BUILDING ENVELOPE TECHNOLOGY SYMPOSIUM

Development of Energy Ratings for Insulated Wall Assemblies

Hakim Elmahdy; Wahid Maref; Mike Swinton; Hamed Saber; and Rock Glazer

Institute for Research in Construction/ National Research Council of Canada

1200 Montreal Road, M-24, Ottawa, ON, Canada K1A 0R6

Phone: 613-993-9752 • Fax: 613-998-6802 • E-mail: hakim.elmahdy@nrc.ca

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ABSTRACT

This paper provides some of the testing and simulation results of a major joint research project on the development of energy rating of insulated walls. The project included the development of test procedure to determine the wall energy rating (WER) of glass fiber and spray polyurethane foam insulated walls. The experimental portion included an extensive testing program to determine the wall air-leakage rate at different pressure differentials and their thermal-resistance R-value at different temperatures.

This paper presents the results of six walls included in this project. The paper focuses on offering a brief summary of the project objective, testing protocol, and theoretical approach to determine the WER for the six walls. In addition, the test procedures, experimental results (air leakage and R-value), wall sample construction, and a sample of the analytical results is presented.

SPEAKER

Hakim Elmahdy — Institute for Research in Construction/National Research Council of Canada

Hakim Elmahdy is a leader in defining, planning, and executing major research projects related to buildings and associated systems. This has been demonstrated in several research projects under the Canada/U.S. joint research on window performance and other related committees. Elmahdy has over 35 years of experience in teaching, as well as execution and management of research projects, thus leading to a practical application of research relevant to the industry and the professional community. Such application includes the incorporation of the results of the research projects into the system simulation programs, the National Building Code, and the National Energy Code through extensive work on standard development and performance evaluation of envelope systems. He has published over 160 technical and scientific papers.

Development of Energy Ratings for Insulated Wall Assemblies

INTRODUCTION

Spray polyurethane foam (SPF) insulation has been gaining considerable attention in North America for a number of reasons, including the following:

- Claim of better thermal performance of foamed walls relative to conventional poly-wrapped, batt-insulated walls,
- Better air-leakage performance, and
- The introduction of environmentally friendly blowing agents to reduce greenhouse gas emission.

A few years ago, the North American SPF industry joined forces to develop a replacement of the commonly used chlorofluorocarbon blowing agent. The introduction of the second generation of blowing agents (namely hydrochlorofluorocarbon [HCFC]) was seen as a positive step in the processing of SPF. Other agents were also developed, and their performance was assessed and reported.[1,2]

In recent years, the focus of building code and regulatory officials, professionals, and researchers has shifted towards the performance of the entire wall system. The emphasis is on the contribution of SPF and other insulated walls to the control of heat, moisture, and air through the system. Therefore, it is not sufficient to characterize the wall by its R-value alone, as was the case in the past.

This paper is one in a series to present information generated from a research project conducted jointly by the National Research Council Institute for Research in Construction (NRC-IRC) and the polyurethane industry (contractors and material suppliers) to assess the overall performance of insulated walls. In an earlier paper,[3] the authors presented a brief outline of the project objectives and a limited set of results of two walls that were available at that time. A second paper was presented at an ASTM Symposium,[4] where the test results of six walls were presented. These walls included glass fiber poly-sealed (two reference walls) as well as four walls of medium-density foam (closed-cell foam) insulation.

In this paper, more details about the testing program for six walls are presented, in addition to a brief description of the analytical approach used to determine the wall energy rating (WER) of insulated wall assemblies. Four of the six walls presented here were insulated with light-density (open-cell, 6.8 to 12 kg/m^3 nominal density) spray polyurethane foam, and the remaining two walls were reference walls insulated with poly-wrapped glass fiber batts. The work in this project is progressing, and the plan is to test additional walls to improve the correlation of data.

PROJECT OBJECTIVES

The main objective of this project is to develop an accurate and reliable combined testing and analytical procedure to determine the WER of the insulated wall assemblies. In addition, it is meant to introduce a new concept that combines the heat loss due to air leakage with that due to thermal conduction, showing the interaction and impact of both on the overall thermal performance of wall assemblies.

METHODOLOGY

The approach taken to achieve the project goals included two parallel paths: experimental and analytical. The experimental path is designed to determine the wall air-leakage rate (before and after wall conditioning), the thermal resistance (R-value before and after wall conditioning), and material characterization.

The analytical path is designed to predict the "apparent R-value" of walls with the presence of air leakage. It also provides a detailed account of the air flow path, particularly around the corners and hidden joints. Once the results from laboratory testing and computer simulation are compiled, the next step is to utilize all of the results to determine their correlation and to characterize the combined air leakage and conduction heat losses through the wall assemblies. The result is an expression to determine WER as a function of R-value, air-leakage rate, and temperature difference.

