ASSESSMENT OF THE ENERGY RATING OF INSULATED WALL ASSEMBLIES- A STEP TOWARDS BUILDING ENERGY LABELING

Hakim Elmahdy, Wahid Maref, Hamed H. Saber, Mike C. Swinton and Rock Glazer
Institute for Research in Construction (IRC) - National Research Council of Canada (NRC)
Ottawa, Ontario, Canada

ABSTRACT

Considerable efforts are recently focusing on energy labeling of components and systems in buildings. In Canada, the energy rating of windows was established, which provides a protocol to rate different types of windows with respect to their energy performance. It takes into account the interaction between: solar heat gain, heat loss due to air leakage and due to the thermal properties of the entire window assembly.

A major research project, jointly sponsored by NRC-IRC and the polyurethane spray foam industry, was established to assess the thermal and air leakage performance of insulated walls with the focus on developing an energy rating procedure for insulated wall assemblies. This paper is one in a series of publications to present partial results of this project. Experimental data and computer simulation comparison of a set of wall specimens are presented together with a summary of the proposed procedure for the determination of the energy rating of insulated walls (WER).

INTRODUCTION

There are a number of challenges facing the Spray Polyurethane Foam (SPF) industry including the use of environmentally friendly blowing agents to minimize the negative impact on environment. A research project was conducted at the National Research Council Institute for Research in Construction (NRC-IRC) to develop the second generation of blowing agents (namely HCFC). The results of this effort were published in 1990 (Bomberg et. al., 1989 and Kumaran, et. al., 1990). At present, the focus is on the assessment of the performance of the entire wall assembly to meet the requirements of building codes and regulatory bodies. This implies that a decision on the SPF cost is made in relation to its overall performance and in particular its contribution to heat, air and moisture transfer, and not on the steady state thermal performance alone (e.g., R-value).

In an effort to meet the demand of the regulatory bodies, the polyurethane foam industry joined NRC-IRC to develop an energy rating procedure to rank wall assemblies regarding their total energy performance. This means including the effect of wall tightness and its air leakage characteristics on the overall wall energy performance. Several wall samples were constructed and insulated with poly-wrapped and unsealed (glass fiber batts) insulation as reference walls, and light (open cell) and medium (closed cell) density foam insulation. Some walls were opaque and others were built with penetrations to simulate ducts, pipes, electric boxes, etc. through the wall.

A number of papers (Elmahdy, et. al., 2009A, Maref, et. al., 2009, Elmahdy et. al., 2009 B, Saber et. al. 2010A, Saber et. al. 2010B, and Tariku et. al., 2010) resulting from this joint research project have been published. Each paper documented the results of testing and simulation results at a certain stage of the project. In this paper, an overview of the project is presented in addition to a selected set of results reflecting the state of the project. The ultimate objective of this project is to develop a national and international standards to determine the wall energy rating (WER) of insulated wall assemblies.

OBJECTIVES AND SCOPE

The main objective of the project is to develop an experimental and analytical procedure to determine the energy rating of insulated wall assemblies. The procedure takes into account the heat loss due to air leakage and the thermal characteristics of the wall sample.

The scope of the project includes: constructing wall samples insulated with poly-wrapped and unsealed (glass fiber batts), as reference walls, and different types of foam insulation (open cell and closed cell foam), perform thermal and air leakage tests on wall samples and developing experimental and analytical procedures to determine WER. Finally, to present a final draft of a protocol to determine WER based on minimum laboratory tests. The latter would pave the way to the development of a national standard to determine WER.

EXPERIMENTAL TASK

In this task, laboratory testing is performed on each wall sample to determine: air leakage and overall thermal resistance (R-value). In addition, separate insulation material sample are prepared to conduct material characterization according to the established standards. In some cases, the air leakage rate and R-value tests are performed before and after sample conditioning, as will be explained later.

NUMERICAL SIMULATION TASK

In this task, an advanced 3D computer model (hygIRC-C) was developed to simulate the wall assembly and to determine (numerically) the R-value of each wall with and without air leakage (Saber et. al., 2010A and Saber et. al., 2010B). This model has been used in several related studies (Elmahdy et al., 2009B, Saber et al., 2010A and 2010B, and Saber and Swinton, 2010). The 3D version of this model was used to conduct numerical simulations for different full-scale wall assemblies with and without penetration to predict the "apparent" thermal resistance (R-value) with and without air leakage. The predicted R-values for these walls were in good agreement (within ± 5%) with the measured R-values in NRC-IRC's Guarded Hot Box (GHB) (Elmahdy et al., 2009B, and Saber et al., 2010A).

