Nano-Scale Insulation at Work: Thermal Performance of Thermally Bridged Wood and Steel Structures Insulated with Local Aerogel Insulation

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ABSTRACT

Aerogel, an extremely light, nano-scale thermal insulation, which is popularly called "frozen and smoke," has been known since the early 1930's. For many years it had been only an object of research studies without any specific practical applications. Finally, during the last two decades this material began to be used by different industries. The best-known historical application of aerogel insulation was in NASA's space suits. Now, flexible fiber-reinforced aerogel composites are studied for use as insulation materials for a future Moon and Mars exploration [Tang 2006]. Underwater insulation for oil pipelines is another current application of aerogel insulation.

During 2005 and 2006, the Oak Ridge National Laboratory (ORNL) Buildings Technology Center (BTC) team analyzed the potential for the application of aerogel insulation in building envelope components. Due to the relatively high price of this material, its application was considered only in locations where high-R-value insulation is needed and can be economically justified. Three-dimensional computer simulations helped in this task. Next, a series of hot-box tests were performed on residential steel and wood-framed walls and commercial low-slope roofs. In all tested applications aerogel was used as a local thermal insulation in areas with limited space.

This paper discusses thermal performance predictions and experimental results of the first-ever, full-scale, tests performed on wall and roof assemblies using aerogel insulation. For many building envelope applications with limited space aerogels can be an effective remedy for intense thermal bridging. High flexibility and good thermal insulation properties of fiber-reinforced silica aerogel composites make it a promising insulation candidate for future buildings.

INTRODUCTION

Aerogels are insulation materials of very low-density that exhibit extraordinarily low thermal and acoustic conductivities. They were developed by Steven Kistler in 1931 [Kistler - 1931, Kistler - 1932]. The first aerogels were based on silica gels. Aerogels are open cell nanoporous materials usually made from gels where the liquid component of the gel is replaced with gas. Their unique physical properties include the highest thermal resistivity, the highest specific surface area, the lowest density, the lowest refractive index, and the lowest dielectric constant of all solid materials. These properties give aerogels the potential for a wide range of unique applications.

Aerogels can be made of many different materials; Kistler's work involved aerogels based on silica, alumina, chromia, and tin oxide. Aerogels typically consist from 90 to 99.8% of air. They are composed of a network of interconnected nanoparticles. Their nanoscale structure resembles a sponge. Today, the term "aerogel" is typically used for silica (SiO_2), aerogel, which is especially a good conductive insulator; due to the fact that silica is a relatively poor heat conductor because its fine particles disrupt gas-phase conduction.

Today aerogels are produced of many additional materials including silica alumina (Al_2O_3), metal oxides, metal chalcogenides (such as CdS and CdSe), organic and inorganic polymers, and carbon. Carbon aerogels are good insulators as well,

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because carbon absorbs infrared radiation. They were first developed in the early 1990s [Pekala - 1989].

APPARENT THERMAL CONDUCTIVITY MEASUREMENTS OF AEROGEL INSULATING BLANKETS

In this project, fiber-reinforced silica aerogel composites were used as building component insulations. The apparent thermal conductivity of commercially-available aerogel insulating blanket was measured using a heat-flow meter apparatus operated in accordance with ASTM C518 procedure [ASTM - 1991] with a mean specimen temperature of 70^{o}F (21^{o}C). The density of the tested aerogel blanket was about 9 lb/ft^3 (144 kg/m^3). The measured apparent thermal conductivities were used as an input in finite difference computer simulations utilized for thermal performance predictions of building envelope components. Results of the thermal measurements for the aerogel insulation material are presented in Table 1. The same insulation material was used for the hot-box experiments presented in this paper.

