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Energy rating of polyurethane spray foamed walls: procedures and preliminary results

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ABSTRACT: Spray polyurethane foam (SPF) insulation is used in buildings to provide a durable and efficient thermal barrier. In addition to its thermal insulation property, it is claimed to provide an effective air barrier system. A joint research project between NRC-IRC and a consortium of SPF manufacturers and contractors was conducted to develop thermal and air barrier characteristics as well as a wall energy rating (WER) system for SPF walls.

Experimental and analytical work was performed to determine the WER of SPF walls. The experimental part included air leakage and thermal transmission (R-value) tests to determine the wall air leakage rate at different conditions (e.g., ΔP= 50, 75, 100 Pa) and the R-value at different temperature differences, (e.g., ΔT= 40 and 55 K). An analytical method was also developed to calculate WER by combining the heat loss due to thermal transmission by conduction and that due to air leakage.

Ten conventional wood stud walls (i.e., 2” by 6” studs), 2.4 m by 2.4 m (nominal size) of different insulation material (e.g. glass fibre batts, and of SPF), some with penetrations were constructed and tested. The testing included: (i)- initial air leakage and thermal resistance; (ii)- the walls were conditioned in the Dynamic Wall Test Facility (DWTF) according to an established routine; (iii)- then they were tested again for air leakage and thermal resistance after conditioning.

This is the first of a series of papers to present the results of this major project. In this paper, an overview of the project, its objectives and the theoretical approach to determine the WER are presented. A description of air leakage and R-value test procedures, wall samples construction and the experimental results of two walls and a sample of the analytical results of the same two walls will also be presented. Future papers will summarize the experimental and analytical results of the remaining walls, along with the results of the computer modelling of the air leakage and thermal performance of all the walls tested in this project.

1 INTRODUCTION

The Spray Polyurethane Foam (SPF) industry faces a challenge. On one hand the industry supports responsible use of hydrochlorofluorocarbon (HCFC’s), while, on the other hand, the high performance of SPF in buildings dealing with air, heat and moisture movement results in reduction of greenhouse gas production.

The situation is similar to one existing 12 years ago, when the Canadian and American SPF industry decided to develop better tools enabling the transfer of technology developed with the CFC blown foams to the second generation of blowing agents, namely HCFC. The research was performed under SPF industry/NRC consortium using an arbitrarily developed foam system “Base 88” (Bomberg & Kumaran, 1989 and Kumaran & Bomberg, 1990). This foam system was used together with a number of different blowing agents to develop accelerated prediction of thermal performance for cellular plastics (foams) independent of the polymeric composition and blowing agent used.

Today’s marketplace, however, is focused on the system performance rather than a “drop-in” blowing agent replacement, as it was 12 years ago. This implies that a decision on the SPF cost is made in relation to its total performance that includes SPF contribution to heat, air and moisture aspects not only on the basis of steady state "R-value". Therefore, it is important to evaluate total performance of SPF insulated walls with the third generation of blowing agents as well as meeting air barrier requirement (as required by building codes bodies).

This paper is one of a series of papers to present the results of a joint research project between the NRC-IRC and SPF producers, contractors and certifying organizations. The main focus of the project is to develop analytical and experimental procedures to determine the energy rating of SPF insulated walls. This would take into account the effect of air leakage and thermal transmission characteristics of SPF insulated walls. The focus of this paper is on the procedures and some limited results obtained from testing two reference walls: one SFP insulated wall and the other is a glass fiber insulated wall. Other papers in the series will present the results of the other eight walls together with more analytical results and analysis.

2 PROJECT OBJECTIVES

The main objective is to develop experimental and analytical procedures to determine the energy rating of SPF walls. In addition, the foam producers and applicators desired to demonstrate that the use of medium-density foam (when applied properly) could also provide an air barrier system that meets the performance requirements given in the Canadian Construction Material Centre Guide 07272 (CCMC, 1996).

3 APPROACH

The work in this project consists of both experimental and analytical tasks that would be performed simultaneously and would feed information back and forth across their boundaries.