Recently, the 2D version of the present model was used to conduct numerical simulations in order to investigate the effect of the emissivity of foil on the effective thermal resistance of a foundation wall system with foil bonded to expanded polystyrene foam in a furred assembly with airspace next to the foil (Saber and Swinton, 2010).

Furthermore, the 3D version of this model was used to investigate the thermal response of Insulated Concrete Form (ICF) wall assemblies (Saber et al., 2010D). Subsequently, the hygIRC-C model was benchmarked against the measured data. Results showed that the predictions of the present model were in good agreement with experimental data. In this work (Elmahdy et al., 2009B, Saber et al., 2010A, 2010B, 2010D, and Saber and Swinton, 2010), no moisture transport was accounted for in predicting the thermal performance of different types of walls.

In the case of accounting for moisture transport, the present model was used to predict the drying rate of a number of wall assemblies subjected to different exterior and interior boundary conditions (Saber et al., 2010C and Maref et al., 2002). The model predictions were in good agreement with the experimental data (within ±5%)

WALL DESCRIPTION

In this paper, six walls are selected to demonstrate the process to develop WER procedure. More walls are being tested and modeled using hygIRC-C, and the results will be reported in the future.

All wall samples described in this paper are constructed using conventional 2" by 6" wood stud frame, and insulated with: poly-wrapped and unsealed insulation (glass fiber batts) and open cell spray polyurethane foam (SPF). The overall dimension of the wall is 2.4 m by 2.4 m (a standard size to fit the NRC-IRC' guarded hot box apparatus).

Table 1 provides full description of the six wall samples reported in this paper. This set of walls include: poly-wrapped and unsealed (glass fiber batts) insulated walls, insulated walls with open cell foam. In addition, some walls are with penetrations and others are without penetrations. The idea is to present a variety of walls and demonstrate the applicability of the proposed procedure for different types of wall samples.

It is worth noting that the SPF is provided by different manufacturers, and all foams meet the Underwriter Laboratory Canada (ULC 2005) standards and CCMC guides (CCMC 1996).

Table 1 Summary of wall description

Wall #	Wall Description
WER-1	Reference wall, poly-wrapped unsealed (glass fiber), no penetration
WER-5	Reference wall, poly-wrapped unsealed (glass fiber), with penetration
WER-AA	Open cell foam-NO penetration
WER-BB	Open cell- WITH penetration
WER-CC	Open cell foam-NO PENETRATION
WER-DD	Open cell foam-WITH penetration

With regard to WER-1 and WER-5 walls, it is important to note that those walls were built to common field installation practices and are intentionally not to the requirements of Part 9 of the National Building Code (NBC) to introduce a wide range of air leakage rates. Part 9 NBC gives two options for air barrier continuity:

1. Sealing the joint, or
2. Lapping the joint by not less than 100 mm and clamping between framing members and rigid panels

The second option was selected for this project, with the understanding that it is likely less effective in controlling air leakage.

NBC 2005 also requires sealing of windows, piping, ducting and electrical boxes to maintain the integrity of the air barrier. For the purpose of having a wide range of air leakage rate, all penetrations were not sealed to meet the NBC requirements. Therefore, WER-1 and WER-5 do not meet all of the air barrier requirements of NBC 2005.

Figure 1 A vertical cross section of WER-1.

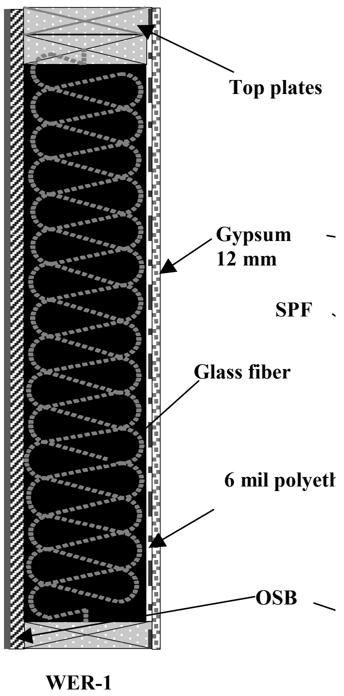

Figure 1 shows a schematic of poly-wrapped and sealed glass fiber batts insulated walls and Figure 2 is a cross section of a wall insulated with open cell SPF filled the entire stud cavity.

Figure 3 is a schematic vertical cross section of a poly-wrapped unsealed (glass fiber) insulated wall, and Figure 4 shows a vertical cross section of an open cell spray foam insulated wall.

