Effects of Air Infiltration and Mean Temperature on the Thermal Performance of Insulated Frame Wall Assemblies

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ABSTRACT

This paper presents and analyzes the experimental results from a full-wall (guarded hot box) thermal testing study performed by Architectural Testing, Inc., of York, PA. The tests were performed on 8 ft. x 8 ft. wood frame walls insulated with three types of cavity insulations: fiber glass batts, open-cell spray polyurethane foam (ocSPF) and closed-cell spray polyurethane foam (ccSPF). In addition, thermal performance of a combination of ccSPF and polyisocyanurate insulated sheathing is also measured. This full-scale test method goes beyond simple thermal conductivity testing of insulation materials and includes real-world effects of air infiltration and mean temperature. Specifically, it includes the effect of air infiltration by simulating a 15 mph wind applied to the outside surface of the test walls. In addition, the effect of mean test temperature on wall thermal performance is measured using outdoor temperatures of -15ºF, 25ºF and 115ºF. A Wall Performance Index (WPI) is determined for the different walls tested, providing a rating of actual versus expected thermal performance. Results show WPI is dependent upon mean temperature and air infiltration. The WPI for fiber glass insulated walls are significantly reduced by wind loading and changes in the mean test temperature. Walls made from open-cell foam show consistent WPI values that are lower than expected, but relatively unaffected by wind load and external temperature. Closed-cell spray foam shows WPIs that are consistently at or above expected values, regardless of mean temperature and air infiltration. Reasons for these observed effects are discussed.

BACKGROUND

Insulation or Material-Level Thermal Performance

When measuring the thermal performance of building insulation, the most common metric is the R-value[1, 2]. R-value, or thermal resistance, is a measure of the material's ability to resist conductive heat flow. The higher the R-value, the better the material resists heat flow. Materials with low thermal conductivity have high R-values. Likewise, increasing the materials thickness will increase R-value.

R-value is defined by the amount of conducted heat, *Q*, passing through a specified area, *A*, of a material with a differential temperature imposed upon two parallel surfaces at different temperatures (T_{hot} - T_{cold}). This relationship is shown in Equation 1.

$$Q = UA(T_{hot} - T_{cold}) = \frac{A}{R}(T_{hot} - T_{cold}) \qquad (1)$$

Thermal resistance or R-value is the inverse of the thermal transmittance, *U*, and is also related by two fundamental properties of the material: its thermal conductivity, *k*, and it's thickness, *t*, according to the relation:

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$$R = \frac{t}{k} = \frac{1}{U} \tag{2}$$

R-value has been routinely used by building codes for decades to prescribe minimum insulation requirements, it does not completely represent the amount of heat that is transferred through a building envelope under real-world conditions. R-value is measured under laboratory conditions by standards set forth by the American Society for Testing and Materials (ASTM). For building insulations, R-value is measured using a heat flow meter or guarded hot plate [1,2]. In these tests, a known temperature difference is applied to a slab of material having a known thickness, t, and area, A. The heat flow, Q is measured, and the R-value, R, is calculated using Equation 1.

This test is performed in an air-sealed chamber to minimize external heat flow. Since the test chamber is sealed and oriented so heat flows in a vertical direction, it minimizes heat transfer by convection. Additionally, test standards require that the test be performed at an average temperature $(T_{hot}+T_{cold})/2$ at a fixed temperature difference, $T_{hot} - T_{cold}$. Many insulation material specifications require R-values to be tested at a 75ºF mean temperature and a 40ºF temperature difference. Air permeable building insulations like fiber glass and cellulose generally perform very well when convective effects are minimized and testing is performed at moderate mean temperatures. Often these insulation materials are designed to provide maximum R-value under these conditions. To further complicate matters, some manufacturers report R-values without a specified mean temperature or temperature difference.

While R-value is very useful as a parameter to monitor and control quality of insulation materials during production, it is not as useful as a predictor of building thermal performance. While R-value is used to calculate the thermal resistance of a wall structure and ultimately the heating and cooling energy needs of a building, it does not tell the complete story. Because heat can be transferred by convection, R-value alone is not a suitable predictor of how the insulation material will perform in a wall system.

Within fibrous insulations like cellulose and fiberglass, which depend on still air as the insulating medium, small temperature differences can create convection looping within and through contiguous pockets of air in the insulation, reducing R-value. In real buildings air leakage can occur through cracks and crevices in the building envelope and infiltrate or ‘wind-wash’ through porous insulations – degrading thermal performance even further. If left unchecked, air infiltration can account for as much as 30% to 40% of the heating/cooling energy requirements of a building [3].

Building Envelope or System-Level Thermal Performance

To measure the performance of insulation in real buildings, an ideal solution would be to construct several identical buildings on the same location, with the same orientation and controlled interior conditions, and monitor the energy requirements over one or more years. While this approach is used occasionally, it is a very expensive way to measure and compare real performance of the building envelope.

As a compromise building scientists have developed a whole-wall measure of thermal performance using a device called a guarded hot box [4]. In this approach, a complete wall section is constructed, including cladding, framing, sheathing and insulation. In some cases windows, electric outlets and perforations for plumbing, wiring and ventilation are added to the wall to simulate real conditions [5].

In a guarded or metered hot-box apparatus, a temperature difference is applied across the thickness of the wall specimen. Generally, there is an ‘indoor’ side where temperatures are controlled to match typical room temperature conditions. Likewise, there is an ‘outdoor’ side where temperatures are controlled to simulate extremely cold or hot climates. Heat flow through the wall section is monitored using a variety of sophisticated metering methods. In addition, many hot-box setups have provisions to simulate the effects of wind loads and forced air infiltration. This is accomplished by applying an equivalent differential air pressure on the inside and/or outside wall surfaces. There are even more sophisticated hot-box designs that can introduce moisture [6] and can orient the wall from vertical to horizontal to measure the performance of walls, roofs, ceilings and floors [7].