THE EXPERIMENTAL PATH

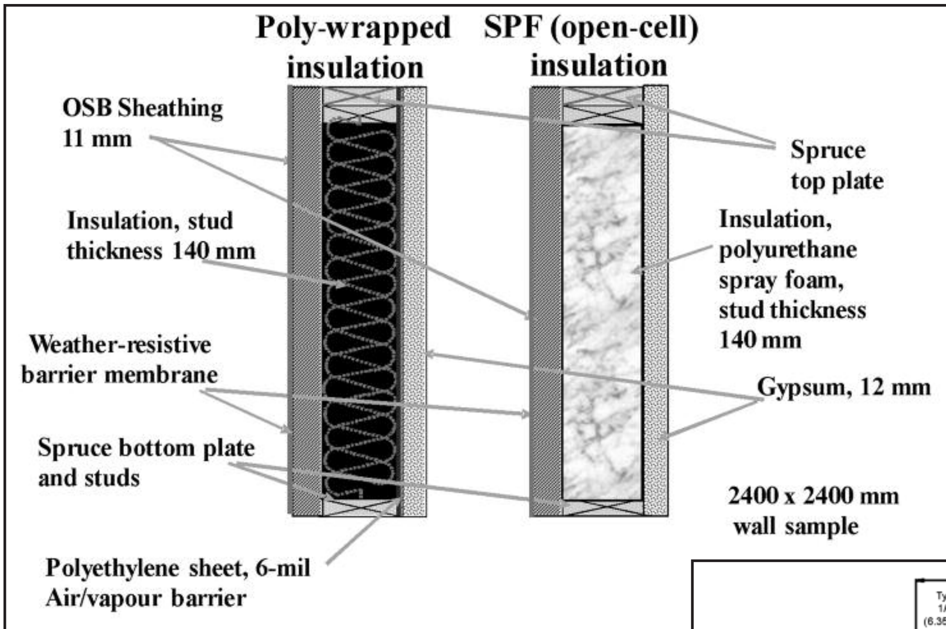
A number of wall samples were constructed and instrumented to record the intended measurements. Several tests were performed on all wall samples, which included air-leakage tests, thermal-transmission properties (R-value), and sample conditioning. Material characterization tests were performed on the foams only. Details of these tests are given in the following sections.

WALL SAMPLE DESCRIPTION

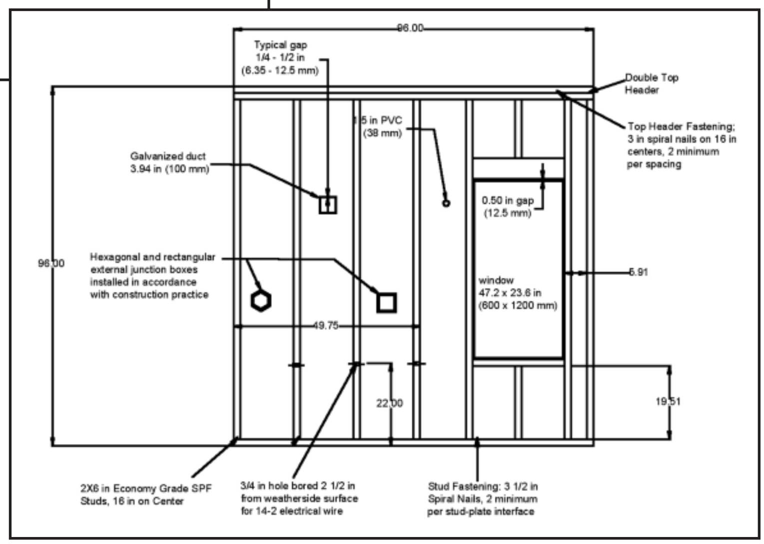
Wall samples were constructed according to common practices in the construction industry in Canada (and perhaps in parts of the U.S.). *Table 1* provides a brief description of the six walls included in this paper. *Figure 1* shows a schematic cross-section diagram of a wall sample illustrating the construction details.

All walls included in this project were built using the conventional 2-in by 6-in

WALL #	WALL DESCRIPTION	COMMENTS
WER-AA	Open-cell foam, no penetration	All walls were built according to common construction practices.
WER-BB	Open-cell foam with penetration	Foam is applied in the full cavity.
WER-CC	Open-cell foam, no penetration	Same as above.
WER-DD	Open-cell foam with penetration	Same as above.
WER-11	Poly-wrapped glass fiber, no penetration	Poly sheets are overlapped and sealed.
WER-12	Poly-wrapped glass fiber with penetration	Poly sheets are overlapped and sealed.



(CCMC Air Barrier Guide 07272



wood stud frame construction. There were two reference walls filled with poly-wrapped and sealed glass fiber batts (WER-11 and WER-12) and four other walls (WER-AA to WER-DD) insulated with light-density, open-cell (6.8-12 kg/m^3) SPF insulation. Three walls were opaque, and the other three included variations of penetrations to simulate a window, electric boxes (indoor and outdoor), air vents (and ducting), and plastic pipes, as per the *Canadian Construction Materials Centre (CCMC) Air Barrier Guide 07272*.[5] *Figure 2* is a schematic of a wall sample with penetrations.

