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# The Thermal and Air Leakage Performance of Residential Walls

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## RÉSUMÉ

Dans le cadre de son programme continu de recherches sur la performance de l'enveloppe du bâtiment et en collaboration avec le Programme de bourses de recherches SIP/CNRC, l'Institut de recherche en construction a récemment entrepris la réalisation de projets visant à évaluer la performance des murs à ossature de bois des habitations au points de vue thermique et fuites d'air.

L'évaluation de la performance thermique a consisté à mesurer, à l'aide de la chambre à double atmosphère de l'Institut, la résistance thermique d'échantillons de 2,4 × 2,4 m sous trois températures moyennes. Les essais ont porté sur quatre échantillons comportant de l'isolant de polyuréthane projeté en place.

L'évaluation de la performance au niveau fuites d'air a consisté à mesurer le taux de fuite d'air à travers des échantillons de 2,4 × 2,4 m sous des différences de pression correspondant à celles qui s'exercent normalement sur l'enveloppe du bâtiment, et à déterminer la performance structurelle du système de pare-air sous des écarts de pression correspondant aux charges de bourrasque. La performance au niveau fuites d'air a été évaluée au moyen de l'appareil de mesure des fuites d'air de l'Institut. Les essais ont été réalisés sur un échantillon comportant de l'isolant de polyuréthane projeté en place.

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# THE THERMAL AND AIR LEAKAGE PERFORMANCE OF RESIDENTIAL WALLS

by W.C. Brown[1] and N.V. Schwartz

## ABSTRACT

As part of its continuing program of research on performance of the building envelope and in cooperation with the SPI/NRC Fellowship Program, the Institute for Research in Construction recently undertook projects to evaluate the thermal performance and air leakage performance of wood frame residential walls.

Evaluation of thermal performance included measurement of the thermal resistance of 2.4 x 2.4 m test specimens at three mean temperatures. Thermal resistance of the specimens was measured using the Institute's guarded hot box apparatus. Four specimens with sprayed-in-place polyurethane insulation were included in the project.

Evaluation of air leakage performance included measurement of the air leakage rate through 2.4 x 2.4 m test specimens at pressure differences corresponding to those normally exerted on the building envelope, and assessment of the structural performance of the air barrier system at pressure differences corresponding to gust wind loading. Air leakage performance was evaluated using the Institute's air leakage apparatus. One specimen with sprayed-in-place polyurethane insulation was included in the air leakage project.

This paper describes the test procedures used in the test series and reports on the initial results of the test program.

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## INTRODUCTION

The Institute for Research in Construction (IRC) is engaged in research on performance of the building envelope with regard to climatic factors such as heat, moisture and air. Research project objectives range from determination of fundamental principles of building science to evaluation of in-use performance of building envelope systems. Funding for the majority of the projects is from public sources, although an increasing number of projects are being funded by industry.

The Society of the Plastics Industry (SPI) has funded a Fellowship position at IRC. The research undertaken by the SPI/NRC Fellow aims to establish procedures for assessing the value-in-use of residential thermal insulation materials and systems. These would include materials such as polyurethane, polystyrene and glass fibre insulations.

In support of both the IRC research program and the SPI/NRC Fellowship program, IRC undertook projects to evaluate the thermal performance and air leakage performance of residential walls. The objectives were:

a) to produce measured values of performance;

b) to assess the accuracy of available prediction models.

The majority of the specimens in the thermal performance project were insulated with glass fibre insulation in the stud space. The effect of insulating sheathing, stud depth and stud spacing were examined in the project. Four wood frame specimens containing sprayed-in-place polyurethane insulation were included in the test program. This paper reports on the results from the polyurethane specimens and, for comparison, four glass fibre insulated specimens.

The majority of the specimens in the air leakage performance project used wood stud framing as the main structural element. One wood frame specimen containing sprayed-in-place polyurethane insulation on fiberboard sheathing was included in the test program. Test results from this specimen are reported in this paper. Since there is no standard test procedure to evaluate the air leakage performance of walls, a procedure developed by IRC was used for this purpose.