3.1 *Experimental Tasks*

In this task, laboratory testing protocols were developed to characterize the thermal and air leakage characteristics of walls under investigation. This included: air leakage test, R-value test using guarded hot box apparatus, material thermal characterization (only for foam insulation) using heat flow meter apparatus and wall conditioning. A data reduction and calculation method was developed to determine the WER of each wall assembly.

3.2 *Analytical task*

The advanced NRC-IRC hygrothermal model, hygIRC-2D (Karagiozis 1993, Karagiozis; Salonvaara and Kumaran, 1996 and Karagiozis, 1997) is used for thermal analysis of all wall assemblies. The model is capable of analysing transient heat, air and moisture transfer through building envelope components. However, in this research project its applicability is limited to simulating heat and airflow transfer.

3.3 *Wall sample description*

All walls included in this project were built using the conventional 2" by 6" wood stud frame construction. This included reference walls (filled with glass fiber and SPF insulation) and other walls that incorporated penetrations to simulate building components such as windows, electric boxes (indoor and outdoor), air vents and plastic pipes, according to the test requirements specified in the CCMC Air Barrier Guide. Figure 1 is a schematic of a cross section of the two walls: glass fiber insulated wall (WER-1) and SPF insulated wall (WER-2) presented in this paper.

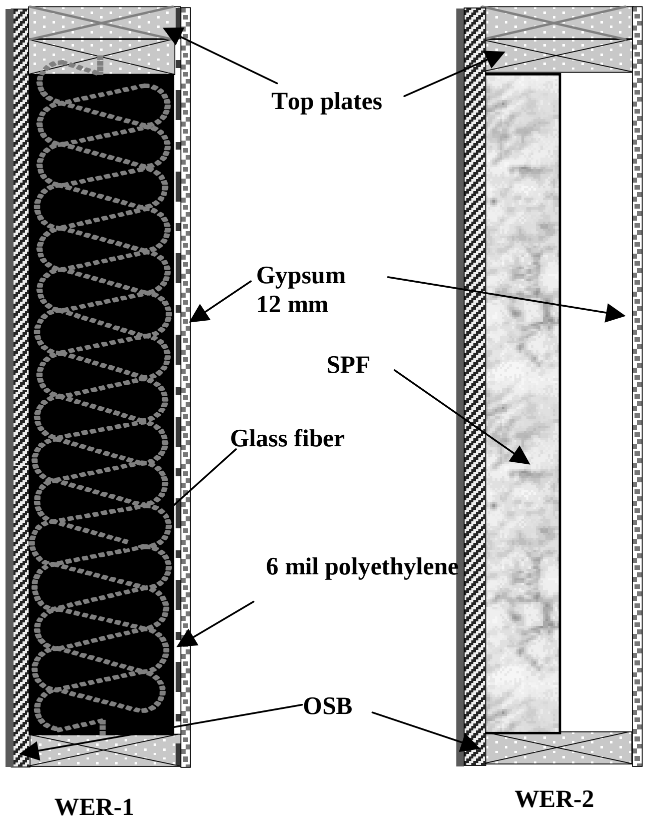

Figure 1. A schematic showing cross section of WER-1 and WER-2.

Figures 2 and 3 are photos of the two wall assemblies.

Figure 2. A photo of WER-1 (glass fiber insulated wall)

3.4 *Wall energy rating calculations*

The wall energy rating (WER) calculations is performed using the experimental results obtained from testing the wall assembly. The procedure to determine WER will be presented later and the results for the two walls reported in this paper will be summarized.