PROTOTYPE WOOD-FRAMED WALL WITH AEROGEL STRIPS INSTALLED ON STUDS

Two configurations of 2x4 wood framed walls insulated with prototype 3-in. (7.6-cm.) thick fiberglass batts and ½-in. (1.27-cm.) thick layer of the sprayed polyurethane (PU) foam were tested in the guarded hot box using ASTM C-1363 procedure [ASTM - 1997]. In both walls 2x4 wood studs were installed 16-in. (40.6-cm.) on center and ½-in. (1.27-cm.) thick oriented stand board (OSB) sheathing was used. Sprayed open-cell PU foam was installed on both walls over the OSB sheathing. On the opposite side of the wall ½-in. (1.27-cm.) thick gypsum board was installed which is depicted in Figure 1. As stated above, in this wall, prototype 3-in. (7.6-cm.) thick fiberglass batts R-12 (2.11 m^{2}K/W) were used together with ½-in. (1.27-cm.) thick PU foam. Comparing to the conventional wall assembly with R-15 fiberglass batts, installation of sprayed PU foam of effective thermal resistivity, about R-3 per inch (20.80-mK/W) replaced ½-in. (1.27-cm.) thick layer of better-insulating fiberglass. According to the supplier of this wall system, the primary role for the PU foam was enhancement of air and moisture tightness.

Designers of this novel wall configuration tried to match or exceed the thermal performance of the conventional 2x4 wood stud wall insulated with R-15 (2.64 m^{2}K/W) fiberglass batts. To help in thermal wall design, three dimensional finite difference modeling, using Heating-7.3 computer code [Childs - 1993] was utilized. For the conventionally-arranged 2x4 wood stud wall insulated with R-15 (2.64 m^{2}K/W) fiberglass batts, finite difference computer simulation yielded surface-to-surface R-value of 13.4-hft^{2}EF/Btu (2.36 m^{2}K/W). For the wall configuration presented on Figure 1, computer-generated surface-to-surface R-value was only 11.86-hft^{2}EF/Btu (2.09 m^{2}K/W). The above modeling showed a significant R-value gap between the two above walls, being most-likely a result of replacement of the R-15 (2.64 m^{2}K/W) fiberglass batts by less-insulating the configuration of open-cell PU foam and fiberglass.

In the next step, aerogel insulation was utilized to help in reaching the target R-value of the 2x4 wall insulated with R-15 batts. The second wall configuration that was simulated was similar to the one from Figure 1. Wood studs were additionally insulated with ¼-in. (0.6-cm.) thick and 2.5-in. (6.35-cm) wide aerogel strips (due to the installation of aerogel, the total thickness of the wall was increased as well). As shown in Table 1, the tested thermal resistivity of the aerogel insulation was R-10.14 per in. (70.3 mK/W). Figure 2 shows configuration of the wall containing aerogel local insulation. Simulated surface-to-surface R-value for this wall configuration was 13.47-hft^{2}EF/Btu (2.37 m^{2}K/W). The target R-value of the 2x4 wall insulated with R-15 batts was met.

Next, as described above, configurations of 2x4 wood frame walls insulated with prototype 3-in. (7.6-cm.) thick fiberglass batts and ½-in. (1.27-cm.) thick layer of the sprayed PU foam were tested in the guarded hot box using ASTM C-1363 procedure. During both tests, temperature differences across the hot box were about 50^{o}F (28^{o}C) with the mean temperatures close to 75^{o}F (23.9^{o}C).

To enable direct comparisons between different wall configurations, most of the lightweight walls hot-box tested by ORNL used the same temperature profiles. Historical hot-box test data is available at the ORNL Building Envelopes Program homepage: http://www.ornl.gov/sci/roofs+walls/AWT/Ref/TechHome.htm.

For the wall specimen containing 3-in. (7.6-cm.) thick fiberglass batts and approximately ½-in. (1.27-cm.) thick layer of the sprayed PU foam (as shown in Figure 1), the surface-to-surface R-value was R-12.20 hft^2 F/Btu (2.15 m^{2}K/W). During foam installation, the thickness of the spayed PU foam was difficult to control, that is why tested wall configuration cannot be considered as fully equivalent to the wall presented on the Figure 1. Hot-box test of the wall specimen containing wood studs insulated with ¼-in. (0.6-cm.) thick aerogel strips, 3-in. (7.6-cm.) thick fiberglass batts, and ½-in. (1.27-cm.) thick layer of the sprayed PU foam (as shown in Figure 2), yielded surface-to-surface R-value of R-13.26 hft^2 F/Btu (2.33 m^{2}K/W).