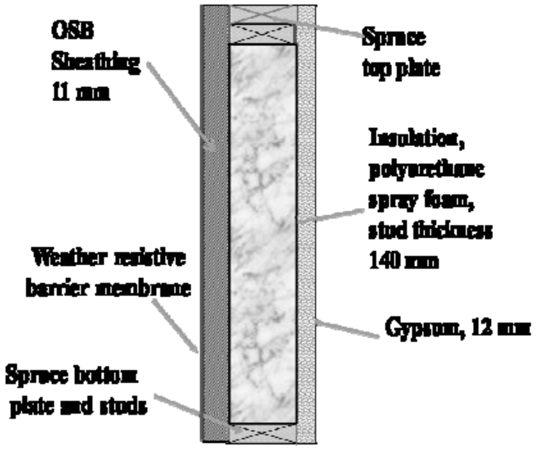

Figure 2 A vertical cross section of open cell insulated wall

Figure 3 A poly-wrapped and unsealed (glass fiber) insulated wall.

Figure 4 Open cell foamed wall prior to testing.

WALL SAMPLE PREPARATION

Each wall is furnished with an array of thermocouples and in case of the poly-wrapped and unsealed (glass fiber) walls, heat flux transducers are also installed to measure the local heat flow. These transducers are used for more in depth analysis of thermal bridging and will be the subject of future publication. Some interstitial thermocouples are also installed to measure the surface temperature at different layers of the wall. Figure 5 shows the thermocouples mounted on the wall surface, and Figure 6 shows the interstitial thermocouple locations.

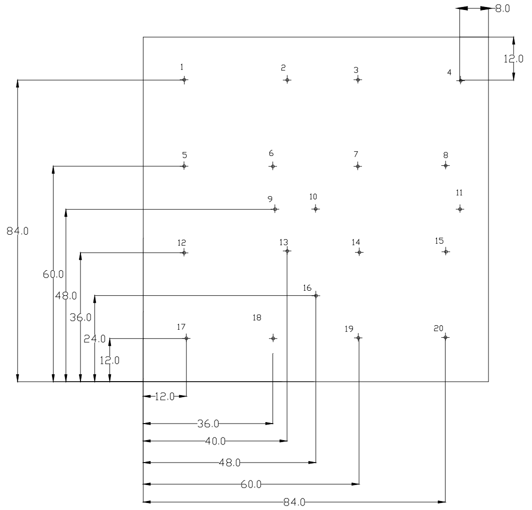

Figure 5 Surface thermocouples locations (dimensions are in inch).

Some walls are opaque (no penetrations), while others included penetration according to the CCMC Air Barrier Gide (CCMC 1996). These penetrations simulate air ducts, a window, electric boxes and water pipes. Figure 7 shows a schematic illustrating all the penetrations considered in the test specimens.

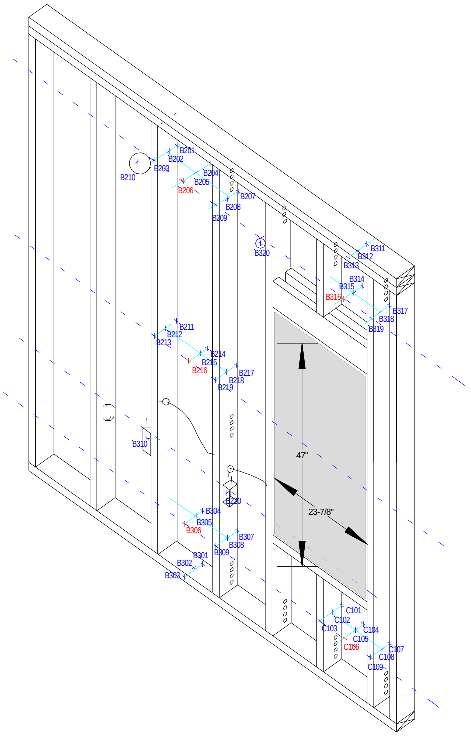

Figure 6 Interstitial thermocouple locations (dimensions are in inch).

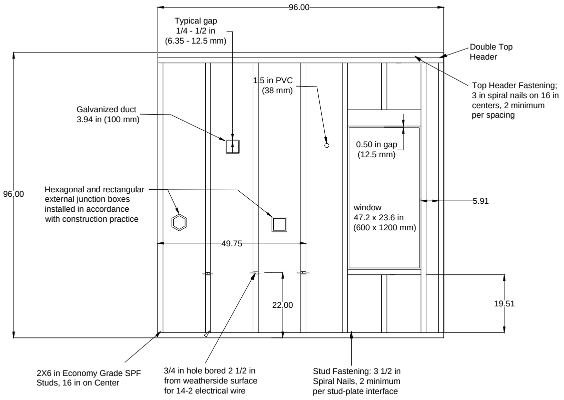

Figure 7 A schematic illustrating wall penetrations (dimensions are in inch)..

TEST SEQUENCE

Each wall sample is subjected to a series of tests. This included:

- Air leakage test before conditioning
- Sample conditioning
- Air leakage test after conditioning
- Thermal resistance test before and after conditioning (in the early stage of the project).