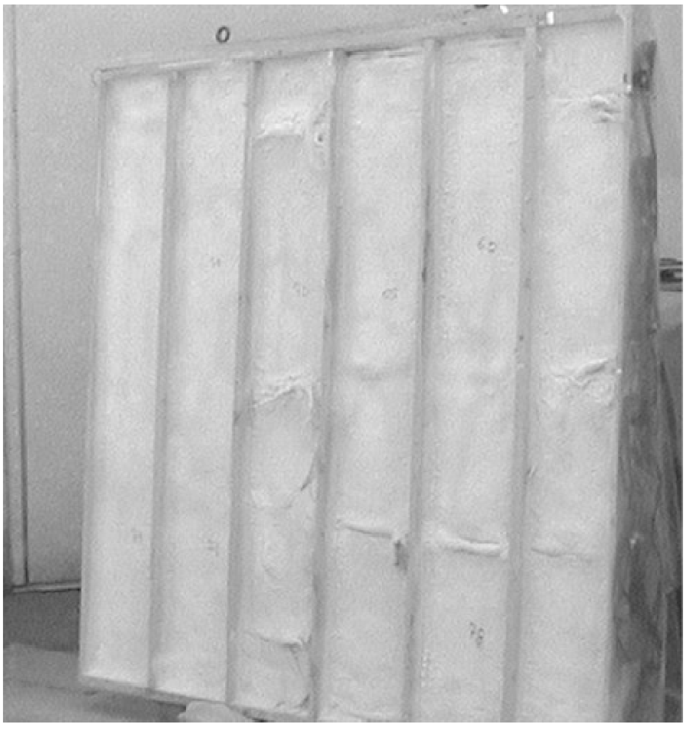

Figure 3. A photo of WER-2 (SPF insulated wall)

4 TEST PROCEDURE AND APPARATUS

A series of laboratory testing was performed on each wall assembly. The following is a summary of the testing protocol:

- Air leakage test
- Thermal resistance test (using guarded hot box)
- Material characterization (only for the spray urethane foam) using heat flux meter. Data for glass fiber was obtained from standard database information (Kumaran et al, 2004).
- Sample conditioning (or weathering) according to the CCMC Air Barrier Guide protocol (CCMC, 1996).

It should be noted that although 10 wall samples were included in this project, only the data and results for two walls (reference wall with glass fiber and a reference wall with SPF insulations) are reported in this paper.

As indicated earlier, a certain testing sequence was followed during this project. The test sequence is as follows: air leakage, thermal transmission, sample conditioning, air leakage and thermal transmission again (after sample conditioning). Figure 4 is an illustration of the test sequence followed in this project.

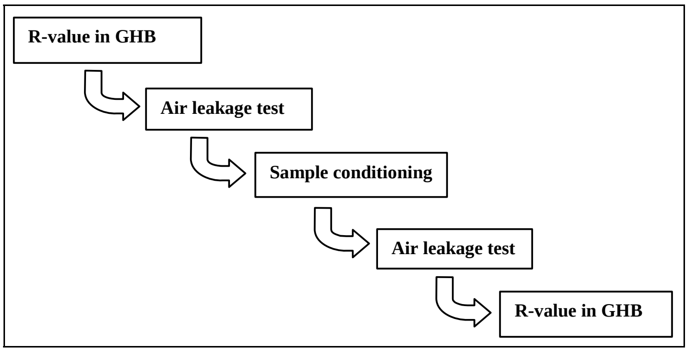

Figure 4 Illustration of the testing sequence.

4.1 *Air leakage test*

Air leakage tests were performed on WER-1 and WER-2. The test procedure used is in accordance with ASTM E283 standard (ASTM, 1997). A special air leakage test apparatus was designed to test the wall sample (2.4 m by 2.4 m in size). Special considerations were taken to minimize the extraneous (system) air leakage in each test. Figure 5 is a schematic illustrating the mounting of the wall specimen in the air leakage test apparatus.

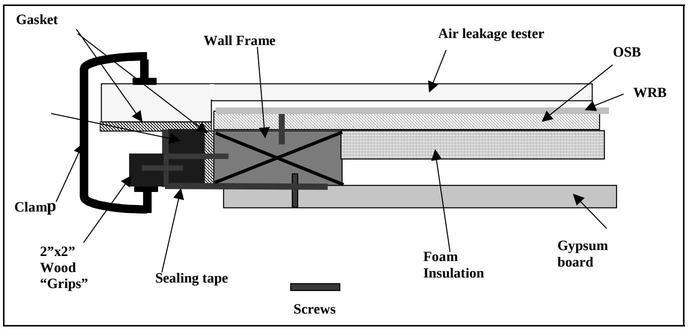

Figure 5. A schematic illustrating the wall mounting in the air leakage tester.

