PROCEEDINGS

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THE EFFECTS OF TEMPERATURE ON INSULATION PERFORMANCE: CONSIDERATIONS FOR OPTIMIZING WALL AND ROOF DESIGNS

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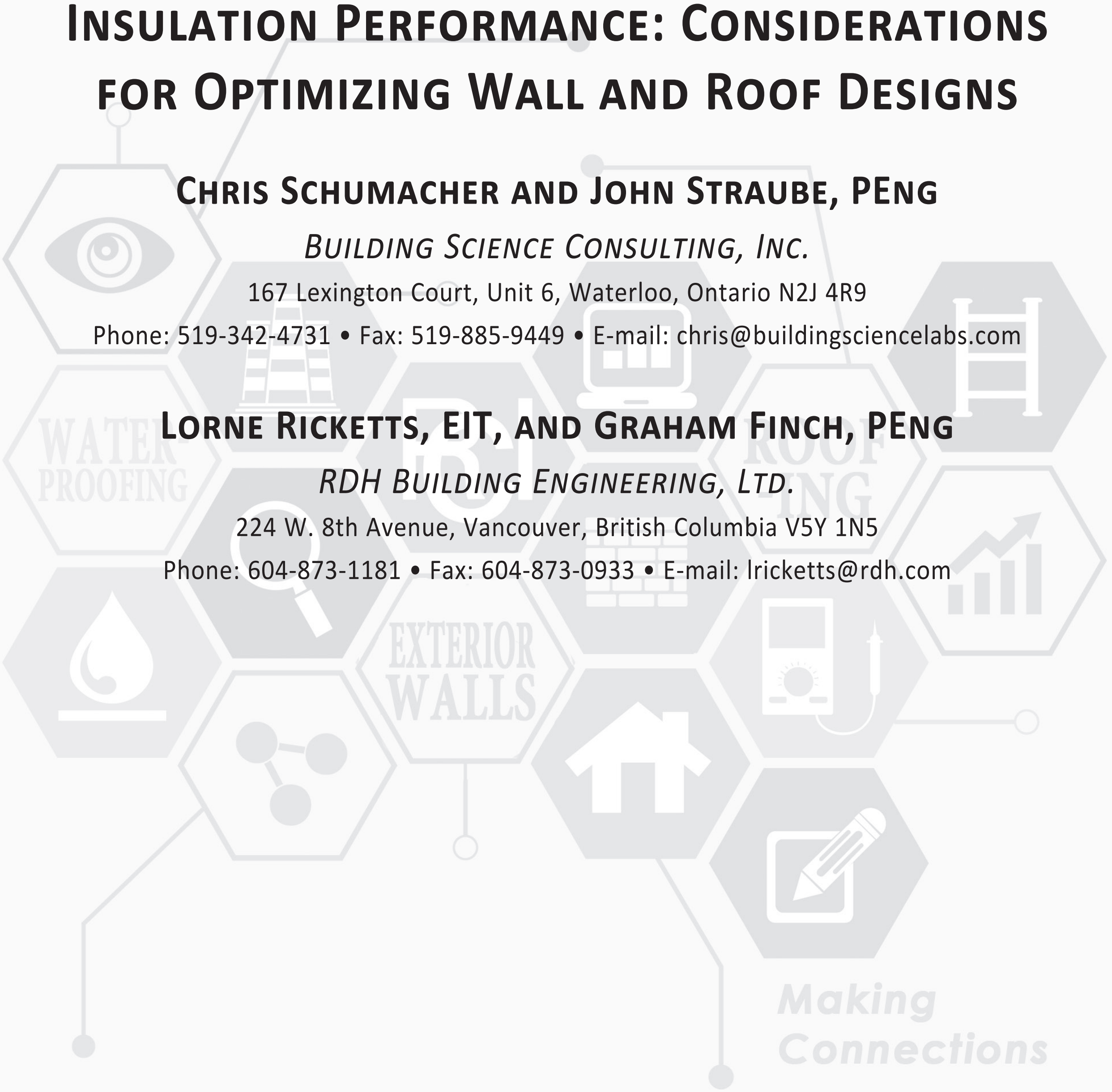

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ABSTRACT

Recent research into the real-world performance of insulation materials in roofs and walls has shown that the industry's reliance on R-value at a standard temperature does not always tell the whole story. This paper will present measurements from several field-monitoring studies across North America that demonstrate how insulated roofs and walls exhibit thermal performance that is different than assumed by designers. Specifically, results show that insulation properties vary with temperature (i.e., performance changes at high or low temperatures). This is important because of peak energy demand, annual heating and cooling costs, occupant comfort, and durability considerations.

SPEAKERS

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CHRISTOPHER SCHUMACHER is a principal with Building Science Consulting, Inc. (BSCI), a consulting firm specializing in design facilitation, building enclosure commissioning, forensic investigation, and training and communications. Its research division, Building Science Laboratories (BSL), provides a range of research and development services. Schumacher's presentations on temperature-dependent R-values include the Westford Building Science Symposium in 2011 and the Rockwool Research Symposium in 2014. He has also written on this topic for buildingscience.com.

