Thermal Performance Evaluation of Innovative Metal Building Roof Assemblies

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Keywords

American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.; ASHRAE; building envelope; energy efficiency; hot box; IECC; International Energy Conservation Code; MBMA; Metal Building Manufacturers Association; Oak Ridge National Laboratory; ORNL; roofing; thermal performance; U-factor; R-value

Abstract

The Metal Building Manufacturers Association (MBMA) and Oak Ridge National Laboratory (ORNL) began collaborating during the summer of 2009 to develop and document the thermal performance of new and innovative insulated metal building roof assemblies.

The impetus for this work was the ongoing effort to increase the energy efficiency of building envelope assemblies used in nonresidential (conditioned) and semi-heated applications. Because metal buildings are used in approximately 40 percent (by square footage [1]) of all low-rise nonresidential construction, this is an important construction type for any overall effort to achieve better energy performance.

The model energy-conservation codes such as ASHRAE Standard 90.1 and the International Energy Conservation Code (IECC) set minimum requirements for building

insulation based on previously tested assemblies and economic analyses to determine whether sufficient cost savings can be achieved that offset the first cost of added insulation. Because ASHRAE 90.1 and IECC are undergoing significant increases in required efficiency, additional high-performance roof assembly details are needed beyond those that originally were used to set the minimum requirements. Innovations in construction techniques and insulation materials also have taken place in recent years that are not accounted for in the previously tested designs. Therefore, a new set of high-performance roof assemblies is needed to continue making progress toward lower energy use in buildings.

The ongoing work conducted by MBMA and ORNL thus far includes hot box tests of four innovative metal roof assembly modules. The goals for this work were to produce constructible metal roof assemblies that will achieve an overall U-factor between U-0.02 and U-0.04 Btu/h·ft^2·°F and have the potential to be economically viable. The assemblies considered were developed taking into consideration thermal bridging through metal components, isolating the steel roof framing members (z-purlins) and maximizing the effectiveness of various insulation materials. In addition to the thermal performance, consideration also was given to constructibility, durability and structural integrity.

Authors

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Jerry Atchley is an engineering technologist who has been working at ORNL's Building Technology Center in the Building Envelopes Program since 1993. His responsibilities include setting up instruments and assisting principal investigators with performance testing and data acquisition on experimental test sections. Atchley earned his associate degree in electronics in 1991.

Preface

MBMA and ORNL do not promote the use of any particular type or combination of insulations to meet code requirements. The research discussed herein was intended to explore the possibilities and practicality of high-performance metal building roof constructions. This work is ongoing, and further research reports of this nature will be released once that work is completed. MBMA cooperated with ORNL in this research with the hope that it will stimulate future research by others who have an interest in improving the energy performance of building roof construction and, in particular, metal building roofs.

Introduction

ASHRAE 90.1, "Energy Standard for Buildings Except Low-Rise Residential Buildings" [2], provides the minimum standards for the energy efficiency of commercial buildings. The standard is written in mandatory language so it can be adopted by local municipalities. In recent years, the stringency of the energy codes has come into sharp focus with lawmakers and elected officials calling for greater energy efficiency in the codes. Several stakeholders—such as the Department of Energy (DOE), The American Institute of Architects, ASHRAE and other influential groups—have developed plans to move the energy codes toward specific improvement targets. ASHRAE's plan was to develop a 2010 edition of ASHRAE 90.1 that would be 30 percent more energy-efficient than the 2004 edition. To meet this challenge, a number of significant changes to the standard needed to take place for design requirements in lighting, HVAC equipment and various building envelope improvements.

History of 90.1 Building Envelope Designations

In 1999, the format and compliance options for the building envelope provisions of ASHRAE 90.1 moved away from a single minimum U-factor (thermal transmittance) for walls and another for roofs (regardless of construction type). This change was made in an attempt to recognize the variety of constructions commonly found in the U.S. building stock. Three categories of roof constructions were established at that time: “Insulation Entirely Above Deck,” “Metal Building” and “Attic & Other.” Likewise, the following common building wall types were established: “Mass,” “Metal Building,” “Steel Framed” and “Wood Framed & Other.” The “other” designation is included to ensure roof or wall types not specifically defined still must meet one of the minimum performance requirements.

Eight climate zones have been established in ASHRAE 90.1 to recognize the variety of weather (e.g. hot, cold, humid or dry) throughout the U.S. For each defined roof and wall construction, the minimum building envelope U-factor, F-factor and C-factor requirements for each climate zone are determined based on the economic benefit that selecting the specific performance requirement will yield for the end-user.

How Minimum Requirements are Determined

Energy code requirements are not life-safety driven as building codes are. Codes for fire prevention and structural safety issues are developed to mitigate damage to buildings and protect occupants from harm resulting from environmental catastrophes such as fires, earthquakes and windstorms. At their core, life-safety codes use statistical probability and safety factors derived from reliability analysis to set minimum design standards to safeguard people and property. Because building energy use is not a life-safety issue, energy codes instead must focus on mandates of efficiency or economic cost justification to determine reasonable requirements given a certain payback period. At the current time, ASHRAE 90.1 is focused on both, having adopted a plan to reduce the total energy use of new buildings by 30 percent, while attempting to do so cost effectively.

To cost effectively achieve the 30 percent energy savings goal, the savings must be derived from a blend of cost-effective measures, including improved insulation and fenestration performance; reducing air infiltration through walls, windows and doors; improved HVAC efficiency; and requiring more efficient lighting systems and controls.