4.2 *Thermal resistance test*

The thermal resistance test was performed in the guarded hot box. The test method follows that described in ASTM C1199 and ASTM E1423. These are well established procedures developed at IRC and formed the basis of the ASTM test standards (ASTM, 1998-a and ASTM, 1998-b). Figure 6 is a picture of the NRC-IRC guarded hot box apparatus.

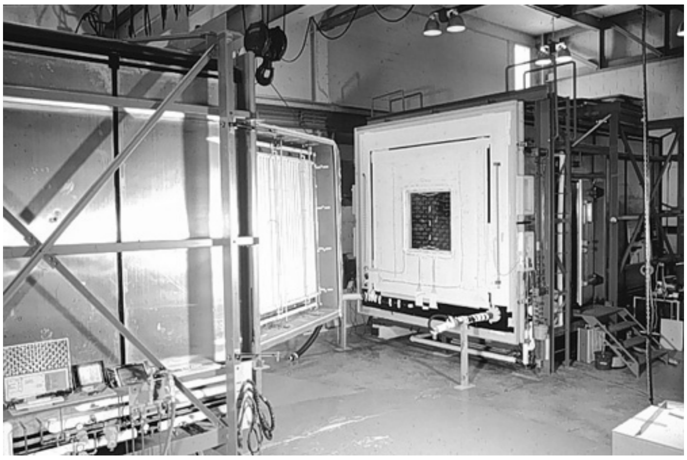

Figure 6 A photo of the NRC-IRC guarded hot box apparatus

4.3 *Material characterization*

The material characterization was performed according to ASTM C518 (ASTM, 2004) using the heat flow meter apparatus.

The test specimens were placed horizontally in a 60 cm x 60 cm heat flow meter apparatus. Heat flowed vertically upwards through the specimens during the tests.

4.4 *Sample conditioning*

All wall samples were conditioned under wind cyclic and gust loads as described in the CCMC Technical Guide for Air Barrier Systems for Exterior Walls of Low Rise Buildings (CCMC, 1996). The cyclic wind conditioning consists of, sequentially:

1 1000 cycles of positive pressure, where pressure is driven from zero to 800 Pa (P2) in one second, held at that pressure for three seconds and then decreased to zero Pa pressure in one second, followed by a three second dwell at zero Pa pressure before repeating the cycle.

2 1000 cycles of 800 Pa (P'2) negative pressure, where pressure is driven from zero Pa pressure to -800 Pa in one second, held at that pressure for three seconds and then increased to zero Pa pressure in one second, followed by a three second dwell at zero pressure before repeating the cycle.

3 Gust wind conditioning consists of, sequentially One cycle of positive pressure, where pressure is driven from zero Pa to 1200 Pa (P3) in one second, held at that pressure for three seconds and then decreased to zero Pa pressure in one second, followed by a three second dwell at zero Pa pressure before the following gust cycle begins. One cycle of negative pressure, where pressure is driven from zero to -1200 Pa (P'3) in one second, held at that pressure for three seconds and then increased to zero Pa pressure in one second.

The total time required to carry out this conditioning would be about 4 hours 45 minutes.

Figure 7 shows a representation of the pressure cycles and the duration of each cycle for both the cyclic loading and the gust wind.

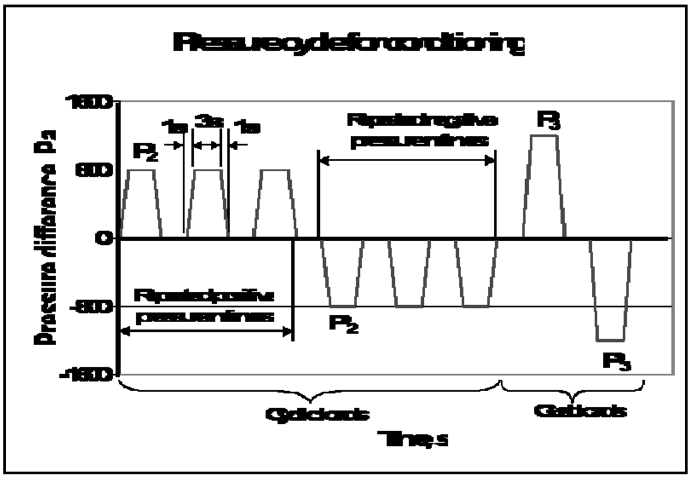

Figure 7 A schematic of the pressure cycle during conditioning.