TESTING OF THE STEEL FRAME WALL WITH AEROGEL STRIPS INSTALLED ON STUD FLANGES

Two configurations of steel-framed walls insulated with R-13 (2.29 m^{2}K/W), 3.5-in. thick – (8.9-cm.) fiberglass batts were tested. In these walls, 2x4 steel studs were installed 24-in. (61-cm.) on center as shown on Figure 3. Conventional ½-in. (1.27-cm.) thick OSB sheathing and ½-in. (1.27-cm.) thick gypsum boards were used for exterior and interior wall finish. In these test configurations clusters of steel studs with the internal spaces between stud flanges and stud webs were uninsulated.

Table 1. Thermal Conductivity of the Aerogel Insulation Material—ASTM C518 Test Results

Insulation Thickness as Tested, in. (mm)	Size of the Test Sample, in. (mm)	Conductivity k_a, Btu·in./h ≅ ft^2 ≅ EF (W/m·K)	Resistivity R/in., h ≅ ft^2 ≅ EF/Btu·in. (m·K/W)
0.292 (7.4)	12 × 12 (305 × 305)	0.099 (0.014)	10.14 (71.42)

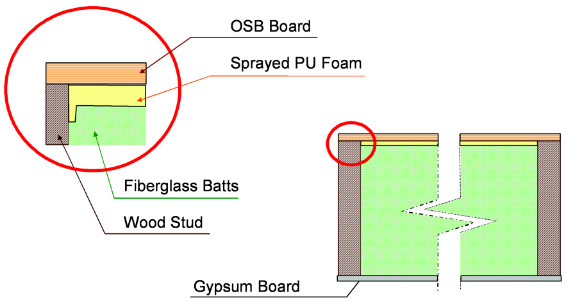

Figure 1 *Material configuration for the hot-box test of the wall using fiberglass and foam cavity insulation.*

