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Measured Thermal Resistance of Frame Walls with Defects in the Installation of Mineral Fibre Insulation

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ABSTRACT: Studies have shown that convective air flow can significantly reduce the thermal resistance of frame walls insulated with mineral fibre insulation (MFI). It has also been shown that convective air flow can be avoided if the MFI products are installed with at least one face against an air impermeable material. The evolution of MFI products has seen the introduction of products with smaller fibre diameters and lighter densities, and there is a dominance of the frame wall insulation market by friction fit products. The effect of these changes on the installed (field) performance of MFI products is unknown, as is the effect of "minor" installation defects on the performance of frame wall insulation systems. This article examines, through a program of full scale laboratory measurements, the effect of corner installation defects and product density on the thermal resistance of frame walls insulated with MFI products.

1. INTRODUCTION

WOOD CHIPS, SHREDDED newspaper, and dried seaweed have been used in the past to insulate walls of Canadian houses. For example,

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a project was recorded in 1926 in Saskatchewan where cavities of a wood frame wall were filled with shredded newspaper blown through holes drilled in the external sheathing. These early insulation materials were gradually replaced by mineral fibre insulation (MFI) in the form of batt (material cut to cavity size) and blankets (material in roll form). (Note that the phrase "mineral fibre" is used as the generic term for both glass fibre products and basalt or slag fibre products and as the specific term for the latter product.) The first batts and blankets had fibre diameters larger than 9 microns and were covered with a kraft paper facing to protect workers handling them. They were also at least 25 mm thinner than the stud spaces in which they were installed.

In the 1970s, "friction-fit" MFI products became widely available in the marketplace. These products filled the whole cavity space and contained no protective covering. They were slightly oversized in all dimensions so that they would be held in place by the friction between the product and the cavity surfaces. Further improvements in manufacturing technology over the last two decades have led to significant reductions in the diameter of the glass fibres. Glass fibre batts and blankets have been manufactured at densities as low as 8–9 kg/m^3, a value which is about half that from the late 1960s. These products retain almost the same nominal thermal resistance when measured under laboratory conditions, but often have lower stiffness than the older products.

But does material thermal resistance measured under standard laboratory conditions adequately represent field performance of the material installed in a wall? Field performance measured for some insulation systems has confirmed laboratory values [1]. Others have not. One documented case of disagreement occurred in the early 1980s when a significant reduction of thermal resistance was measured in a full-scale study of preformed, loose-fill glass fibre insulation on an attic floor [2]. This reduction, which was caused by convective air flow cells, was not predicted by the material testing. The situation was exacerbated by the loose-fill product being applied in the field at much lower density than that used in laboratory evaluation of the material. Similar results on loose-fill attic insulation were reported in Reference [3].

In response to these findings, the manufacturer modified the MFI product to make it less prone to convective effects, and the Canadian standard for MFI [4] was amended to require a minimum thermal resistivity for loose-fill insulations. The latter response was based on the following reasoning.

- Thermal resistivity is determined by the structure of the material.
- The structure of the material controls the permeability of the material.
- The permeability of the material limits air flow through the material.

Therefore, setting a minimum for thermal resistivity limits the conditions that contribute to convective air flow to some extent. Manufacturers in the USA did not follow suit. In fact Oak Ridge National Laboratory (ORNL) recently reported that full-scale measurements of a similar type of loose-fill glass fibre product showed a discrepancy of more than 30% between predicted and measured full-scale performance [5].

The ORNL report again brings into question the relationship between material and installed performance, not only for ceiling/attic installations but also for wall installations. There may be a difference between the performance of Canadian and American MFI products because the degree of reliance on friction fit to hold the batt in place is not the same in both countries. This difference could result in a different degree of installation workmanship; consequently it could produce different field performance. Similarly, the differences between North American MFI products and European products may produce different in-use performance.

Despite changes in MFI manufacturing technology (lower density products) and installation techniques (friction fit batts now dominate the frame wall insulation market in Canada), little is known quantitatively about the effects of "minor" installation defects on installed thermal performance. Many studies have demonstrated that full air spaces on both sides of friction fit products can produce a significant reduction in installed thermal resistance. However, the limits on the size of the defect necessary for the onset of convective air flow has not been investigated completely. Because of the renewed interest in the performance on installed MFI products, a research project to investigate the thermal performance of frame walls with "imperfect" installation was initiated. In contrast with previous studies where performance was investigated with full air spaces on either side of the insulation, the current study investigated the effect of partial defects, namely, vertical air gaps in the corners of stud cavities which simulate imperfect installation.

2. FACTORS AFFECTING FRAME WALL THERMAL RESISTANCE

2.1 Insulation

MFI products ranging from 9 kg/m³ density glass fibre to 40 kg/m³ density mineral fibre, either basalt or slag fibre, are available commercially. Not only do these MFI products have different initial thermal and mechanical properties but also they are affected to various degrees by environmental factors prior to their installation. Of particular significance is their ability to recover if the compressed material has been stored for an extended period of time, or if it has been exposed to high humidity as a consequence of a puncture in the packaging. Materials that do not recover properly may be especially prone to poor installation.

2.2 Wood Framing

According to the National Building Code of Canada, wood used for framing members should have a moisture content less than 19% by weight. However framing lumber in Canada often has significantly higher moisture content and its drying may introduce a large degree of warping and cupping [6]. Furthermore double studs at windows and corners result in cavities with non-standard dimensions. While this does not affect the structural performance of the wall, it may cause a significant degree of additional cutting and fitting during the installation of MFI batts.