SAMPLE CONDITIONING

Each wall is conditioned (after initial air leakage) according to the CCMC guide. The wall sample is subjects to cycles of positive and negative pressure as follows:

- A positive pressure rise from 0 to +800 Pa in 1 second, remains constant for 3 seconds, down to 0 Pa in one second and remains at 0 Pa for 3 seconds. This cycle is repeated 800 times
- A negative pressure is applied from 0 to – 800 Pa in one second, remains at – 800 Pa for 3 seconds, increases to 0 Pa in 1 second, and remains at 0 Pa for 3 seconds. This cycle is repeated 800 times.
- Gust wind: two cycles from 0 to + 1200 Pa (and another to – 1200 Pa) in a similar cycle.

Figure 8 illustrates the conditioning pressure cycles.

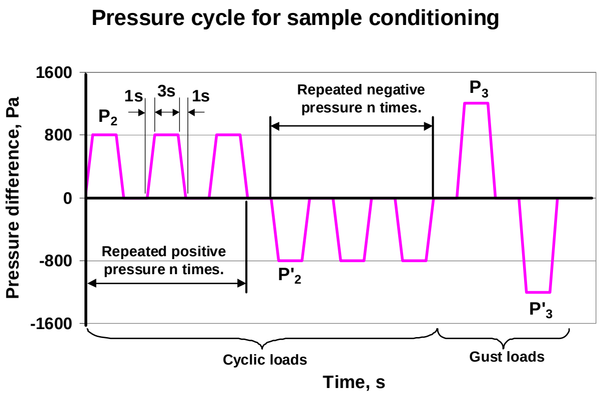

Figure 8 A schematic of the pressure cycle during sample conditioning.

MATERIAL CHARACTERIZATION

The material characterization was performed using heat flow meter according to ASTM C-518-98 standard (ASTM 2004) on all foams used in this project. 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. The thermal conductivity was determined at five different mean temperatures. However, only the foam thermal properties reported in this paper is at mean temperature of around 0.2 ± 1°C. Table 2 provides a summary of the results of material characterization of the foams used in WER-AA, WER-BB, WER-CC and WER-DD.

The thermal properties of glass fiber used in constructing WER-1 and WER-5 were obtained from published thermal properties of insulation materials databases (Kumaran et. al. 2004).

Table 2 Summary of material characterization tests on all foamed walls.

Wall Parameter	Symbol	WER-AA & BB	WER-CC & DD
Test Mean temperature	**T_m (°C)**	**0.2**	**0.3**
Material density	**ρ (Kg/m^3)**	**12.0**	**7.8**
Thermal conductivity, SI units	**λ (W/(m.K))**	**0.0352**	**0.0388**

R-VALUE TEST RESULTS

The R-values of all walls are determined in the NRC-IRC guarded hot box facility (ASTM 1998A, ASTM 1998B and ISO 12567). Figure 9 shows a picture of a wall mounted in the mask wall of the guarded hot box.

As indicated earlier, the R-value of some walls (see Table 3) was determined after sample conditioning. In the early stage of the project, the wall R-value was determined before and after conditioning. Since there was not a significant change in the R-value after conditioning compared to the values before conditioning, it was decided not to repeat the R-value test after condition to conserve time, money and energy (Elmahdy et al., 2009). Also, the R-values were determined at a warm side temperature of 20±1°C while the cold side was maintained at -20±1°C and -35±1°C.

Table 3 provides a summary of R-values of the six walls at the two temperature differences as mentioned above, and Figure 9 is a bar chart showing the R-values of the six walls at two different set of temperature difference. As shown in this figure, the difference between the R-values of each wall at the two different temperature differences is within the uncertainty (±6%) of the GHB (Elmahdy 1992 and ISO 12567).

Figure 8 NRC-IRC guarded hot box

AIR LEAKAGE TEST RESULTS

All wall samples are tested to determine their air leakage performance at different pressure differential (ASTM 1997). Figure 10 shows a wall mounted in the air leakage tester. Also, the same test facility is used for the sample conditioning.

Following the mounting of the wall sample, the extraneous air leakage (system air leakage) is determined. Ideally, the extraneous air leakage should be less than 10% of the expected air leakage rate (as per the ASTM standard). After many modifications, the system now has almost zero extraneous air leakage rate.

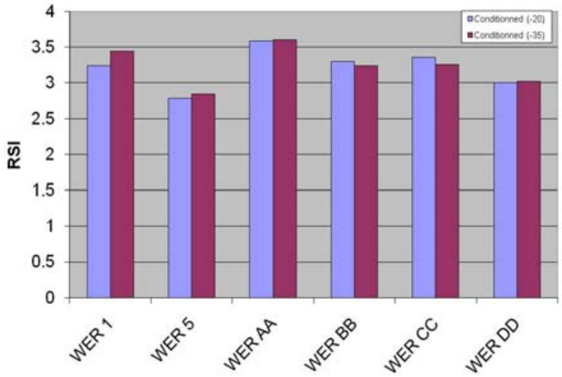

Figure 9 R-value of six walls at two sets of temperature difference.