TESTING PROTOCOL AND SEQUENCE

All wall samples were subjected to a series of tests to determine:

- Air-leakage rate before conditioning (at ΔP = 50 to 150 Pa),
- Sample conditioning,
- Air-leakage rate after conditioning, and
- R-value in a guarded hot box at zero air leakage (and ΔT = 40 K)

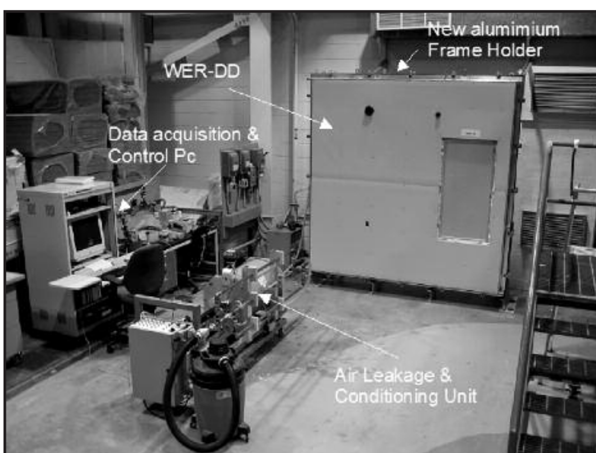
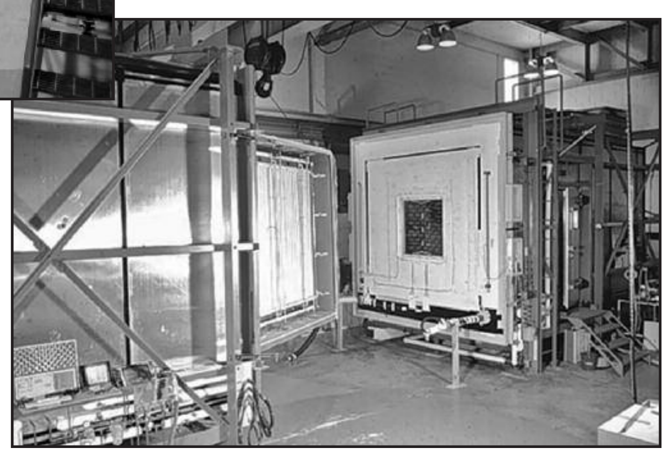
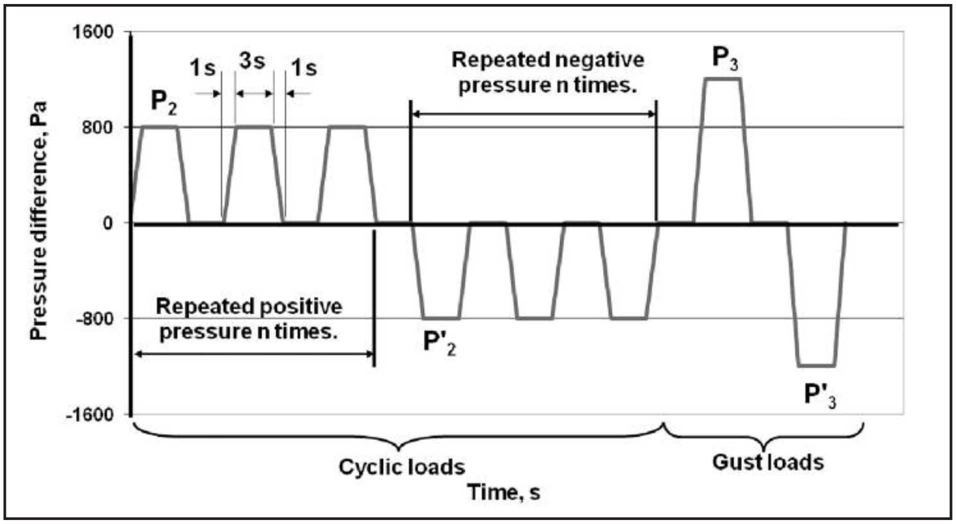


Figure 3 shows the air leakage and sample conditioning test facility, and *Figure 4* is a picture of the NRC-IRC guarded hot box (GHB). The test method used to determine the wall R-value is a well-established procedure developed at NRC-IRC that formed the basis for the ASTM GHB test standard and practice.[7,8]

The material characterization of the open-cell foam (light density, 6.8 to 12 kg/m^3) was performed according to ASTM C518 standard.[9] The test specimen was prepared according to the procedure outlined in ULC standard.[10]

All wall samples were conditioned according to the procedure





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detailed in the *Canadian Construction Materials Centre (CCMC) Air Barrier Guide 07272.*[5] A pressure cycle between +800 Pa and -800 Pa was applied to the sample in 2,000 cycles (1,000 cycles for +ve and 1,000 for –ve pressure). A gust wind was simulated by a pressure wave of 1,200 Pa (both negative and positive pressure pulse) and was applied accordingly to the wall sample. *Figure 5* is a diagram showing the pressure cycles during the condition routine. The total estimated time for sample conditioning is 5 hours and 30 minutes.

Figure 5 illustrates the wall sample conditioning routine as specified in the *CCMC Air Barrier Guide*. It shows the pressure cycle due to strong wind (up to 800 Pa), as well as the gust wind (up to 1,200 Pa pressure pulse) in both positive and negative pressure pulses. This wall conditioning is a requirement to pass the CCMC certification. *Figure 6* shows a wall sample mounted in the air leakage and conditioning test facility. The air leakage test method used is in accordance with ASTM E283.

RESULTS OF THE EXPERIMENTAL PATH

A summary of the test results of all wall samples included in this paper is reported in the following sections. This includes air-leakage tests before and after sample conditioning, GHB R-value, and thermal conductivities of foam samples (material characterization).