## THERMAL PERFORMANCE

In an evaluation of thermal performance, the primary concern is assessment of heat transfer due to temperature gradient. This includes heat transfer by conduction, radiation and convective air flow. It does not include heat transfer due to vapour movement, which is driven by vapour pressure gradient, or air leakage, which is driven by air pressure gradient. Thermal resistance is the standard measure of the effectiveness of a system at controlling heat transfer due to temperature gradient.

A secondary concern in an evaluation of thermal performance is assessment of surface temperature performance. This is important because of its effect on condensation. In general, wood frame walls do not present problems with surface temperature if the stud space is filled with insulation and the vapour and air tightness control planes are at the interior surface.

### Thermal Test Procedure

The thermal performance tests were performed in the Full Scale Thermal Test Facility of IRC. This facility conforms, in general, to that standardized by ASTM C236 - Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box (ASTM 1986a). It consists of a cold chamber (test temperatures between 0°C and -40°C), a metering box (test temperatures between 15°C and 25°C), and a chamber that serves as the thermal guard for the metering box. The metering box, with a 2.4 x 2.4 m test area, measures the heat flow through a 2.4 x 2.4 m test specimen. Thermocouples are used to measure average warm and cold surface temperatures. Specimen thermal resistance is calculated from the measured temperature difference and heat flow.

Because thermal resistance of insulating materials varies with mean temperature, specimen thermal resistance was measured at three mean temperatures. These measurements were performed with a metering box temperature of approximately 21°C and cold chamber temperatures of approximately -7°C, -21°C and -35°C. A mean temperature of 0°C was chosen as the basis for comparing thermal resistance for different specimens. This value was determined from a least squares linear fit to the three measured values of thermal resistance.

## Thermal Prediction Models

Two simplified heat transfer models are generally used to predict the thermal resistance of wood frame walls. The first is referred to as the "parallel" model, while the second is referred to as the "series-parallel" model (ASHRAE 1985). The "parallel" model assumes that there is no lateral heat flow between paths and the average thermal resistance of the assembly is the area weighted average of the thermal resistance of the individual paths. The "series-parallel" model assumes that there is perfect lateral heat flow between paths and the average thermal resistance of the assembly is the sum of the thermal resistances of the individual layers. Thermal resistance of layers with multiple paths is calculated using the "parallel" model. ASHRAE notes that the actual thermal resistance of an assembly will fall between the values calculated by the two models.

## Thermal Test Specimens

The thermal performance test specimens were wood frame wall sections constructed of 38 mm x 89 mm pine studs located on 406 mm centers. Half width studs, 19 mm thick, were installed at the sides of the specimens, which were constructed with a double top plate and single bottom plate. An inside finish of painted 12 mm gypsum board was installed on the specimens. This was sealed at all joints to prevent air leakage through the specimens. Each of the thermal test specimens had a different combination of stud space insulation, exterior sheathing and exterior cladding. These details are listed in Table 1.

The glass fibre insulated specimens (1 to 3) used the same stud/insulation system; that is, specimens 2a, 2b and 3 were constructed by modifying the exterior of specimen 1. The polyurethane insulated specimens (4 to 7) were constructed on four separate stud frames. Specimens 4 and 5 were foamed by one operator, while specimens 6 and 7 were foamed by a second operator. The same chemicals were used for the standard density foams in specimens 4, 5 and 6, while different chemicals were used for the low density foam of specimen 7. The same equipment was used to foam all four specimens. Both operators were instructed to foam to a depth of 75 mm. However, in all cases the foam exceeded the depth of the studs at points and some trimming was required. After trimming excess foam back to the face of the studs, the average thickness of foam in the specimens varied from a low of 71.4 mm (specimen 4) to a high of 85.5 mm (specimen 7).

To determine the accuracy of the models used to predict wall thermal resistance, thermal resistance of samples of all insulation used in the specimens was measured by IRC. These measurements were performed using an ASTM C518 heat flow meter apparatus (ASTM 1986b) at a mean temperature of 24°C. Table 2 lists the thermal resistance measured for all insulation used in the full scale specimens.

