Thermal Performance of Gas-Filled Panels with Reflective Surfaces Installed in an Attic

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ABSTRACT

The thermal performance of gas-filled panels (GFPs) with internal and external reflective surfaces were measured in the Large-Scale Climate Simulator (LSCS) at Oak Ridge National Laboratory. Prototype panels filled with argon and panels filled with air were evaluated for both winter and summer conditions. The nominally 1.5 in. (38.1 mm) thick GFPs were installed on top of 3.5 in. (88.9 mm) thick nominal R-13 (RSI-2.29) fiberglass batts to simulate retrofit attic insulation installation. Analysis of the experimental results provided the thermal resistance of the batts, the thermal resistance of the GFPs, and the radiant barrier contributions to the overall thermal resistance between the attic floor and the roof sheathing.

The total contribution of the GFP layer installed above fiberglass batt insulation was 5 to 6 $ft^2 \cdot h \cdot °F/Btu$ (0.88 to 1.06 $m^2 \cdot W/K$) for winter conditions with an outside temperature of 25°F (–3.9°C) and an inside temperature of 70°F (21.1°C). The GFPs added 12 to 13 $ft^2 \cdot h \cdot °F/Btu$ (2.11 to 2.29 $m^2 \cdot W/K$) to the attic thermal resistance with an outside temperature of 115°F (46.1°C) and a roof sheathing temperature of 150°F (65.6°C) due to simulated solar radiation. The summer radiant barrier contribution to the attic thermal resistance was about 6 $ft^2 \cdot h \cdot °F/Btu$ (1.06 $m^2 \cdot W/K$) for both the argon-filled and air-filled GFPs. This project included 11 steady-state LSCS measurements (ASTM 2006a) complemented by material R-value measurements made with a heat-flowmeter apparatus (ASTM 2006b).

INTRODUCTION

The concept of using low thermal conductivity gases such as argon or krypton to produce insulating panels has been described by Griffith and Arasteh (1992) and Griffith et al. (1991). Griffith and Arasteh (1992) estimated gas-filled panel (GFP) thermal resistivities of 5.2 $ft^2 \cdot h \cdot °F/Btu \cdot in.$ (36.1 $m \cdot W/K$) for air, 7.1 $ft^2 \cdot h \cdot °F/Btu \cdot in.$ (49.2 $m \cdot W/K$) for argon, and 12.5 $ft^2 \cdot h \cdot °F/Btu \cdot in.$ (86.7 $m \cdot W/K$) for krypton. Thermal measurements on handmade specimens resulted in 4.3 $ft^2 \cdot h \cdot °F/Btu \cdot in.$ (29.8 $m \cdot W/K$) for air, 6.3 $ft^2 \cdot h \cdot °F/Btu \cdot in.$ (43.7 $m \cdot W/K$) for argon, and 10.1 $ft^2 \cdot h \cdot °F/Btu \cdot in.$ (70.0 $m \cdot W/K$) for krypton. While the measured values were lower than the estimates, the results indicated the possibility of a new type of building insulation with thermal resistance values greater than conventional air-filled insulations. Griffith et al. (1994) discussed the economics for GFPs with proposed design guidelines. The thermal performance of practical GFPs depends on the introduction of internal reflective material to reduce the radiant transport across the material. This suggests a combining of reflective insulation technology with the favorable aspects of GFPs. A third step in the development of a novel insulation system was to introduce an exterior low-emittance surface so that the panel becomes an attic radiant barrier when installed.

A series of thermal tests that included two types of GFP reflective insulation was designed to test at near full scale the performance of prototype GFPs with interior reflective surfaces and low-emittance exterior surfaces to serve as an attic radiant barrier. It is not practical to evaluate this type of assembly using a conventional hot-box facility because of the limited specimen thicknesses that can be tested. For the same reason, conventional hot-box facilities are not used to evaluate radiant barrier systems. The Large-Scale Climate Simulator

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(LSCS) at Oak Ridge National Laboratory was chosen for the evaluation because it is configured to measure vertical heat flow across large test specimens. This apparatus satisfies the requirements of ASTM C 1363 (ASTM 2006a) and can accommodate test specimens several feet thick.