LORNE RICKETTS, EIT — RDH BUILDING ENGINEERING, LTD.

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THE EFFECTS OF TEMPERATURE ON INSULATION PERFORMANCE: CONSIDERATIONS FOR OPTIMIZING WALL AND ROOF DESIGNS

ABSTRACT

Recent field and laboratory research into the real-world performance of insulation materials in roofs and walls has shown that the industry's reliance on R-value at a standard temperature does not always provide the whole picture. Insulation properties vary significantly with cold to hot temperatures, meaning that heat loss or gain into a building is not always as predicted using standard calculation techniques. This is a consideration for all insulation types, in particular those used in roofing or continuous exterior insulation applications where they are exposed to more extreme cold or hot temperatures.

This paper will present measurements from field-monitoring studies, which identify and demonstrate how insulated roofs and walls exhibit thermal performance that is different than assumed by designers. This is important because of peak energy demand and annual heating and cooling costs, as well as comfort and durability considerations.

Laboratory testing results are also presented to demonstrate and explain these phenomena. New testing methods have been developed to quantify this temperature dependency. Temperature-dependent R-value curves will be presented for all common building insulation materials.

Finally, computer simulations were prepared using the updated insulation properties. These were calibrated with the field data and extended to demonstrate the impact that these insulation properties have on the actual energy use, temperature profiles, moisture risk, and thermal comfort implications in buildings. The computer simulations allow us to explore possible solutions for the building industry, including optimizing the design of roof and wall assemblies in different climate zones.

INTRODUCTION

In North America, the thermal performance of building materials is most commonly reported in terms of R-value, and most insulation materials have label R-values stamped on them (or at least displayed in large print on the packaging). R-value is a measure of the thermal resistance of a material—it tells how effectively a layer of material limits heat flow (for a given thickness).

Many credit Everett Shuman with proposing R-value as an easy-to-compare, repeatable measure of insulation performance. Shuman was the director of Penn State's Institute for Building Research through the 1960s. He may not have been the first to introduce the concept of thermal resistance, but he actively promoted the concept on the basis of its simplicity (Moe, 2014). Prior to the adoption of R-value, thermal performance was expressed in terms of conductance or the ability of materials to conduct heat. Materials provide better performance when they have lower thermal conductance, but industry decision makers felt that consumers would be confused by the concept that "smaller is better." When thermal performance is expressed in terms of R-value or thermal resistance, higher numbers represent better performance.

The R-value went on to become the de facto metric across North America, familiar to both consumers and professionals. It has helped many designers and consumers make more energy-efficient choices, but its importance in influencing purchase decisions has also led to some unscrupulous marketing claims. In the aftermath of the 1970s energy crisis[1] in the United States, fraudulent R-value claims became so widespread the United States Congress passed a consumer-protection law in response, the "R-Value Rule" (16 Code of Federal Regulations [CFR] Part 460, "Trade Regulation Rule Concerning the Labeling and Advertising of Home Insulation").

Measurement of Label R-Values

Under this rule, claims about residential insulation must be based on specific ASTM procedures. The most commonly used are ASTM C177, *Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus*, and ASTM C518, *Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus.* Tests can be quickly completed using commercially available machines and small, easy-to-handle samples—typically between 12 x 12 in. (305 x 305 mm) and 24 x 24 in. (609 x 609 mm). Samples are placed in direct contact with a pair of air-impermeable hot and cold plates in the machine. The rule requires R-value tests to be conducted at a mean temperature of 24°C (75°F) and a temperature differential of 27.8°C (50°F). For reasons of technical ease, this means insulation is usually tested with the cold side at approximately 10°C (50°F), and the warm side at around 38°C (100°F).[2] In other words, the label R-value typically only provides a metric of a material's thermal performance under one standard test condition.

Industry Use of Label R-Values

Label R-values are used by designers, contractors, code officials, etc. to:

1. Verify code compliance
2. Assess energy performance
3. Assess durability/moisture performance[3]

Some codes simply require that insulation materials meet a specific label R-value; however, codes are moving towards requiring assemblies with specific effective R-values that account for thermal bridging through penetrating slabs, roof, and wall framing; primary, secondary, and cladding-related structural elements; and, in some cases, even through fasteners. Label R-values are used in all code-compliance applications, but this does not accurately reflect in-service performance.

Label R-values might provide a good starting point for assessing energy performance and durability/moisture performance; however, as this paper illustrates,

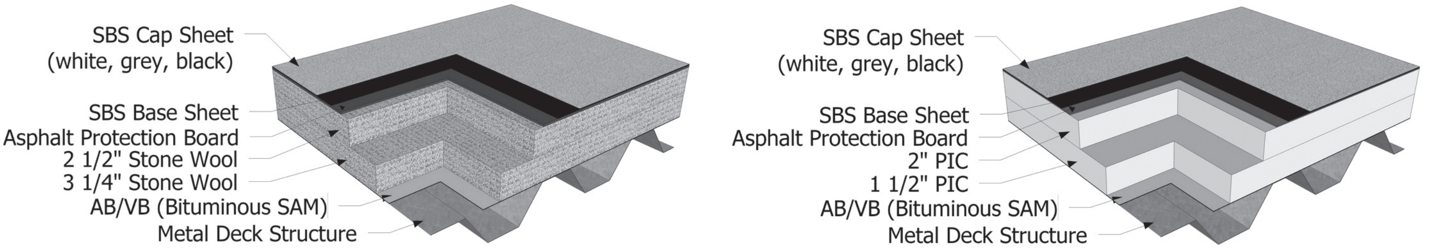


Figure 1 – PIC-only roof assembly (left) and stone wool only roof assembly (right).