A hot-box apparatus can provide a much more meaningful measure of insulation performance when used as part of a building envelope system. Most hot-box testing systems measure the thermal conductance, or overall heat transfer coefficient of the wall, *U*, from Equation 1. *U* is also the inverse of the overall wall R-value, and includes all modes of heat transfer, such as:

- conduction through all materials in the wall system
- convection within and on the outer surfaces of the wall specimen
- radiation between internal and external surfaces
- forced air infiltration (when a pressure is applied).

A hot-box test is more complex than a simple R-value test of the material's thermal conductivity using a heat flow meter. However, it provides a far more realistic measure of how the insulation performs in a real wall system; a fact well known by building scientists and most architects. As a result, there are several research programs underway to define a hot-box test protocol that could augment or potentially replace R-value testing of insulation as the primary predictor for thermal performance for buildings.

TESTING PROGRAM

Recognizing that thermal performance of insulation is more than just a measure of R-value, the Spray Polyurethane Foam Alliance (SPFA) decided to commission Architectural Testing, Inc. (ATI) of York, PA to perform guarded hot-box measurements on several different wall configurations using a variety of cavity insulations including open-cell and closed-cell spray foam. This paper provides a summary of that experimental program and analysis of the data prepared for SPFA[8,9,10] in 2006 and includes a "base case" using fiberglass batts originally documented in ATI lab reports prepared for the American Chemistry Council's Plastics Division (ACC-PD)[11].

SPECIMEN PREPARATION

Four 8' x 8' wall specimens were tested using the ATI guarded hot-box apparatus. Each wall section was identically fabricated as shown in Figure 1. Framing was assembled using 2"x 4"x 93" wood studs spaced on 16" centers. The wall framing included a single bottom plate and a double top plate where the two elements of the double top plate were nailed together on 12" spacing. Each interior stud was laterally drilled with a ½" diameter hole to simulate continuity between stud cavities from holes used for electrical wiring.

The exterior surfaces of the fiberglass wall were covered with 7/16" thick oriented strand board (OSB) sheathing. The spray foam insulated walls used ½" thick OSB. Screws were applied to fasten the OSB sheathing at 6" spacing around the perimeter of each board, and 12" spacing along the intermediate studs. All OSB sheets were glued to the studs using a continuous bead of glue and all seams and fasteners were sealed (see *Air Leakage Control* section).

The fourth sample replaced the OSB with ½" foil-faced polyisocyanurate (PIR) insulated sheathing. The PIR sheathing was attached with 1.5" long plastic capped nails applied at 12" spacing along the perimeter edges and 16" spacing along the interior studs. All seams and perimeter nail caps were taped with 3" foil tape.

The interior surfaces of all four specimens were made from ½ " thick gypsum board. Two empty outlet boxes were installed in the outboard cavities as shown, perforating only the gypsum board (interior) surface. Several 1-3/8" drywall nails were applied to fasten the gypsum board at 8" spacing around the perimeter of each board. All screw heads and seams were sealed with a single coat of drywall finishing compound.

The primary difference in each wall specimen is the type of cavity insulation used, as defined below:

- **Wall A: Baseline Fiberglass** – With 7/16" OSB sheathing, Wall A had all cavities filled with asphalt-kraft faced R-13 batts of fiberglass insulation installed using the face stapling technique per North American Insulation Manufacturer's Association (NAIMA) standards.
- **Wall B: Open-Cell SPF** – With ½" OSB sheathing, this wall had all cavities filled with open-cell spray polyurethane foam insulation. This foam was applied so that the material expanded to the front face of the

studs. In the sample tested, shown in the photograph of Figure 2, about 40% of the material expanded beyond the interior stud faces and was shaved. The remaining 60% of the cavity was sprayed to an approximate mean thickness of 3.25”. This application technique was used to minimize waste after trimming.

- **Wall C: Closed-Cell SPF -** With ½” OSB sheathing, Wall C had all cavities sprayed with a single pass application (approximately 1.5” thick) of closed-cell spray polyurethane foam insulation.
- **Wall D: Closed-Cell SPF+PIR Sheathing** – Identical to Wall C, with the OSB sheathing replaced by ½” thick PIR insulated sheathing, installed with foil joint sealing tape per manufacturers instructions.

TEST PROCEDURE

Air Leakage Control

Walls built in the field are rarely built with the care and precision used to make wall test panels. To produce a fair comparison between different wall constructions, it is necessary to construct each wall with minimal variation. To achieve this, thermal measurements were first taken for all materials of construction[11]. To avoid shrinkage due to drying, each wood member was measured for moisture content. If the moisture content of the studs and OSB exceeded 15% and 10%, respectively, they were rejected for use. Most wood components had measured moisture contents of between 8 and 9%.

Due to inherent material variances, there were concerns with variations in air leakage caused by inconsistent sealing between the face of the studs and the rough inner surface of the OSB sheathing. To overcome this concern, joints between the studs and OSB sheathing of Walls A, B and C were sealed and a series of small holes, or leakage ports, were intentionally drilled around the perimeter of the sheathing as shown in the photograph in Figure 1. Holes were not used in Wall D, which was sheathed with polyisocyanurate board and sealed with foil tape per manufacturer’s installation instructions.

To determine the number and size of these holes, a wall panel without cavity insulation and drywall, made only of the framing and OSB sheathing, was tested for air leakage per ASTM E-283 [12] at a pressure difference of 75 Pa (1.57 lbs/ft^2). The measured air leakage was 4.8 cubic feet per minute (cfm). The same wall was then sealed at all fasteners and joints and re-tested. Holes were drilled into the wall until the leakage rate returned to 4.8 cfm. Using this procedure, it was determined that forty-nine (49) 1/8” diameter holes were needed.