Thermal tests involved both winter and summer conditions for each of three attic insulation systems. The first system consisted of nominal R-13 (RSI-2.29) fiberglass batts on the attic floor. The second system had air-filled panels (and a radiant barrier) installed on top of the batts; the third system had argon-filled panels (with a radiant barrier) installed above the batts. The GFPs were installed perpendicular to the joists in both cases. The three systems were tested with the same thermal boundary conditions to facilitate comparisons of the steady-state performances. The thermal resistivity of the batt insulation and the GFPs were evaluated using ASTM C 518 (ASTM 2006b) to provide supplementary data.

An evaluation of the performance of GFPs installed in an attic space requires a large-scale test since there are three factors that contribute to the system performance. These factors are the thermal resistance of the GFP, the reduction in heat flux through the floor of the attic due to the attic radiant barrier part of the GFP, and changes in the operating temperature of the attic floor insulation. These contributions to the overall performance are outside the scope of ASTM C 518.

TEST FACILITY

The LSCS is a hot-box facility capable of testing 12 × 12 ft (3.66 × 3.66 m) assemblies with heat flow up (winter condition) or down (summer condition). Horizontally oriented test assemblies are positioned above a calorimeter (metering chamber) that represents the interior side of the building envelope. The metering chamber contacts an 8 × 8 ft. (2.44 × 2.44 m) section in the center of the 12 × 12 ft. (3.66 × 3.66 m) attic module. Heat flow in or out of the calorimeter was used to determine the steady-state heat flux through the test assemblies. The test module had a roof with 5/12 pitch enclosing an attic space with a maximum vertical distance of about 30 in. (0.76 m).

The test module was an attic section with a floor area of 144 ft^2 (13.4 m^2) bordered by nominal 2 × 10 in. (50.8 × 254 mm) framing. Trusses with nominal 2 × 4 in. (50.8 × 101.6 mm) joists and 2 × 6 in. (50.8 × 152.4 mm) rafters were set on 24 in. (0.610 m) centers. The floor of the attic was 0.5 in. (12.7 mm) thick gypsum attached to the bottom side of the joists. The gypsum was the ceiling of the metering chamber. The ends of the test module were enclosed with 0.5 in. (12.7 mm) thick plywood. The roof sheathing was also 0.5-in. (12.7 mm) 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.

Figure 1 shows the test module before the roof sheathing was installed. The fiberglass batt insulation can be seen on the floor of the attic between ceiling joists. Netting was used to maintain a batt thickness of 3.5 in. (88.9 mm) during the course of the measurements. Figure 2 shows the completed module before roofing felt was attached. Figure 3 shows the interior of the test module with foil-faced panels installed above the fiberglass insulation. Figure 4 shows the finished attic module installed in the LSCS with heat lamps above the module to simulate summer solar radiation.

The test assemblies had arrays of thermocouples at (1) the bottom of the attic floor material, (2) the top of the attic floor material, (3) the top of the batt insulation, (4) the top of the GFPs, (5) the attic air, (6) the bottom of the roof sheathing, and (7) the top of the roof sheathing. The metering chamber temperature and the exterior (climate-side) temperature were also monitored. The LSCS has a computer data acquisition system that records the temperatures and heat flow in or out of