Test samples of the glass fibre insulation and insulating sheathings were selected from the material used in the full scale specimens. For the polyurethane insulation, test samples were sprayed at the same time as the full scale specimens. Measured thermal conductivity for Type A and Type B polyurethane was the same (0.017 W/(m•K)) and slightly lower than that measured for Type C polyurethane (0.018 W/(m•K)). Thermal resistance for the polyurethane, which varied from a low of 4.20 $m^2$•K/W to a high of 4.75 $m^2$•K/W, was calculated from the measured thermal conductivity and measured average thickness. Measurements were made on unaged foam, 21 to 28 days old.

## Thermal Test Results

Thermal resistance values measured for the glass fibre insulated specimens are shown in Figure 1.

The measured thermal resistance for specimens 2a and 2b was the same, indicating that, from the viewpoint of these thermal tests, there is no difference between vinyl and aluminum siding. The difference between the results from these specimens and that from specimen 1 indicate that a thermal resistance of 0.13 $m^2$•K/W was added by both sidings. This compares favourably with the value of 0.11 $m^2$•K/W quoted for hollow-back aluminum siding in the ASHRAE Handbook of Fundamentals (ASHRAE 1985).

The difference between the thermal resistance measured for specimen 3 and that measured for specimen 2b indicates that a net thermal resistance of 1.06 $m^2$•K/W was added by the Type IV polystyrene insulating sheathing. Assuming the plywood sheathing on specimen 2b has a thermal resistance of 0.11 $m^2$•K/W (ASHRAE 1985), a total thermal resistance of 1.17 $m^2$•K/W can be attributed to the sheathing on specimen 3.

Thermal resistance values measured for the polyurethane insulated specimens are shown in Figure 2.

It was intended that specimens 4 to 7 have similar quantities of polyurethane in the stud space in order to make a direct comparison of measured thermal resistances values. However, because of the variation in insulation thermal resistance, a direct comparison was not possible. Accurate prediction models must therefore be used to provide a basis of comparison.

To make an accurate comparison between measured and calculated thermal resistance, both values must be determined at a common mean temperature. Since specimen thermal resistance cannot be measured at 24°C mean temperature and material thermal resistance has not been measured at 0°C mean temperature, a compromise solution was to extrapolate the linear fit of specimen thermal resistance to 24°C mean temperature. It is recognized that this is an incomplete solution, since the thermal resistance of polyurethane does not vary linearly with mean temperature. However, it does provide a first approximation of the accuracy of the thermal resistance prediction models.

The comparison of measured and calculated thermal resistance is shown in Figure 3. Thermal resistance calculated by the "parallel" and "series-parallel" models for each specimen are shown and labeled with the number of the specimen. The solid line in Figure 3 is the line of perfect agreement between measured and calculated values; the dashed lines enclose an envelope representing calculated values within 10% of measured values.

While both models predict approximately the same value for specimens of low thermal resistance, the difference between the predictions tends to increase as the specimen thermal resistance increases. In most cases the predicted values bracket the measured value and, except for specimen 5, all predictions are within 10% of that determined from the measurements. For the range of thermal resistance considered, the simplest approach to a more accurate prediction is to take an average of the two values predicted by the models. This conclusion will be checked further with the addition of measured results from other residential wall constructions. It is also planned to compare results at 0°C mean temperature using insulation thermal resistance measured at that point.

## AIR LEAKAGE PERFORMANCE

Uncontrolled air leakage through residential walls can lead to a number of problems. These include problems with interstitial condensation and higher than necessary energy cost. In an evaluation of air leakage performance, the primary concern is assessment of air flow under pressure gradient. Standards for building components (e.g. windows, doors) specify that the air flow rate at 75 Pa be used as the measure of the effectiveness of the component at controlling air leakage. However, it is not possible at present to set such a test condition for walls. Instead, the flow vs pressure difference relationship can be determined for pressure differences up to 100 Pa.

A secondary concern in an evaluation of air leakage performance is assessment of structural performance of the air barrier system. For a system to be effective at controlling air leakage, it must be capable of resisting the pressure differences exerted on it. These include pressure differences generated by stack effect and wind and, for some buildings, by mechanical ventilation systems.

