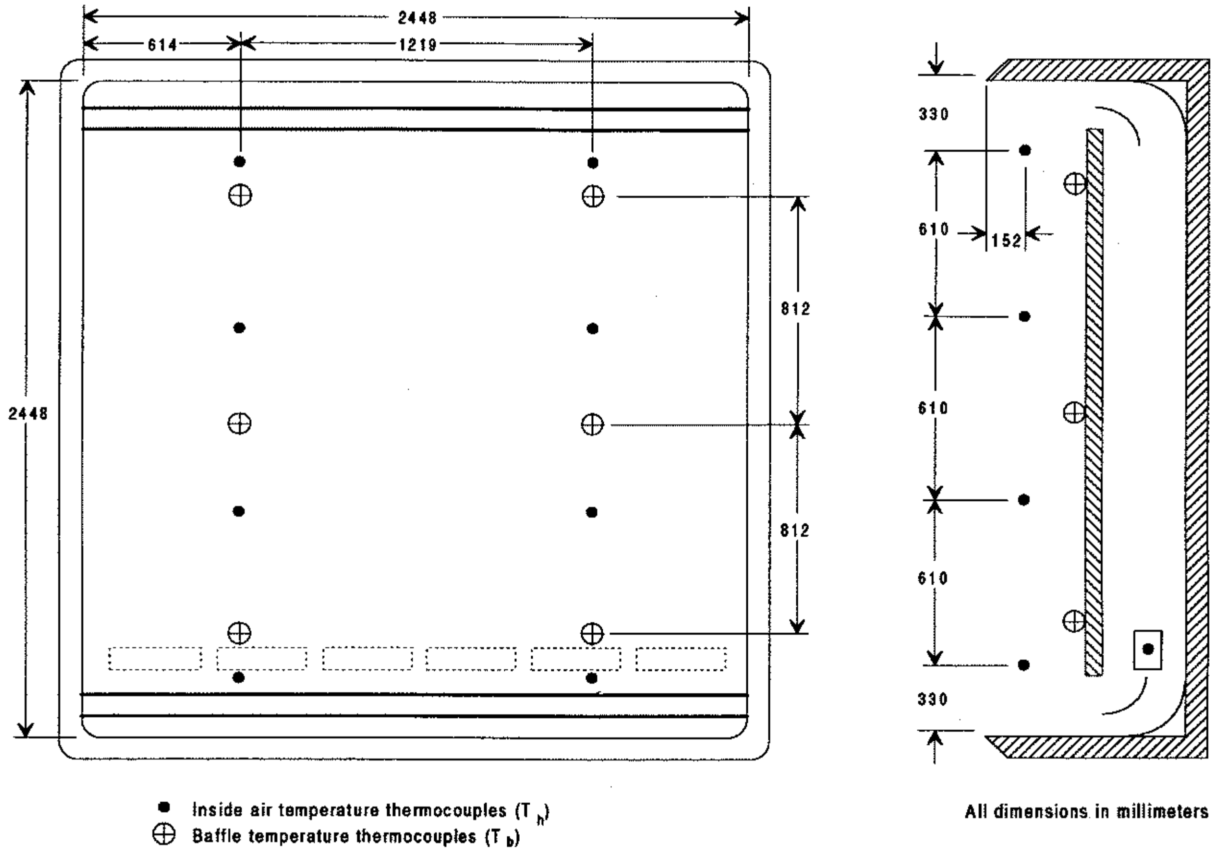
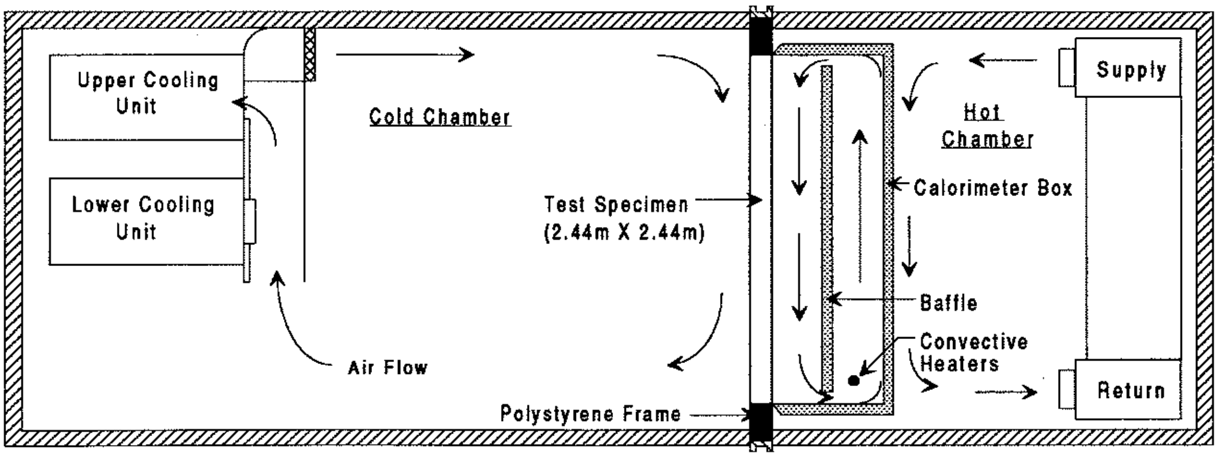


Figure A2. IRC/NRCC Environmental Test Facility - Vertical Section



APPENDIX B

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
T_i = 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
i=3 for mask $F_{13} = 0.040$
i=4 for baffle $F_{14} = 0.674$
i=5 for calorimeter $F_{15} = 0.116$
σ = the Stefan-Boltzmann constant = 5.6703×10^{-8} W / ($m^2 \bullet K^4$)
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

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

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

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:

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

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

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

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

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

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 • K) (weather-side film resistance R_{fo} is then 0.04 m^2·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:

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

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

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

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 wall, 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 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 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)