These intentional leakage holes provided an effective leakage area of 0.53 in^2, as calculated using Equation 33 on page 27.12 of the 2005 Handbook of ASHRAE fundamentals [13]:

$$A_{L:} = KQ_r \frac{\sqrt{\rho / 2\Delta P_r}}{C_D} \tag{3}$$

where

A_L = effective air leakage area, in^2
Q_r = air flow rate, 4.8 cfm
ρ = air density, 0.075 lbm/ft^3
ΔP_r = reference pressure difference, 0.3 in of water column
C_D = discharge coefficient (assumed to be 0.6)
K = unit conversion factor = 0.186

Guarded Hot-Box Measurements

Each wall specimen was tested in a guarded hot box apparatus, schematically sketched with portions photographed in Figure 3. This apparatus conforms to the requirements of ASTM C1363-05 [4] for thermal testing and ASTM E283-04 [12] for air leakage testing. During thermal testing, the cold room was maintained at the specified exterior temperatures, while the metering chamber, warm room and guard room were maintained at the specified indoor temperature. The test wall specimens were mounted and sealed between the cold room and the metering chamber.

Twenty-two thermocouples were applied on both the outside surfaces of the exterior sheathing and the interior gypsum board as shown in Figure 4. These 22 thermocouples pairs measured surface temperatures on opposing sides of the wall specimen. These warm room and cold room temperatures are used to define the T_{hot} and T_{cold} temperatures of Equation 1. Knowing the metering area of the wall, A, the wall R-value ($R_w = 1/U_w$) is then determined for each specimen. Results are shown in Table 1.

A pressure differential was applied to the cold room side, simulating the effects of a 15 mph exterior wind load. Using Appendix X of the ASTM C 1363 standard, and ensuring that no airflow was allowed to bypass around the sample, pressure was applied to the exterior wall surface, according to the Bernoulli equation:

$$p_v = \frac{\rho_a U^2}{2cg_c} \tag{4}$$

where
p_v = wind velocity pressure on the wall (inches of water)
Q_r = air flow rate, 4.8 cfm
ρ_a = air density in cold room, lbm/ft^3
U = wind velocity
g_c = gravitational constant, (32.2 ft/s^2)
c= unit conversion factor = 0.414

Since air density varies with temperature, different pressures were needed for each of the different outside air temperatures used in the test. For the 15ºF test, the air density is 0.088 lb/ft^3 and applied pressure difference from Equation 4 is approximately 31.7 Pa. For the 25ºF test, the air density is 0.080 lb/ft^3 and applied pressure difference is 28.8 Pa.

For the 115ºF temperature conditions, the elevated temperature was applied on the gypsum side of the panel and the sheathed side of the panel was held at 70ºF. Wind pressure was applied on the cooler sheathing side of the test panel. This arrangement prevents condensation on the thermocouples from hot moist air moving towards a colder surface. While the panel orientation could have been reversed, this was not done because reorientation could introduce unwanted variations in air sealing.

The cold room fans provide uniform air distribution. Air flow in the metering chamber was allowed to move freely to achieve natural convection conditions. An exhaust air blower in the warm room was operated to maintain a constant specified pressure difference between the exterior wall and metering chamber.

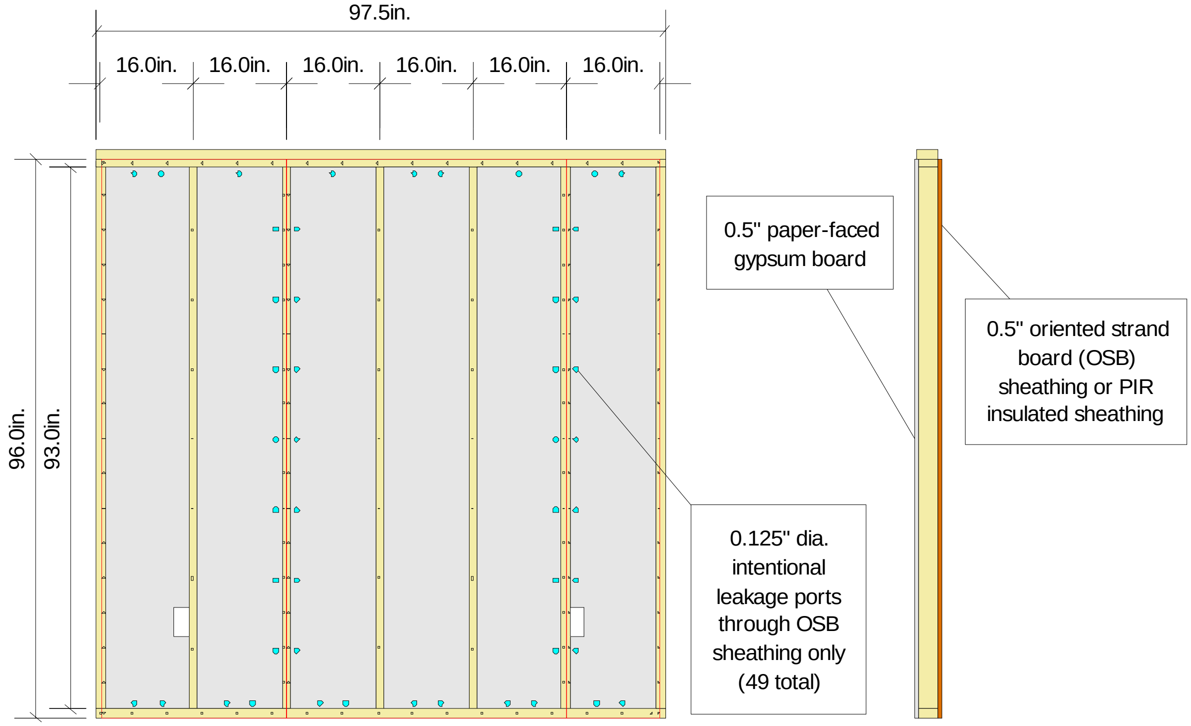

Figure 1. *Detail of wall test specimen construction. Dimensions in inches (red outline shows perimeter of sheathing and gypsum board)*