2.3 Installation of MFI Batts and Blankets

Not much has been published on installation practices of MFI products. Some of the limited information available is documented in Swedish studies performed from 1961 to 1967 and coordinated by the Royal Institute of Technology.

Dahlberg and Hedman [7] examined seventeen buildings, six of which were also studied during the construction stage. Methods of fitting batts fell into three general categories:

1. Precise cut (11 buildings)
2. Undersize cut, in which spaces were fitted with extra pieces (5 buildings)
3. Slightly oversize, in which pieces that were too large were squeezed at the stud to fit into the cavity (4 buildings), and significantly oversize, in which buckling occurred (5 buildings)

Methods 1 and 2 resulted in a large number of narrow (7 mm wide on average) open joints between insulation pieces or between insulation and wood frame, but no wide open joints were observed. The total length of open joint observed per square meter ranged from 100 mm to 750 mm. Method 3 frequently produced a large number of air spaces between the insulation and the sheathing. Because it was thought that convective air flow requires both open joints and air spaces, this aspect received special attention. It was observed in three walls, but in only one case did it appear to be significant—cracks of 130 mm length per square meter of wall and air spaces between the insulation and sheathing on 50% of the face with an average depth of 10 mm.

2.4 Installation Defects

An extensive study of convective air flow effects with MFI in wood-frame walls was performed in 1962–3 by Wolf, Solvason and Wilson [8]. Two

Table 1. Thermal resistance of wall with and without convection barrier (polyethylene) as measured by Wolf et al. [9].

Insulation	Horizontal Dividers	R-Value* ($m^2 \cdot K/W$) w/Barrier	R-Value* ($m^2 \cdot K/W$) w/o Barrier	Reduction
A	none	1.91**	0.88	46%
A	mid-height	1.87	1.01	54%
B	none	1.91	0.99	51%

*Includes inside and outside film resistances during the test.
**Barriers on both sides of insulation.

types of MFI were used—Type A with density ranging between 13 and 14.5 kg/m^3 and Type B with density between 32 and 40 kg/m^3. The test specimen, 2440 mm × 2440 mm, was finished with plywood sheathing. The insulation batts, 50 mm thick, were installed in the stud cavity with 19 mm deep air spaces on either face. Thermal resistance of the test specimens was measured in a guarded hot box with a temperature difference of about 50 K.

The results (Table 1) showed large reductions of thermal resistance when both sides of the insulation were exposed to the air spaces. Conversely, only a minor reduction occurred when a convection barrier was installed on both sides or one side with the other side exposed to air. Swedish studies [9,10] reported similar effects. Reduction of thermal resistance occurred with air spaces on both sides of the insulation but good agreement between measured and calculated thermal resistance was observed when stud cavities were completely filled.

These Canadian and Swedish studies show that the reduction of thermal resistance that follows faulty installation technique depends primarily on the existence of air spaces on both sides of the insulation. Subsequent research [11,12] has investigated the effectiveness of sheet materials such as weather barriers or vapour barriers to ensure that installed thermal resistance of insulated walls matches predicted values. The National Building Code of Canada recognizes the potential for poor thermal performance arising from faulty installation technique and includes the following specific installation requirement for insulation [13]:

> 9.25.4.2. Batt-Type Insulation. *Batt-type insulation manufactured with no membrane on either face shall be installed so that at least one face is in full and continuous contact with cladding, sheathing or other air-impermeable membrane.*

The issue of convective air movement and its effect on the thermal resistance of frame walls with MFI appears often in the literature, mainly as experimental studies highlighting the need for controlling convective air flow in the cavity [14,15] or improvements in computational models [5,16,17]. One work [18] provided an experimental demonstration of the "threshold gap" necessary to connect two air spaces existing on both sides of the insulation. The studied example included foil faced 50 mm thick insulation placed between two 15 mm thick air spaces. A variable gap was provided at the ends of the cavity to connect these two spaces. In the horizontal orientation gaps 4–5 mm wide were necessary to initiate convective air flow. However, in the vertical orientation gaps less than 1 mm wide were found to be sufficient to initiate convective air flow.

3. DETERMINATION OF FRAME WALL THERMAL RESISTANCE

3.1 Calculations Based on ASHRAE Models

Two simplified ASHRAE heat transfer models, generally referred to as the "parallel" and "series-parallel" models, are used to predict the thermal resistance of wood frame walls [19]. The first model assumes only parallel flow, i.e., the shortest heat flow path without any contribution from the lateral heat flow. The overall thermal resistance is obtained from the area weighted average of parallel path conductance values. The second model assumes another extreme case, namely, a perfect equalization of temperature at each material layer interface; the overall thermal resistance is the sum of the thermal resistances of each layer.

These models represent two limiting cases of multidirectional heat transfer; the actual thermal resistance of an assembly must fall between them. The higher the ratio between the longest and the shortest heat flow paths across the assembly, the closer the actual thermal resistance comes to the series-parallel model. For instance a good approximation for the thermal resistance of multi-slotted ceramic or concrete hollow blocks can be obtained by using 2/3 of the R-value from the series-parallel model and 1/3 of the R-value from the parallel model. A 50/50 mixing rule has been shown to produce better than 5% agreement between measured and calculated values for insulated wood frame walls [20].