When considering thermal performance, the entire wall construction contributes to the thermal performance of the wall. However, air leakage performance is best provided by a plane of air tightness. This may be attained with a single air tight, strong material. More commonly an air tight material must be supported by a structural material. The materials in the plane of air tightness may be those which make up the fabric of the building (e.g. glass, metal pans), or they may be materials added specifically to improve air tightness. In all cases, it is important that the various materials in the "plane of air tightness" be joined with strong, leak-free joints.

A test procedure to measure air flow under pressure gradient is standardized as ASTM E283 - Standard Test Method for Rate of Air Leakage Through Exterior Windows, Curtain Walls and Doors (ASTM 1986c). A test procedure to measure structural performance under pressure gradient is standardized as ASTM E330 - Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference (ASTM 1986d). Neither of these procedures is directly applicable to testing the air leakage of opaque walls. However, the apparatus specified in them can be used on full size wall specimens.

## Air Leakage Test Procedure

The air leakage performance test was performed in the Air Leakage Test Facility of IRC. This facility conforms, in general, to those described in ASTM E283 and ASTM E330. It consists of an air tight test chamber to which a test specimen 2.4 x 2.4 m is clamped with an air tight connection. Positive and negative pressure differences are applied across the specimen by pressurizing or evacuating the space between the back of the specimen and the chamber. Air flow through the specimen is measured with laminar flow meters, while pressure difference across the specimen is measured with electronic pressure sensors.

The test procedure consisted of two parts. In the air leakage part, the air flow vs pressure difference curve was determined for pressure differences up to 100 Pa. In the structural performance part, pressure differences of 250, 500 and 1000 Pa, simulating sustained wind loading, were applied for one hour and pressure differences of 1500, 2000 and 2500 Pa, simulating gust wind loading, were applied for ten seconds. After each of the structural performance test conditions, the specimen was visually checked for structural damage and the air flow at 75 Pa was measured and compared to that measured during the air leakage test. All pressure conditions were applied in both a positive and negative direction.

## Air Leakage Test Specimen

The air leakage performance test specimen was a wood frame wall section constructed of 38 mm x 89 mm pine studs located on 406 mm centers. The specimen was constructed with a double top plate and single bottom plate. Fibreboard sheathing, 11 mm thick, was installed on one side of the wood frame and approximately 75 mm of standard density sprayed-in-place polyurethane foam insulation (Type B) was installed in the stud space. No inside finish or exterior siding was installed on the specimen.

## Air Leakage Test Results

The air leakage performance tests were conducted 28 days after foaming the specimen. The air flow vs pressure difference curve measured for the specimen is shown in Figure 4. Included on the figure are the flow rates measured for the specimen at the sustained wind load structural performance test.

The flow rate determined for the specimen at 75 Pa pressure difference (0.02 $L/(s \cdot m^2)$ is considerably less than that measured for fibreboard alone (1.6 $L/(s \cdot m^2)$ (Bomberg and Kumaran, 1985). The specimen showed no visible damage during the negative pressure structural performance tests and no change to the flow rate at 75 Pa. At 500 Pa positive pressure, the fibreboard showed signs of being pushed off the nails holding it to the studs. However, the re-test of the flow rate at 75 Pa showed no change. No further visible damage appeared during the remainder of the positive pressure structural performance test and there was no change to the flow rate at 75 Pa.

## CONCLUSIONS

A number of preliminary conclusions can be drawn from the work to date. In general, both the "parallel" and "series-parallel" models of heat transfer can be used to predict thermal resistance of residential walls to within 10% of measured values. A more accurate prediction is obtained from an average of the values predicted by the two models. While an existing standard test procedure can be used to assess thermal performance, there is need for a standard test procedure to assess air leakage performance. Such a procedure, currently under development at IRC, has been used to show that unaged polyurethane foam can improve the air leakage performance of a wood frame specimen sheathed with fibreboard.

Work on both the thermal performance project and the air leakage performance project is continuing. For the thermal performance project, it is planned to measure the performance of several more residential wall constructions. These include specimens constructed with 38 x 140 mm studs and specimens representing designs typical of those used in the R2000 program. All of the measured results will be used to further assess the accuracy of the prediction models.

