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ABSTRACT

This paper discusses the application of Gas-Filled Panels to the building thermal envelope. Gas-Filled Panels, or GFPs, are thermal insulating devices that retain a high concentration of a low-conductivity gas, at atmospheric pressure, within a multilayer infrared reflective baffle. The thermal performance of the panel depends on the type of gas fill and the baffle configuration. Heat-flow meter apparatus measurements have shown effective apparent thermal conductivities of 0.194 Btu·in/h·ft^{2}·°F (0.028 W/m·K) with air as the gas fill, 0.138 Btu·in/h·ft^{2}·°F (0.020 W/m·K) with argon, and 0.081 Btu·in/h·ft^{2}·°F (0.012 W/m·K) with krypton. Calorimetric measurements have also shown total resistance levels of about R-12.6 h·ft^{2}·°F/Btu (2.21 m^{2}·°C/W) for a 1.0-inch (25.4 mm) thick krypton panel, R-25.7 h·ft^{2}·°F/Btu (4.52 m^{2}·°C/W) for a 2.0-inch. (50.8 mm) krypton panel, and R-18.4 h·ft^{2}·°F/Btu (3.24 m^{2}·°C/W) for a 1.0-inch. (25.4 mm) xenon panel. GFPs are flexible, self-supporting and can be made in a variety of shapes and sizes to thoroughly fill most types of cavities in building walls and roofs, although the modular nature of the panels can lead to complications in installing them, especially for irregularly shaped cavities. We present computer simulation results showing the improvement in thermal resistance resulting from using an argon-GFP in place of glass fiber batt insulation in wood-frame construction. This report also presents estimates of the quantity and cost of material components needed to manufacture GFPs using current prototype designs.

INTRODUCTION

Insulation materials are critical in buildings designed for low energy use and good thermal comfort. Increasing the overall level of thermal resistance, or R-value, of the insulation is an effective strategy to lower heating costs when thermal loads are dominated by the building envelope. Building codes require the installation of minimum levels of insulation and in many locations, codes have increased R-value requirements in recent years because of growing concern to reduce energy use in buildings. Although most builders simply meet the code requirements for R-values, if insulation exceeds code requirements significantly, we can achieve building envelopes that combine high levels of insulation with appropriate air/moisture barriers and high-performance windows to eliminate the need for heating altogether; solar and internal heat gains are sufficient to heat such a building.

In order to attain higher R-values, traditional insulation materials, such as batts, loose-fills, and foam boards, are typically used in increasing thicknesses and increased densities. Foam board insulations are commonly used in a nearly continuous layer of semistructural insulated sheathing, which has the advantage that thermal bridges through the primary structural parts are significantly reduced. The better foam sheathing products trap low-conductivity chemical gases inside closed cells. However, most traditional insulations rely on trapping air in the material to achieve low effective conductivity. An advanced insulation system known as Gas-Filled Panels (GFPs) traps low-conductivity inert gas rather than air in an attempt to improve R-values. GFPs are one of a new generation of advanced insulation technologies being developed that offer improved thermal performance compared to traditional materials.

GFPs offer the potential to achieve super insulated-buildings that do not require heating energy and at the same time reduce buildings costs without requiring major changes in typical framing. Currently, in many parts of the country, small houses that would have been built with 2x4 construction are now built with 2x6 construction to allow wall cavities large enough to accommodate R-19 glass fiber batts or cathedral ceilings are built with 2x12 construction to allow R-30 insulation even though structural requirements would not always require such large dimension lumber. In contrast, GFPs can achieve R- 19 in 2x4 cavities and R-30 in 2x6 cavities. To date however, there has been little effort to develop GFPs for buildings because research has focused on applications in refrigerators. Lawrence Berkeley National Laboratory has been researching Gas-Filled Panel technology since 1989 and a number of earlier papers describe more details [Griffith 1991, Griffith 1992]. This paper summarizes GFP technology, results of thermal evaluations of prototype GFPs, results of two-dimensional computer simulations of GFPs in wood building construction, and discusses issues related to applying the technology to the building envelope.

TECHNOLOGY SUMMARY

Gas-Filled Panels are composed of thin polymer films and a low-conductivity gas, in contrast to most other advanced insulation technologies, which maintain a vacuum inside. GFPs are essentially hermetic plastic bags that have a box-like shape. Two types of thin films are used in GFPs. Metalized films are used in a bonded assembly called the ***baffle,*** which produces a cellular structure inside the panel. Low-diffusion gas barrier films are used in a hermetic ***barrier*** that retains the panel's gas fill. The baffle suppresses convection and radiation, and the barrier allows control of the fill gas. The resulting panel thermal performance approaches the level of the fill gas's still thermal conductivity.