5 RESULTS

The following is a summary of the results of air leakage, thermal transmission properties, material characterization, simulation and the WER calculation.

5.1 *Summary of air leakage test results of WER-1 and WER-2*

The air leakage tests were performed at several pressure differentials from ΔP=50 to 150 Pa. Figure 8 shows a summary of the net air leakage test results for WER-1 before and after sample conditioning. Also shown in Figure 8 is the maximum allowable air leakage to meet the requirements given in the CCMC Air Barrier Guide (set at 0.05 l/(s.m^2) at ΔP=75 Pa). The net air leakage is calculated after subtracting the extraneous (system) air leakage from the total quantity.

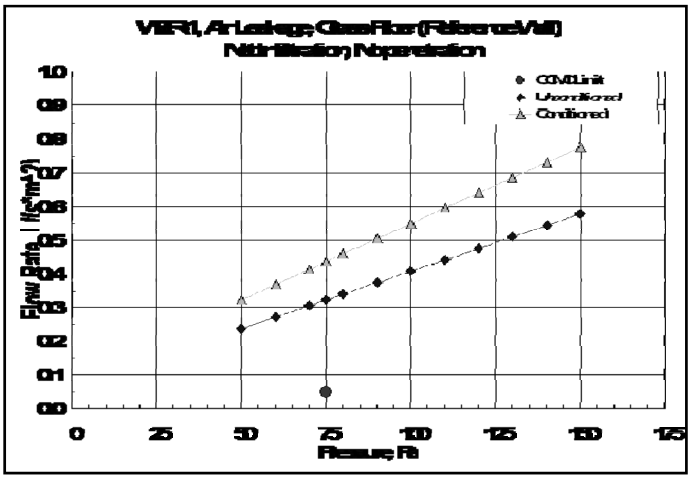

Figure 8 A summary of the air leakage test results of WER-1

All air leakage values reported in this paper are normalized to the standard temperature and pressure conditions (101.325 Pa and 20 °C).

Figure 9 presents the air leakage results for WER-2. Also shown on Figure 9 is the CCMC air leakage limit (set at 0.05 l/(s.m^2) at ΔP=75 Pa).

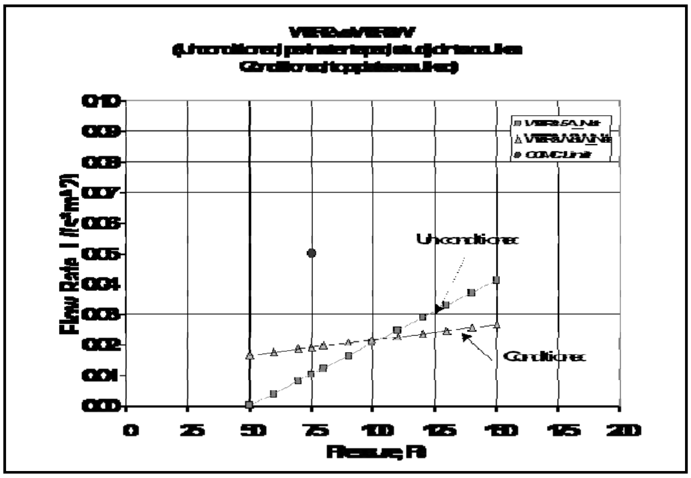

Figure 9 Air leakage results for WER-2

From Figures 8 and 9, it is clear that WER-2 shows a remarkable decrease in air leakage rate compared to WER-1. It is also clear that WER-1 did not meet the CCMC requirement as an air barrier and WER-2 does meet that requirement. It is worth noting that many tests were performed on both walls to perfect the test procedure and minimize the extraneous (system) air leakage to less than 0.02 l/(s.m^2). In fact, latest modifications to the air leakage tester showed zero extraneous air leakage rate when testing the rest of wall samples in this project. Full details for the results will be presented in future publications, since they were not available at the proper time for this paper.