Figure 2. *Open-cell spray foam wall*

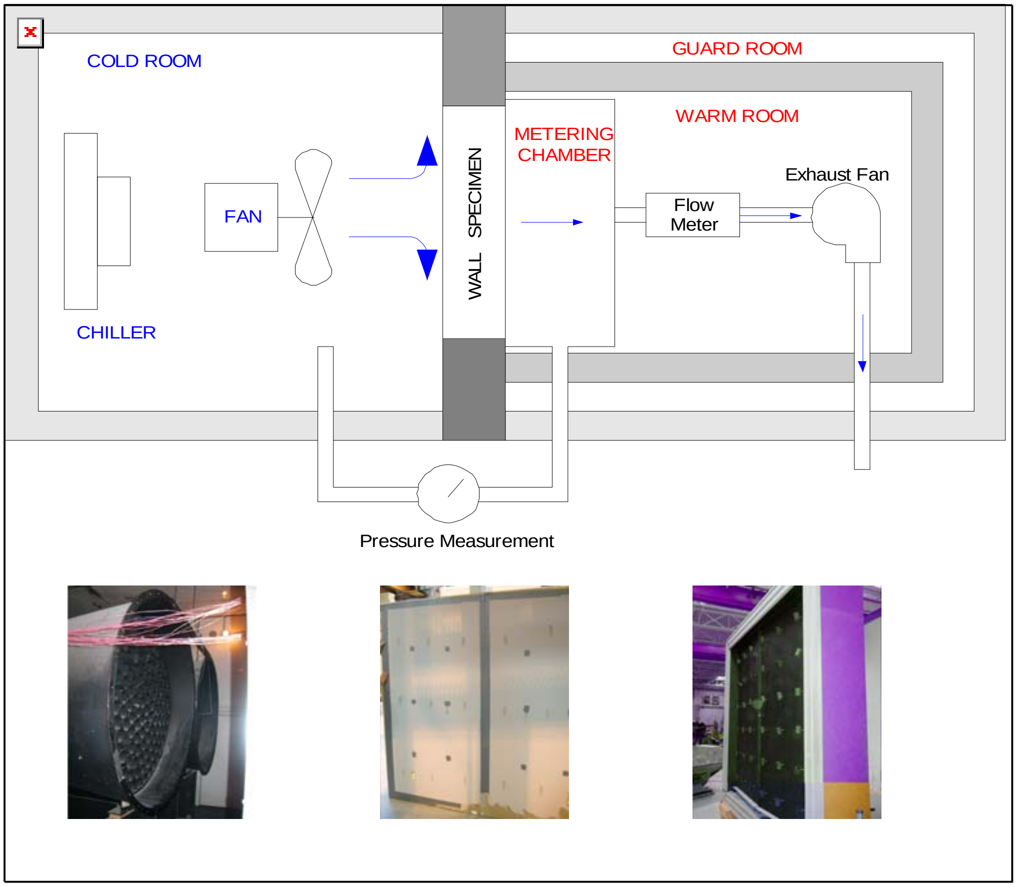

Figure 3. *Schematic diagram of ATI guarded hot-box apparatus*

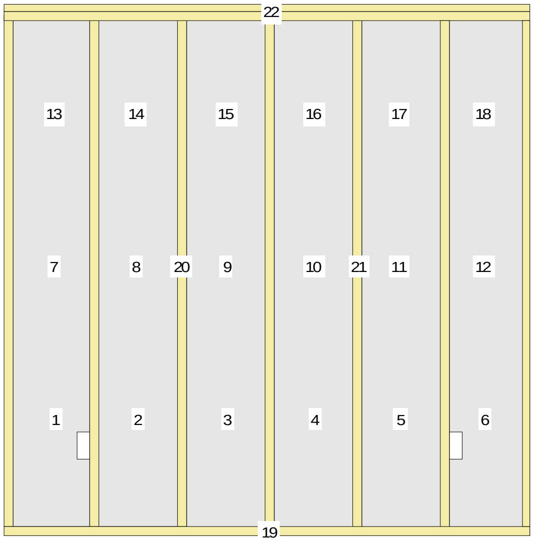

Figure 4. *Thermocouple map for wall test specimens*

RESULTS

Test results, shown in Table 1, include wall thermal conductance and wall thermal resistance. Note that two values of thermal conductance and resistance are reported. The first set, R and U, includes the convection effects at the surfaces by using the controlled chamber temperatures as the T_{hot} and T_{cold} temperatures in the heat flow calculation. The second set, labeled U_w and R_w, excludes surface convection effects by using the aggregate thermocouple surface temperatures in the calculation. Air infiltration results include measured pressure differential (pressure in cold room minus pressure in warm room) and the measured air flow through the metering chamber.

The labeled cavity insulation R-value in Table 1 reflects the manufacturer-reported R-values, based on the installed thickness. For the kraft-faced fiberglass batts, this is simply the nominal R-value printed on the facing. For the cavities insulated with spray foam, this is the manufacturer-reported R-value per inch, multiplied by the installed thickness.

The open-cell foam, reporting R 3.6 per inch, was not installed to a uniform full-cavity thickness of 3.5 inches. Normally, open-cell foam is installed so that all of it expands beyond the inside stud face. The excess foam is then trimmed flush with the stud faces to allow installation of the gypsum board. In this study, the open-cell spray foam was filled so that it expanded just to the front of the stud face. About 40% of the foam in the cavity expanded beyond the stud face and was trimmed. The remaining 60% of the cavity was filled to an average thickness of about 3.25”. The installed R-value of the open-cell insulation was estimated as follows from Equation 5:

$$R_{ocSPF} = \left(0.40 \times 3.5in + 0.60 \times 3.25in\right) \times \frac{R3.6}{inch} = R12.06 \tag{5}$$

For the closed-cell foam, the initial R-value of R7.0 per inch is multiplied by 1.5” to obtain R10.5. Initial R-values for the closed-cell foam were used, since these walls were not aged before testing. In actual walls the aged R-value should be used for design purposes. The manufacturer of the closed-cell spray foam used in this study reports an aged R-value of R6.4 per inch.