3.2 Measurement of Thermal Resistance of Frame Walls

The Guarded Hot Box (GHB) Test Facility at the National Research Council conforms, in general, to that standardized in ASTM C236 [21] (Figure 1). It consists of a cold (weather) chamber where air temperatures can be set between 0°C and −40°C, a calorimeter (metering box) with 2440 mm × 2440 mm test area where air temperatures can be set between 15°C and 25°C, and a room chamber that acts as a thermal guard for the metering box. The calorimeter is constructed with 76 mm thick poly-

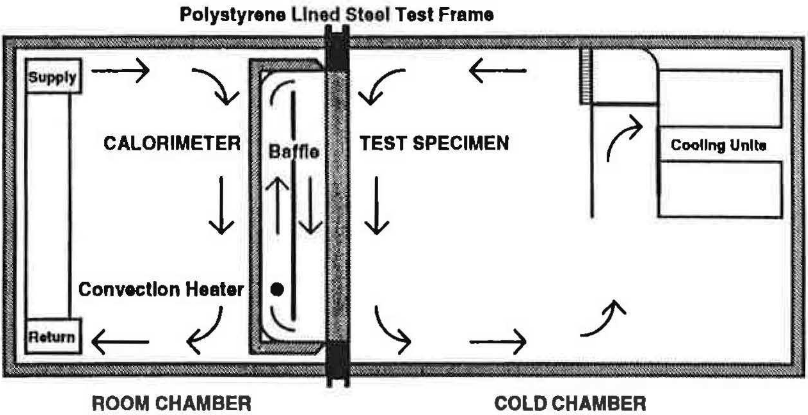

FIGURE 1. Vertical section through NRC's guarded hot box test facility.

isocyanurate foam covered on both sides by fiberglass-reinforced polyester resin. All walls of the calorimeter are instrumented with a thermopile that forms a sensitive heat flux transducer. This heat flux transducer is used to adjust the room chamber air temperature so that there is negligible heat transfer through the walls of the calorimeter.

A 40 mm thick baffle is located 230 mm from the back wall of the calorimeter. It stretches the full width of the calorimeter, but leaves a gap 238 mm high at the top and the bottom. A row of electric heaters is installed behind the baffle and convective air circulation from the heater carries heat to the test specimen surface. There is, however, also the radiative heat transfer from the baffle and calorimeter surfaces to the specimen. To account for these two mechanisms of heat transfer an equivalent hot side temperature is calculated such that, if both the air and the baffle temperatures had this equivalent temperature, the same heat flow would result [22]. Power to the calorimeter is measured continuously; 6 hour averages are recorded. A test is considered to be at steady state when four consecutive averages change less than 1%.

PRECISION

There are two aspects of precision, the measurement precision and the ability to build identical specimens. The second aspect is addressed later during discussion of the test results. NRC has two GHB facilities [22,23] that are identical in size, but differ in the heat transfer mechanisms in both the calorimeter and the cold chamber. An estimate of the first aspect of precision, the measurement precision, can be obtained by measuring the thermal resistance of the same test specimen in both facilities. Results of one series of such measurements are presented in Table 2. The difference between thermal resistance measured in the two facilities is significantly less than 1%, displaying a level of precision similar to that obtained from small scale tests performed in the Thermal Insulation Test Facility [24,25].

4. THERMAL RESISTANCE OF FRAME WALLS WITH INSTALLATION DEFECTS

4.1 Scope of the Research Program

The objective of this research study was to examine the effects of material density and installation defects on the thermal resistance of wood frame walls. Three MFI products were included in the study: Product 1 was a medium density glass fibre batt, Product 2 was a high density mineral fibre batt, and Product 3 was a low density glass fibre blanket that was cut to length to produce batts of the required size. These batts represent the range of MFI structure (fibre structure, density, permeability) available commercially. The installation defect selected for this study was an empty space in the sheathing/stud corner, as would be created by incomplete batt recovery or by edge squeeze as observed in Reference [7]. Anecdotal information, including non-systematic site surveys, had indicated that MFI products were being installed in frame walls with such defects. Three levels of defects were examined in the study, namely, 0%, 3%, and 6% of the cross section area of the MFI product.

4.2 Test Specimens

SELECTION OF INSULATION MATERIALS

For each MFI product, a sample lot consisting of at least 20 batts were numbered for identification; recovery thickness and mass were measured for each batt. The density of the batts was calculated for the installed thickness of 140 mm. Batts with the lowest recovery thickness, and lowest and highest density were discarded leaving 13 batts representing each product in the

Table 2. Thermal resistance of a round-robin wall test specimen measured in NRC's two guarded hot box test facilities.

	GHB #1			GHB #2		
T_{hot},* °C	33.2	19.3	18.6	35.3	20.2	20.2
T_{cold},* °C	−2.0	−5.1	−34.9	−0.9	−5.0	−35.0
R-value, m²·K/W	1.96	2.06	2.14	1.96	2.05	2.14

* T_{hot} is the equivalent temperature for the baffle and air temperature.

study. The thermal resistance of a batt with average density was measured in the Thermal Insulation Test Facility at NRC at the installed thickness (140 mm), while the remaining 12 batts were randomly installed in the wall test specimen.

The labeled (nominal) thermal resistance of Product 1 was 3.5 $m^2 \cdot K/W$ at a thickness of 152 mm. This product showed good recovery thickness, ranging from 156 mm to 168 mm; the density ranged from 12.9 kg/m^3 to 14.2 kg/m^3 with an average of 13.7 kg/m^3. Selected batts had density ranging from 13.5 kg/m^3 to 14 kg/m^3.