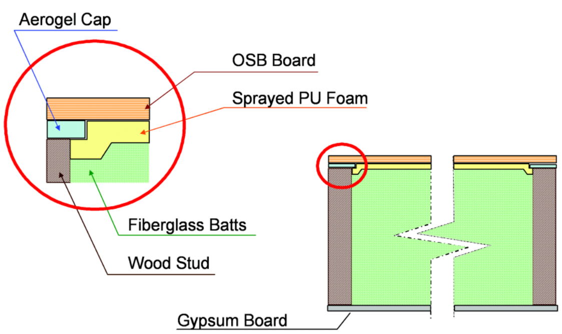

Figure 2 *Wall configuration for the hot-box test with aerogel caps.*

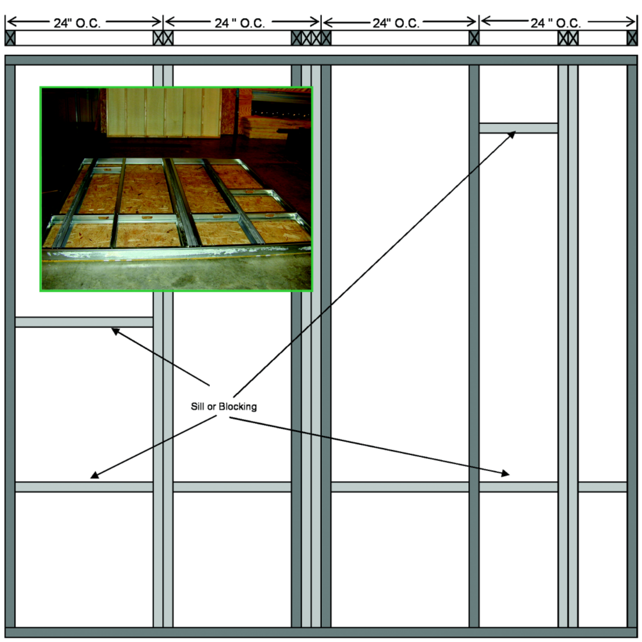

Figure 3 *Configuration of the test steel stud walls.*

A 2002 report prepared by Enermodal Engineering for the California Energy Commission, reports 27% framing in current residential walls in California [CEC -2001]. A similar study performed by ASHRAE in 2003 concluded an average 25% of framing factor for all US residential buildings [Carpenter - 2003]. Assuming that 25% of framing was computed for 16-in. stud spacing (dominant in wood-framed walls), described above, test steel stud walls with 24-in. stud spacing had the amount of framing close to 22%.

In these walls, due to the complex geometry, cavity fiberglass batts were custom-cut for each specific cavity, to ensure a perfect fit.

The second of tested steel stud walls was additionally insulated with ¼-in. (0.6-cm.) thick and 2.5-in. (6.35-cm.) wide aerogel strips, which were installed on top of the stud flanges on the side where gypsum board was used.

Both the walls described above were tested using ASTM C-1363 procedure. During both tests, the temperature difference across the hot box was about 50^{o}F (28^{o}C) with the mean temperatures close to 75^{o}F (23.9^{o}C). For the wall specimen containing only R-13 (2.29 m^{2}K/W) fiberglass insulation in the wall cavity, the surface-to-surface R-value was R-6.09 hft^2 F/Btu (1.07 m^{2}K/W). Hot-box tests of the wall specimen containing steel studs insulated with ¼-in. (0.6-cm.) thick aerogel strips yielded surface-to-surface R-value R-7.84 hft^2 F/Btu (1.38 m^{2}K/W).

Steel framed walls, due to intense thermal bridging caused by the steel structural members, have relatively low thermal resistance in comparison with wood framed assemblies [Kosny et. al. – 1997, NAHB – 1994]. Another often-reported problem associated with the steel framing is significant temperature variations on the wall internal surfaces. The places over the steel profiles represent usually significantly different temperatures from areas adjacent to wall cavities. Sometimes, a notable discoloration can be observed in these areas as well. The authors believe that the local aerogel insulation can be used to reduce this effect.

A series of finite difference simulations were utilized to investigate potential improvements in surface temperature distribution in steel-framed walls. Material configurations of simulated assemblies were identical to the steel-framed walls used for hot-box testing. Figure 4 depicts temperature fields in simulated walls. Simulated temperature difference across both walls was 50^{o}F (28^{o}C) - with interior air temperature 70^{o}F (21.1^{o}C) and ambient air temperature 20^{o}F (-6.7^{o}C). In case of the wall using only fiberglass batt insulation, the surface temperature difference between center of the cavity and the