For the air leakage performance project, it is planned to continue to assess the suitability of the air barrier test procedure by applying it to a number of residential air barrier systems. The test procedure will also be adapted to include the testing of air barrier system joints.

To assess the effect of field conditions on the performance of polyurethane specimens, three of the thermal specimens (4, 6 and 7) and the air leakage specimen will be installed in an exterior wall at IRC. The specimens will be left in place over the winter and retested in the spring to determine if their performance has changed.

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J.A. Richardson constructed and instrumented the thermal test specimens and conducted the thermal tests. G.F. Poirier constructed and instrumented the air leakage test specimen and conducted the air leakage tests.

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TABLE 1

Thermal Performance Project
Details of Test Specimens

| Specimen No. | Stud Space Insulation | Exterior Sheathing | Exterior Siding |
|---|---|---|---|
| 1 | glass fibre | plywood | none |
| 2a | " | " | hollow back vinyl |
| 2b | " | " | hollow back aluminum |
| 3 | " | Type IV polystyrene | " |
| 4 | std. density PUF (Type A) | plywood | " |
| 5 | " | Type IV polystyrene | " |
| 6 | std. density PUF (Type B) | Type I polystyrene | hollow back vinyl |
| 7 | low density PUF (Type C) | Type IV polystyrene | " |

Note: The following characteristics were common to all specimens:
a) 38 mm x 89 mm pine studs at 406 mm on center
b) 19 mm pine studs (half studs) on sides
c) double top plate and single bottom plate, all pine
d) 12 mm gypsum board interior finish, sealed to prevent air leakage

TABLE 2

Thermal Performance Project
Measured Insulation Thermal Resistance

| Material | Thickness mm | Density $kg/m^3$ | R-value $m^2 \cdot K/W$ | Specimen No. |
|---|---|---|---|---|
| <u>stud insulation</u> | | | | |
| glass fibre batts | 89 | | 2.17 | 1, 2a, 2b & 3 |
| std. density PUF (Type A) | 71.4<br>73.6 | 35.0 | 4.20<br>4.33 | 4<br>5 |
| std. density PUF (Type B) | 75.8 | 36.9 | 4.46 | 6 |
| low density PUF (Type C) | 85.5 | 27.6 | 4.75 | 7 |
| <u>sheathing</u> | | | | |
| Type IV polystyrene | 37 | | 1.34 | 3, 5 & 7 |
| Type I polystyrene | 37 | | 0.92 | 6 |

Note: R-value of PUF (polyurethane foam) calculated from measured average thickness of PUF in the specimen and thermal conductivity measured at 24°C mean temperature.

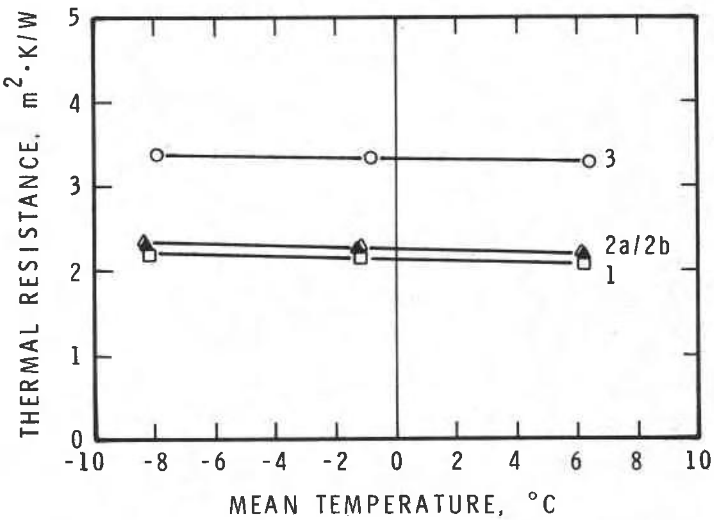


Figure 1 Measured thermal resistance of glass fibre insulated specimens.