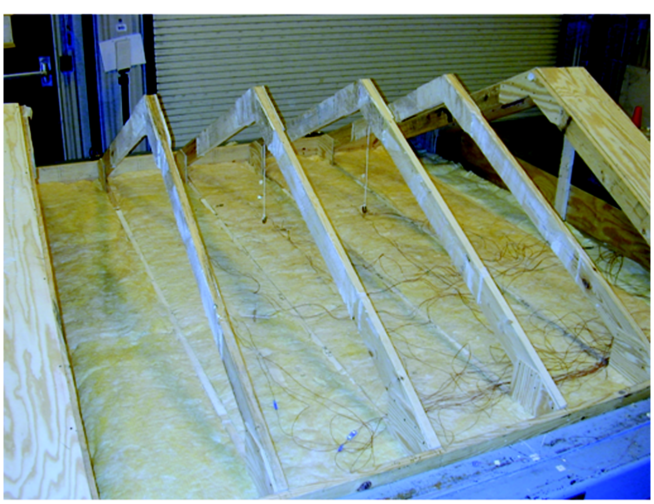

Figure 1 *Attic test module without roof sheathing.*

Figure 2 *Complete attic module without roofing felt.*

Figure 3 *GFPs installed in test module.*

Figure 4 *Finished attic module in the LSCS.*

the metering chamber. The measured heat-flux data and temperature differences were used to calculate thermal resistances (temperature difference divided by steady-state heat flux) across layers of material and the attic air space. The analysis can be characterized as one-dimensional steady-state measurement and analysis.

TEST RESULTS

Material Measurements

Fiberglass batt insulation at a thickness of 3.5 in. (88.9 mm), air-filled GFPs, and argon-filled GFPs were tested for thermal performance using ASTM C 518 (ASTM 2006b). The apparent thermal conductivities, k_a, and the thermal resistivities, $R*$, of each of these materials were measured. The results are shown in Tables 1, 2, and 3 with an equation for k_a as a function of temperature shown for the fiberglass batt insulation. The thermal test specimens for the fiberglass insulation were taken from the same lot of material that was used in the LSCS measurements. Equation 1 is a correlation of apparent thermal conductivity with temperature for the data shown in Table 1. The thermal resistances of the GFPs were determined at a single temperature.

The measured thermal resistivities of the GFPs tested in this project are smaller than those reported by Griffith and Arasteh (1992) and Griffith et al. (1991). The GFPs used in this project were from a full-scale manufacturing facility, whereas the early measurements were made on hand-prepared prototypes. The smaller-than-expected difference between the air-filled and argon-filled GFPs is likely due to the thicknesses of the panels that were tested. The internal design of the two panel types is the same. The argon panel, however, has more solid material per unit thickness than the air-filled panel. This at least partly compensates for the low thermal conductivity of the argon fill gas.

Table 1. R^* and k_a for the Fiberglass Batt Insulation Used in the LSCS Project Measured at 3.5 in. (88.9 mm) Thickness

Average Temperature, °F (°C)	k_a, Btu·in./ft²·h·°F (W/m·K)	R^*, ft²·h·°F/Btu·in. (m²·K/W)
60.0 (15.6)	0.265 (0.038)	3.77 (26.3)
75.0 (23.9)	0.278 (0.040)	3.60 (25.0)
90.0 (32.2)	0.293 (0.042)	3.41 (23.8)
100.0 (37.8)	0.303 (0.044)	3.30 (22.7)

Table 2. R^* and k_a for Argon-Filled GFP*

Temperature, °F (°C)	Thickness, in. (mm)	k_a, Btu·in./ft²·h·°F (W/m·K)	R^*, ft²·h·°F/Btu·in. (m²·K/W)
75.1 (23.9)	1.181 (30.0)	0.277 (0.040)	3.61 (25.0)†

* 12 × 12 in. (3.5 × 3.5 mm) panel.
† R-value per inch (meter) of thickness.

Table 3. R^* and k_a for Air-Filled GFP*

Temperature, °F (°C)	Thickness, in. (mm)	k_a, Btu·in./ft²·h·°F (W/m·K)	R^*, ft²·h·°F/Btu·in. (m²·K/W)
75.1 (23.9)	1.575 (40.0)	0.319 (0.046)	3.13 (21.7)†

* 12 × 12 in. (3.5 × 3.5 mm) panel.
† R-value per inch (meter) of thickness.

$$k_a = 0.2073 + 0.0009537 \cdot T \quad (1)$$

where k_a is in Btu·in/ft^2·h·°F and T is in °F. For the result in W/m·K, divide k_a by 6.933.

