R&D Services

Large-Scale Tests of Spray-Applied Polyurethane Foam Insulation Installed below Roof Sheathing

Introduction

A series of thermal tests that included two types of spray-applied polyurethane foam installed on the bottom side of roof sheathing have been completed using the Large-Scale Climate Simulator at the Oak Ridge National Laboratory (ORNL). Loose-fill fiberglass installed on the floor of the attic test module was also tested in this project. The thermal tests involved both winter and summer conditions for each of the three attic insulation systems that were studied. The three systems were tested with the same thermal boundary conditions, inside temperature and outside temperature, to facilitate comparisons of performance.

This research was carried out in the Large-Scale Climate Simulator (LSCS) at the Oak Ridge National Laboratory. The LSCS is a unique hot-box facility that operates in accordance with ASTM C 1363. [1] Material R-values for the insulations included in the study were determined using a heat-flow meter apparatus operated in conformance with ASTM C 518. [2]

Research Plan

The base-line insulation for this project was loose-fill fiberglass insulation installed on the attic floor to a depth of 14 inches. The insulation label for the fiberglass indicated that this depth of insulation provides R 38 $ft^2 \cdot h \cdot ^\circ F/Btu$ at 75 ºF.

Two spray-applied polyurethane foam systems were tested in the same attic module as the loose-fill fiberglass. The first was low-density open cell polyurethane foam with a nominal density of 0.5 lb/ft^3. The second foam system was closed-cell spray-applied polyurethane foam with a nominal density of 2 lb/ft^3. The attic module and the thermal conditions were the same for all three tests.

Test Facility

The LSCS at ORNL is a hot-box facility capable of testing 12x12 ft assemblies with heat flow either up (winter condition) or down (summer

condition). Horizontally oriented test assemblies are positioned above a
conditioned enclosure (metering chamber) that represents the interior side
of the building envelope. The metering chamber contacts an 8x8 ft. section of the
12x12 ft. attic module. The test module can be many shapes including a typical
shingled roof construction with 5/12 pitch such as that used in this study. Figure 1
contains a photograph of the test module before the roof sheathing was completed.
The photograph shows the loose-fill fiberglass on the floor of the attic. The 8x8 ft
metering area is partitioned from the rest of the attic space with extruded
polystyrene board stock that forms a wall around the metered area.

Figure 1. Photograph of Attic Test Module without Roof Sheathing

The exterior side of the test module, the region above the roof, is a controlled
region that can simulate either summer or winter conditions.
The metering chamber is instrumented to measure either the heat added or heat
removed from the metering chamber to maintain constant temperature.
Figure 2 is a photograph of the enclosed test module. Figure 3 shows asphalt
shingles being applied to the roof.

Figure 2. Photograph of Complete Attic Module without Roof Shingles

Figure 3. Photograph of Roof Shingles being Applied to the Test Module

The LSCS has a computer data acquisition system that records temperatures and heat flows at selected locations in the test assembly. Heat-flux data and temperature difference s are used to calculate thermal resistance. The analysis can be characterized as one-dimensional steady-state measurement and analysis.

The test module was an attic section with a floor area of 144 ft^2 bordered by nominal 2x10 inch framing. Trusses with nominal 2x4 inch joists and 2x6 inch rafters were set on 24-inch centers. The floor of the attic was ½-inch thick gypsum attached to the bottom side of the joists. The gypsum was as a result the ceiling of the metering chamber. The ends of the test module were enclosed with ½-ich thick plywood. The rood sheathing was also ½-inch thick plywood. All joints and spaces were either taped or caulked to eliminate air exchange between the attic air and the exterior of the module.

An extension or chimney can be seen in Figure 1. This extension was fabricated from rigid foam board insulation that was instrumented to determine

horizontal heat flow from the enclosed region of the attic. The horizontal heat flow was included in the analysis of the thermal performance of insulation systems.

Test Results

The results for thermal testing done in accordance with ASTM C 518 and ASTM C 1363 are summarized in this report. The thermal performance of three insulation products that were included in the project were determined as a function of temperature by R & D Services, Inc. using ASTM Test Method C 518. The thermal performances of three systems each including one product were determined as a function of temperature using the Large Scale Climate Simulator at the Oak Ridge National Laboratory. The LSCS operates in accordance with ASTM Test Method C 1363.