The next step is to subject the wall samples to pressure difference that varied between 0 and ~150 Pa, and determine the wall air leakage rate before and after conditioning. The CCMC Air Barrier Guide sets the maximum allowable air leakage rate for the product to be labeled as "air barrier". This limit is set at 0.05 L/(m^2.s) at ΔP= 75 Pa.

AIR LEAKAGE RESULTS OF SELECTED SAMPLES

The results of air leakage of two walls (WER-1 and WER-DD) are shown in Figures 11 and 12, respectively. These figures are meant to illustrate the air leakage performance of those two walls as well as the effect of wall conditioning on their tightness performance. Both figures show the CCMC air leakage limit at ΔP= 75 Pa, as designated by a red circle. In general, the figures show that the air leakage rate increases with the increase in the pressure difference across the wall. Also, for WER-1 the graph shows that the air leakage rate is slightly higher after the wall conditioning over ΔP= 0 to 100 Pa. This is the result of applying the pressure cycles and gust pressure across the wall. On the other hand, for WER-DD, its air leakage performance does not show a noticeable change before and after conditioning.

In general, the SPF walls show a lower air leakage rates compared to the poly-wrapped insulated walls as a result of the adhesion of the spray foam to the wall elements, which improves the wall tightness and sealing of the cracks. In addition, the nature of the lumber used in building the walls and some deficiencies in sealing the poly may have contributed to this difference in air leakage performance of the walls.

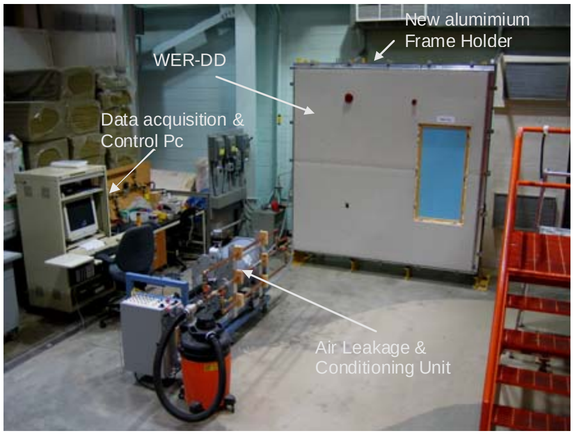

Figure 10 A wall sample mounted in the air leakage tester

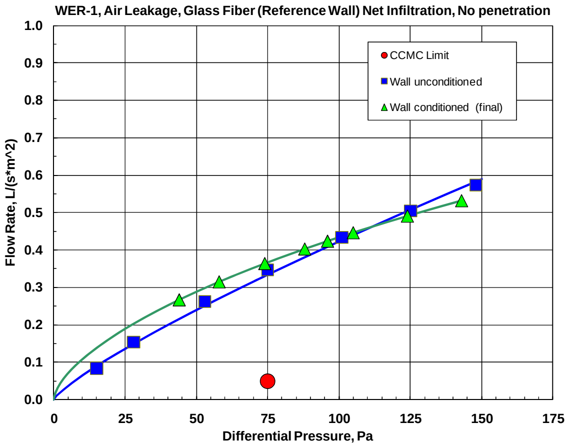

Figure 11 Air leakage results of WER-1

Also, the wall with penetrations (WER-5) is less tight than WER-1 (without penetrations). This is expected as a result of not sealing around the interface of the penetration and more construction tolerance at all solid-solid interfaces of the wood frame of the penetration, see Table 4 (also, see Saber et. al., 2010A and Saber et. al., 2010B for more details).

It is important to repeat here that both WER-1 and WER-5 were not sealed according the Building Code requirements.