The labeled thermal resistance of Product 2 was 3.76 $m^2 \cdot K/W$ at a thickness of 140 mm. This product showed good recovery thickness, ranging from 142 mm to 149 mm; the density ranged from 32.1 kg/m^3 to 37.3 kg/m^3 with an average of 35.1 kg/m^3. Selected batts had densities ranging from 32.9 kg/m^3 and 37.1 kg/m^3.

The labeled thermal resistance of Product 3 was 3.35 $m^2 \cdot K/W$ at a thickness of 159 mm. This product showed poor recovery thickness, ranging from 143 mm to 160 mm, and the density ranged from 7.6 kg/m^3 to 9.7 kg/m^3 with an average of 9.0 kg/m^3. Selected batts had densities ranging from 8.2 kg/m^3 to 9.5 kg/m^3. (It should be noted that while three rolls were purchased, one roll was rejected prior to specimen selection because its color and thickness were not consistent with the other two rolls.)

CONSTRUCTION OF THE TEST SPECIMENS

The test specimen (Figure 2) was 2440 mm × 2440 mm and of 38 mm × 140 mm wood frame construction. It was constructed with a single bottom plate, a double top plate, and the studs were located at 406 mm on

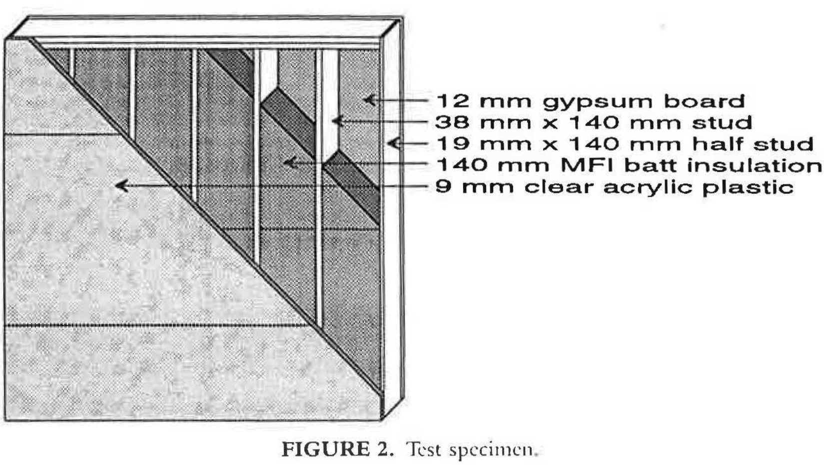

FIGURE 2. Test specimen.

centre. To provide precise and reproducible dimensional and thermal resistance of the frame, clear "C" selected pine with moisture content not greater than 9% was used as the framing lumber. Furthermore, to eliminate any potential air movement between the adjacent cavities, 25 mm wide by 3 mm thick strips of open cell foam were adhered to the faces of the top and bottom plates and the studs to form a gasket with the interior and exterior finishes.

The interior (hot) side was covered with 12 mm gypsum board finished with two coats of vapour barrier paint. The gypsum board was fastened to the frame by No. 8 × 32 mm drywall screws approximately 200 mm on centre; it was installed with two horizontal joints, each about 610 mm from the top or bottom and sealed with vinyl tape. The gypsum board remained in place for the entire test program.

The exterior (cold) side was covered with 9 mm clear acrylic plastic, predrilled at 204 mm intervals and countersunk with No. 6 × 32 mm wood screws used for mounting. (Note that the infra-red transmission characteristics of acrylic plastic are such that the material can be used in place of an opaque sheathing material.) Taped, horizontal joints were located opposite the joints in the gypsum board. All changes to the insulation were made from the cold side by removing the acrylic plastic.

The insulation was carefully installed in the stud cavity for the 0% defect test specimen. For the 3% and 6% defect test specimen, the installation defects were located at the four vertical corners of the stud cavity. To ensure consistency, fibreglass screening material was used to maintain the shape of the defects (Figure 3).

INSTRUMENTATION OF THE TEST SPECIMENS

The test specimen was mounted into a 2440 mm × 2440 mm opening of a polystyrene-lined steel test frame. The perimeter was taped to eliminate air leakage around the test specimen.

Air temperature of the calorimeter and of the cold chamber were each measured with eight equally spaced thermocouples and six thermocouples measured the calorimeter baffle temperature. Figure 4 shows the locations of 30 gauge Type T thermocouples used to measure specimen surface temperatures and Figure 5 shows the locations of 36 gauge Type T thermocouples used to measure temperatures within the test specimen. These thermocouples were located in the two center stud cavities and at the three levels shown in Figure 4. Thermocouples mounted to the wood studs were soldered to 5 mm × 10 mm copper shims to average local temperature variations. All thermocouples are calibrated to ensure precision of ±0.1°C.

One differential pressure transducer measured the pressure difference between the warm and cold surfaces of the insulation at the mid-height of a

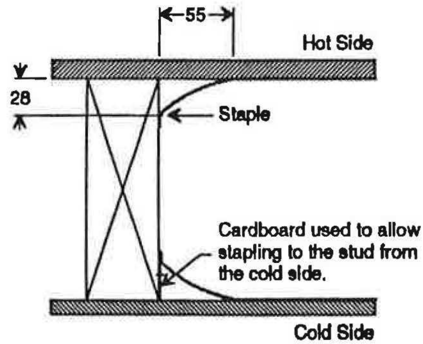

FIGURE 3. Detail of 6% installation defect.