To select appropriate prescriptive insulation performance requirements for roofs and walls, two basic pieces of information must be known for each evaluated assembly: the total insulating performance (thermal transmittance) and total per-square-foot in-place cost of each proposed assembly. The thermal transmittance accounts for the thermal bridges (short circuits) that occur in assemblies because of framing, voids, gaps and fasteners. In this research, the focus was on improving the thermal transmittance of metal building roof systems.

The method used to determine the thermal transmittance (U-factor) performance of each of the studied assemblies was ASTM C1363, “Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus.” [4] This method was chosen because ASHRAE specifically recognizes it as being an appropriate method of determining the U-factor of a metal building roof assembly. At the current time, ASHRAE does not allow calculation procedures for determining U-factors for metal building assemblies because of their complexity and the potential for thermal bridging of metal components.

A diverse working group of professionals representing manufacturers and suppliers to the metal building industry was formed by MBMA to help design experiments that might uncover potential areas for improving existing common details and to conceive new, more energy-efficient roof details for metal building systems. The group also set a target performance of U-0.040 Btu/(h·ft^2·°F) or better.

Reason for the Research

At the time ASHRAE 90.1-1999 was developed, there were only a handful of metal building roof details with performance data provided by the North American Insulation Manufacturers Association (NAIMA). NAIMA’s data was developed through hot box testing and finite difference modeling. Normative Appendix “A” of ASHRAE 90.1 contains a library of known U-factors for various construction types, including those for metal building roof and wall systems.

The call for a 30 percent decrease in total building energy use for ASHRAE 90.1 prompted MBMA to review the known insulation systems in Appendix “A.” Because the details were developed in 1999 and at that time the insulation requirements in ASHRAE 90.1 were relatively low, Appendix “A” did not contain a variety of high-performance metal building roof system designs. Also, for metal buildings, the appendix was based on the use of mostly fiberglass insulation and does not contain many of the alternative insulation options that have become available since that time. Space limitations exist because of the construction details of typical metal building roof assemblies; therefore, details that used combinations of fiberglass, rigid board or reflective insulations were considered to be possible solutions that had not yet been studied or verified through hot box testing.

Performance Experiments

The Buildings Technology Center (BTC) at ORNL was used to conduct steady-state guarded hot box evaluations in its Large Scale Climate Simulator (LSCS) to determine the overall U-factor of MBMA’s standing-seam (SSR) metal roof systems with purlins 4-foot on center (4 ft oc). The LSCS provides controlled conditions above and below roof test sections to conduct evaluations of the test module in accordance with ASTM C1363 [4]. Figure 1 is a sketch of the LSCS to show the relationship between the chambers and test section. The test module dimensions are 12.5 feet by 12.5 feet with a metering area of 8 feet by 8 feet with an effective metering area of 69.44 ft^2.

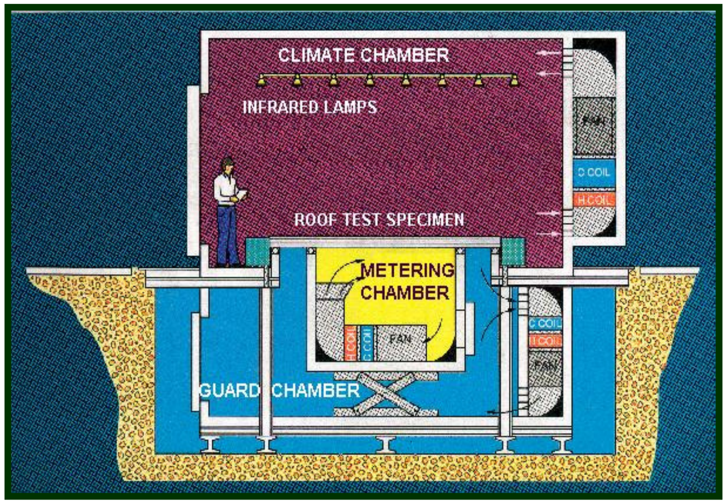


Figure 1. Sketch of the Large Scale Climate Simulator (LSCS)

Experienced industry personnel completed the design and construction of the four tested assemblies. Tests were conducted with two purlins (effectively 4 ft oc) in the metered area of the LSCS. It is worth noting that typical roof purlin spacing for metal buildings is 5 ft oc. The metering area of the LSCS is not compatible with 5 ft oc. It is possible to evaluate the performance of assemblies with compatible smaller and larger spacings and then develop a curve fit to estimate performance with 5 ft oc. For this research, the decision was made to test the assemblies at 4 ft oc to obtain performance results directly from testing instead of a curve fit. Further, by performing the tests at a smaller spacing, the thermal bridging of these assemblies should be greater than those spaced at 5 ft oc and therefore is conservative.