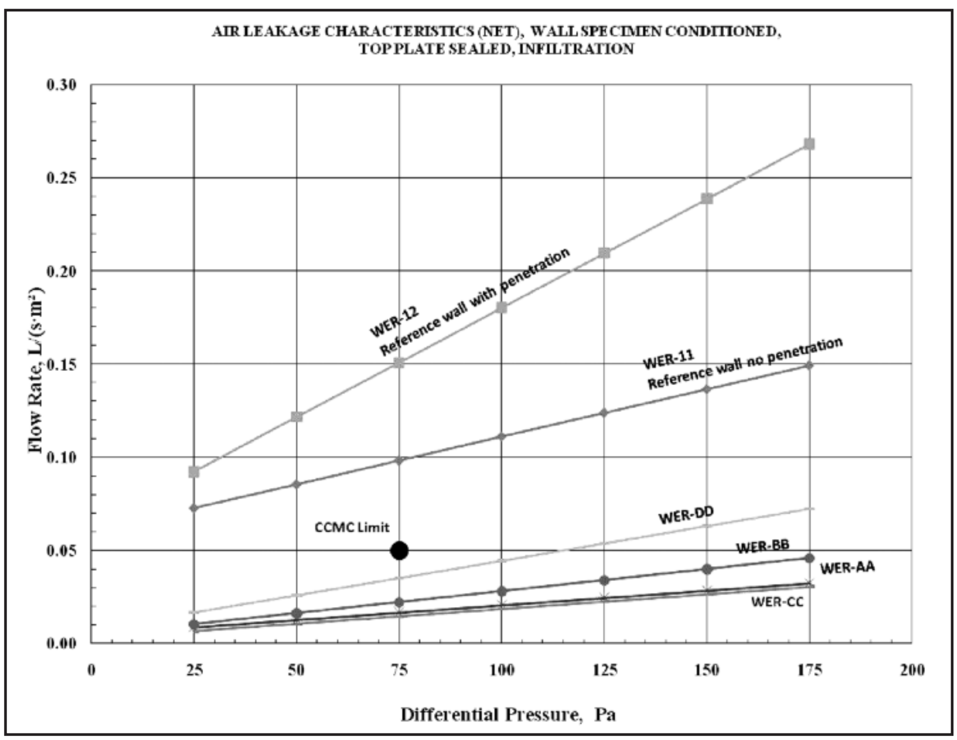
SUMMARY OF AIR-LEAKAGE TEST RESULTS

Figure 7 shows a summary of the air-leakage test results of the six walls presented in this paper (i.e., two poly-wrapped and sealed glass fiber and four open-cell foamed walls). The solid circle on the chart in *Figure 7* signifies the maximum air-leakage rate allowable to meet the CCMC air barrier requirements for walls (set at 0.05 l/(m^2.s) at ΔP = 75 Pa).

Figure 7 also shows that all foamed walls have met the CCMC requirement for air barriers, whereas the two reference walls (poly-wrapped and sealed glass fiber walls) showed a much higher air leakage rate at ΔP = 75 Pa.

There are a number of factors that may have contributed to the higher air-leakage rates of the reference walls (WER-11 and 12). For example, cracks around the electric outlets and other penetrations were not sealed perfectly (compared to those in the SPF walls), and cracks at the corners where the studs meet the top and bottom plates may have experienced similarly imperfect seals. WER-11 and -12 were constructed according to common practices, and some efforts were made to improve their airtightness. However, it was beneficial to have wall samples that are "not very airtight" to check the validity of the developed WER procedure.

It is worth mentioning that many walls similar to WER-11 and -12 have passed the CCMC requirements as air barriers. Therefore, it is important to interpret the results with caution.



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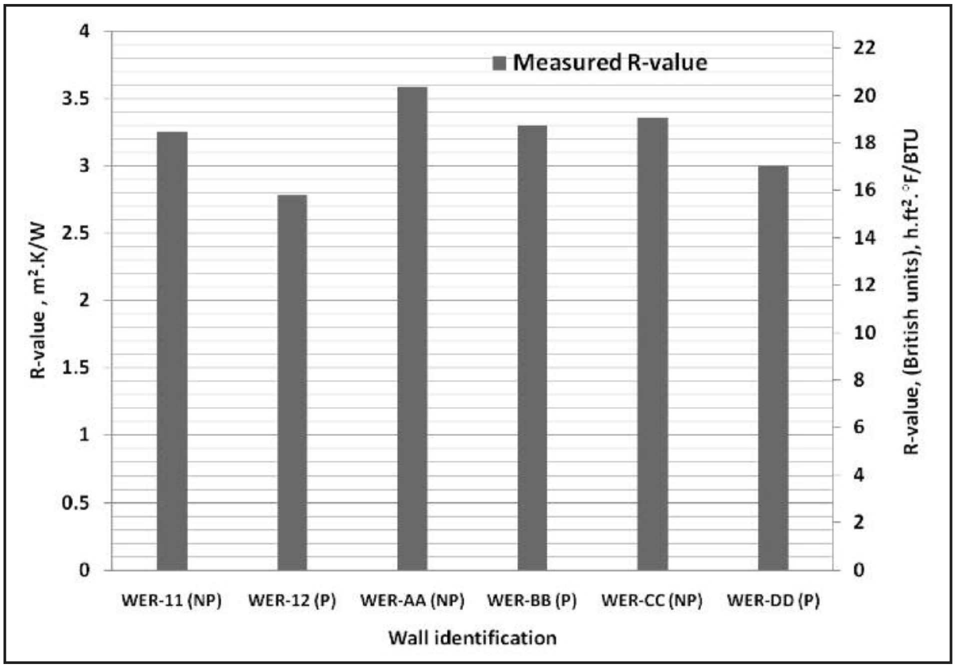