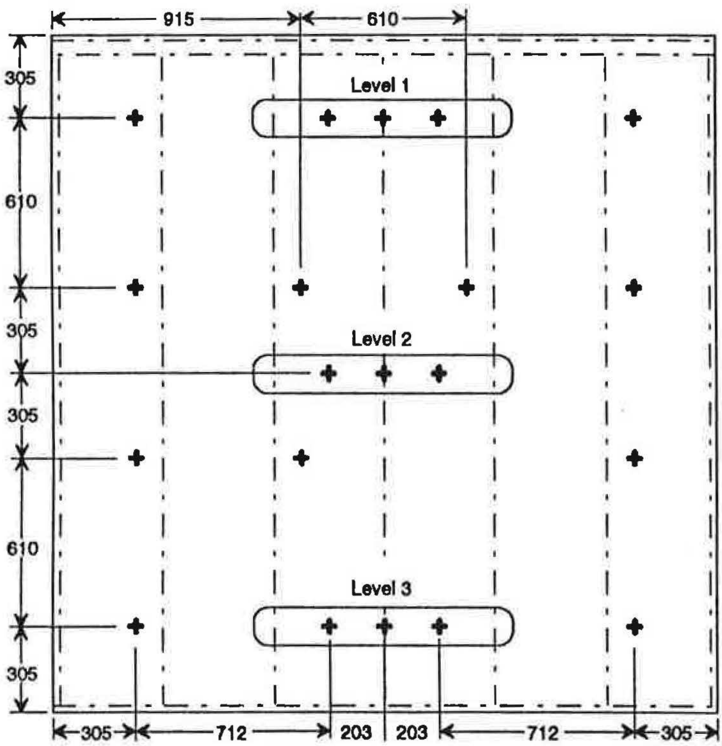

FIGURE 4. Location of thermocouples on surface of the test specimen.

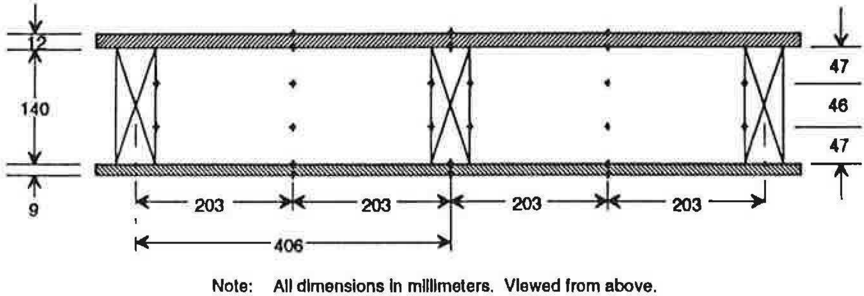

FIGURE 5. Location of thermocouples in the cross section of the test specimen.

stud cavity. A second transducer measured the differential pressure between the top and bottom of a cavity along a stud on the cold side.

4.3 Measured Thermal Resistance of the Test Specimens

Table 3 lists the surface-to-surface thermal resistance measured for test specimens insulated with the three MFI products included in the study. Note that the thermal resistance for Products 1 and 3 with 0% defects was not measured with −20°C cold side temperature.

4.4 Measured Temperature Distributions

Figure 6 presents a sample of temperature measurements from within the specimen, in this case from Level 2 of the test specimen insulated with Product 1 with 6% defects. Differences of temperature for otherwise identical locations are attributed to slight differences in the placement of thermocouples and to variations in the structure of the material. However these differences are small and generally speaking all measured temperatures show a consistent pattern. Average test temperatures for the two instrumented stud cavities were normalized to the hot/cold air temperature difference. Table 4

Table 3. Thermal resistance measured for frame walls insulated with three different MFI products installed with three different levels of defects.

	Product 1			Product 2			Product 3		
T_{cold}	0%	3%	6%	0%	3%	6%	0%	3%	6%
−5°C	3.15	3.08	2.87	3.29	3.22	3.10	2.95	2.80	2.53
−20°C	—	3.07	2.62	3.37	3.23	2.97	—	2.76	2.24
−35°C	3.38	2.96	2.35	3.43	3.12	2.75	3.14	2.68	2.00

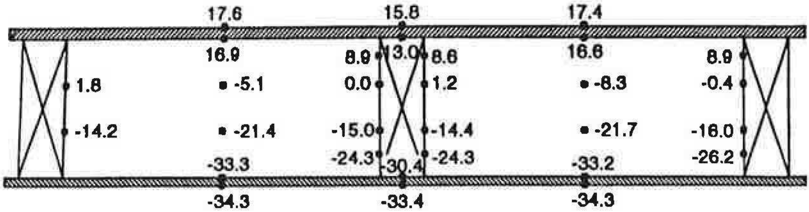

FIGURE 6. Temperatures measured at Level 2 of test specimen with Product 1 with 6% defects.

lists the normalized temperatures measured in the test specimens insulated with the three MFI products included in the study.