Figure 2 – Photo of test roof area showing three different roof membrane colors: black, white, and gray.

they may not result in accurate predictions of performance. Thermal bridging is only one factor that influences in-service performance of building assemblies. Aging, thermal mass, moisture impacts, and temperature dependence are but some of the other factors that explain why label R-values do not adequately reflect in-service performance of building assemblies and materials. Where appropriate, aging or long-term thermal resistance (LTTR) can be accounted for using methods described in ASTM C1303 and CAN/ULC S770-09. Codes and practices are established to prevent insulation materials from accumulating moisture at levels that have a significant impact on thermal performance. Researchers at Oak Ridge National Lab evaluated the benefit of thermal mass across a range of different climates and demonstrated opportunity for energy savings (Kosny et al., 2001). This paper focuses on the role of temperature dependence—that is, the change in an insulating material's apparent thermal resistance (or conductivity) with change in temperature (i.e., the mean temperature, which is defined as the average of the temperatures on hot and cold sides of the layer of insulation material).

The potential issues are demonstrated through comparisons between predicted performance and field-measured performance of roof and wall assemblies.

Predicted Vs. Measured Field Performance of Low-Slope Roofs

A recent study of conventional roof assemblies in the Lower Mainland of British Columbia, a Zone 4 climate, assessed the in-service thermal performance of different assemblies installed on the same building (Rickets et al., 2014). For comparison, two different insulation arrangements—polyisocyanurate (PIC) only, and stone wool (SW) only—and three different roof membrane colors (white, gray, and black) were investigated, for a total of six different roof assemblies as shown in *Figure 1*. The two insulation combinations were designed to have similar label R-values (R-21.0 and R-21.9

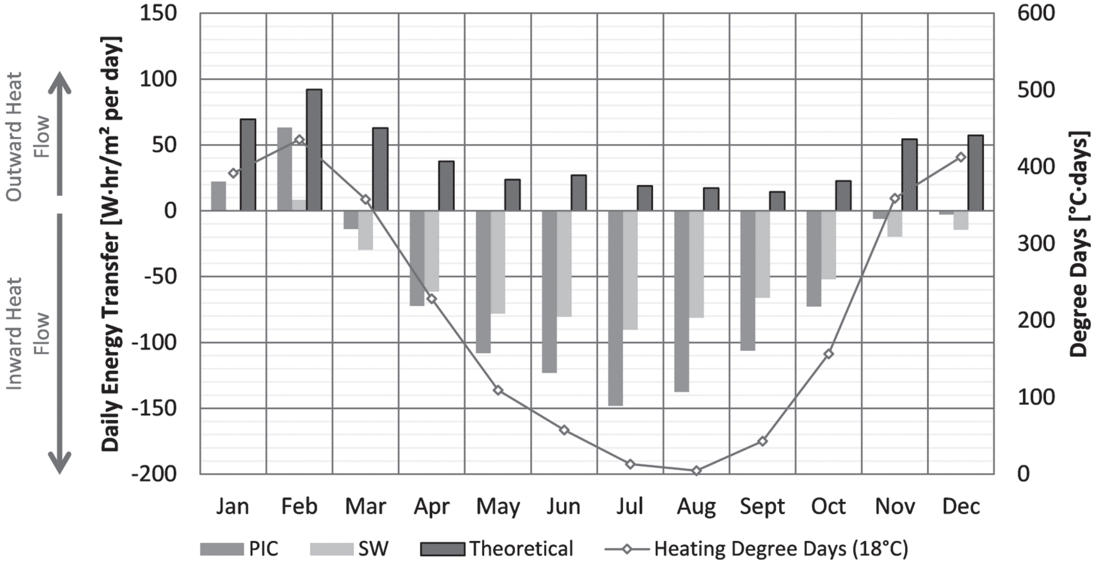


Figure 3 – Chart comparing theoretical calculated heat flux and measured heat flux through the average of the PIC and SW roof assemblies in the study for the year 2014.

for the PIC and SW arrangements respectively) to allow for direct comparison of their in-service performance. An image of the test roof area is provided in *Figure 2* (Finch et al., 2014).

To date, this field study has been running for approximately three years, with hourly monitoring of performance parameters, including heat flux, temperatures, and relative humidity (RH) levels within the assemblies. *Figure 3* and *Figure 4* show the theoretical heat flux through the roof assemblies calculated using ambient air temperature, interior temperature, and the label R-values as compared to the measured heat flux.