It should be noted that WER-1 was built with a 6-mil polyethylene air barrier and was installed in a fashion that was considered representative of the typical field practices. Also, the SPF insulated wall (i.e., WER-2,) was sealed at the top plates. These practices will be recommended to standard committee to achieve such levels of air tightness in SPF walls.

5.2 *Summary of the thermal resistance tests*

The thermal resistance (R-value) tests were performed before and after sample conditioning at room side temperature of 20±1°C and a cold side temperature at -20±1°C and -35±1°C. Table 1 provides a summary of the R-value tests before and after conditioning for WER-1 and WER-2.

Table 1 R-value for WER-1 and WER-2

Wall Designation	R-value, m^2.K/W			
	Before cond.		After cond.	
	Cold side temperature, °C			
	-20	-35	-20	-35
WER-1	3.24	3.38	3.25	3.44
WER-2	3.60	3.57	3.53	3.50

Table 1 also shows that the thermal resistance of both walls slightly increases as the cold side temperature decreases. Surprisingly however, the conditioning of the walls did not result in considerable change in the walls R-value.

5.3 *Summary of material characterization tests*

The material characterization for glass fiber wall (WER-1) is available in thermal properties data bases (Kumaran, et al, 2004), and therefore it was not performed in the laboratory. For the SPF insulated wall (WER-2), the material characterization was performed at a number of mean temperatures, the results of which are summarized in Table 2.

Table 2 Summary of the material characterization of the foam in the SPF insulated wall (WER-2)

		Mean Temperature T_{mean}, °C				
Parameter	Symbol units	24.4	24.3	2.5	20.4	24.0
Average thickness	L mm	97.5	98.2	98.2	98.2	95.0
Density	ρ kg/m^3	34.9	34.9	34.9	34.9	35.1
Hot surface temperature	T_h °C	35.3	35.2	19.6	40.4	35.1
Cold surface temperature	T_c °C	13.5	13.3	14.6	0.4	12.9
Temperature difference	ΔT K	21.8	21.9	34.2	40.0	22.2
Mean temperature	T_m °C	24.4	24.3	2.5	20.4	24.0
Heat flux	q W / m^2	4.11	4.23	6.46	8.01	4.56
Thermal conductance C = q / ΔT	C $W/(m^2 \bullet K)$	0.189	0.19	0.19	0.20	0.205
Thermal resistance R = ΔT / q	R $m^2 \bullet K/W$	5.30	5.18	5.29	4.99	4.87
Thermal conductivity λ=L/R	λ W/(m•K)	0.018	0.019	0.019	0.0197	0.0195
Thermal resistance per unit thickness r =R/L	r m•K/W	54.4	52.7	53.9	50.9	51.2

5.4 *Simulation results*

The thermal resistances as determined by hygIRC program for the two walls (WER-1 and WER-2) are summarized in Table 3. The results presented in this section are at the temperature difference of ΔT = 40°C (warm side at 20 °C and cold side at –20 °C) and ΔP = 0 Pa for both the experimental and simulation cases. In addition, the apparent R-value was determined at ΔP = 0, 75 and 150 Pa for both walls.

Table 3 Experimental and simulation comparison of R-value for WER-1 and WER-2.

RSI , m^2.K/W @ ΔT = 40 °C				
WALL ID	**Experiment RSI_{ghb} m^2.K/W**	**Modelling R-value, RSI_{wer} m^2.K/W**		
	ΔP, Pa	**ΔP, Pa**		
	0	**0**	**75**	**150**
WER 1	**3.24**	**3.29**	**1.99**	**1.37**
WER 2	**3.60**	**3.58**	**3.40**	**3.30**

The simulation results need to be analyzed and interpreted based on the following important assumptions:

a- The material layers are in perfect contact with each other

b- Adiabatic (no heat loss) conditions at the perimeters of the wall assembly

c- Airflow path is predefined

d- Glass fibre insulation completely filled the cavity between the studs

e- SPF insulation thickness is uniform throughout the stud cavity.