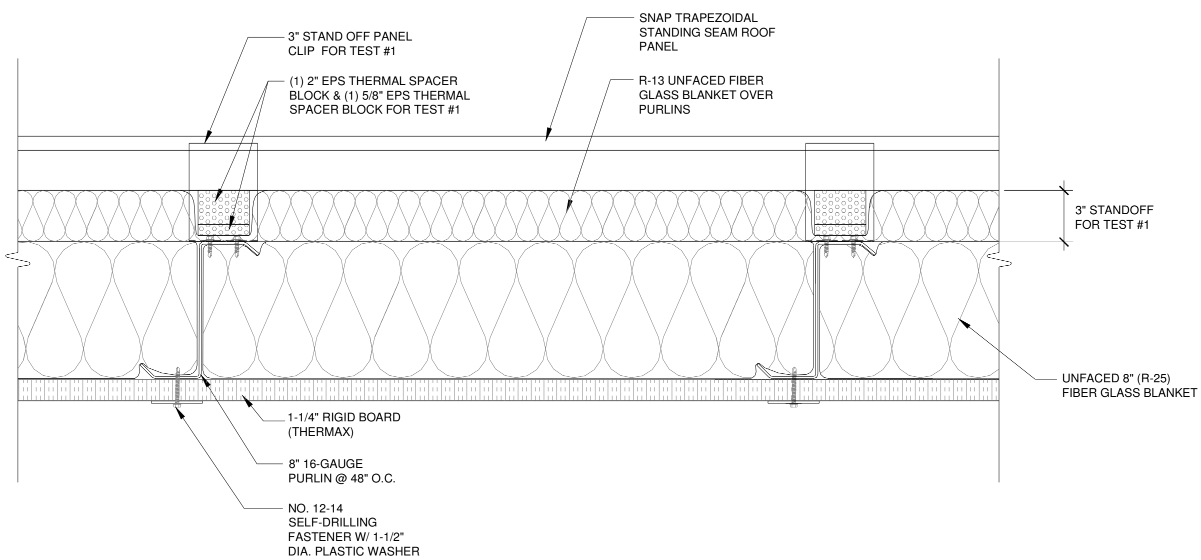
Details of Test Sections, Construction and Instrumentation

Two test assemblies (Modules 1 and 2) used R-25 unfaced fiberglass insulation in the cavity between purlins and R-13 unfaced fiberglass insulation over the purlins with approximately 1.25-inch-thick foil-faced polyisocyanurate board insulation attached to the bottom of the purlins. Figure 2 shows the details of test Modules 1 and 2. Modules 1 and 2 were the same base assembly with only one variation, which was roof clip height. Module 1 used a specially fabricated 3-inch stand-off panel clip with 2-5/8 inch thick thermal spacer blocks between clips to support the metal roof panel in the flats. Module 2 used a standard 1-3/8 inch stand-off panel clip with 5/8 inch thick thermal spacer blocks between clips. Great care was taken to prevent disturbing the fiberglass and rigid board insulation during the change from Module 1 to Module 2.

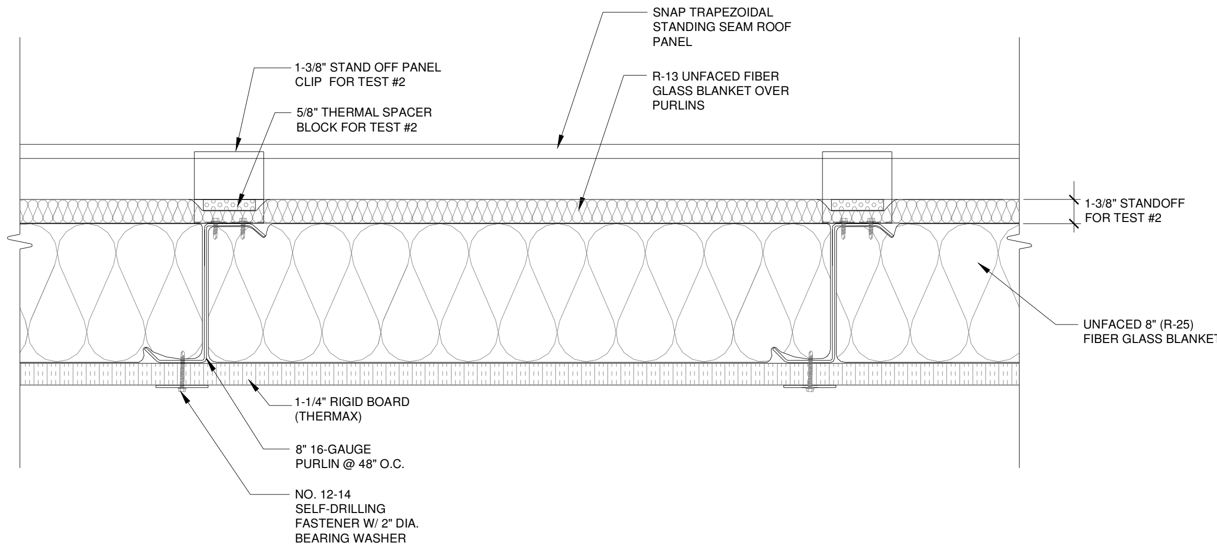
The third module (Module 3) was constructed by replacing the R-13 fiberglass top layer and 5/8-inch thermal spacer blocks in Module 2 with 3/8-inch reflective insulation and 1 inch thick thermal spacer blocks. The detail for Module 3 is shown in Figure 3. The nominal R-values for the expanded polystyrene thermal spacer blocks is expected to be approximately R-3.85 per inch and R-6.5 per inch for the rigid board used in Modules 1 through 3.

Module 4 consisted of two metal panels with the first panel being the “metal liner panel” installed by screwing it directly to the purlins. Roof stand-off clips (12 inches tall) were used to raise the roof surface above the purlins. R-30 and R-13 unfaced fiberglass were used on top of the metal liner panel. The top panels were installed using zero clearance roof clips attached to hat bar channels (Figure 4).