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SUMMARY OF R-VALUE TEST RESULTS (GHB)

Figure 8 provides a summary of the R-value of the six walls as measured in the GHB at ΔP = 0 Pa and ΔT = 40 K (i.e., room-side temperature = 20 ± 1ºC and weather-side temperature = -20 ± 1ºC).

The R-value of all walls was expected to be close to RSI 3.52 (or R-20 on the British scale). However, construction details and other factors such as nonuniform thickness of foam, variability of foam density (see material characterization below), the presence of thermal bridges (such as wood studs), and a dummy window (that was substituted by extruded polystyrene insulation), all contributed to the variation of the thermal resistance of the wall assemblies.

Although the focus of this study is not to determine the variability of the thermal resistance of wall assemblies or to compare the R-value of walls, it was critical for the development of the WER to determine, with GHB precision, the actual R-value of each wall.

SUMMARY OF MATERIAL CHARACTERIZATION

Table 2 provides a summary of the material characterization test results of the SPF as determined in the heat-flow meter apparatus.[11]

The thermal properties of the glass-fiber insulation used in WER 11 and WER 12 were obtained from a published thermal properties of insulation materials database.[12]

As indicated earlier (when comparing the R-value of walls), the variability in the foam density from different manufacturers may have contributed to the difference in the final R-value of the walls. This is also reflected in calculated thermal resistivity (and thermal conductance) of the SPF.

THE ANALYTICAL PATH

In this task, the focus is to develop a procedure to determine the WER of insulated wall assemblies. In addition, it is intended to reduce the financial burden on wall manufacturers by reducing the laboratory tests to a minimum. This is achieved by combining computer simulation models and wall test results to arrive at an accurate and reliable procedure to determine WER of walls constructed with different insulation materials, with and without penetrations. The following is a summary of this task. More details about this task will be the subject of other publications to be released in the future.

COMPUTER SIMULATION

The NRC-IRC hygrothermal computer model, hygIRC-2D Model[13-18] was first used for the thermal- and air-leakage analysis of the wall assemblies. However, an advanced version of this computer model, a 3-D program called hygIRC-C, was used to determine the "apparent R-value" of wall assemblies with the presence of air leakage. The 3-D model (hygIRC-C) was built on the same principles as hygIRC-2D and was benchmarked (supported with experimental work) against the 2-D version. The comparison of hygIRC-2D and hygIRC-C produced almost the same R-value results, except that hygIRC-C provided better analysis around the corners in 3-D fashion (see Reference #4 for detailed benchmarking of the two programs).

A brief summary of the computer model results and a comparison of the R-value of the six walls determined experimentally and analytically is presented below.

COMPARISON OF THE EXPERIMENTAL AND ANALYTICAL RESULTS

The hygIRC-C was used to calculate the R-value of all walls in the absence of air leakage through the assemblies. *Table 3* and *Figure 9* provide a summary of the GHB-measured R-value at ΔP = 0 Pa, room-side temperature of 20 ± 1ºC and cold side

WALL # ⟶ / PARAMETER ↓	SYMBOL	UNITS	WER-AA	WER-BB	WER-CC	WER-DD
Mean temperature	T_m	ºC	0.20	0.20	0.30	0.30
Material density	ρ	kg/m³	12.0	12.0	7.8	7.8
Thermal conductivity, SI and IP units	λ	W/(m.K)* [Btu.in/(h ft².ºF)]	0.0352 (0.244)	0.0352 (0.244)	0.0388 (0.269)	0.0388 (0.269)
Thermal resistivity, SI and IP units	r	m.K/W* [h ft².ºF/(Btu.in)]	28.41 (4.10)	28.41 (4.10)	25.77 (3.72)	25.77 (3.72)

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*IP (British) units are shown in parentheses ( ).

WALL ID ⟶	WER-11 No penetration	WER-12 With penetration	WER-AA No penetration	WER-BB With penetration	WER-CC No penetration	WER-DD With penetration
Measured R-value in GHB, m^2.K/W	3.25* (18.45)	2.78 (15.79)	3.59 (20.38)	3.30 (18.74)	3.36 (19.08)	3.00 (17.03)
Calculated R-value using hygIRC-C, m^2.K/W	3.20 (18.17)	2.88 (16.35)	3.44 (19.53)	3.28 (18.62)	3.21 (18.23)	3.11 (17.66)