The thermal conductivities of the gypsum wall board and the lumber used for joists shown in Table 4 were measured at 75°F (23.9°C) since these materials were adjacent to the metering chamber.

System Measurements Using ASTM C 1363 (LSCS Apparatus)

The attic modules and the LCSC test conditions are listed in Table 5. The interior temperature is for the calorimeter (metering chamber) while the exterior is the climate side of the test module.

Heat flux and temperature data were used to calculate the thermal resistances for the eleven test sequences listed Table 5.

Table 6 contains the thermal data obtained for the fiberglass batt insulation by test methods ASTEM C 518 (ASTM 2006b) and ASTM C 1363 (ASTM 2006a). The table also contains measured thermal resistances for the combination of fiberglass batt insulation and ceiling joists. The R-values from the two methods show an average absolute difference of about 2% when Equation 1 is used to represent the results of the ASTM C 518 measurements. The batts were labeled R-13 (RSI-2.29) at 75°F (23.9°C). Equation 1 gives R-12.6 (RSI-2.22) at 75°F (23.9°C) and 3.5 in. (88.9 mm).

The LSCS data were used to calculate the overall thermal resistances between the roof sheathing and the top of the gypsum that formed the floor of the attic in Table 7. The overall thermal resistance was obtained from Equation 2, where the heat flux, Q, is for the 64 ft^2 (5.95 m^2) region above the metering chamber. The thermal resistance of the attic air space between the top of the attic floor insulation and the roof sheathing is the difference between the overall thermal resistance and the thermal resistance for the layer consisting of batts and joists. In this case, the air space is bounded by high-emittance surfaces.

$$R_{overall} = | T_{roof\ deck} - T_{gypsum} | / | Q | \quad (2)$$

Tests 12, 13, and 13a involved summer temperatures. Tests 12 and 13b included simulated solar flux to the roof deck with corresponding high roof-deck temperatures. Test 13a did not include solar flux. The average winter attic air thermal resistance was 1.26 ft^2·h·°F/Btu (0.222 m^2·K/W) while the average summer value was 1.77 ft^2·h·°F/Btu (0.312 m^2·K/W) for the measurements that included simulated solar input. The measured attic air space R-value without a radiant barrier was subtracted from the attic air space R-value with a radiant barrier to obtain the contribution of the radiant barrier to the overall thermal resistance. Tests 15 and 16 involved argon-

Table 4. R^* and k_a for Gypsum Board and Ceiling Joist Lumber

Material	Temperature, °F (°C)	Thickness, in. (mm)	k_a, Btu·in./ft^2·h·°F (W/m·K)	R^*, ft^2·h·°F/Btu·in. (m^2·K/W)
gypsum	75.1 (23.9)	0.509 (12.9)	1.06 (0.153)	0.48 (0.085)*
joist	75.1 (23.9)	1.750 (44.5)	0.747 (0.108)	4.69 (0.826)†

* R-value for the thickness that was tested.
† R-value for a thickness of 3.5 in. (88.9 mm). The test specimen was 1.75 in. (44.5 mm) in thickness.

Table 5. System Tests Using the ORNL LSCS

Description	Test ID	Temperature, °F (°C)	
		Interior	Exterior
Fiberglass batt insulation on floor of attic with thickness not constrained	10	70.0 (21.1)	20.0 (–6.67)
	11	70.0 (21.1)	25.0 (–3.89)
	12	70.0 (21.1)	114.9 (46.06)
Fiberglass batt insulation on floor of attic with thickness constrained	13a	70.0 (21.1)	114.8 (46.0)
	13b	70.0 (21.1)	115.0 (46.1)
	14	70.0 (21.1)	26.2 (–3.2)
Argon-filled GFP above fiberglass batt insulation	15	70.0 (21.1)	24.7 (–4.06)
	16	70.0 (21.1)	115.0 (46.1)
Air-filled GFP above fiberglass batt insulation	17	70.0 (21.1)	115.0 (46.1)
	18	70.0 (21.1)	25.2 (–3.78)
	17r	70.1 (21.2)	115.0 (46.1)