Figure 5 shows test Module 1 inside the LSCS. The test module was fully instrumented with thermocouples on the upper and lower surfaces (Figure 6). A grid was positioned above the upper surface to measure the air temperature in the climate chamber with 24 thermocouples. A similar grid is in place permanently in the metering chamber below its top edge with 21 thermocouples. The additional insulation placed around the perimeter of the assembly is also shown. The purpose of this insulation is to lessen the thermal load on the guard chamber. The amounts of insulation around the perimeter and the quality of its installation do not affect the energy flow through the metered area of an assembly. The metering chamber was raised and sealed against the bottom of each test module. Masking tape was used to seal the outside top edges of the metering chamber walls. No air pressure differences were imposed between the guard and metering chambers below the test section or between these chambers and the climate chamber above the test section. All heat was assumed to flow into or out of the metering chamber by conduction through the test section and metering chamber walls.



a) Module 1



b) Module 2

Figure 2. Details of Test Modules 1 and 2

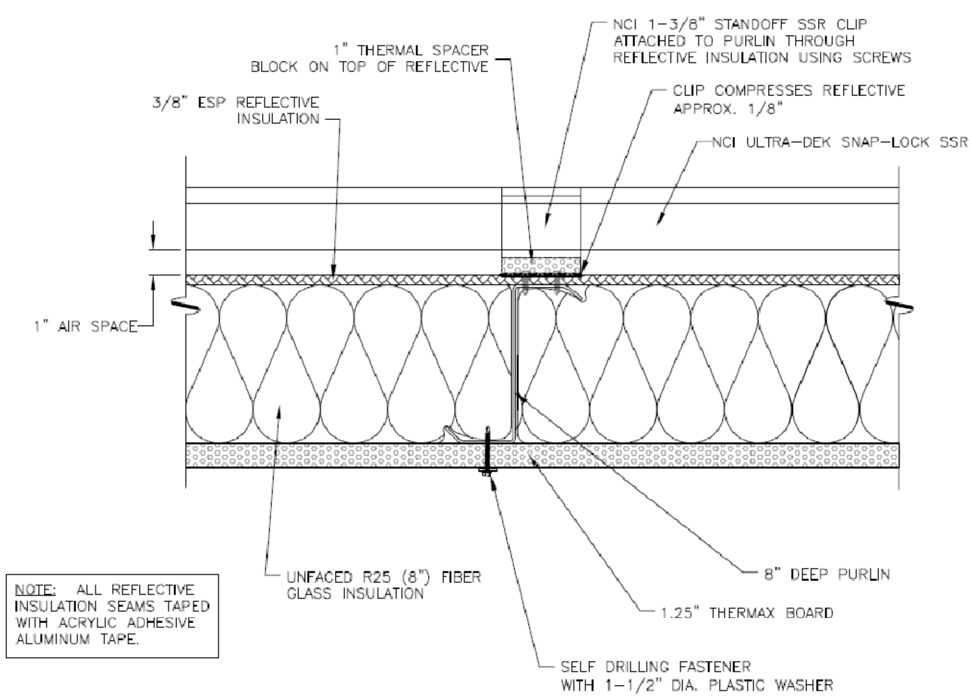


Figure 3. Detail of Test Module 3

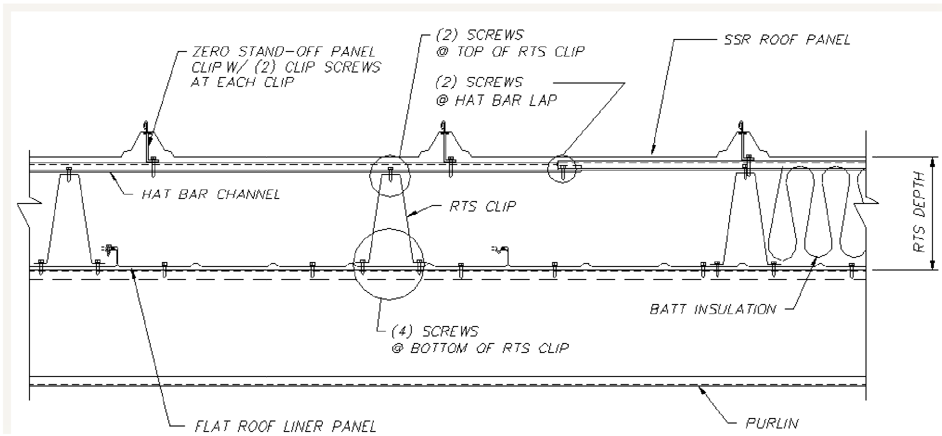


Figure 4. Typical Details of Test Module 4

Energy into or out of the metering chamber was measured in accordance with ASTM C-1363 [4]. The energy flow for the walls and floor was determined as a function of the measured surface temperature imbalance by previous use of a calibration panel—that is, a simple test section with known thermal resistance. Energy flow through the metering chamber walls and floor is the sum over all faces. On each wall and the floor, the average temperature difference measured by nine differential thermocouples is multiplied by the component’s area and divided by its R-value.

Figure 5. Module 1 in the LSCS

After the final test temperature conditions are reached (thermal steady-state condition), at least five successive repeated data acquisition sets were obtained. These sets were obtained at a data set time interval equal to the time constant of three hours for a total of 18 hours of data taken every five minutes. Reported values are averages of the readings during these 18 hours of thermal steady-state condition. Reported deviations are two standard deviations of the readings during the same period.