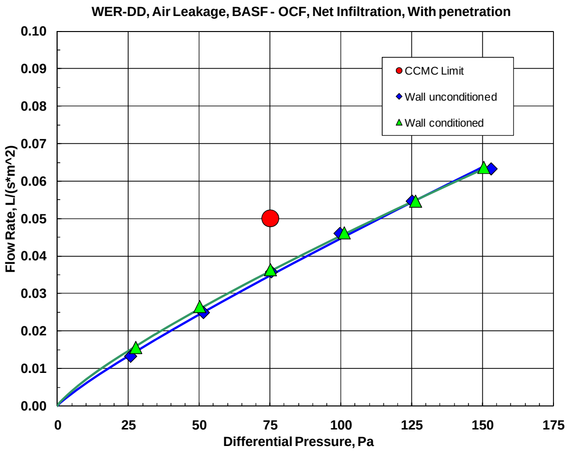

Figure 12 Air leakage results of WER-DD

It is important to realize that in our previous publications on results of this project (Elmahdy, et al. 2009A, Maref, et al. 2009, Elmahdy et al., 2009B, Saber et al. 2010A, and Saber et. al 2010B), the correlation between the air leakage rate and the pressure differentials were performed by using a "straight line" fit. However, for more realistic representation of the air leakage data, an "exponential fit" is used. Therefore, the air leakage plots in Figures 11 through 12 are done using the exponential fit. Incidentally, the air leakage rate at ΔP=75 Pa does not change from the linear fit to exponential fit because it was a measured value (or close to it)

Table 3 Summary of R-values determined in the guarded hot box

Cold temperature	**-20 °C**		**-35 °C**	
	R-value of conditioned walls, m^2.K/W			
Wall #	**m^2.K/W**	**°F.ft^2.hr/BTU**	**m^2.K/W**	**°F.ft^2.hr/BTU**
WER-1	**3.25**	**18.45**	**3.44**	**19.53**
WER-5	**2.78**	**15.79**	**2.84**	**16.13**
WER-AA	**3.59**	**20.38**	**3.60**	**20.44**
WER-BB	**3.30**	**18.74**	**3.24**	**18.39**
WER-CC	**3.36**	**19.07**	**3.26**	**18.51**
WER-DD	**3.00**	**17.03**	**3.02**	**17.14**

Table 4 Summary of measured R-value, air leakage rate at 75 Pa, β-value and WER number for the six walls

Wall*	Measured RSI$_0$ (m^{2}K/W)	Measured leakage rate ξ @75 Pa (L/(s.m^2))	Calculated β-value @75 Pa	WER number @ 75 Pa
WER-1 (NP)	3.24	0.369	0.533	26.82
WER-5 (P)	2.78	0.62	0.368	10.90
WER-AA (NP)	3.59	0.013	0.968	38.49
WER-BB (P)	3.3	0.022	0.950	37.24
WER-CC (NP)	3.36	0.014	0.966	37.68
WER-DD (P)	2.99	0.036	0.924	35.52

NP-No penetrations P-With penetrations

COMPUTER SIMULATION

As indicated earlier, a 3D computer model (hygIRC-C) is used to predict the wall R-value in the absence of air leakage. The results are compared to those determined by testing the walls in the guarded hot box. Figure 13 shows the comparison of the R-value of all walls as determined numerically (hygIRC-C model) and experimentally (guarded hot box). As it is shown on Figure 13, the agreement is very good and the variations are within the allowable tolerance of the guarded hot box at about ±6% (Elmahdy 1992).

The next step is to determine the "apparent R-value" of walls with the presence of air leakage. Since this could not be done in the guarded hot box, the hygIRC-C model is used to numerically predict the apparent R-values at different pressure differentials.

R-VALUE RATIO β

The R-value ratio β is defined as follows:

$$\beta = \frac{RSI_L}{RSI_o} \qquad (1)$$

Where:

RSI_L The predicted "apparent" R-value , and

RSI_0 The measured R-value in guarded hot box

Theoretically, the ratio β varies between 0 and 1. The next step is to correlate the factor β with the wall air leakage rate, ξ, (L/(m^2. s)). Figure 14 shows the correlation of the R-value ratio β, with the air leakage rate determined at ΔP = 75 Pa for all walls.

The relationship between β and ξ is expressed as:

$$\beta = \exp(a\,\xi^{b}) \qquad (2)$$

Where:

$a = -1.53\ (L/(m^2 .s))^{-0.89}$, and $b = 0.89$

The above expression predicts the β -values for the six wall specimens at air leakage rates determined at ΔP =75 Pa to within ±3%. Note that the calculated β -value using the expression above goes to 1.0 as the air leakage rate, ξ , approaches to 0.0.

It is important to indicate that Equation (2) is an interim expression of the ratio β. As more walls are tested and included in the correlation, the values of a and b change very slightly. It is expected that by the time this project is completed, more than 16 different walls will be included, which will provide a more accurate coefficients. Others papers, to be published at a later date, are being prepared to report this notion.

DETERMINATION OF THE WALL ENERGY RATING, WER

The procedure to determine WER is in line with that followed by Canadian Standards Association window energy rating (CSA 2004). WER is determined by calculating the net energy loss from the wall due to thermal conduction and due to air leakage.