*R-values in IP units are shown in brackets ( ), h. ft^2.ºF/Btu

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WALL	MEASURED R-VALUE * (m^{2}K/W)	APPARENT R-VALUE USING hygIRC-C (m^{2}K/W)		
	DP = 0 Pa	DP = 0 Pa	DP = 75 Pa	DP = 150 Pa
WER-11 (NP)	3.25 (18.45)*	3.20 (18.17)	2.58 (14.65)	2.38 (13.51)
WER-12 (P)	2.78 (15.79)	2.88 (16.35)	2.13 (12.09)	1.84 (10.45)
WER-AA (NP)	3.59 (20.38)	3.44 (19.53)	3.31 (18.80)	3.23 (18.34)
WER-BB (P)	3.30 (18.74)	3.28 (18.62)	3.14 (17.83)	3.04 (17.26)
WER-CC (NP)	3.36 (19.08)	3.21 (18.22)	3.12 (17.72)	3.04 (17.26)
WER-DD (P)	3.00 (17.03)	3.11 (17.66)	2.89 (16.41)	2.70 (15.33)

*R-values in IP units are shown in brackets ( ), h. ft^2.ºF/Btu

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temperature of -20 ± 1ºC, and those calculated using the hygIRC-C computer model at ΔP = 0 Pa. It is reported in the literature that the GHB test results are accurate within ± 6%;[19] however, the comparison between the GHB R-value and those determined by the hygIRC-C model shows agreement better than ± 6%.

The next step is to use the hygIRC-C model to determine the apparent R-value of the wall assemblies with the presence of air leakage. *Table 4* provides a summary of the GHB R-value and the "apparent R-value" as determined using the hygIRC-C computer model at three different pressure differentials across the walls (ΔP= 0, 75, and 150 Pa).

Table 4 shows that the presence of air leakage has a negative impact on the R-value of the wall assemblies; hence, the overall thermal performance of the wall is decreased. The result of this interaction between the air leakage and R-value is captured during the development of the WER.

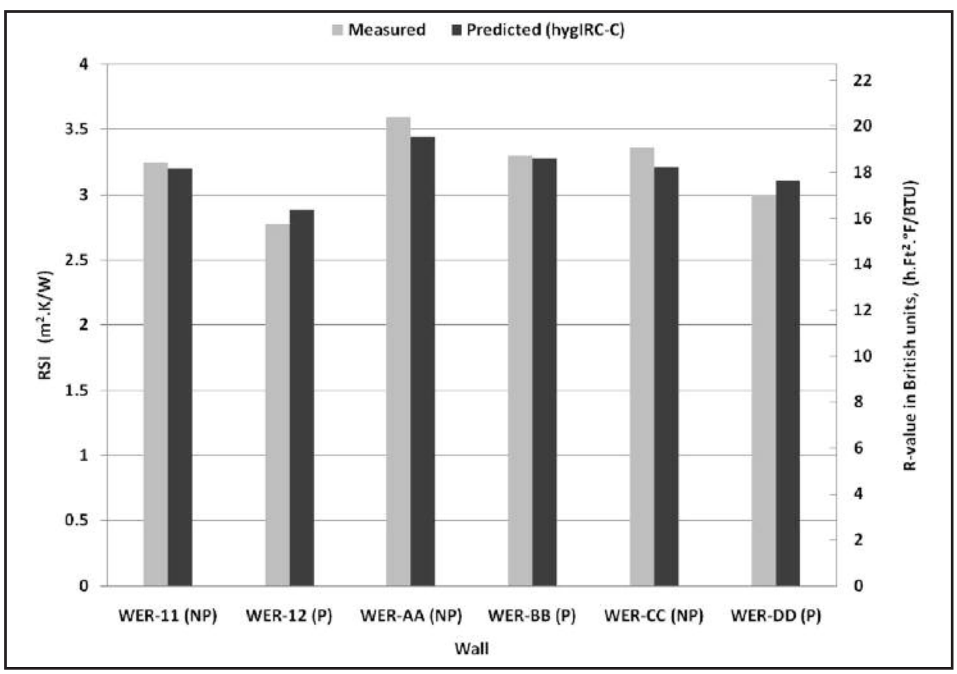
In *Table 4*, the measured R-value (second column from the left) and the computer predicted R-value (at DP = 0 Pa) are very close and within the experimental tolerances. This comparison enhances the level of confidence in the computer prediction of the thermal resistance of walls.

CORRELATION OF EXPERIMENTAL AND ANALYTICAL RESULTS

As indicated earlier, the main objective of this project is to develop a procedure to determine the overall WER of insulated walls that would take into account the impact of the air leakage on the overall thermal performance of the wall assembly. *Figure 9* provides a comparison of the walls' R-value as determined by measurements (in GHB) and as predicted using the hygIRC-C 3-D computer model. This comparison is critical for the next step, when the wall's "apparent R-value" is predicted with the presence of air leakage.

As explained above, and by investigating *Table 4*, it is observed that as the air leakage rate increases, the apparent R-value of the wall decreases. In order to capture the interaction between the air-leakage rate and the apparent R-value of the walls determined with air leakage, R_L, the results shown in *Table 4* were used to develop a correlation between the air-leakage rate (ξ, l/(s. m^2) and the R-value ratio β, where R_o is the measured R-value at ΔP = 0 Pa. The parameter β is defined as (see *Equation 1*):

$$\beta = \frac{Apparent\ R - value\ \ at\ \Delta P = 75\ Pa\ ((hygIRC - C\ output), R_L)}{Measured\ R - value\ (GHB\ output),\quad R_o}$$



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The final expression for β is given by the following equation:

$$\beta = e^{a.\xi^{b}}$$

The resulting correlation of the data generated for the six walls is shown in *Figure 10*.