The same calibration panel is used periodically to establish the accuracy and precision of energy balances for the metering chamber [5]. The accuracy generally is of the order of ±10 percent. The precision or reproducibility generally is of the order of ±1 percent as a result of excellent control of imposed conditions by the control system. Proportional-integral control is achieved using a Programmable Logic Controller (PLC).

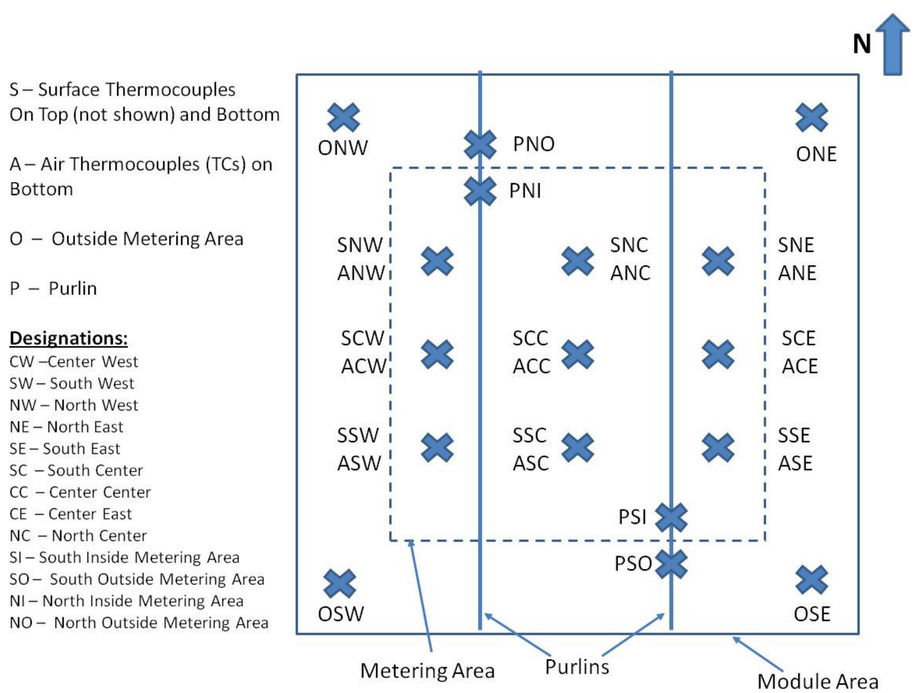


Figure 6. Modules Instrumentation–Thermocouples Array

Test Results and Discussion

The air temperatures imposed in the climate and metering chambers yielded a mean insulation temperature of 75°F for heat flow up tests (winter condition). The heat flow up evaluations were conducted with the climate chamber at 50°F and metering chamber at 100°F. Guard chamber temperatures were kept at the metering chamber condition to minimize the heat flow between the guard and metering chambers.

Table 1 gives detailed results from the evaluation, including the measured R-values ($R_{air\text{-}air}$) and nominal ASHRAE R-values (R_{ASHRAE}). The nominal ASHRAE R-values use the ASHRAE recommended values for the air films above and below the assemblies instead of the ones measured in these evaluations (R_{top} film and R_{bottom} film listed in Table 1). Winter ASHRAE R-values (heat flow upward) use 0.17 for the top film (15-mph wind over the roof) and 0.61 for the bottom film (free convection upward to nonreflective surfaces). These values are given in Table 1 of Chapter 26 of the *ASHRAE Handbook of Fundamentals* [6]. These film R-values also are specified in A9.4.1 of ASHRAE 90.1 [2]. ASHRAE R-values were determined by the following equation:

$$R_{ASHRAE} = R_{air-air} - (R_{top\ film} + R_{bottom\ film})_{measured} + (R_{top\ film} + R_{bottom\ film})_{ASHRAE}$$

The ASHRAE R-values measured for Modules 1 and 2 were R-37.2 h·ft^2·°F/Btu (U-0.0269 Btu/[h·ft^2·°F]) and R-33.0 h·ft^2·°F/Btu (U-0.0303 Btu/[h·ft^2·°F]) respectively. Lower R-values of Module 2 compared with Module 1 are a result of the compression of the insulation with shorter clips. It should be noted the deviation values shown in Table 1 are two standard deviations of the readings over the 18 hours of steady-state data showing excellent control of imposed conditions by the LSCS control system.

Following the completion of the heat flow up test on Module 2, the heat flow up test was repeated to check the reproducibility of the results (Table 1). R_{ASHRAE} for this repeat test was found to be R-33.3 h·ft²·°F/Btu (U-0.0300 Btu/[h·ft²·°F]). This shows a difference of 0.97 percent as a result of excellent control of imposed conditions by the control system.

The ASHRAE R-values measured for Modules 3 and 4 were R-30.6 h·ft²·°F/Btu (U-0.0327 Btu/[h·ft²·°F]) and R-32.1 h·ft²·°F/Btu (U-0.0312 Btu/[h·ft²·°F]), respectively. The variability of our procedure also was tested with the removal of Module 4 from the LSCS and reinstallation at a later date. The reinstalled Module 4 was re-evaluated in the LSCS at the heat flow up condition. The ASHRAE R-value for the reinstalled Module 4 was found to be R-30.1 h·ft²·°F/Btu (U-0.0332 Btu/[h·ft²·°F]). This shows a variability of approximately 6 percent.