Table 1: *Guarded Hot Box Test Results*

Wall	R-ins	Warm room temp (F)	Cold room temp (F)	Wind Speed (mph)	Cold room air press (psi)	Metering chamber air flow (CFM)	U	R	Uw	Rw
A: FG+OSB	13	70	25	0	0.013	0.00	0.073	13.743	0.081	12.28
		70	-15	15	0.126	1.85	0.102	9.829	0.110	9.08
		70	25	15	0.115	1.71	0.097	10.316	0.105	9.53
		115	70	15	0.099	2.10	0.113	8.85	0.121	8.25
B: ocSPF+OSB	12.1	70	25	0	0.000	0.00	0.081	12.358	0.094	10.60
		70	-15	15	0.127	0.34	0.093	10.809	0.100	10.00
		70	25	15	0.115	0.34	0.09	11.076	0.098	10.19
		115	70	15	0.097	0.28	0.101	9.908	0.111	9.02
C: ccSPF+ OSB	10.5	70	25	0	0.000	0.00	0.078	12.823	0.090	11.17
		70	-15	15	0.109	0.27	0.087	11.431	0.095	10.55
		70	25	15	0.101	0.21	0.084	11.866	0.092	10.91
		115	70	15	0.082	0.18	0.092	10.891	0.100	9.98
D: ccSPF+ PIR	10.5	70	25	0	0.026	0.00	0.064	15.695	0.071	14.09
		70	-15	15	0.125	0.53	0.081	12.384	0.087	11.54
		70	25	15	0.114	0.36	0.073	13.643	0.079	12.70
		115	70	15	0.096	0.62	0.087	11.521	0.094	10.64

ANALYSIS AND DISCUSSION

Effective R-value of Cavity Insulation

To best quantify the effects of mean temperature and wind loading on the different wall systems, one considers the wall R-value (R_w of Table 1). This measured wall R-value is related to test conditions by Equation 1. For walls of identical area, A_w, and temperature differential, the wall R-value, R_w, is inversely proportional to the heat transmitted through the wall. Likewise, R_w is inversely proportional to the conductance, $U_{w.}$

Using an isothermal planes calculation procedure outlined in the ASHRAE Handbook [13], the expected wall R-value can be determined using the measured thermal resistance of each component, as defined by Equation 6. Using the thermal conductivities or R-values of each component measured by ASTM C518, the baseline wall R-value, R^*_w, is calculated and shown in column 12 of Table 2.

$$R_w^* = R_{gypsum} + R_{studs+ins} + R_{sheathing} = R_{gypsum} + \frac{1}{\dfrac{A_{stud}}{AR_{stud}} + \dfrac{A_{ins}}{AR_{ins}}} + R_{sheathing} \qquad (6)$$

where:

$R_{gypsum} = 0.52$*

$R_{sheathing} = R_{OSB} = 0.60$* or $R_{PIR} = 3.20$*

$R_{stud} = 4.47$*

A = overall area of wall sample = 96” x 96” = 9,216 in^2

A_{ins}/A = (6 x 14.5” x 93”) / (96” x 96”) = 87.79%

A_{stud}/A =100% – A_{ins}/A = 12.21%

* As measured and reported in Table 2, Reference 11, at a mean temperature of 75ºF and no forced convection.

Normalizing the measured wall R-value by the expected wall R-value value defines the Wall Performance Index, WPI, given by Equation 7. The WPI defines how the wall performs at different test conditions compared to how it is expected to perform at baseline conditions (mean test temperature of 75ºF, no wind) based on the materials used to construct the wall. A WPI greater than 100 indicates the wall resists heat flow better than expected at baseline conditions. Likewise, a WPI less than 100 indicates the wall transmits more heat than a standard wall under the test conditions. The WPI for each wall is shown in the last column of Table 2.

$$WPI(\overline{T}, \Delta p) = \frac{R_w(\overline{T}, \Delta p)}{R_w^*(\overline{T}^*, \Delta p^*)} \qquad (7)$$

where:

$\overline{T}$ = mean applied test temperature, $(T_{hot}-T_{cold})/2$, from ASTM C 1363 test

Δp = applied air pressure difference from ASTM C 1363 test

$\overline{T}^*$ = standard mean temperature from ASTM C 518 test = 75ºF

Δp^* = standard pressure difference from ASTM C 518 test = 0 Pa

$R_w(\overline{T}, \Delta p)$ is measured from ASTM C 1363 test

$R_w^*(\overline{T}^*, \Delta p^*)$ is calculated using Equation 6

Table 2: *Guarded Hot Box Test Results including WPI*

Wall	R-ins	Warm room temp (F)	Cold room temp (F)	Wind Speed (mph)	Cold room air press (psi)	Metering chamber air flow (CFM)	U	R	Uw	Rw	R*w	WPI
A: FG+OSB	13	70	25	0	0.013	0.00	0.073	13.743	0.081	12.28	11.66	**105.3**
		70	-15	15	0.126	1.85	0.102	9.829	0.110	9.08		**77.8**
		70	25	15	0.115	1.71	0.097	10.316	0.105	9.53		**81.7**
		115	70	15	0.099	2.10	0.113	8.85	0.121	8.25		**70.8**
B: ocSPF+OSB	12.1	70	25	0	0.000	0.00	0.081	12.358	0.094	10.60	11.11	**95.4**
		70	-15	15	0.127	0.34	0.093	10.809	0.100	10.00		**90.0**
		70	25	15	0.115	0.34	0.09	11.076	0.098	10.19		**91.8**
		115	70	15	0.097	0.28	0.101	9.908	0.111	9.02		**81.2**
C: ccSPF+ OSB	10.5	70	25	0	0.000	0.00	0.078	12.823	0.090	11.17	10.14	**110.2**
		70	-15	15	0.109	0.27	0.087	11.431	0.095	10.55		**104.1**
		70	25	15	0.101	0.21	0.084	11.866	0.092	10.91		**107.6**
		115	70	15	0.082	0.18	0.092	10.891	0.100	9.98		**98.5**
D: ccSPF+ PIR	10.5	70	25	0	0.026	0.00	0.064	15.695	0.071	14.09	12.74	**110.6**
		70	-15	15	0.125	0.53	0.081	12.384	0.087	11.54		**90.6**
		70	25	15	0.114	0.36	0.073	13.643	0.079	12.70		**99.7**
		115	70	15	0.096	0.62	0.087	11.521	0.094	10.64		**83.5**

Thermal Performance – No Wind Load

When no wind loading is applied, all walls except Wall B have WPIs greater than 100. This indicates that, with the exception of the open-cell foam insulation, the walls are performing at or above their rated R-value. Labeled R-values are provided for the kraft-faced batt insulation by the manufacturer (R-13). For spray foam cavity insulation, the extrapolated R-values are based on installed thickness and are calculated based on the product of the manufacturer's reported R-value/inch and the average installed thickness. The open-cell spray foam manufacturer reports 3.6 R per inch, while the closed-cell spray foam product reports an aged R-value of 6.4 R per inch and an initial R-value of approximately 7.0 per inch. The initial or un-aged R-value for the closed-cell spray foam was conservatively used to calculate the wall R-value for Walls C and D.