5. ANALYSIS OF MEASURED RESULTS AND DISCUSSION

5.1 Repeatability of Specimen Construction

Table 5 lists thermal resistance measured in a repeated test of Product 2 and third test involving Product 2′, all with 0% defects. The rebuilt specimen was constructed with all batts installed in the same locations in the test specimen. Product 2′ was manufactured on the same product line as Product 2 and the average density installed in the test specimen was within 2% of that of Product 2 (35.8 kg/m³ vs. 35.1 kg/m³). The results indicate that the thermal resistance measured for the first specimen built with Product 2 (October 1992) was 2–3% higher than that measured for the rebuilt specimen (March 1993). However, the thermal resistance measured for the test specimen with Product 2′ was quite close to that measured for the rebuilt Product 2 specimen.

Table 4. Normalized temperatures in 1/3 and 2/3 of the insulation thickness at three levels on test specimens subjected to 55 K air to air temperature difference.

	Product 1			Product 2			Product 3		
	0%	3%	6%	0%	3%	6%	0%	3%	6%
Level 1 1/3	0.48	0.65	0.72	0.48	0.58	0.73	0.64	0.66	0.80
2/3	0.24	0.33	0.41	0.22	0.29	0.39	0.30	0.33	0.46
Level 2 1/3	0.53	0.50	0.53	0.47	0.50	0.52	0.59	0.54	0.52
2/3	0.22	0.21	0.25	0.22	0.21	0.24	0.30	0.24	0.24
Level 3 1/3	0.51	0.35	0.21	0.49	0.34	0.27	0.56	0.38	0.18
2/3	0.21	0.13	0.06	0.21	0.15	0.08	0.28	0.16	0.05

Table 5. Thermal resistance measured for test specimens with Product 2 with 0% defects built in October 1992 and rebuilt in March 1993 and Product 2′ built in February 1993.

	Product 2		Product 2′
T_{cold}	Oct '92	Mar '93	Feb '93
−5°C	3.36	3.29	3.32
−20°C	—	3.37	3.36
−35°C	3.54	3.43	3.43

The temperatures measured in the October and March tests indicated that, while the temperature gradient through the studs remained the same for both tests, the temperature gradient through the insulation changed measurably. The conclusion is that the thermal performance of the insulation was different for the two test specimens, but it could not be established whether the change was a consequence of handling the batts during removal and placement in the test specimen or whether it should be attributed to other effects. Given that the second test result agrees well with that of Product 2′, the second results will be used as the baseline for Product 2.

The repeatability of test specimen defect construction was also checked. Table 6 lists thermal resistance measured in a repeated test of Product 2 with 3% defects. The rebuilt specimen was constructed with all batts installed in the same locations in the test specimen. The results show excellent agreement between thermal resistance measured for a specimen built in November 1992 and rebuilt in January 1993 and indicate that the defects can be constructed with the same precision as the rest of the specimen.

The results presented in Table 5 indicate that the uncertainty attainable on "ideal" specimens is 2–3%. However, combined with the results in Table 6,

Table 6. Thermal resistance measured for test specimens with Product 2 with 3% defects built in November 1992 and rebuilt in January 1993.

	Product 2	
T_{cold}	Nov '92	Jan '93
−5°C	3.22	3.20
−20°C	3.23	3.20
−35°C	3.12	3.12

Table 7. Thermal resistance measured and calculated for 0% defect test specimens.

	Product 1			Product 2			Product 3		
T_{cold}	Parallel	Meas.	Ser.-Par.	Parallel	Meas.	Ser.-Par.	Parallel	Meas.	Ser.-Par.
−5°C	3.15	3.15	3.23	3.25	3.29	3.34	2.92	2.95	2.98
−35°C	3.30	3.38	3.39	3.41	3.43	3.52	3.11	3.14	3.19

they also provided an estimate of the repeatability of test specimen construction, the second component of the measurement precision. It is evident that the effect of installation defects on the thermal resistance of wood frame walls can be measured with an uncertainty of 3% or less.

5.2 Thermal Resistance of 0% Defect Test Specimens

To evaluate the effects of installation defects on the thermal resistance of walls it is first necessary to establish the thermal resistance of a wall with a "perfect" installation (baseline). This determination can be done in two ways. One, by measuring the thermal resistance of wall test specimens with 0% defects, i.e., the insulation is carefully installed in the cavity; two, by calculating the thermal resistance using the ASHRAE parallel and series-parallel models and independently determined thermal resistance of each material can be determined as a function of temperature. Table 7 compares these two approaches. The agreement between measured and calculated values is excellent for all three products.

5.3 Temperature Gradients

Evidence of convective air flow is provided in Table 4, which shows the indexed temperatures measured with a cold side temperature of −35°C at 1/3 and 2/3 of the insulation thickness for the three MFI products. Note that the normalized temperatures measured in the insulation with 0% defects were the same for both −5°C and −35°C cold side temperature.

One set of temperature distributions, those measured through Product 1 with a cold air temperature of −35°C, are plotted in Figure 7. Temperature profiles were identical at the three measured levels (Figure 4) for 0% defects. They become more skewed and dependent on the level in the insulation with 3% and 6% defects. The pattern shown in Figure 7 is characteristic of that measured for all three MFI products. The difference in curvature between the top and bottom levels increases with both magnitude of the defect and temperature difference across the test specimen.