Table 1. Detailed Test Results of Modules 1 through 4 - Heat Flow Upward

Module 1								
Imposed Temperature		Insulation	Resulting heat flow, R-values and U-factor					
Climate Air (°F)	Meter Air (°F)	Average Temperature (°F)	$Q_{thru\ roof}$ (Btu/h)	$R_{air\text{-}air}$	$R_{top\ film}$	$R_{bottom\ film}$	R_{ASHRAE}	U_{ASHRAE}
50.08 ±0.10	99.94 ±0.03	74.85 ±0.06	-92.37 ±1.57	37.49 ±0.64	0.44 ±0.04	0.66 ±0.03	37.17	0.0269
Module 2								
Climate Air (°F)	Meter Air (°F)	Average Temperature (°F)	$Q_{thru\ roof}$ (Btu/h)	$R_{air\text{-}air}$	$R_{top\ film}$	$R_{bottom\ film}$	R_{ASHRAE}	U_{ASHRAE}
50.29 ±0.09	99.98 ±0.04	74.95 ±0.04	-103.88 ±1.54	33.22 ±0.49	0.40 ±0.04	0.63 ±0.03	32.96	0.0303
50.31 ±0.09	99.94 ±0.04	74.94 ±0.05	-102.69	33.56 ±0.36	0.41 ±0.04	0.64 ±0.03	33.28	0.0300

			±1.04					
Module 3								
Climate Air (°F)	Meter Air (°F)	Average Temperature (°F)	$Q_{thru\ roof}$ (Btu/h)	$R_{air\text{-}air}$	$R_{top\ film}$	$R_{bottom\ film}$	R_{ASHRAE}	U_{ASHRAE}
49.94 ±0.09	99.99 ±0.04	74.84 ±0.04	-113.13 ±0.83	30.72 ±0.23	0.39 ±0.04	0.53 ±0.03	30.58	0.0327
Module 4								
Climate Air (°F)	Meter Air (°F)	Average Temperature (°F)	$Q_{thru\ roof}$ (Btu/h)	$R_{air\text{-}air}$	$R_{top\ film}$	$R_{bottom\ film}$	R_{ASHRAE}	U_{ASHRAE}
50.18 ±0.12	100.03 ±0.02	74.84 ±0.04	-106.68 ±1.40	32.45 ±0.43	0.41 ±0.06	0.73 ±0.02	32.09	0.0312
49.94 ±0.09	99.94 ±0.05	74.59 ±0.05	-114.34 ±0.99	30.37 ±0.27	0.32 ±0.04	0.71 ±0.03	30.12	0.0332

Notes:
1. Values shown are two standard deviations of the readings during an 18-hour period.
2. R-values are in h·ft^2·°F/Btu and U-factors are in Btu/(h·ft^2·°F).
3. Effective Metering Area of 69.44 ft^2)
4. Module 2 had one repeat test conducted as shown.
5. Module 4 had one repeat test conducted as shown to check variability of procedure.

Characterization of Insulation Used in the MBMA Test Modules 1 through 3

Three samples of R-13 unfaced fiberglass blanket used over the purlins in MBMA Modules 1 and 2 configurations were taken for testing in accordance with ASTM C518, “Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus” [7]. Samples taken from the metered area of Modules 1 and 2 (sample size of approximately 2 feet by 2 feet) were loaded into a heat flow meter apparatus to determine thermal conductivities at 75°F mean temperature, as well as mean temperatures of 50°F and 100°F at various thicknesses (resulting in thermal conductivities for different densities). The weight of each sample was measured for the

2 feet by 2 feet area, as well as the core area of the sample (12.5 inches by 12.5 inches) representing the area between the transducers in the heat flow meter apparatus. Table 2 shows the results of these evaluations. It should be noted the densities are based on the samples' core areas.

Table 2. Results of Thermal Conductivity Measurements on Samples of R-13 Fiberglass Blanket Insulation at Various Mean Temperatures

Average Thermal conductivity (Btu·in./[h·ft²·°F])	Average Thickness (Inches)	Average R-value (h·ft²·°F/Btu)	Average Density (lb/ft³)	Weight (lb)
R-13 blanket, 50°F				
0.2650	4.00	15.09	0.744	0.269
0.2436	3.00	12.32	0.992	0.269
0.2236	2.00	8.94	1.487	0.269
0.2058	0.94	4.57	3.165	0.269
0.2023	0.67	3.31	4.440	0.269
R-13 blanket, 75°F				
0.2874	4.00	13.92	0.744	0.269
0.2631	3.00	11.40	0.992	0.269
0.2392	2.00	8.36	1.487	0.269
0.2177	0.94	4.32	3.165	0.269
0.2132	0.67	3.14	4.440	0.269
R-13 blanket, 100°F				
0.3131	4.00	12.77	0.744	0.269
0.2836	3.00	10.58	0.992	0.269
0.2555	2.00	7.83	1.487	0.269
0.2300	0.94	4.09	3.165	0.269
0.2247	0.67	2.98	4.440	0.269

Similarly, three samples of R-25 fiberglass used between the purlins in MBMA Modules 1 through 3 were taken from the metering area. Table 3 shows the results of these evaluations with densities based on the samples' core areas. The evaluation of R-25 fiberglass samples were started with thickness of 7 inches because of the limitation of the heat flow meter apparatus. The R-30 fiberglass was not evaluated because of the 7-

inch limitation of the apparatus; however, the following correlation (Equation 1) is expected to be applicable to R-30 also. The average thermal resistances were within approximately 10 percent of the nominal R-value ratings.