Figure 3 and *Figure 4* clearly indicate that theoretically calculated heat flux through the roof assemblies is substantially different from that measured in-service. This difference is a clear example of how label R-values do not account for all aspects of heat flow through an assembly—even at locations where there are no thermal bridges or other discontinuities in the insulation (i.e., clear wall locations). Incorrect accounting of assembly thermal performance in design calculations has real-world implications for building energy consumption, thermal comfort, and moisture risk. Energy modelling has shown that the heating and cooling energy consumption for a commercial retail building can be underpredicted by up to 15% when not accounting for temperature-dependent thermal conductivities and roof color (Finch et al., 2014).

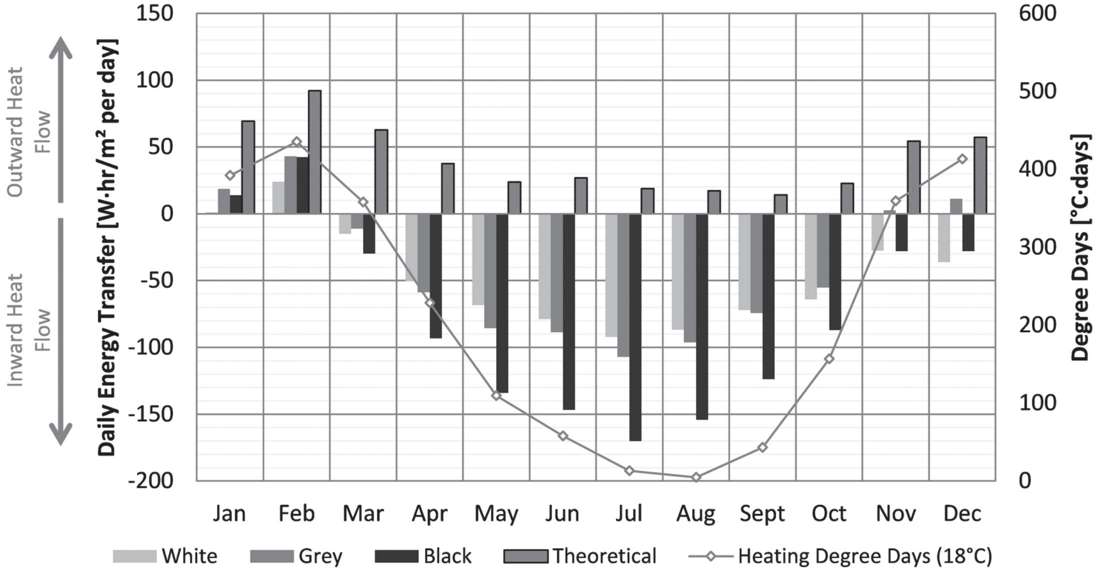
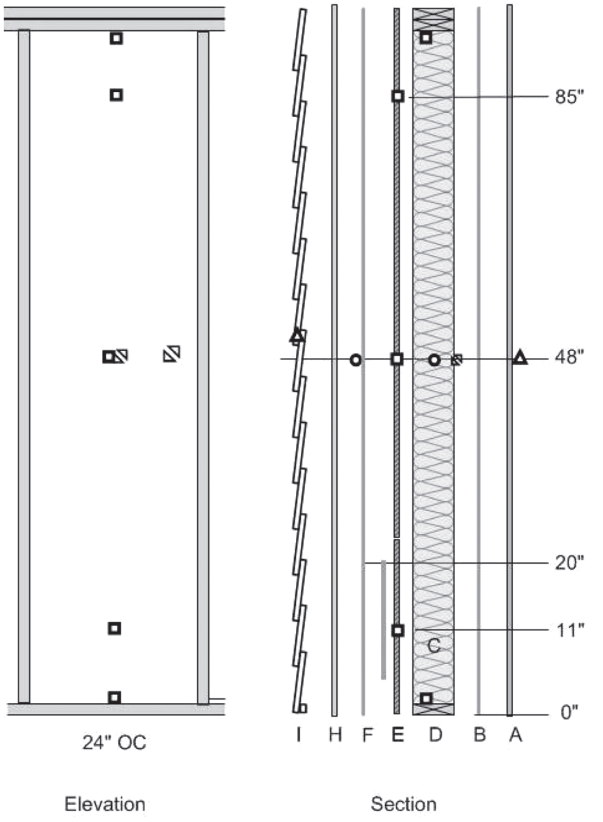


Figure 4 – Chart comparing theoretical calculated heat flux and measured heat flux through the average of the black, gray, and white roof assemblies in the study for the year 2014.

Datum Fibre Cement, Tyvek, OSB, 2x6, R-22 fibreglass batt, 6 mil poly, latex paint (Base Wall)



Assembly

Layer	Function	Description
A	Interior Finish	Painted gypsum board
B	Vapor Control	6 mil poly
C	Studspace	R-22 fiberglass batt
D	Framing	2x6
E	Sheathing	7/16" OSB
F	Membrane	Tyvek
G	Insulation	none
H	Drainage	1x3
I	Cladding	Cement fibre lap siding

Sensor Package

Layer	Code	Location
A	taem	Interior finish, interior face, 48"
C	r/tcnm	Studspace, interstitial, 48"
D	m/tdet	Framing, exterior edge, top plate
D	m/tdel	Framing, exterior edge, bottom plate
E	m/teiu	Sheathing, interstitial, 80"
E	m/teim	Sheathing, interstitial, 48"
E	m/teil	Sheathing, interstitial, 16"
G	r/tinm	Drainage space, interior, 48"
I	tjem	Cladding, interstitial, 48"

Figure 5 – Datum test wall assembly.