Material Measurements Using C 518

Loose–fill fiberglass insulation at density 0.44 lb/ft³, low-density spray-applied polyurethane foam at density 0.60 lb/ft³, and high–density spray–applied polyurethane foam at density 2.6 lb/ft³ were each used in the attic test module at ORNL. The apparent thermal conductive k_a, and the thermal resistively, R*, of each of these products was determined. The results are contained in Tables 1, 2 and 3 with equations for k_a as a function of temperatures below each of the three tables. The test specimen for the low-density foam was a nominal one-inch thick slice cut from the core of a four-inch thick piece of the insulation that was collected when the foam was installed in the LSCS test module. The test specimens for high-density foam were nominal one-inch thick slices cut from the core of a four-inch thick section of foam that were approximately 34 days old when tested using C 518.

Table 1.   R* and k_a for the Loose-Fill Fiberglass used
**   in the Spray-Foam Project**

Average Temperature (°F)	k_a (Btu·in/ft²· h·°F)	R* (ft²·h·°F/Btu·in.)
45.00	0.3943	2.536
75.06	0.4511	2.217
105.11	0.5066	1.974

$$k_a = 0.001868T + 0.310443 \tag{1}$$

Table 2. R* and k_a for Low-Density Spray-Applied Polyurethane Foam

Average Temperature (°F)	k_a (Btu·in/ft²·h·°F)	R* (ft²·h·°F/Btu·in.)
64.25	0.2680	3.731
75.06	0.2767	3.614
85.86	0.2856	3.200
96.66	0.295^+	3.100

$$k_a = 0.000843T + 0.213577 \tag{2}$$

Table 3. R* and k_a for High-Density Spray-Applied Polyurethane Foam

Average Temperatures °F	k_a (Btu·in/ft²·h·°F)	R* (ft²·h·°F/Btu·in.)
64.27	0.1415, 0.1430	7.067, 6.993
75.09	0.1460, 0.1473	6.849, 6.789
8589	0.1509, 0.1520	6.627, 6.579
96.69	0.1561, 0.1570	6.406, 6.369

$$k_a = 0.000441T + 0.113698 \tag{3}$$

System Measurements Using C 1363

Three attic insulation systems were tested in the LSCS for both winter and summer conditions. The systems and the test conditions are listed in Table 4. The thermal test section was 8x8 ft. and 64 ft^2 in area.

Table 4. System Tests Using the ORNL LSCS

Test Element Test ID Temperature		Interior Temperature (^{o}F)	External Temperature (^{o}F)
Loose-fill fiberglass on floor of attic (depth 14 in.)	1a	69.99	0.20
	1b	69.98	0.09
	1c	69.96	30.12
	1d	70.06	109.93
Low-Density foam between rafters (depth 5.5 in.)	2a	70.02	-0.21
	2b	70.01	0.00
	2c	69.99	30.15
	2d	70.03	109.87
High-Density foam between rafter (depth 4.0 in.)	3a	70.03	0.10
	3b	70.02	0.23
	3c	70.01	29.99
	3d	69.97	109.95

Heat flux and temperature data were used to calculate thermal resistance and overall heat transfer coefficients for the twelve cases listed Table 4. The results are shown in Table 5.

Table 5. R and U-Values for the Twelve LSCS Measurements

Test Number R-Values			U-Value	
	Insulation	Ceiling-to-Deck	Air-to- Air	Air-to-Air
Fiberglass				
1a	17.7	19.2	22.2	0.045
1b	17.7	19.3	22.4	0.045
1c	29.0	31.2	34.5	0.029
1d	20.2	21.6	23.4	0.043
Low-Density Foam				
2a	14.7	13.9	16.9	0.059
2b	14.7	14.0	17.0	0.059
2c	13.6	13.2	16.0	0.063
2d	12.1	12.2	14.6	0.068
High-Density Foam				
3a	22.8	20.1	23.7	0.042
3b	22.7	20.0	23.6	0.042
3c	19.8	17.9	21.3	0.047
3d	18.1	17.0	19.4	0.052

The insulation R-Values in Table 5 are calculated from the measured heat-flux across the insulation and the measured temperature difference across the insulation. The results have been corrected for the presence of framing. The framing correction is negligible in the case of the attic-floor insulation (loose-fill fiberglass) while the correction is significant for the foam installations since the foam regions are in parallel with word framing for their entire thickness.