The correlation coefficients (α = -1.75 and β = 0.92) in *Equation 2* are applicable to the six walls included in this paper. Currently, more walls are being tested, and revised correlation coefficients are determined. They vary slightly from the values shown above. Obviously, the more wall samples included in the development of *Equation 2*, the better the final results one might expect.

FINAL FORM OF WER OF INSULATED WALLS

The expression for WER is a simple relationship in terms of the air-leakage rate, ξ, and the measured R-value of the wall at no air leakage (R_o in SI units). The final form is similar to that developed for the energy rating of windows (ER) published by the Canadian Standards Association, CSA A440.2 Standard.[20] *Equation 3* provides the final expression for WER.

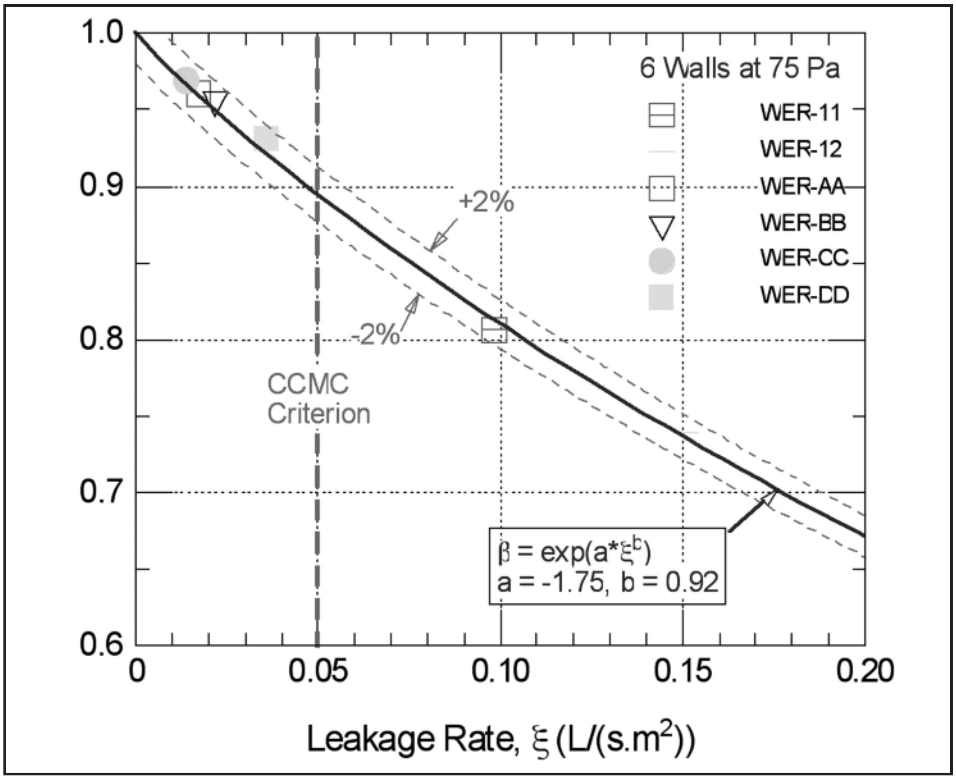
Where:

$$WER = 50 - C\left(\underbrace{\frac{\Delta T}{RSI_0}}_{\text{Conduction heat loss}} + \underbrace{\frac{\Delta T}{RSI_0}\left(\frac{1-\beta}{\beta}\right)}_{\text{Air leakage heat loss}}\right)$$

ΔT = 40 K is the temperature difference in the GHB

C = 1 m^2/W is a constant to normalize WER

The constant 50 in *Equation 3* is intended to normalize the WER value and to make WER a positive number, since the other two terms are always negative. In addition, to present a mathematically correct formula, a constant (C=1 m^2/W) was introduced in *Equation 3* in order to have a dimensionless WER in its final form. Therefore, WER in *Table 5* is dimensionless and should be used only for product-comparison purposes and not to be multiplied by area of a wall to give the heat loss in Watt/m^2.



– ξ β

Table 5 provides a summary of WER determined for the six walls in this paper.

To illustrate the benefits and use of WER, three different cases are presented to show the impact of air leakage on the overall thermal performance of wall assemblies with different air-leakage rates.

Figures 11 through *13* provide three cases of insulated walls with different air-leakage rates. In each case, the difference between the height of the bar on the left and that on the right is the reduction in WER as a result of air leakage through the wall. As the air-leakage rate increases, the difference between the height of the two bars (in each figure) increases, hence a reduction in the overall thermal performance of the wall.

FUTURE WORK

This project is a work in progress. New walls constructed with different insulation materials (e.g., cellulose fiber, blown fibers, etc.) are being considered for evaluation. It is imperative to add as many wall samples as there are different designs and configurations to the group of walls already tested. This will add more data points to obtain better correlation coefficients that could be used widely in the construction industry. Ultimately, a draft of a national (and perhaps an international) standard will be considered by the relevant organizations. In addition, a proposal is being prepared for submission to the Canadian Construction Materials Centre for the development of a guide to determine WER of insulated walls.