Gases

The leading candidates to fill GFPs are the inert noble gases, argon and krypton. These gases have lower still gas conductivity than air, which allows for high levels of thermal performance. Air-filled panels yield an effective apparent conductivity of about 0.2 Btu·in/h·ft^2·°F (0.029 W/m·K), which means that, if the panel fails or is punctured and air leaks in, the panel still has relatively low conductivity. Argon appears to be the best choice for most building envelope applications because of its abundance and low cost (about $0.002/liter). It is already contributing to significant increases in the performance of building thermal envelopes because of its widespread use in the insulated glazing units of modern windows. Like the other inert, noble gases, argon is distilled from the atmosphere and its subsequent release back to the atmosphere would not contribute to global warming or to ozone depletion. The effective apparent conductivity of a GFP filled with argon is about 0.14 Btu·in/h·ft^2·°F (0.020 W/m·K), similar to the level achieved by the best foam board insulations currently used in buildings. Krypton yields GFPs with a much lower effective apparent conductivity of about 0.08 Btu·in/h·ft^2·°F (0.012 W/m·K). Krypton is useful for situations, such as refrigeration, where space is limited, R-values must be high, and the temperature differential is great; however its relative scarcity and higher cost (about $0.35/liter) make it a poor candidate for wide application in the building envelope. Xenon is expected to yield GFPs with an extremely low effective apparent conductivity of about 0.055 Btu·in/h·ft^2·°F (0.008 W/m·K). The cost of xenon (about $4.00/liter), however, makes it useful for only exotic applications. Current long-term research is focused on exploring new cheaper techniques for distilling krypton and xenon from the atmosphere. A host of other chemical gases are being investigated as long-term replacements for ozone-depleting chlorofluorocarbons (CFCs) and many could also be given consideration for use in GFPs.

Baffle

The baffle of a GFP is a specially designed reflective insulation composed of many layers of continuous thin films that are adhered to each other in a pattern of lines. It is assembled in a flat stack and expanded to create a series of cavities or cells. The cellular structure is expanded by bonding both faces to the barrier envelope, which is forced apart by the gas fill. A GFP baffle differs from most radiant barrier and reflective insulations in that convection is more thoroughly suppressed. This design results in an effective resistivity that is more like a traditional insulation in which the overall resistance varies uniformly with thickness. Most GFP baffles have geometry similar to the honeycomb cores of sandwich panels though the core stacks are not sliced and are used in a perpendicular orientation. Reflective properties are imparted to the polymer film substrate from an aluminum coating deposited using vacuum vapor techniques, a metalizing process that is also widely used to make barrier film for food packaging. A baffle typically has cavities that are open to the edges of the panel to allow removal of air and subsequent filling with the desired gas. The baffle also helps the panel maintain its desired shape.

One important design parameter is the number of cavities used in the baffle. Previous work by the authors discusses this in more detail [Griffith 1993]. More baffle layers improve thermal performance until the baffle material itself becomes a significant fraction of the gas volume. Using more layers, however, also results in greater cost with a diminishing return on thermal performance improvement. There is usually an optimal number of baffle layers to use for a panel with a specific gas fill and thickness and also for the temperature differential found in the insulation application.

Barrier

The barrier component is a hermetically sealed enclosure that retains the desired fill gas. Most GFP barriers are flexible bags made from food packaging film that is sealed around the perimeter of the panel. Panel shape is attained because the film is folded, sealed, and supported by the baffle and the gas. GFPs can also use thermoformed barrier material where the desired shape is molded into the polymer. The barrier is usually bonded to the faces of the baffle which helps to maintain a flat aspect.

The multilayer film technology used in barriers already exists: multilayer films combine the properties of different polymers to make a durable, easily sealed film that has a low rate of diffusion for gas molecules.

THERMAL EVALUATION

Prototype GFPs have been measured for their effective apparent thermal conductivity. This paper presents recent heat flow meter apparatus measurements conducted by Oak Ridge National Laboratory (ORNL). Thermal performance results are also presented from recent calorimetric measurements conducted by the National Institute of Standards and Technology (NIST). Hot box measurements of wall assemblies have not been made; building wall performance is, therefore, assessed by modeling thermal bridging through framing components using a two-dimensional, finite element analysis, heat transfer code called THERM.

Center-of-Panel Measurements

Prototype GFPs have been fabricated to fit into a commercial heat flow meter apparatus (HFMA) and have been measured by Oak Ridge National Laboratory using the standard test procedure ASTM C-518, which is for evaluating homogeneous insulation materials. Although GFPs are not homogeneous, this type of testing is conducted on advanced insulations in order to gain an understanding of the center-of-panel performance. Table 1 shows the results of selected measurements [Graves 1993, 1994]. Two different HFMAs were used in these measurements. The 12-inch (300 mm) unit has a metering area of three inches (75 mm) square and was operated at a mean temperature of 75.0°F (23.9°C). The 24 inch (600 mm) unit has a metering area of 10 inches (250 mm) square and was operated at mean temperature of 74.7°F (23.7°C).