Walls C and D, both using closed-cell spray foam in the cavity had WPIs of greater than 110 when no wind loading is present. One possible reason for this performance difference in the closed-cell spray foam walls is the effect of the air-gap is included. Note that when 1.5" of closed-cell spray foam is used, a 2.0" air gap will exist between the closed-cell spray foam and the gypsum board. This air gap, although susceptible to convection looping at high temperature differences, can provide some additional R-value, especially at small temperature differences through the wall.

Wall B, made from open-cell spray foam, has WPI of only 95.4. This 4.6% reduction in performance could be due to a specimen thickness effect. It is well known that radiation scattering and dissipation effects in low-density insulations like fiberglass and cellulose can cause a slightly non-linear relationship between k-value and thickness, where the thermal conductivity measured at larger thickness is slightly higher than the conductivity measured on thinner specimens [14,15].

It is possible that a similar non-linear thickness effect is present in open-cell spray foam. One open-cell spray foam manufacturer publishes data that shows a non-linear thickness dependency, where R-value at 1.0 inch is R-3.83 (R-3.83 per inch), R-value at 2.0 inches is (R-3.38 per inch) and R-value at 4.0 inches is 13.0 (R-3.25 per inch) [16]. This open-cell spray foam product indicates about a 17% reduction in R-value measured at an installed thickness of 4.0" versus the R-value extrapolated from the R-value measured on a 1" thick sample. If this 17% reduction is applied to the R-labeled value of R12.6 for the open-cell foam, the calculated R^*_w value for Wall B decreases from R11.11 to R9.81. This reduced baseline will then increase the respective WPI by 11-12 points, closer to the WPI measured for the closed-cell spray foam wall.

These results for the open-cell wall indicate that extrapolating R-value for real wall thicknesses by multiplying the R-value measured from a 1" sample by its installed thickness will under-predict the R-value of this insulation. Recent changes to Section 6.0 of the ICC-Evaluation Service's AC 12, Acceptance Criteria for Foam Plastic Insulation [17] now require manufacturers to perform R-value testing using at least two different thicknesses (1" and the maximum installed thickness) to check for this non-linear effect.

Thermal Performance – With Wind Load

When a 15 mph wind loading is applied to the exterior surface, different rates of air leakage will occur in the different wall specimens. As would be expected, Wall A, containing fiberglass batts, has by far the greatest measured air leakage rates – with an average of 1.88 CFM. Wall C, made using closed-cell spray foam, has the lowest average air leakage rate of 0.22 CFM. Wall B, made with open-cell spray foam, has an average measured air leakage of 0.32 CFM that is nearly 50% more air permeable than the closed-cell spray foam Wall C. The surprising result is found in Wall D, which measures average leakage at 0.50 CFM - nearly double the leakage rate of the other two spray foamed walls. Perhaps there may be a tighter air seal created when SPF is applied to OSB than when applied on the foil-faced PIR insulated sheathing board, but this will need further study.

At an exterior temperature of 25°F, all four wall specimens were tested with and without wind loading. As wind loading is applied, the WPI of all walls decreased. This decrease in WPI is likely caused by two distinct mechanisms; air leakage around and through the cavity insulation and air movement across the exterior face of the cavity insulation (wind washing). A summary of these results is shown in Figure 5.

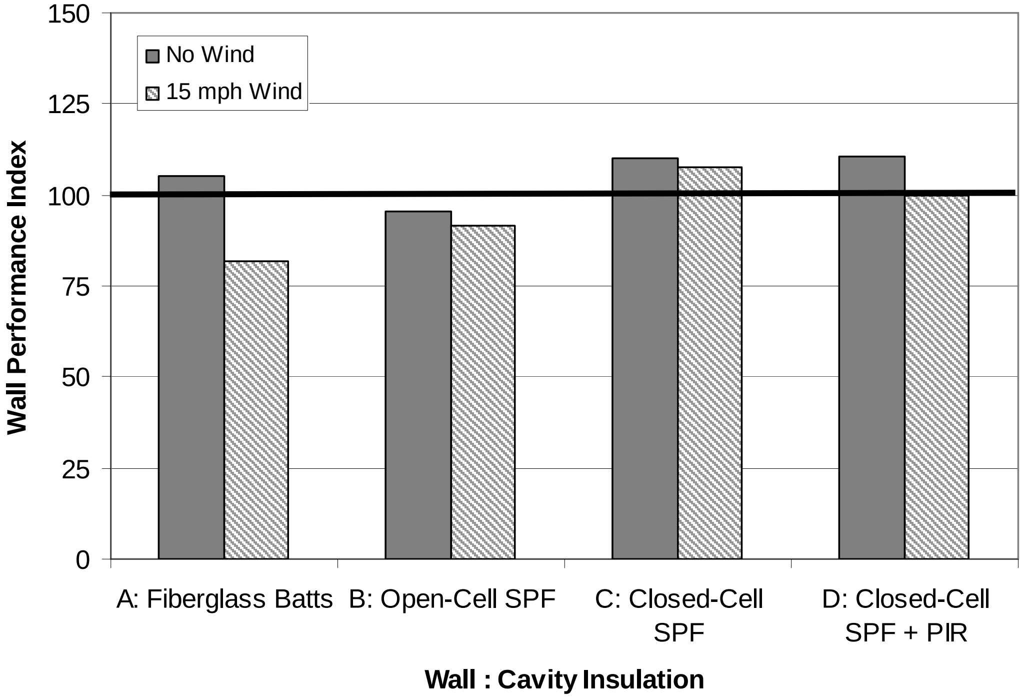

Figure 5. *Effect of air infiltration on WPI measured at 25ºF exterior temperature*