The slight non-linearity of the temperature profile for the 0% defect in-

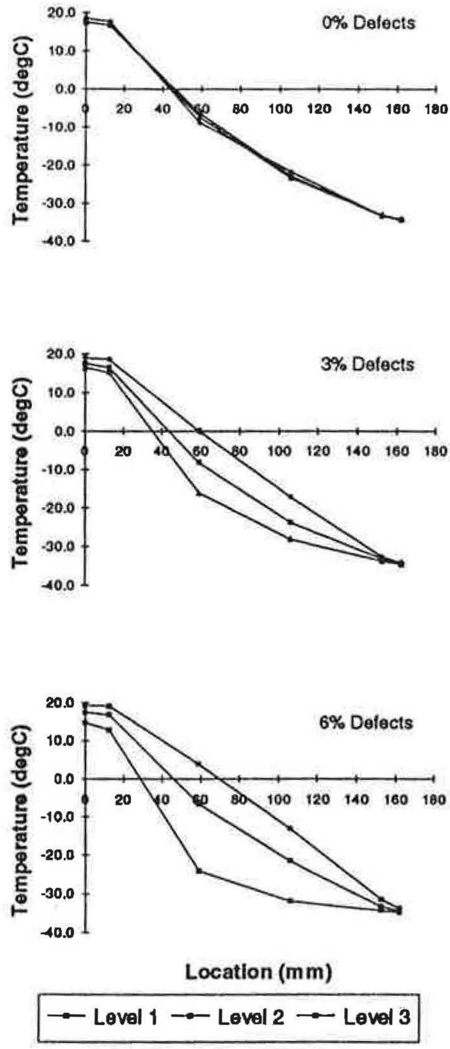

FIGURE 7. Temperature distributions for Product 1 with 0%, 3% and 6% defects measured at −35°C cold air temperature.

sulation is caused by radiative heat transfer. For an optically thick layer, the semi-empirical model of heat transfer in dry MFI [26] predicts radiation proportional to the third power of the mean temperature. Even though air conduction, another component of heat transfer, is inversely related to the mean temperature and the interaction between conduction and radiation will also counteract and partly reduce the non-linear effect of radiation, the net result is that the effective thermal conductivity varies non-linearly across the MFI batt. Since radiation has a stronger temperature dependence, it produces a non-linear (depressed) temperature profile under steady state conditions, as is observed for all three products with 0% defects.

Warm air moving within the insulation will have an effect similar to that of radiative heat transfer, namely it can modify the temperature gradient to a level beyond that justified by the balance of conductive heat transfer [27,28]. Warm air moving in the direction of the thermal gradient will decrease the curvature of the temperature profile, cold air moving in the counteractive flow will increase the curvature. The temperature profiles for Product 1 with 3% defects exposed to a cold temperature of −35°C show no change in curvature at Level 2 relative to the 0% defect case, a depression at Level 1, and an elevation at Level 3 (Figure 7). This result indicates a flow of cold air towards the hot side at the bottom and a flow of warm air toward the cold side at the top. A similar, but more pronounced, pattern is exhibited with 6% defects at the same conditions. The difference between top and bottom profiles grows with increasing temperature difference and percentage defect. For specimens with 6% defects and −35°C cold side temperature this effect is so large that the top temperature profile becomes convex instead of concave as shown for all other cases.

5.4 Pressure Difference in Stud Cavity

While there is no doubt that 3% and 6% defects produce significant convective air flow, we may only speculate on the conditions at the onset of convection. The pressure difference across the insulation was below ±1.0 Pa, the resolution of the first differential pressure transducer. Similarly, the pressure difference from top to bottom of the cavity were below ±0.5 Pa, the resolution of the second differential pressure transducer. Such small differences combined with the large reductions of thermal resistance points out the significance of the continuous vertical air gap created by the defects in each corner. It appears that the convective air flow was initiated in the cross section between the hot/cold pairs of air gaps and then spread through the rest of the insulation. A contributing factor is the fact that the air permeability along the MFI product, the manufacturing plane, is much higher than that across the product.

5.5 Thermal Resistance of Walls with Installation Defects

Table 3 presents the thermal resistance measured for the three MFI products with different defects and temperature conditions. The effect of defects is smallest for Product 2, the high density mineral fibre, and largest for Product 3, the low density glass fibre. It is clear that low density MFI, which has a lower resistance to air flow, has a higher propensity for convective air flow.

Figure 8 shows the thermal resistance measured for walls with the glass fibre products (Products 1 and 3) with 0%, 3% and 6% defects. As expected from the labeled values for the materials, the thermal resistance for the wall with Product 1 with 0% defects is slightly higher. The difference between these products is evident when comparing derating of the thermal resistance caused by 3% defects at the smallest temperature difference (−5°C cold side). Under these conditions, the derating for Product 3 is twice that of Product 1. Increasing the temperature difference across the test wall from 25 K to 55 K or increasing the percentage of defects from 3% to 6%, further decreases the thermal resistance of the walls, although in almost parallel fashion. The effect of defects is largest (36% @ 6% defect) for the lower density product. While these numbers on the effect of convective air flow in walls are of the same magnitude as previous NRC studies [8,12,14], it must be stressed that in the current study the convective flow was initiated only