The deviation between the simulation and experimental results is less than 6%, which is the usually acceptable uncertainty level of the experimental measurement (Elmahdy, 1992). In addition to the ±6% experimental uncertainty, the modeling assumptions outlined above contributed to the deviations of the results. More importantly, the modelling assumption ‘uniform SPF insulation thickness’ might be the primary reason of the differences in WER-2. As shown in Figure 10, the SPF insulation thickness is not uniform in a real wall assembly. Since the actual thickness profile of the SPF insulation in the wall assemblies were not available at the time computer simulations were carried out, the SPF insulation thickness was assumed to be 80 mm and uniform throughout the cavity.

Figure 10. A photo showing the non-uniform thickness of the foam

The computer program used (hygIRC-2D) predicts the temperature and air flow fields inside the cavity of the wall. The convection loops inside the cavity (vertical cross section of the SPF insulated wall (WER-2) is shown in Figure 11.

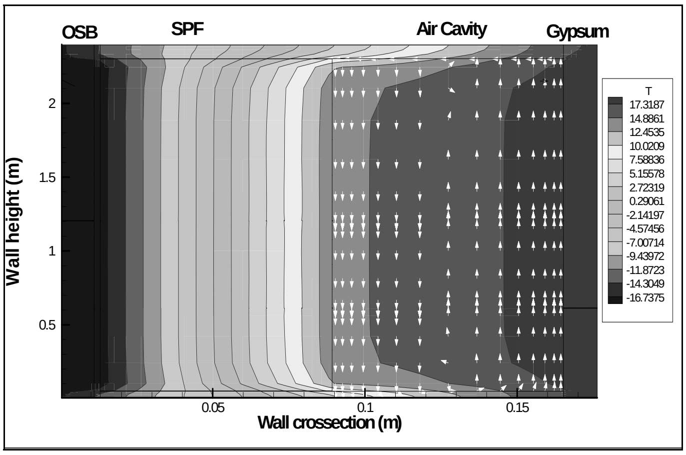

Figure 11 Convection loops in the air cavity of SPF wall (WER-2).

A similar temperature profile and convection loops for the glass fiber wall (WER-1) is shown in Figure 12. As Figure 11 shows, the SPF insulation provides a good air barrier, where as Figure 12 indicates that the glass fiber insulation allows air to flow through any opening, such as the electric box on the right side of the figure.

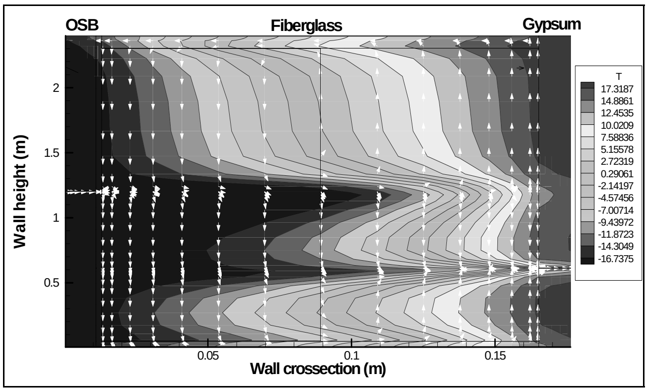

Figure 12. Convection loops and temperature profile of the glass fiber wall (WER-1).

5.5 *WER calculation*

The wall energy rating (WER) is determined by combining the heat transmission loss due to air leakage and conduction through the wall assembly. The following is a summary of the calculation procedure to determine the WER.

The total heat loss can be expressed as:

$$WER = Q_{con} + Q_{air} \qquad (1)$$

where Q_{con}=heat loss due to conduction (W); Q_{air}=heat loss due to air leakage (W); WER=wall energy rating (W).

First, using the experimental results, the quantities on the right hand side of Equation 1, the RSI_{wer} could be expressed as:

$$RSI_{wer} = A\frac{\Delta T}{Q_{con} + Q_{air} - f_i \cdot Q_{air}} \qquad (2)$$

where RSI_{wer}=apparent thermal resistance (RSI) accounting for conduction and air leakage loss as determined from the simulation (m^2.K/W) at ΔT = 40°K and ΔP = 75 Pa; f_i=factor of interaction.