The ceiling-to-deck R-Values are based the temperature differences between the top of the gypsum that forms the floor of the attic and the bottom of the plywood that was used as roof sheathing. The air-to-air R-Values and U-

Values are based on the difference in temperature between the metering chamber and the climate chamber.

Table 6 compares the material R-Values for the three insulations determined from the LSCS (ASTM C 1363) measurements and k_a measured in accordance with ASTM C 518. The k_a and R-Values are at the average insulation temperatures determined in the LSCS. The thickness of the fiberglass insulation was 14 inches, the thickness of the low-density foam was 5.5 inches, and the thickness of the high-density foam was 4.0 inches. The high-density foam was 34 or 35 days old at the time thermal resistance was measured using ASTM C 518. The high-density foam was 20 to 30 days old during the LSCS test. The thermal resistance for the fiberglass are based on an area of 64 ft^2 while the foam values are based on 70.7 ft.^{2} The k_a-values in Table 6 were calculated from Equations 1,2, or 3 as appropriate. The variation of R with temperature is qualitatively correct for the foam test. The low-density loose-fill fiberglass insulation exhibited significant reduction in thermal resistance at low temperature due to free convection.

Table 6. Material R-Values Determined by Two Methods

Test Number	Insulation Temp (°F)	R (C 1363)	k_a (C 518)	R (C 518)
1a	38.01	17.7	0.3814	36.7
1b	38.03	17.7	0.3815	36.7
1c	51.75	29.0	0.4071	34.4
1d	88.97	20.2	0.4766	29.4
2a	32.61	14.7	0.2411	22.8
2b	32.73	14.7	0.2412	22.8
2c	48.49	13.6	0.2545	21.6
2d	93.00	12.1	0.2920	18.8
3a	32.89	22.8	0.1282	31.2
3b	33.01	22.7	0.1283	31.2
3c	48.79	19.8	0.1352	29.6
3d	93.07	18.1	0.1547	25.9

Table 7 - Comparison of Tested R-Values and Labeled R-Values

Insulation	Test Number	Insulation Temperature	Labeled R-Value	Tested R-Value (C 1363)	% Labeled
Blown Fiber Glass @ 14 inches	1a (low temp)	38.01	38	17.7	47
	1b (low temp)	38.03		17.7	47
	1c (avg temp)	51.75		29.0	76
	1d (high temp)	88.97		20.2	53
Low-Density SPF @ 5.5 inches	2a (low temp)	32.61	19.8	14.7	74
	2b (low temp)	32.73		14.7	74
	2c (avg temp)	48.49		13.6	69
	2d (high temp)	93.00		12.1	61
High Density SPF @ 4.0 inches	3a (low temp)	32.89	27	22.8	84
	3b (low temp)	33.01		22.7	83
	3c (avg temp)	48.79		19.8	73
	3d (high temp)	93.07		18.1	67

Summary

This research provides a comparison of the performance of roof-deck applied spray-applied polyurethane foam insulation with loose-fill fiberglass insulation installed on the attic floor of a test module.

● The R-values determined from LSCS measurements for loose-fill fiberglass were less than the material R-values measured using a heat-flow meter apparatus. The differences at low temperatures were most likely due to free convection, The loose-fill fiberglass provided about 56% of the thermal resistance measured by the heat-flow meter apparatus.

● The low-density open-cell spray-applied polyurethane foam installed below the roof sheathing provided about 69.5% of the R-value measured by the heat-flow meter apparatus. The thermal performance was consistent over the range of temperatures investigated.

● The high-density closed-cell spray-applied polyurethane foam installed below the roof sheathing performed at about 77% of the R-values measured by the heat-flow-meter apparatus. The air-to-air U-values for the high-density foam were less than the corresponding U-values for the fiberglass insulation for winter conditions. The air-to-air U-values for the high-density foam were greater than the U-values for the fiberglass insulation under summer conditions.

References

[1] ASTM C 1363, "Standard Test Method for the Thermal Performance of Building Assemblies by Means of a Hot Box Apparatus", 2002 Annual Book of ASTM Standards, Vol. 04.06 (2002) pp. 739-769.

[2] ASTM C 518, "Standard test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus", 2002 Annual Book of ASTM Standards, Vol. 04.06 (2002) pp. 156-167.

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