Predicted Vs. Measured Field Performance of Exterior-Insulated Wall Assemblies

Another recent study assessed the thermal and moisture performance of exterior-insulated wall assemblies on the north- and south-facing orientations of a test hut in Waterloo, Ontario, a Zone 5/6 climate (Straube, 2015). On each orientation, four base wall assemblies (each 4 x 8 ft.) were constructed using ½-in. gypsum wallboard (GWB) on a 2 x 6 wood frame with fiberglass batt insulation (label R-value of R-22),

Figure 6 – Exterior-insulated (three on left) and datum (one at middle) test wall assemblies before siding.

7⁄16-in. OSB sheathing, a spun-bonded polyolefin water-resistive barrier (WRB), a ¾-in. drained and ventilated air space, and clad with fiber cement clapboard siding. North and south datum walls were designated and completed without any exterior insulation. A 6-mil polyethylene vapor retarder was installed in accordance with Canadian Building Code requirements, on the inside of the stud frame, as shown in *Figure 5*. The remaining six walls (three north and three south) were completed without interior vapor retarders, but with exterior insulation installed between the WRB and the air space. Three types of exterior insulation were investigated (three in stone wool, 2.5 in. extruded polystyrene [XPS], and two in PIC). In each case, the thickness of the exterior insulation was specified to achieve a label R-value of R-12. *Figure 6* shows the exterior-insulated and datum test wall assemblies prior to installation of the fiber cement clapboard siding.

The test wall assemblies were monitored for more than two years. Temperature, wood moisture content, and RH were measured at key points. The monitoring facilitated an assessment of the moisture sensitivity of the different systems under normal operating conditions, as well as their resilience when subjected to simulated rain leaks (via injection of water at the sheathing layer) or imposed air leakage (via a controlled flow rate from the interior).

In cold climates, continuous exterior insulation may be applied over structural sheathing (e.g., OSB) to increase sheathing temperatures, reducing the potential for air leakage condensation and moisture accumulation in the sheathing. *Figure 7* plots the temperature measured at the indoor side of the OSB sheathing (i.e., the condensing plane) of the four north-facing test walls over the first 10 days of 2014. As expected, the sheathing temperatures track the outdoor temperature, and the datum wall (without exterior insulation) exhibits the lowest temperatures. The other three test walls exhibit higher sheathing temperatures, owing to the exterior insulation.

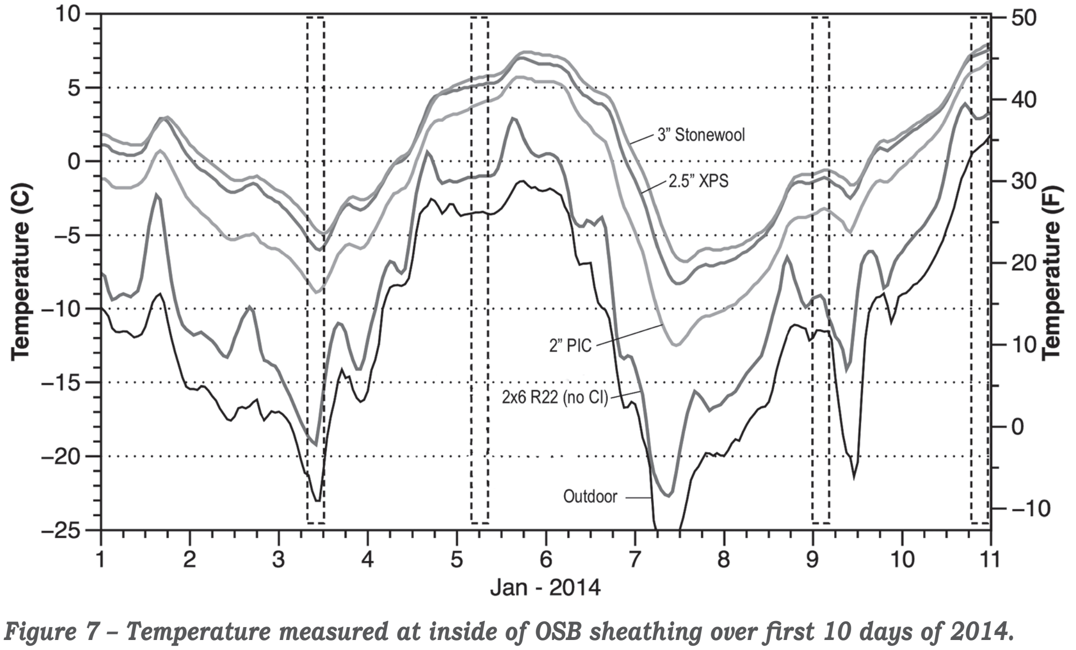


Figure 7 – Temperature measured at inside of OSB sheathing over first 10 days of 2014.