The factor of interaction (representing the degree of interaction between heat loss terms) is expressed as a fraction, ranging from 0 for no interaction, to an increasing fraction towards 1 for greater interaction.

Equation 2 could be rewritten as:

$$RSI_{wer} = \frac{\Delta T}{\left(\left(A \cdot \Delta T / RSI_{ghb40}\right) + A \cdot (1 - f_i) \cdot q_{p75} \cdot 3.6 \cdot \rho_a c_{p,a} \Delta T\right)} \qquad (3)$$

where A=area of the wall sample (5.95 m^2); ΔT=temperature difference (40 °K); RSI_{ghb40} =thermal resistance as determined by the guarded hot box (m^2.k/W); q_{p75} =air leakage rate determined at ΔP = 75 Pa (l/(s.m^2)); ρ_a = density of air (1.2 kg/m^3); $c_{p,a}$ = specific heat capacity of air (0.279 W.hr/kg.K).

Equation 3 could be simplified and re-written as:

$$RSI_{wer} = \frac{1}{\left(\left(1 / RSI_{ghb40}\right) + (1 - f_i) \cdot q_{p75} \cdot 1.21\right)} \qquad (4)$$

Finally, the WER (normalized) is expressed in a form consistent with the Canadian window standard by adding a constant (set at 50 W/m^2) to make all values positive and the final expression for the WER could be expressed as:

$$WER = 50 - \frac{\Delta T}{RSI_{wer}} \qquad (5)$$

where WER=wall energy rating (W/m^2).

The experimental data was used to determine the factor of interaction (f_i) and WER. Table 4 provides a summary of the final results for the two walls covered by this paper.

Table 4 Summary of WER calculations for WER-1 and WER-2

Wall ID	Measured RSI m^2.K/W	Measured air leakage rate L/(s.m^2)	Derived factor of interaction f_i	RSI_{wer} m^2.K/W	WER W/m^2
WER-1	3.25	0.369	0.56	1.97	29.7
WER-2	3.53	0.013	0.07	3.42	38.3

6 DISCUSSION

The challenges facing the spray polyurethane foam insulation industry prompted development of energy rating of SPF insulated walls to confirm their field performance as an effective air barrier system. The information presented in this paper for two walls has shown that it is possible to rate walls for energy performance based on their thermal and air leakage characteristics. It is critical to ensure a high degree of accuracy in all measurements in order to obtain wall energy rating that could be used to meet building code requirements.

The results given in Table 4 show that for airtight walls (e.g. WER-2) there is little interaction between conduction and air leakage streams. On the other hand, in the case of a less tight wall (e.g. WER-1), there is apparent interaction between the two components of heat loss. This is demonstrated by comparing the factor of interaction, f_i, of both walls.

It is clear that more examples of demonstrating the performance of walls of different foams and penetration elements (e.g. electric boxes, pipes, air vents, etc.) should be tested and evaluated using the procedures outlined in this paper. This is essential in order to provide conclusive proof of the applicability of the procedures, and use and approval by building designers of code officials. A total of ten walls with different foams and penetrations are being tested and evaluated. Another paper in the series to present more data was submitted to an ASTM symposium (Maref et. al, 2009).

7 CLOSING REMARKS

Experimental and analytical methods were developed to determine the energy rating of polyurethane foam insulated walls for the purpose of providing tools to rate the overall thermal performance of SPF insulated walls. The preliminary results from the evaluation of two walls indicated that the methods developed are adequate to differentiate between airtight and less tight walls. The data also showed that for airtight walls, there is not a strong interaction between the heat loss due to air leakage and that due to conduction heat loss. Such interaction increase as the wall becomes more less tight.

In order to generalize the use of this approach, more walls of different configurations and design will be tested and evaluated using the reported methodology. The results will be published in the near future, and a proposal to develop a Canadian standard on the topic will be proposed in the near future.

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