Table 3. Results of Thermal Conductivity Measurements on Samples of R-25 Fiberglass Blanket Insulation at Various Mean Temperatures

Average Thermal conductivity (Btu·in./[h·ft²·°F])	Average Thickness (Inches)	Average R-value (h·ft²·°F/Btu)	Average Density (lb/ft³)	Weight (lb)
R-25 blanket, 50°F				
0.2525	7.00	27.72	0.852	0.539
0.2419	6.00	24.80	0.993	0.539
0.2337[a]	5.00	21.39	1.092	0.494
0.2269[b]	4.61	20.32	1.349	0.562
R-25 blanket, 75°F				
0.2753	7.00	25.43	0.852	0.539
0.2603	6.00	23.05	0.993	0.539
0.2520[a]	5.00	19.84	1.092	0.494
0.2437[b]	4.61	18.92	1.349	0.562
R-25 blanket, 100°F				
0.2911	7.00	24.04	0.852	0.539
0.2762	6.00	21.72	0.993	0.539
0.2690[a]	5.00	18.59	1.092	0.494
0.2551[b]	4.61	18.07	1.349	0.562

[a] One of the three samples
[b] Two of the three samples

The experimental thermal conductivities of fiberglass material were correlated into the following equation:

$$k_{fiberglass} = k_{air} + a_0 + a_1\rho + a_2\rho^{-1} + a_3\rho T + a_4\frac{T}{\rho} \quad (1)$$

Where:

$k_{air} = 0.179 + 0.00023933(T - 75)$

k_{air} = thermal conductivity of air [Btu·in./(h·ft²·°F)]
$k_{fiberglass}$ = thermal conductivity of fiberglass [Btu·in./(h·ft²·°F)]
ρ = density of fiberglass (lb/ft³)

T = mean temperature of insulation (°F)
$a_0 = 2.3992 \times 10^{-3}$
$a_1 = 1.7444 \times 10^{-3}$
$a_2 = 3.9982 \times 10^{-2}$
$a_3 = 2.3466 \times 10^{-5}$
$a_4 = 4.8118 \times 10^{-4}$
Number of points = 72
$R^2 = 0.9904$ (R^2 or coefficient of determination is an indicator of how well the correlation fits the experimental data.)

Figure 7 compares the measured thermal conductivities for R-13 and R-25 fiberglass with the calculated values from Equation 1. The 45-degree line shown in Figure 7 represents the perfect fit.

Three samples of foil-faced rigid board used at the bottom of the purlins in MBMA Modules 1-3 were taken from the metered area. Samples of approximately 2 feet by 2 feet were loaded into a heat flow meter apparatus to determine thermal conductivities at mean temperatures of 50°F, 75°F, and 100°F. Table 4 shows the results of these measurements. The average thermal resistances of rigid board were within approximately 6 percent of the nominal R-value ratings.

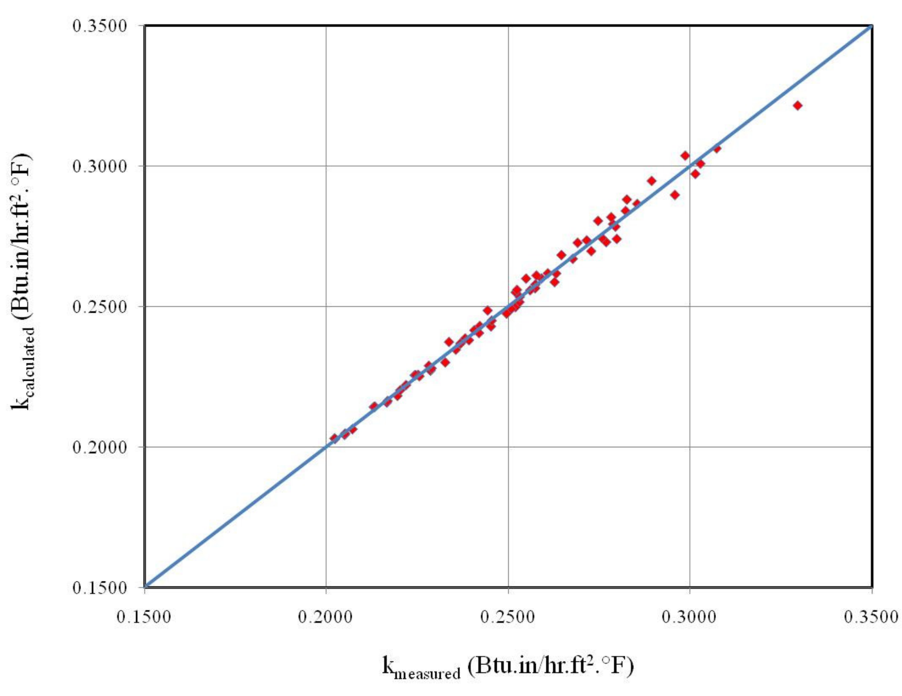


Figure 7. Comparison of Measured Thermal Conductivities with Calculated Values from Equation 1

Table 4. Results of Thermal Conductivity Measurements on Samples of Rigid Board at Various Mean Temperatures