Four snapshots (indicated by the dashed rectangular regions) were identified for further analysis. *Table 1* summarizes the calculated sheathing surface temperatures (based on label R-value) and compares these to the measured temperatures. It is reasonable to expect small differences between the calculated and measured sheathing temperatures for the datum wall because there is little insulation outside of the OSB, so changes in insulation or sheathing R-value have little impact on the predicted surface temperature. However, the other three wall

	Datum				3-In. SW	2.5-In. XPS	2-In. PIC
Snapshot (day)	10	9	5	3	3	3	3
Interior T (°F)	68	68	68	68	68	68	68
Exterior T (°F)	35.6	11.3	25.7	-9.4	-9.4	-9.4	-9.4
Delta T (°F)	32.4	56.7	42.3	77.4	77.4	77.4	77.4
R-value In (ft^2·°F·hr/Btu)	23.2	23.2	23.2	23.2	23.2	23.2	23.2
R-value Out (ft^2·°F·hr/Btu)	2.1	2.1	2.1	2.1	14.1	14.6	15.1
R-value Total (ft^2·°F·hr/Btu)	25.3	25.3	25.3	25.3	37.3	37.8	38.3
Ratio (-)	0.08	0.08	0.08	0.08	0.38	0.39	0.39
Calculated OSB T (°F)	38.3	16.1	29.3	-2.9	19.9	20.6	21.2
Measured OSB T (°F)	37.8	16.0	29.3	-2.6	23.4	21.6	16.7
Difference (°F)	-0.6	-0.1	0.0	0.3	3.4	1.0	-4.5

Table 1 – Comparison between predicted vs. measured sheathing temperature (using label R-values).

assemblies have roughly one-third of the total insulation on the exterior of the OSB sheathing; and for these assemblies, there is more significant difference between the calculated (based on label R-values) and measured temperatures.

Better R-Value Measurement and Documentation

The predicted durability and energy performance of insulations might be improved by moving from a single-label R-value (determined at mean temperature 24°C, or 75°F) to a table of R-values determined over a range of mean temperatures. The National Roofing Contractors Association (NRCA) recommends the use of two R-values for PIC roof insulation: R-5/in. for heating conditions and R-5.6/in. for cooling conditions (Graham 2015). However, even further breakdown (i.e., R-values at more mean temperatures) may be justified. ASTM C1058, *Standard Practice for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation*, suggests six mean temperatures for measuring and documenting the thermal performance of insulation materials intended for building enclosure applications. The suggested mean temperatures and associated hot- and cold-side temperatures are summarized in *Table 2*.[4] In all cases, the temperature difference is 50°F, or approximately 28°C. *Table 3* presents measured R-value/in. for the roof and wall insulation materials employed in the two field studies. Here, PIR refers to polyisocyanurate wall insulation with reflective (foil) facers.

The standard temperature measurements confirm that all of the tested insulation materials exhibit some temperature dependency. Where the R-value exhibits a near-linear temperature dependency, it should be possible to use the data in *Table 3* to predict the material R-value over the full range of temperatures that buildings typically experience. However, in those cases where the temperature dependence does not exhibit a near straight-line relationship, it is necessary to conduct further material testing and analysis.

The authors have developed a measurement and analysis method[5] to produce temperature-dependent R-value curves that can be employed to predict the thermal performance of any insulation material, under any temperature conditions.[6] The method uses regression to determine a convergent R-value curve from numerous measurements made while the temperature difference decreases towards zero.

Figure 8 presents the temperature-dependent R-value curves for the three wall exterior insulation materials and two roof insulation materials used in the field studies.

Mean Temperature		"Hot Side"		"Cold Side"	
(°F)	(°C)	(°F)	(°C)	(°F)	(°C)
25	-4	50	10	0	-18
40	4	65	18	15	-10
50	10	75	24	25	-4
75	24	100	38	50	10
100	38	125	52	75	24
110	43	135	57	85	29

Table 2 – ASTM C1058 suggested mean temperatures for testing building envelope insulations.

Mean Temperature	Roof Insulation		Exterior Insulation for Walls		
(°F)	SW	PIC	SW	XPS	PIR
25	4.2	4.6	4.7	5.5	4.9
40	4.1	5.1	4.5	5.3	5.2
75	3.8	5.3	4.2	4.9	5.4
110	3.7	4.9	3.9	4.6	4.9

Table 3 – Measured R-value/in. at standard mean temperatures.