From Equation (1), the apparent R-value of a wall with air leakage is rewritten as:

$$RSI_L = \beta\ RSI_0\,, \qquad (3)$$

As a result, WER could be expressed as:

$$WER = -\frac{\Delta T}{RSI_L} \qquad (4)$$

Where:

WER is the Wall Energy Rating number (W/m^2),

ΔT is the proposed standard temperature difference for evaluating WER, set at 40 K.

Since Equation (4) will always result in a negative number, and to follow the procedure of CSA standard (CSA 2004), a positive value of 50 was added to ensure that all WER values will be positive. Furthermore, and to make WER dimensionless, a constant C = 1 (m^2/W) is used to normalize WER. The final expression of dimensionless WER is written as:

$$WER = 50 - C\left(\frac{\Delta T}{RSI_L}\right) \qquad (5)$$

Where C is a constant and equals to 1 m^2/W

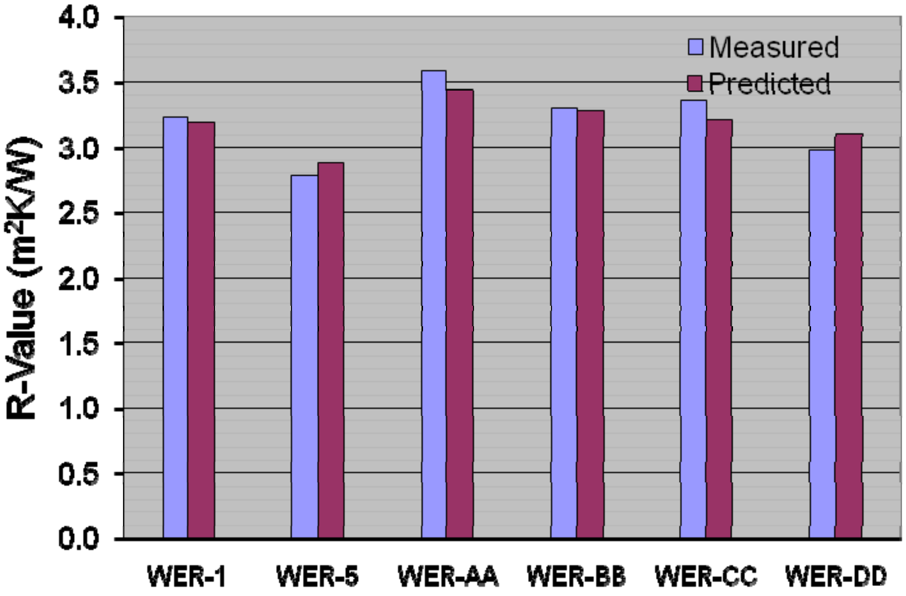

Figure 13 Comparison of measured and predicted R-values of ten walls.

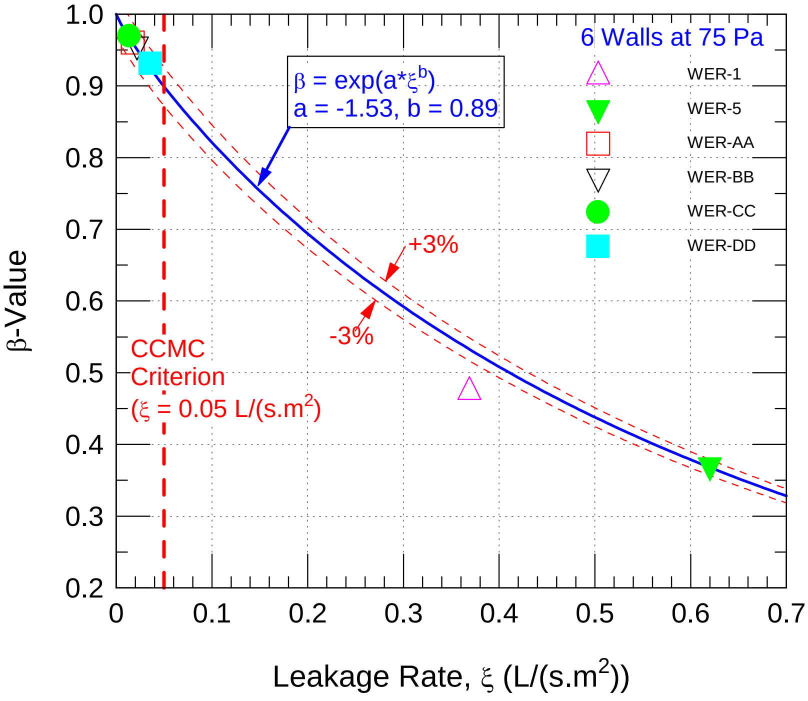

Figure 14 Correlation of R-value ratio β and air leakage rate ξ for six walls.