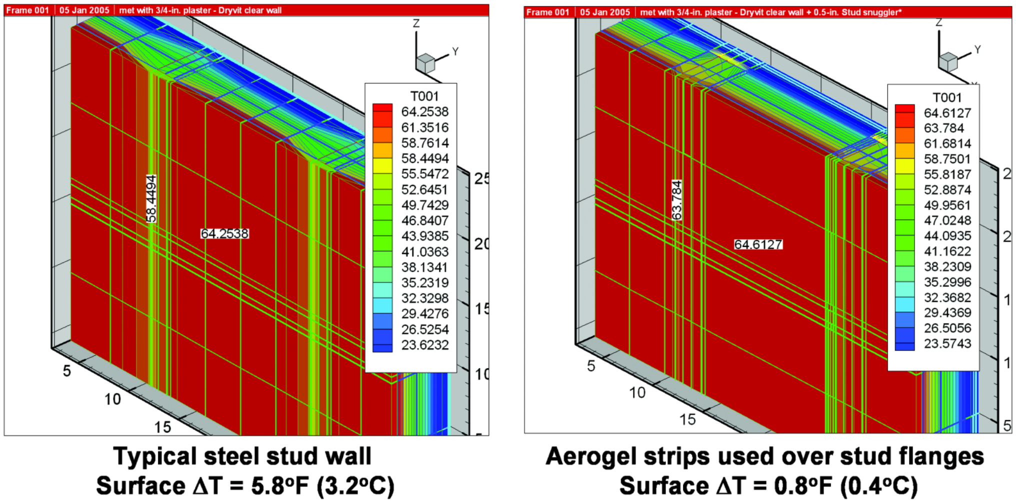

Figure 4 *Simulated temperature fields on the interior-wall surfaces in two configurations of steel-frame walls.*

stud location was 5.8°F (3.2°C). For a wall with additionally installed aerogel strips, this difference was only 0.8°F (0.4°C).

HOT-BOX TESTS OF THROUGH-FASTENED METAL ROOF ASSEMBLIES WITH AEROGEL STRIPS INSTALLED OVER THE PURLINS

A series of steady-state guarded-hot-box tests of commercial metal roofs using aerogel as a local thermal insulation have been completed. The purpose of the tests was to determine the potential for increase in the R-value of through-fastened metal roofs using local aerogel insulation as a thermal block installed over the purlins, as shown in Figure 5. Two sizes of 3-in. and 5-in. (7.6-cm and 12.7-cm) wide 3/8-in. (1-cm) thick aerogel strips were used on top of the steel purlins in areas where fiberglass blanket is compressed with associated reduction of thermal resistance.

As shown in Figure 6, the aerogel was an addition to the compressed fiberglass insulation that was draped over and between the purlins. Three assemblies were constructed to fit the 8 ft. (244-cm) wide metered area of the guarded hot box. Tests were performed with two purlins installed 4 ft. on center (122 cm.).

The test assemblies used 14 gauge steel purlins 8.5-in. (21.6-cm.) high with 3-in. (7.6-cm.) wide flanges. The purlins were covered by fiberglass metal building insulation, faced with plastic scrim kraft (PSK) standard facing, and 24 gauge steel roof deck, through-fastened at 1-ft. (30.5-cm.) intervals with #12 fasteners. When fully expanded to 5.2 in. (13.2-cm) thickness, the nominal R-value of the fiberglass insulation was 19 h•ft•°F/Btu (3.35 m^2K/W). The fiberglass insulation was compressed to 0.58-in. (1.5-cm.) over the purlins and 0.28-in. (0.7-cm.) near the screws.

When aerogel insulation strips were used over the purlins and under the fiberglass, they, too, were compressed from their nominal 0.375 in. (0.95 cm.) thickness. The compressed thickness was 0.25 to 0.34 in. (0.6 to 0.9-cm.) over the purlins and 0.13 to 0.18 in (0.3 to 0.5-cm.) near the screws. The vertical walls of the metering chamber were extended to the bottom of the insulation facing with custom cut pieces of polystyrene foam to match the contour of the insulation between the purlins.

During the tests air temperatures of 100°F (38°C) below and 50°F (10°C) above the assemblies were imposed, yielding a mean fiberglass insulation temperature of about 75°F (24°C) for all tests. The compressed fiberglass and aerogel insulations over the purlins were at about 50°F (10°C) during the tests.

Table 2 lists the detailed results of the tests with two purlins in the metered area – equivalent of 4-ft (122-cm.) spacing. In all tests, the climate chamber air temperature was controlled to 50.0°F (10°C) and the metering chamber air temperature was controlled to 100.0°F (38°C).

Analysis of the test results presented in Table 2 showed that 5-in. (12.7-cm.) wide aerogel strips were very close in thermal performance to 3-in. (7.62-cm.) wide strips. It could be caused by an extra compression of the fiberglass on the edges of the purlin flanges - made by the wider aerogel strips. A complex geometry of the fiberglass insulation (which was very difficult to reproduce during the following tests) is an additional important factor to consider when analyzing these test results.