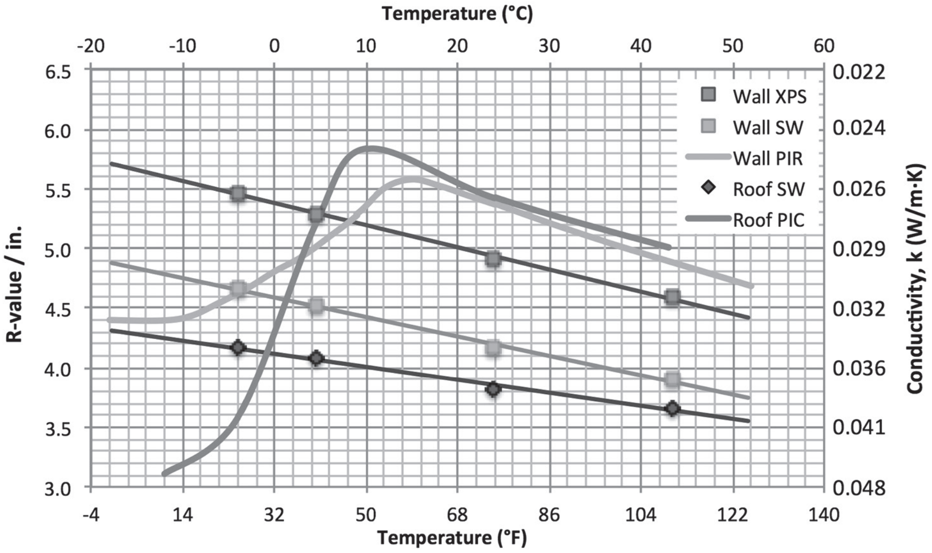


Figure 8 – Temperature-dependent R-value curves for roof and wall insulations studied.

Comparison of "Improved" Predictions Vs. Measurements for Roof

Using the same roof assemblies as previously discussed, it is possible to calculate an improved theoretical estimate of the heat flow through the roof assembly. This improved calculation accounts for actual in-service roof temperatures that are primarily impacted by roof membrane color, but are also influenced by the insulation type and arrangement. The calculation is also improved by accounting for temperature-dependent thermal conductivity for both the PIC and the SW insulations. The nonlinear conductivity of the PIC was measured using the converging delta T method described above. The result of this improved theoretical calculation is compared to the measured results and the original theoretical calculation in *Figure 9* and *Figure 10* for the PIC roofs and the gray roofs, respectively.

Figure 9 and *Figure 10* clearly indicate that when actual in-service roof temperatures and temperature-dependent conductivity effects are accounted for, theoretical calculations more closely match measured results. That said, room for improvement exists, and this may be due, in part, to movement of moisture within the roof assemblies and differences in insulation thermal mass.

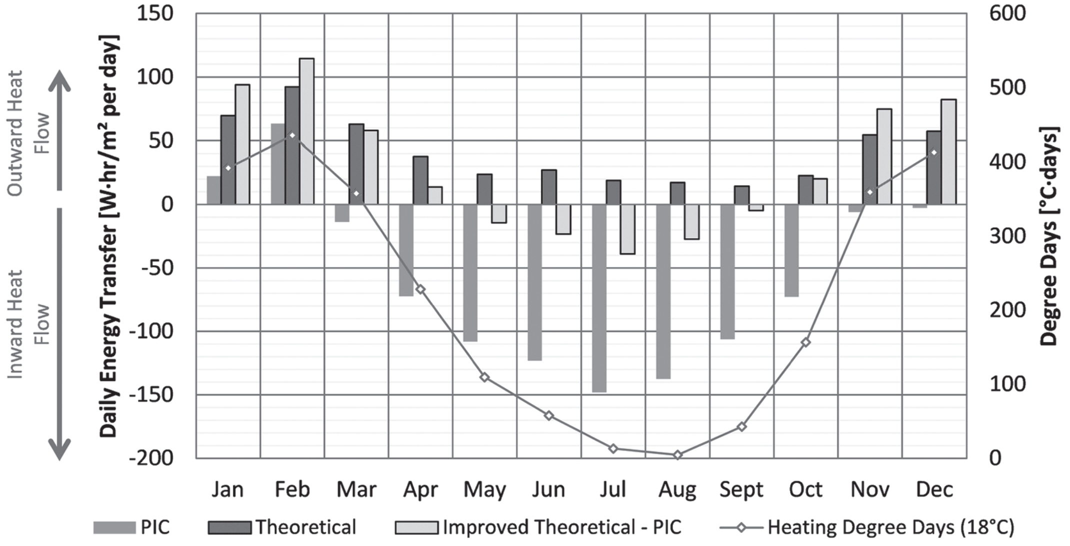


Figure 9 – Chart comparing calculated heat flux using the improved method with that calculated using the original method and the measured heat flux through the average of the PIC roof assemblies in the study for the year 2014.

Comparison of "Improved" Predicted Vs. Measured Performance of Wall Assemblies

The temperature-dependent R-value curves were used to improve the surface temperature predictions made for the OSB sheathings in the wall field study.

Table 4 presents a comparison of the improved predictions and the measured surface temperatures for the Day 3 snapshot. Use of the temperature-dependent R-values results in much better agreement between predicted and measured surface temperatures.