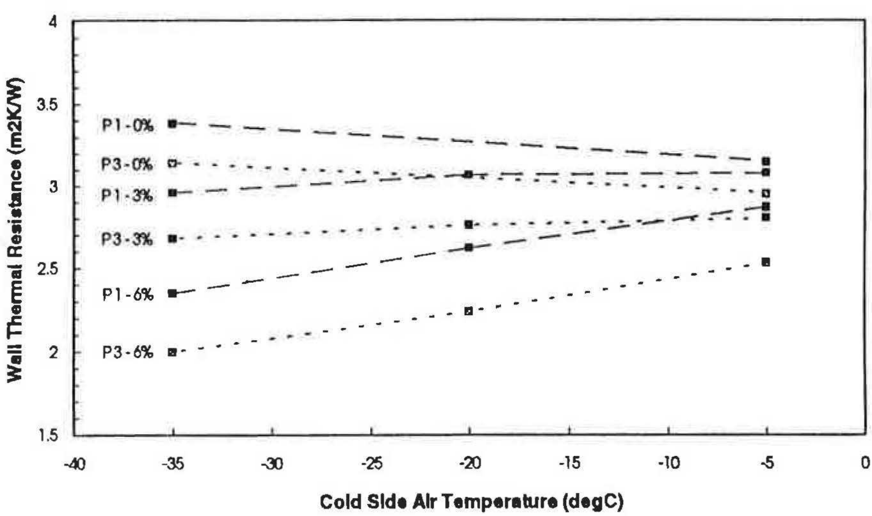

FIGURE 8. Thermal resistance measured for walls with Products 1 and 3 (both glass fibre but different density).

by corner vertical air gaps, not by an air space on the entire face of the insulation as in the previous studies.

Analysis of temperature data measured throughout the test specimens during the tests (see Figures 4 and 5) indicated that the changes in thermal performance of the test specimens was occurring entirely due to a change in heat transfer through the insulated stud cavity. The heat transfer through the material alone was calculated using an iterative procedure that matched measured wall thermal resistance to that calculated from a 50/50 combination of the parallel and series-parallel ASHRAE models. In this procedure, the "effective" thermal performance of the MFI product was varied to obtain an accurate prediction of thermal resistance.

Figure 9 shows the effect of material structure on derating of thermal performance caused by the same percentage of defects. The increase in cavity heat transfer is small for both Product 1 (medium density glass fibre) and Product 2 (high density mineral fibre) at a temperature difference of 25 K. It increases for all three products with both increasing installation defect and decreasing density. The maximum increase in heat transfer exceeds 90% for Product 3 with 6% defect at 55 K temperature difference. In other words, the heat transfer by convective air movement is almost equal to that by conduction and radiation through the MFI product.

6. CONCLUDING REMARKS

In North America, in contrast to European practice, material thermal re-

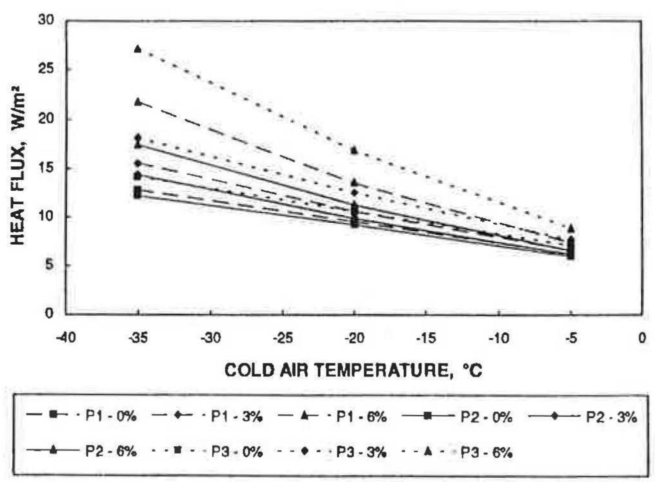

FIGURE 9. Calculated heat flux through the MFI products from full-scale wall tests.

sistance in the laboratory is assumed to be sufficient for estimating system field performance, and it is not general practice to determine field thermal resistance (i.e., design thermal resistance). In this research project the importance of installation practice was again brought into question by showing how the thermal resistance of frame walls can be reduced when mineral fibre batts or blankets do not fill the stud cavity completely. Three materials were included in the study. Product 1 with thermal resistance of 3.5 $m^2 \cdot K/W$ at 152 mm thickness and an average density of 13.7 kg/m^3, Product 2 with thermal resistance of 3.76 $m \cdot K/W$ at 140 mm thickness and an average density of 35.1 kg/m^3, and Product 3 with thermal resistance of 3.35 $m^3 \cdot K/W$ at 159 mm thickness and an average density of 9.0 kg/m^3.

Defective installation of the MFI products was found to reduce frame wall thermal resistance in all cases examined. Temperatures measured throughout the test specimens indicated that the increase in heat transfer occurred entirely within the MFI product and not in the framing. The reduction of wall thermal resistance was shown to be inversely related to the density of the MFI product and directly proportional to the temperature difference across the specimen. For example, the thermal resistance of the wall with Product 2 (the highest density product) with 3% defects at a cold air temperature of −5°C showed a reduction of 2%. The wall with Product 3 (the lightest product) showed a reduction of 5% under the same conditions. These figures increased to 20% and 36% respectively with 6% defects at a cold air temperature of −35°C.

Since the measured thermal resistance of walls with 0% defects agreed with predicted values, it is evident that the material is performing as expected; consequently, the issue of installation practice needs to be examined. Instead of asking what effect will a change of material characteristics have on the thermal resistance of a wall with installation defects, it is necessary to determine material operational characteristics that will minimize installation defects. Ease of handling and an ability to fill the stud cavity, characteristics such as batt tolerances and recovery thickness may become as important a criterion for material selection as its nominal thermal resistance. Issues of MFI product installation, as well as the thermal performance of low density batts with one-sided defects, should be examined in further research.

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