Summarizing, the hot-box test of the prototype commercial metal roof using aerogel as a local thermal insulation, demonstrated a notable improvement of the thermal performance. Wider aerogel strips performed slightly better. It was found that 5-in (12.7-cm.) wide 3/8-in. (0.95-cm.) thick aerogel strips improved overall roof R-value by about 14%. More research with thicker (maybe 0.5-in. or 1.27-cm. thick) and less compressible aerogel material is needed to fully evaluate a real potential of using aerogel profiles for a local insulation of the commercial metal roofs.

Figure 5 *Installation of the aerogel strips on top of the steel purlins.*

Figure 6 *Installation of the fiberglass insulation and through-fastened steel-roof deck over the experimental roof.*

Table 2. Results of Guarded Hot-Box Tests for Through-Fastened Metal Roof Assemblies with no 3 in. (7.6 cm) wide and 5 in. (12.7 cm) wide strips of aerogel over two purlins in the metered area.

	Imposed Temperatures		Measured R-Values			Temperatures Across Assembly			
Aerogel	Climate Air	Meter Air	R_{system}	$R_{top\ film}$	$R_{bottom\ film}$	T_{mean}	T_{surf}	Top Surface	Bottom Air
	°F		h·ft·°F/Btu			°F			
None	50.14	100.04	10.05	0.45	0.36	75.31	–45.85	52.39	99.95
3 in.	49.91	99.96	11.40	0.49	0.41	75.10	–46.11	52.05	99.84
5 in.	50.00	99.97	11.45	0.51	0.40	75.22	–46.00	52.21	99.85
	°C		m^2K/W			°C			
None	10.08	37.8	1.77	0.08	0.06	24.06	–25.47	11.32	37.75
7.6 cm	9.95	37.75	2.01	0.09	0.07	23.94	–25.61	11.14	37.69
12.7 cm	10.00	37.76	2.02	0.09	0.07	24.01	–25.55	11.23	37.69

The above experimental study showed some potential for an application of aerogel as a local insulation in commercial roofs. However, since aerogel is a new material for building envelopes, it requires more work with a special emphasis on improvement of mechanical properties (resistant to compression) and optimization of dimensions for each specific application.

CONCLUSIONS

Analytical and experimental analysis was performed to investigate the potential for building envelope applications of the aerogel insulation in areas with limited space. This paper presented results of analytical thermal performance predictions and experimental data from tests performed on wall and roof assemblies using aerogel insulation.

1. Hot box measurements performed on the wall assemblies using ¼-in. (0.6-cm.) thick aerogel strips demonstrated a good potential for thermal improvement:
    - R-value of the prototype wood-frame wall containing 3-in. (7.6-cm.) thick fiberglass batts and ½-in. (1.27-cm.) thick layer of the sprayed polyurethane foam was improved by about 9%.
    - R-value of the 2x4 steel-framed wall containing

R-13 (2.46 m^2K/W) fiberglass insulation in the wall cavity was improved by about 29%.

2. Finite difference simulations performed on steel-framed wall assemblies using ¼-in. (0.6-cm.) thick aerogel strips showed that aerogel can help in reduction of the surface thermal effects generated by highly-conductive structural steel members. Internal surface temperature differences between the center of the cavity and the stud location were reduced from 5.8°F (3.2°C) to only 0.8°F (0.4°C).
3. In commercial metal roofs aerogel strips can be easily installed on top of the purlin flanges to reduce strong thermal bridges generated by the steel profiles and compressed fiberglass insulation.
4. Hot box measurements performed on the through-fastened metal roof insulated with 5-in (12.7-cm.) wide 3/8-in. (0.95-cm.) thick aerogel strips, showed an increase in the overall roof R-value by about 14%.
5. During hot box tests of the through-fastened metal roof insulated with 3/8-in. (0.95-cm.) thick aerogel strips, the aerogel insulation was severely compressed. The compression rates were between 9% and 33% over the purlins, and 52% to 65% near the screws.

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