Table 6. R-Values for Fiberglass Batt Insulation in the Attic Module

Test ID	Average Insulation Temp., °F (°C)	R (RSI)* C 1363	R (RSI) C 518	% Difference†	R Batts + Joists
10	47.2 (8.44)	13.76 (2.42)	13.85 (2.44)	0.65	12.52 (2.21)
11	49.5 (9.72)	13.69 (2.41)	13.74 (2.42)	0.36	12.47 (2.20)
12	108.9 (42.7)	11.74 (2.07)	11.27 (1.98)	–4.17	10.76 (1.90)
13a	91.8 (33.2)	11.40 (2.01)	11.89 (2.09)	4.12	10.58 (1.86)
13b	108.6 (42.7)	11.31 (1.99)	11.29 (1.99)	–0.18	10.41 (1.83)
14	49.40 (9.67)	13.37 (2.35)	13.74 (2.42)	2.69	12.24 (2.16)
Average of absolute differences 2.03					

* Units for R: ft^2·h·°F/Btu; units for RSI: m^2·K/W.
† $(R_{C\ 518} - R_{C\ 1363}) \cdot 100/R_{C\ 518}$.

Table 7. Measured Overall Thermal Resistance and Attic Air Space Thermal Resistance

Test ID	Temperature, °F (°C)			Direction	Flux*	$R_{overall}$†	$R_{attic\ air}$†
	Gypsum	Roof Deck	Difference				
10	66.2 (19.0)	24.3 (–5.28)	–41.9 (–23.3)	Up	–3.03 (–9.56)	13.83 (2.44)	1.30 (0.229)
11	66.6 (19.2)	28.9 (–1.72)	–37.7 (–20.9)	Up	–2.75 (–8.67)	13.71 (2.41)	1.24 (0.219)
12	77.8 (25.4)	150.4 (65.8)	72.6 (40.3)	Down	5.78 (18.2)	12.56 (2.21)	1.80 (0.317)
13a	74.3 (23.5)	112.7 (44.8)	38.4 (21.3)	Down	3.31 (10.4)	11.60 (2.04)	1.02 (0.180)
13b	78.0 (25.6)	149.5 (65.3)	71.5 (37.9)	Down	5.89 (18.6)	12.14 (2.14)	1.73 (0.305)
14	66.4 (19.1)	29.1 (–1.61)	–3.73 (–20.7)	Up	–2.77 (–8.73)	13.47 (2.37)	1.23 (0.217)

* Btu/(ft^2·h) (W/m^2)
† ft^2·h·°F/Btu (m^2·K/W)

Table 8. LSCS Results for Argon-Filled GFPs

	Summer Condition	Winter Condition
Test sequence	15	16
Gypsum temperature, °F (°C)	74.5 (23.6)	67.1 (19.5)
Roof deck temperature, °F (°C)	150.1 (65.6)	27.9 (–2.28)
Heat flux, Btu/ft^2·h (m^2·K/W)	3.06 (9.65)	–2.05 (–6.47)
Overall thermal resistance	24.7 (4.35)	19.1 (3.36)
Average batt temperature, °F (°C)	92.8 (33.8)	53.4 (11.9)
Batt R-value (RSI)	11.8 (2.08)	13.6 (2.40)
Batt R-value increase (RSI)	0.55 (0.10)	–0.20 (–0.04)
Batt + joist R-value (RSI)	16.8 (2.96)	17.1 (3.01)
GFP R-value (RSI)	5.60 (0.99)	4.50 (0.79)
Attic air R-value (RSI)	7.93 (1.40)	1.98 (0.35)
Attic air R-value (RSI) increase due to radiant barrier	6.16 (1.08)	0.72 (0.13)
Added R-value (RSI) due to GFPs	**12.3 (2.17)**	**5.0 (0.88)**