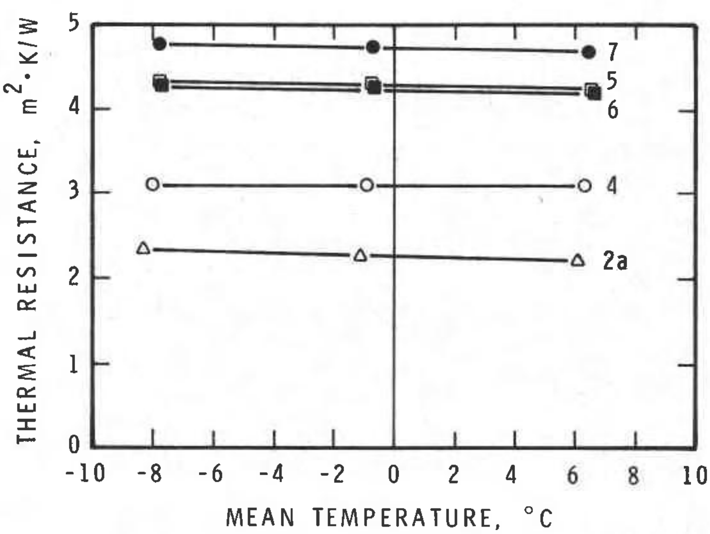


Figure 2 Measured thermal resistance of polyurethane insulated specimens.

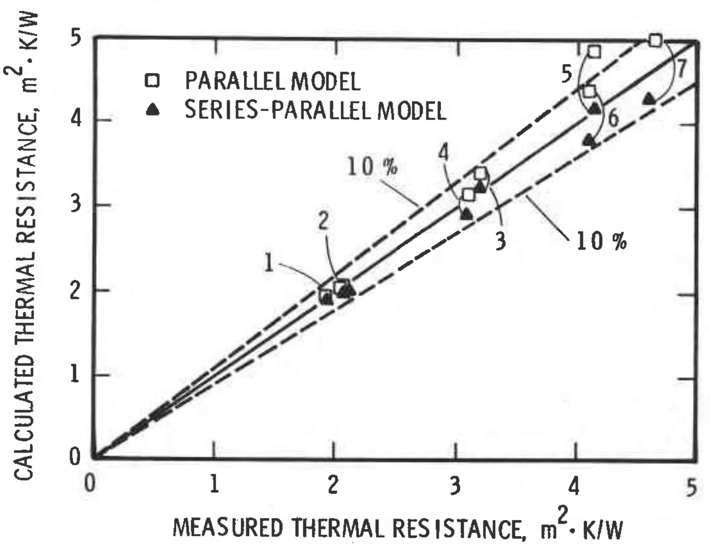


Figure 3 Comparison of "measured" and calculated thermal resistance.

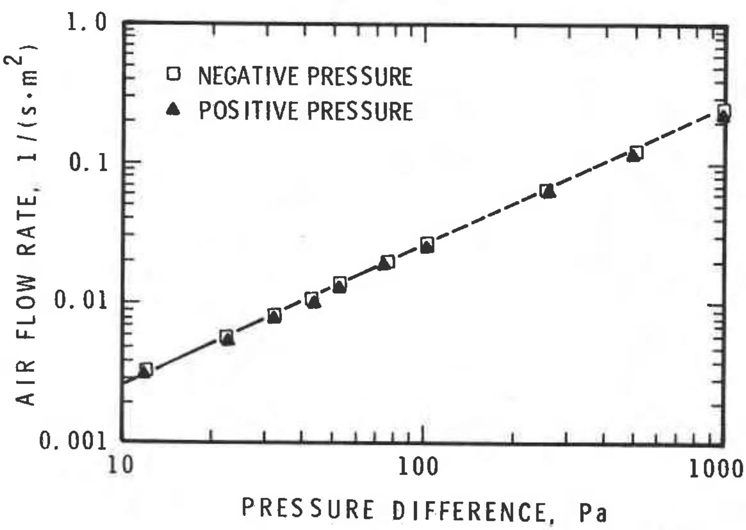


Figure 4 Measured air leakage of polyurethane/fibreboard specimen.

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