CONCLUSIONS AND RECOMMENDATIONS

In North America, building insulation materials are typically tested and labeled in accordance with the "R-Value Rule" (16 CFR Part 460, "Trade Regulation Rule Concerning the Labeling and Advertising of Home Insulation"). Thermal performance, specifically R-value, is assessed under a single set of conditions: at a mean temperature of 74°F (24°C) and under a temperature difference of approximately 50°F (28°C). Laboratory measurements made at other standard mean temperatures (suggested by ASTM C1058) indicate that, for most insulation materials, R-value is temperature-dependent. Many insulation materials exhibit nearly linear temperature dependency, while others exhibit unique temperature-dependent R-value curves. The latter can be characterized and quantified using special measurement techniques.

Field-monitoring studies on roof and exterior insulated wall assemblies suggest that more complex thermal and durability considerations may not be adequately represented using conventional-label R values. The use of temperature-dependent R-values has been demonstrated to improve predictions of the energy performance and moisture durability of building enclosure assemblies.

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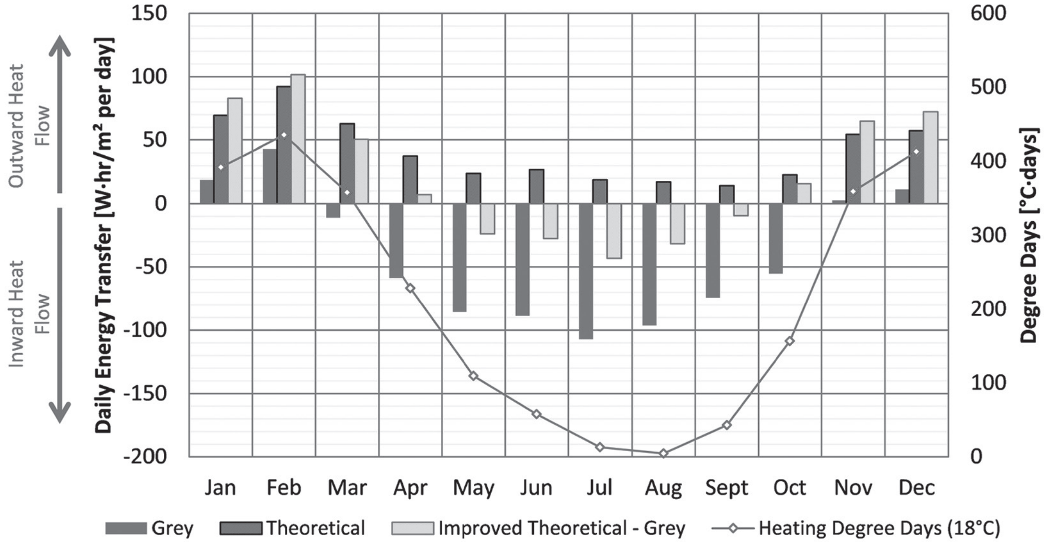

Figure 10 – Chart comparing calculated heat flux using the improved method with that calculated using the original method and the measured heat flux through the average of the gray roof assemblies in the study for the year 2014.

	3 In. SW	2.5 In. XPS	2 In. PIC
Snapshot (day)	3	3	3
Interior T (°F)	68	68	68
Exterior T (°F)	-9.4	-9.4	-9.4
Delta T (°F)	77.4	77.4	77.4
R-value In (ft^2·°F·hr/Btu)	23.2	23.2	23.2
R-value Out (ft^2·°F·hr/Btu)	17.0	15.5	11.3
R-value Total (ft^2·°F·hr/Btu)	40.2	38.7	34.5
Ratio (-)	0.42	0.40	0.33
Calculated OSB T (°F)	23.4	21.7	16.0
Measured OSB T (°F)	23.4	21.6	16.7
Difference (°F)	0.0	-0.1	0.7

Table 4 – Comparison between predicted vs. measured sheathing temperature (using R-value curves).

FOOTNOTES

1. For more information about the 1970s energy crisis, its causes, and effects, the reader is directed to en.wikipedia.org/wiki/1970s_energy_crisis.
2. The actual language of the rule permits test temperature differentials of 27.8°C ± 5.6°C (50°F ± 10°F) for cold-side temperatures of 7.2° to 12.7°C (45° to 55°F) and hot-side temperatures of 35° to 40°C (95° to 105°F).
3. Designers use the label R-values of insulation installed between framing members (i.e., in the stud spaces) and as continuous insulation on the outside of framing (e.g., exterior insulation) to estimate condensing plane temperatures and evaluate the potential for moisture accumulation (due to air leakage and vapor diffusion) and problems in building enclosure assemblies.
4. Some materials exhibit very linear temperature dependence and can be characterized using only two or three set points. Other materials exhibit much more dramatic temperature dependence (as illustrated in this paper) and may require testing at more than the six set points identified in ASTM C1058.
5. This measurement and analysis method is the subject of a draft paper proposed for ASTM C16's Symposium on Advances in Hygrothermal Performance of Building Envelopes: Materials, Systems and Simulations, October 2016.
6. The method specifically addresses the insulation material. It does not address the assembly with all thermal bridges due to framing, fasteners, etc. However, the method does produce data that can be used to evaluate the performance of insulation layers in hybrid-insulated assemblies (e.g., walls with some insulation between the framing members and more installed as continuous exterior insulation).