filled GFPs installed perpendicular to the ceiling joists and above the fiberglass batt insulation. The average thickness of the argon-filled panels determined at the end of the ASTM C 1363 tests was 1.6 in. (40.6 mm). The GFPs added thermal resistance to both the heat-flow path through the regions between joists and the heat-flow path through the joists. As a result, the R-value installed between the joist is increased, the thermal resistance through the joists is increased, and the thermal resistance of the attic air space is increased since the GFPs have a low-emittance exterior surface. The thermal resistance of the batt insulation is a function of temperature, which changes when GFPs are added. Table 8 contains results for the argon-filled GFPs. Table 9 contains the data for air-filled panels. The average thickness of the air-filled panels was 1.8 in. The observed difference in average thickness accounts for the R for air-filled GFPs being equal or larger than the R for the argon-filled GFPs.

Test 17r demonstrated the reproducibility of the test procedure. The difference between the two measurements for air-filled GFPs in summer conditions was less than 2%.

CONCLUSIONS

This research provides a comparison of the performance of two types of GFPs installed on top of fiberglass batt insulation on the floor of a residential attic module.

The installation of both air-filled GFPs and argon-filled GFPs on top of fiberglass insulation results in added thermal resistance in the attic space during both summer and winter conditions. Three components of the increase in attic thermal resistance were measured. Material R-values in the range of 4.5 to 5.6 ft^2·h·°F/Btu (0.79 to 0.99 m^2·K/W) were determined for the argon-filled GFPs. R-values in the range of 4.6 to 5.9 ft^2·h·°F/Btu (0.81 to 1.04 m^2·K/W) were determined for the air-filled GFPs.

The installation of GFPs on top of fiberglass batts resulted in a reduction in the operating temperature of the batts in the

Table 9. LSCS Results for Air-Filled GFP

	Summer Condition		Winter Condition
Test sequence	17	(17r)	18
Gypsum temperature, °F (°C)	74.5 (23.6)	74.5 (23.6)	67.1 (19.5)
Roof deck temperature, °F (°C)	150.0 (65.6)	150.2 (65.7)	28.7 (–1.83)
Heat flux, Btu/ft^2·h (m^2·K/W)	3.04 (9.59)	3.07 (9.68)	–2.03 (–6.40)
Overall thermal resistance	24.8 (4.37)	24.7 (4.35)	18.9 (3.33)
Average batt temperature, °F (°C)	92.6 (33.7)	92.7 (33.7)	53.9 (12.2)
Batt R-value (RSI)	11.87 (2.09)	11.87 (2.09)	13.30 (2.34)
Batt R-value increase (RSI)	0.56 (0.099)	0.56 (0.099)	–0.07 (–0.012)
Batt + joist R-value (RSI)	17.08 (3.01)	16.99 (2.99)	17.23 (3.03)
GFP R-value (RSI)	5.91 (1.04)	5.82 (1.03)	4.63 (0.815)
Attic air R-value (RSI)	7.78 (1.37)	7.66 (1.35)	1.72 (0.303)
Attic air R-value (RSI) increase due to radiant barrier	6.01 (1.06)	5.89 (1.04)	0.46 (0.081)
Added R-value (RSI) due to GFPs	**12.5 (2.20)**	**12.3 (2.17)**	**5.0 (0.88)**

summer simulations with a resulting increase in the R-value of the batts of 0.56 ft^2·h·°F/Btu (0.099 m^2·K/W).

The added thermal resistance of the attic air space above the GFPs averaged 6.0 ft^2·h·°F/Btu (1.06 m^2·K/W) for summer conditions. The overall increase in the attic thermal resistance was determined to be 12.3 ft^2·h·°F/Btu (2.17 m^2·K/W), while the average for simulated winter conditions was 5.0 ft^2·h·°F/Btu (0.88 m^2·K/W).

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