Since fiberglass batts are inherently air permeable, Wall A, as expected, has the largest decrease in WPI: dropping from 105.3 without wind to 81.7 with a 15 mph wind – a 28% decrease. The next most air-permeable wall is Wall D. Here the WPI of the wall decreases from 110.6 to 99.7 when a 15 mph wind load is applied - a 10% decrease. This result, while somewhat surprising for spray foam insulation, can be explained by the unexpectedly high rate of air infiltration measured for this wall – at 0.36 cfm, the air leakage at 25ºF is higher than that of the other two spray foam walls. It is possible that there could be a de-lamination or de-bonding of the spray foam from the foil facing of the insulated sheathing and/or wood framing which could result in a path for air leakage. Alternately, the installation of the spray foam may not have completely sealed each and every cavity. For Wall D, the effect of air leakage becomes more significant at the extreme hot and cold exterior temperatures, suggesting there may be a temperature-dependent mechanical interaction (differential thermal expansion effect) between the spray foam and the insulated sheathing.

Walls B and C both use spray foam applied to OSB sheathing and have significantly less air leakage, resulting in a smaller decrease WPI. The WPI for Wall C, using open-cell foam, decreases from 95.4 to just 91.8 – a decrease of 3.8%. Similarly, the reduction in WPI for the closed-cell spray foam wall, Wall D, is from 110.2 to just 107.6 – a decrease of only 2.4%.

Thermal Performance – Mean Temperature Effects

With a 15 mph wind loading applied, all four walls were tested using three different exterior temperatures: -15ºF, +25ºF and +115ºF, with the interior temperature maintained at +70ºF. This results in a mean test temperature, $\overline{T}$, of approximately 27.5 ºF, 47.5 ºF and 92.5 ºF, respectively.

It should be noted that for the case of the +115ºF exterior temperature, the wall section was reversed in the guarded hot box apparatus so that the sheathing was facing the metering chamber and the gypsum board was facing the cold room. As explained earlier, this was necessary to prevent condensation on the thermocouples. This appears to affect air infiltration results to a slight degree, because the gypsum board will be pressurized for the +115ºF temperature tests, while the sheathing is pressurized for the -15ºF and +25ºF tests – resulting in a reversed air flow for the +115ºF tests. In addition to reversed air flow, the temperatures on the exterior also reversed. This could affect the R-values of the insulated sheathing. But more importantly, the thermal expansion of the sheathing will be reversed which could adversely affect air flow. These factors must be considered when making any conclusions about the data measured during the +115ºF exterior temperature tests.

Figure 6 shows the air leakage rate over the range of temperatures. The diagram shows that air leakage for Walls B and C are relatively independent of temperature. However, Wall A and Wall D appear to have leakage rates that are higher at the two extreme exterior temperatures. This would suggest that these two walls may have small cracks or crevices that change size due to differential thermal expansion of the materials at the extreme temperatures.

Figure 7 shows how air leakage rate can determine the effective R-value of the cavity insulation. For Walls A and D, there appears to be a distinct and expected inverse dependence on effective R-value and leakage rate. As air leakage increases, effective R-value for these walls decreases. Conversely, Walls B and C do not show a distinct relationship between leakage rate and effective R-value.

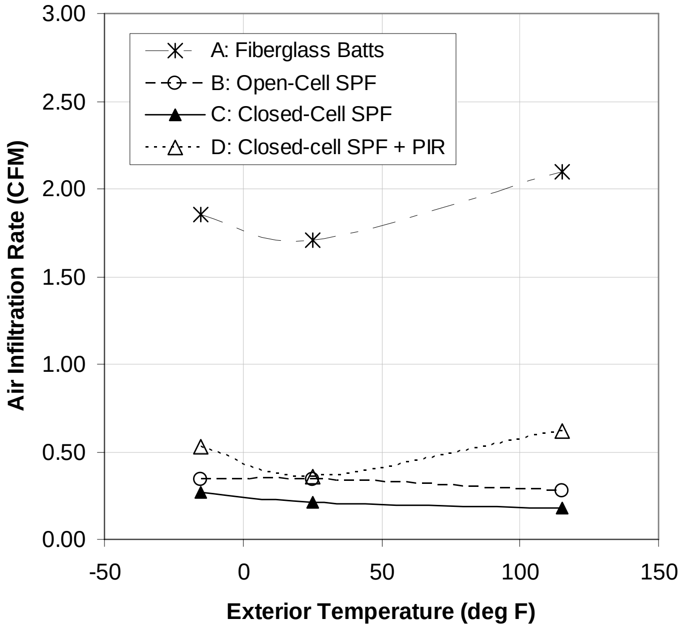

Figure 6. *Effect of exterior temperature on air infiltration rate*

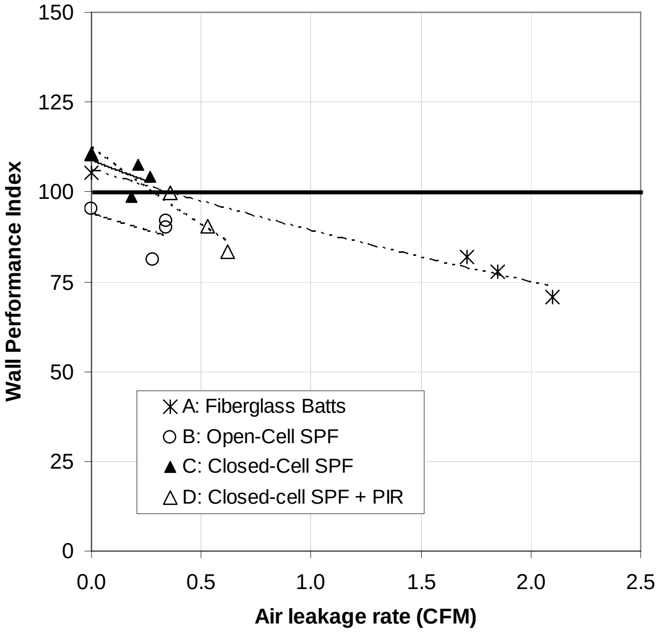

Figure 7. *Effect of air infiltration rate on WPI*

Finally, Figure 8 shows the effect of exterior test temperature on WPI. As expected from the results of Figure 5 and 6, the maximum measured WPI occurs at 25ºF. At the two extreme temperatures, the effective R-values for the cavity insulations in all four walls decrease, with the most significant decrease occurring in Wall D at elevated exterior temperatures.