Equation (5) represents the wall energy rating of insulated wall taking into account the heat loss due to the thermal transmission and due to air leakage characteristics of the wall. Table 4 above shows the WER values for all six walls included in this paper in addition to RSI_0, air leakage rate ξ at $\Delta P=75$ Pa, and the R-value ratio β at $\Delta P=75$ Pa.

COMMENTS ON WER

The numerical values of WER show the degree of interaction between the wall R-value, its air leakage rate and the total heat loss through the wall assembly. As the air leakage increases, the apparent R-value decreases; hence increase of heat loss.

To illustrate this interaction, two different walls are considered: a leaky wall with air leakage rate of 0.62 L/(m^2.s) and a very tight wall with air leakage rate of 0.022 L/(m^2.s). All air leakage rate are measured at ΔP=75 Pa.

The impact of these different air leakage rates (leaky wall and tight wall) on WER is shown in Figures 15 and 16, respectively. Those figures show that as air leakage rate increases, the value of WER decreases relative to a similar wall with no air leakage. Therefore, the overall thermal performance of the wall is affected by the amount of air leaking through the assembly.

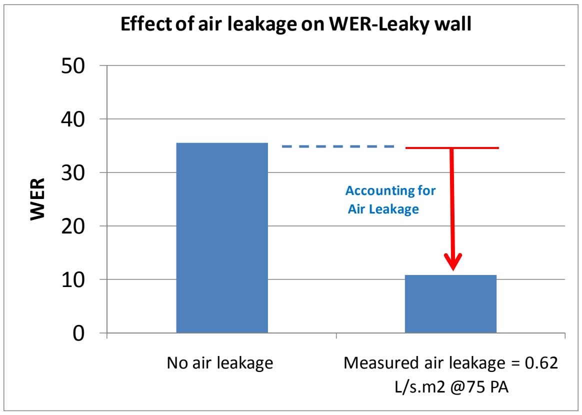

Figure 15 Effect of a leaky wall on WER

WHAT IS NEXT?

The expected outcome of this project is a procedure to determine the energy rating of insulated wall assemblies. There are many products in the market place which could be assessed in a similar manner. Efforts are underway to include other products in the correlation of the R-value and air leakage (the β curve) with the intention to cover most of the products in the marketplace. Also, under investigation, is the effect of the air cavity between the closed cell foam and the dry wall on the overall thermal performance of SPF insulated walls.

In the near future, the reported procedure will be included in a national standard to rate wall assemblies with respect to their energy performance. In addition, there is an ongoing discussion to draft an international standard (within ISO TC163 committee) for the same purpose.

Recently, two walls were constructed to replace WER-1 and WER-5. The replacement walls were built according to the Canadian Building Code requirements and showed substantial improvement in their air leakage performance. In fact, some of these walls performed as good as the SPF walls. The results will be published in the near future.

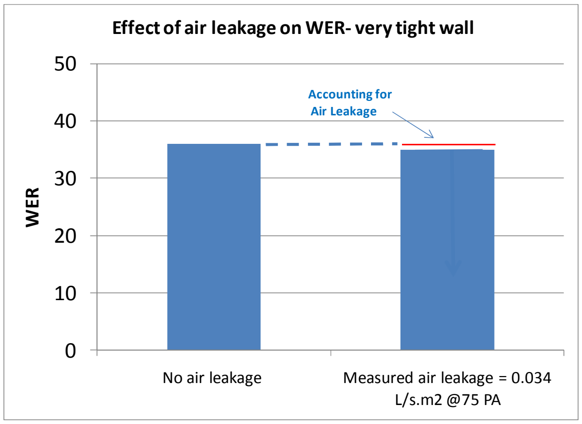

Figure 16 Effect of a tight wall on WER

Finally, the principals developed in this project will be applied on other building elements such as: wall/ceiling joints, wall-basement footing joint and wall/roof joints. A new project is planned to address all these issue in the near future. When completed, it would be possible to integrate the rating of all building components in an effort to rate the entire building with regard to its energy performance.

CLOSING REMARKS

This major project is a good example of the cooperation between industry and government research laboratory to investigate and resolve issues of mutual interest. The procedure developed in this project is sanctioned by industry and building code officials, which makes it easy to be incorporated in the national building and energy codes.

The main outcome of this project shows that the overall thermal performance of insulated walls could not be measured by its R-value alone, due to the fact that walls are not completely air tight. This means that there is always air leaking through the wall system. The overall energy performance of the wall has to include the effect of air tightness on its energy performance. Therefore, efforts should be made to design and build walls as tight as possible in order to improve their overall energy performance.

Since the work in this project resulted in a large amount of information, test results and different products, it was essential to report the results in a number of publications. However, at the end of the project, a summary report will be prepared to capture the most important results and conclusions. This would form the basis of a draft standard to be used in the building energy codes.

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