WALL ID	LEAKAGE AT ΔP = 75 Pa, ξ (L/(s.m^2))	β-VALUE (---)	MEASURED RSI_0 AT ΔP= 0 Pa (m^2K/W) (h.ft^2.°F/BTU)	WER (---)
WER-11 (NP) *	0.098	0.813	3.25 (18.45)	34.86
WER-12 (P)	0.151	0.736	2.78 (15.79)	30.44
WER-AA (NP)	0.017	0.959	3.59 (20.38)	38.38
WER-BB (P)	0.022	0.950	3.30 (18.74)	37.24
WER-CC (NP)	0.014	0.967	3.36 (19.08)	37.68
WER-DD (P)	0.036	0.922	3.00 (17.03)	35.53

(*) NP = No penetration P = With penetration IP units are in (---)

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CLOSING REMARKS

The presence of air leakage through a wall has a clearly negative impact on the overall thermal performance of the wall. This has been demonstrated by laboratory testing and analytical assessment of several walls insulated with different insulation materials.

An innovative procedure to combine laboratory testing and computer simulation was developed to determine the energy ratings of insulated wall assemblies. This procedure proved to be a simple and accurate method and required minimal testing (only R-value in a guarded hot box with zero air leakage and air-leakage tests). The WER procedure is a tool for building designers and construction professionals that could be used to comply with current or future energy code requirements.

ACKNOWLEDGEMENTS

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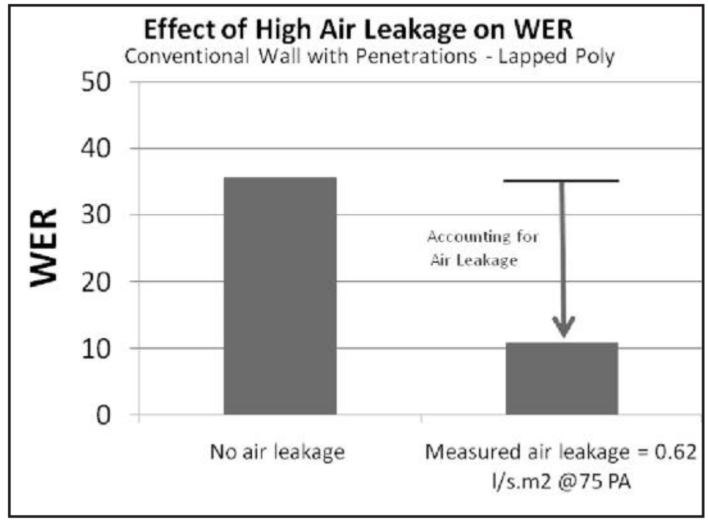

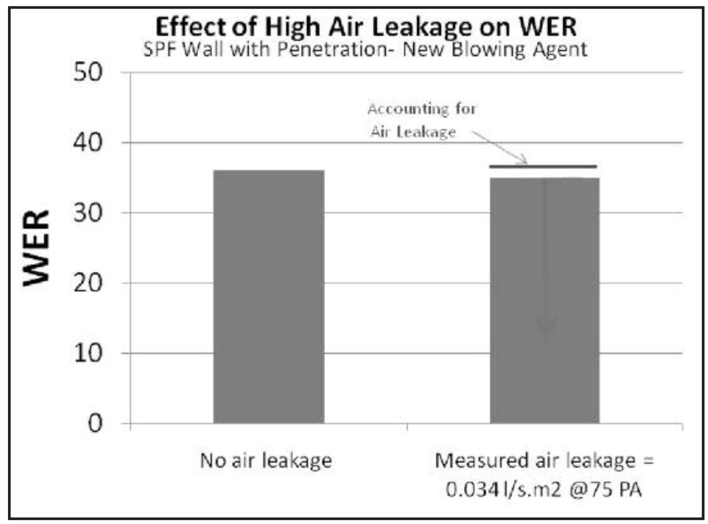

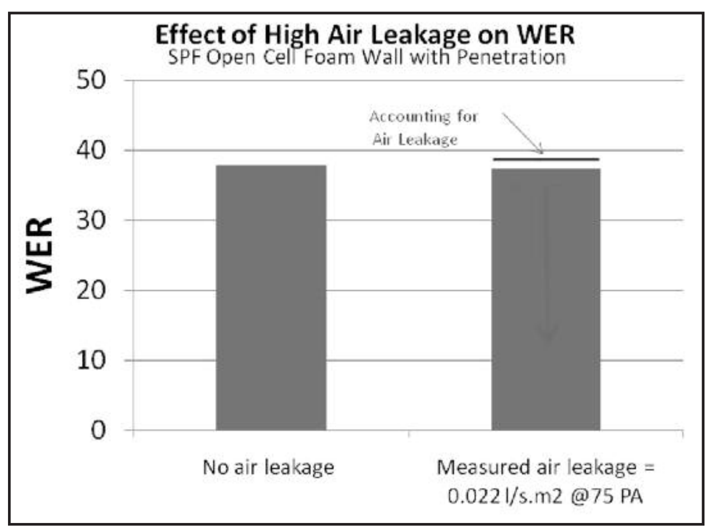

FOOTNOTES

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