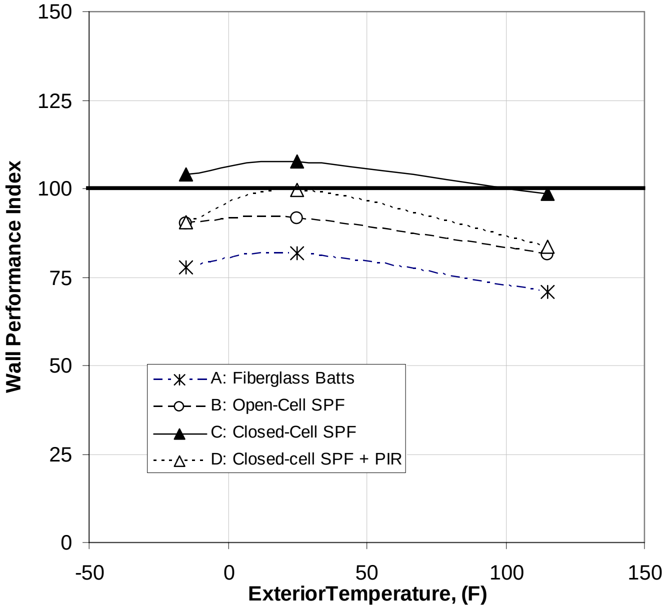

FIGURE 8. *Effect of Mean Temperature on WPI*

It should be noted that other studies have measured the R-value of insulating materials using a heat flow meter over a wide range of temperatures. One study shows that closed-cell foams with HFC blowing agents have significantly higher R-values (lower thermal conductivities) at low temperatures [18]. Testing performed on fiberglass insulation at different temperatures shows that the measured R-value of this material varies with mean temperature [13].

This effect of temperature-dependent R-values was not readily observed in this study, which measures how the cavity insulation performs in a full wall. For example, the effective R-value of the closed-cell foam material increases slightly at colder temperatures. In this study, the effective R-value of closed-cell foam appears to decrease slightly at low temperatures. Based on these observations, it appears that temperature effects on the thermal conductivity of the insulation materials are insignificant relative to the effects of air leakage in all walls tested in this study.

CONCLUSIONS

No Air Leakage

Without air leakage, walls insulated with fiberglass perform about 5% better than predicted wall performance using labeled R-value. Open cell spray foam achieves about 8% below the predicted thermal performance in a 2x4 wall cavity. Walls insulated with closed-cell spray foam have a 10% higher than expected thermal performance.

The performance of spray foam insulations in these wall assemblies suggests that there may be non-linear relationship between R-value and thickness for these materials. Most spray foams publish R-values measured on a 1" thick specimen, and this value is often multiplied by installed thickness to determine installed R-value. A non-linear dependence on R-value could make this extrapolation invalid. A study measuring R-values at different spray foam thicknesses is recommended.

Air Leakage Effects

Under identical test temperatures, air infiltration is most severe in fiberglass walls, where thermal performance decreases significantly with increasing air leakage. This is an expected result for air permeable fibrous insulations like fiberglass. The closed-cell and open-cell spray foams appear less dependent on air-infiltration, with decreases of only 2% and 3% respectively. These small decreases in R-value are most likely the result of low air leakage rate through these foam insulations.

Mean Temperature Effects

When these walls are tested under a range of exterior temperatures, the mean temperature effect on R-value measured by a heat flow meter test was not observed in this study. It appears that extreme hot and cold exterior temperatures may amplify the effects or air leakage in these wall panels. Differential thermal expansion of the construction materials under extreme exterior temperatures could be expanding the size of existing cracks and gaps in the test walls, which in turn, increases air leakage and lowers effective R-values. Based on this relatively unexpected effect, it is not possible to determine if the extreme temperatures alone are reducing the conductive heat transfer through the cavity insulation, or simply allowing heat to be transferred through the wall assembly by air infiltration. The results of this study are further confounded by the practical need to reverse the direction of air infiltration for the hot exterior temperature condition. In any case, it can be concluded from the test results that the effective R-value of the cavity insulation is lower under extreme hot and cold exterior temperatures.

NEXT STEPS

A separate comprehensive study is needed to confirm if and how R-value of cavity insulations are dependent upon thickness. Additional testing is needed to be able to pressurize wall sections in both directions. Due to the nature of most real wall structures, identical pressurization of the interior surface of the wall may not yield the same air leakage rates as the same wall pressurized from the exterior side. In addition, the test capability should be enhanced to support heating and cooling in the cold room side of the guarded hot box apparatus.

Based upon the WPI versus exterior temperature plots of Figure 8 it appears each wall tested exhibits a certain characteristic curve that could change shape and position based on effects such as wind load, moisture content and wall orientation. More work is needed to determine how these characteristic curves can be used in energy efficient design of buildings. One way may be to integrate this curve over specified ranges of temperatures. For example, for walls in predominantly cold climates, the area under the curve between extreme cold temperatures and nominal indoor temperatures could be evaluated to determine a cold climate thermal parameter for the wall. Similarly, in hot climates, the area under the curve could be integrated from room temperature to an extreme hot temperature to determine the hot climate thermal parameter for the wall. These wall parameters could then be used in the thermal load calculations for the building.

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