Average Thermal conductivity (Btu·in./[h·ft²·°F])	Mean Temperature (°F)	Average Thickness (Inches)	Average R-value (h·ft²·°F/Btu)	Average Density (lb/ft³)	Weight (lb)
0.1545	50.0	1.32	8.54	2.182	0.261
0.1634	75.0	1.32	8.08	2.182	0.261
0.1775	100.1	1.32	7.44	2.182	0.261

The experimental thermal conductivities of rigid board were correlated into the following second order polynomial:

$$k_{rigid\ board} = a + bT + cT^2$$

Where:
$k_{rigid\ board}$ = thermal conductivity of rigid board [Btu·in./(h·ft²·°F)]
T = mean temperature of insulation (°F)
a = 1.5269×10^{-1}
b = -1.7432×10^{-4}
c = 4.2186×10^{-6}
Number of points = 9
$R^2 = 0.9988$

Conclusions

Due to variation in the amount, compression or orientation of the insulations used in the four test modules, it is helpful for making comparisons to express the performance of each module by calculating the ratio of the LSCS measurement divided by the sum of the component rated R-values of insulation for each system $R_{measured} / (R_1+R_2+\ldots R_n)$. By doing this, the relative efficiency of each system can be compared even when different types of insulation are used (Table 6). The rated R-value is being used for this comparison because the quality and recovery of fiberglass insulation can vary, and the compression of the fiberglass at supports affects the resistance.

The decrease in relative efficiency of these systems results from compression of the insulation (most prominent in Module 2) or thermal bridging of metal components (seen in Module 4). It is expected the LSCS measured R-values for these systems will improve if a more typical 5 ft oc purlin spacing is used; therefore, the tested values should be considered conservative.

The original goal set for this work was to develop innovative metal building roof assemblies that would perform to at least U-0.04 Btu/(h·ft²·°F). All four test modules exceeded this goal, so the research conducted to date should be considered a success.

Table 6. Comparison of Relative Efficiency of Modules 1 Through 4

Specimen	Rated R-Value of Components	LSCS Measured R-Value of System	Relative Efficiency ($R_{measured}$ / Σ R_{rated})
Module 1	R-13 + R-25 + R-8.1	R-37.17	37.17 / 46.1 = 80.6%
Module 2	R-13 + R-25 + R-8.1	R-33.12	33.12 / 46.1 = 71.8%
Module 3	(R-2 + R-1.6)[1] + R-25 + R-8.1	R-30.58	30.58 / 36.7 = 83.3%

Module 4	R-13 + R-30	R-31.11[2]	31.11 / 43.0 = 72.3%

1. Assumed R-value of reflective insulation foam backing plus R-value of 1-inch air space and assumed effective emittance of reflective surface = 0.20
2. Average value of the two measurements for Module 4

Modules 1 and 2

The results of the tests from Modules 1 and 2 show thermal bridging in metal building roof assemblies can be minimized by increasing the space between the metal roof panel and z-purlin. The amount of allowable space that can be achieved will be practically limited by the structural capacity of the roof system under gravity loads and wind-uplift loading. Although there is an energy savings benefit from increasing the height of the metal roof clip, this must be weighed against the costs of qualifying taller roof clips for structural loads, as well as the practicality of installing thick thermal spacer blocks.

It can be deduced that the compression of the top layer of fiberglass insulation was a significant source of insulation performance loss. The results from the Module 1 and 2 tests should give the metal building industry incentive to explore the practicality of providing taller roof clips to minimize the compression of any top layer of insulation.

Module 3

The reflective insulation performance showed a moderate decrease compared with Module 2, considering an R-13 fiberglass blanket was replaced with the thinner R-2 reflective insulation. Reflective insulation systems can improve the thermal performance of metal building roof systems when used in combination with other forms of mass insulation such as fiberglass and/or rigid insulation. It typically is recommended that reflective insulations be used in combination with other forms of insulation, such as fiber glass or rigid board, in heating-dominated climates.

Further investigations of reflective insulations are recommended to try to understand the sensitivity of the effective R-value of the reflective insulation as a function of the depth of the air space, above and below the reflective insulation. In addition, it is recommended studies be performed for the various ASHRAE climate zones to see whether a potential for condensation exists on the underside of the metal roof panel, which would be exposed to convective currents from any required air space.

Module 4

The performance of Module 4 was comparable to Modules 2 and 3. Even though this module minimizes the compression of the top layer of insulation, the thermal bridging was more significant than in the other tested modules. The construction of this module was more labor-intensive than the others, but this construction has advantages for retrofit use.

Two LSCS measurements were recorded for Module 4 because of necessary equipment recalibration resulting from maintenance of the LSCS at ORNL. This provided an opportunity to test the variability of the measurement for this assembly, which is more complex than a typical calibration panel because of the need to insulate around any gaps between the test assembly and guard area. Although there was no change made to the assembly, there was a measured difference in performance of approximately 6 percent in R-value. This difference is the capability of the LSCS to reproduce R-values, as well as the variability in the test setup and procedure. It is interesting to note that hot box measurements have an inherent amount of uncertainty and steps should be taken to ensure reported values have a reasonable degree of conservatism built in or multiple measurements are used to average the performance of a given assembly.

Future Work

Four additional assemblies are in the design phase and testing is planned to take place in early- to mid-2011. One future area of research may be to find ways to reduce the thermal bridging for the assemblies already tested. A summary report of the findings of these planned tests, as well as the first four test modules, will be made available through ORNL or the MBMA.

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