Table 1. Heat Flow Meter Apparatus Measurements of GFP Prototypes

Panel ID	HFMA Size		Gas	Specimen Thickness		Effective Thermal Conductivity	
	in	mm		in	mm	W/m·K	Btu·in/h·ft^2·°F
262	12	300	krypton	1.07	27.3	0.0117	0.081
229	12	300	argon	1.01	25.7	0.0199	0.138
192	24	600	argon	2.77	70.4	0.0206	0.143
233	12	300	air	1.04	26.3	0.0279	0.194

Whole Panel Measurements

To address the lack of a standardized test procedure for nonhomogeneous advanced insulations, a new procedure based on calorimetric techniques is being used at the National Institute of Standards and Technology [Fanney 1994]. For this procedure, three prototype GFPs were assembled to fit an existing mask wall opening that measured 27.2 inches (0.69 m.) wide by 17.3 inches (0.44 m.) high. The calorimetric procedure measures the heat flowing through the entire specimen and mask wall where flow is driven by different air temperatures. This technique has two advantages: the whole panel (including the barrier) is measured, and the resulting temperature distribution in the panel is more typical of a real installation than the isothermal contacting plates of a heat flow meter apparatus. Table 2 lists preliminary results of the first GFP prototype tests using this new technique [Fanney 1995]. These results are not yet corrected for the three-dimensional heat transfer between the panel and the mask wall which have different thicknesses; this correction typically alters values by less than 3%. These prototypes use krypton and xenon gas fills in order to show the high performance capabilities of GFP technology even though these gases are not suggested for widespread use in building thermal envelopes. Note that the lower mean temperature of the calorimeter testing results in improved resistance compared to the standard mean temperature of 75°F (24°C) because of the reduced conductivity of the fill gas at lower temperatures.

Table 2. Preliminary Results of Calorimeter Measurements of Krypton and Xenon Prototype GFPs from the National Institute of Standards and Testing

Panel Type	Thickness at Room Temperature in. (mm.)	Mean Test Temperature °F (°C)	Total Resistance h·ft^2·°F/Btu (m2·°C/W)
Krypton-GFP	1.0 (25.4)	45.1 (7.3)	12.6 (2.21)
Krypton-GFP	2.0 (50.8)	54.1 (12.3)	25.7 (4.52)
Xenon-GFP	1.0 (25.4)	52.7 (11.5)	18.4 (3.24)

Wood-Frame Installation Thermal Modeling

Computer heat transfer modeling can estimate the effect of thermal bridging that results from framing materials. This thermal bridging tends to decrease the total resistance of the system compared to the level indicated by the R-value of the insulation in the cavities. THERM, a new Windows% o-based finite element analysis computer program, was used to model heat flow through wood-frame assemblies subjected to standard ASHRAE design conditions for heating [Arasteh 1995]. THERM is a two-dimensional, self-contained, finite element analysis program which returns U-values for the system being modeled. Table 3 shows calculated R-values of some wall and ceiling designs with glass fiber batt and argon-GFP insulations. These values are based on modeling heat flow through a stud and cavity wall section between the midpoints of two cavities. For comparison, one-dimensional values of the insulated cavity without the effect of the framing are also provided. The analysis does not include other potentially significant framing features such as plates and headers. Standard design film coefficients of 1.46 Btu/h·ft^2·°F (8.3 W/m·K) and 6.00 Btu/h·ft^2·°F (34 W/m·K) are applied to the warm and cold sides, respectively. Material conductivities are based on values from ASHRAE 1993 Fundamentals, except conductivities for argon-GFPs, which are assumed to perform at an effective apparent conductivity of 0.14 Btu·in/h·ft^2·°F (0.020 W/m·K).

Table 3. 2-D Finite Element Calculations of Wood-Frame Assembly Total Thermal Resistance with Glass Fiber Batts and Argon-Gas-Filled Panels

Wood-frame Wall Assemblies	Cavity Insulation	R-value of Insulated Cavity (without effect of studs)		R-Value with Studs (excludes plates & headers)	
		h·ft^2·°F/Btu	m^2·°C/W	h·ft^2·°F/Btu	m^2·°C/W
1/2" wood siding, 1/2" plywood, 2x4 studs 16" o.c., and 1/2" gypsum board.	R-13 batts	15.8	(2.8)	13.6	(2.4)
	Argon GFP	27.8	(4.9)	20.2	(3.6)
1/2" wood siding, 1" XEPS R-5, 2x4 studs 16" o.c., and 1/2" gypsum board.	R-13 fiber	20.2	(3.6)	18.1	(3.2)
	Argon-GFP	32.1	(5.7)	25.5	(4.5)
1/2" wood siding, 1/2" plywood, 2x6 studs 16" o.c., and 1/2" gypsum board.	R-19 fiber	23.6	(4.2)	19.8	(3.5)
	Argon-GFP	42.2	(7.4)	29.5	(5.2)
1/2" wood siding, 1/2" plywood, 2x8 studs 24" o.c., and 1/2" gypsum board	R-22 fiber	25.0	(4.4)	22.8	(4.0)
	Argon-GFP	56.5	(10.0)	43.3	(7.6)
asphalt shingles, 1/2" plywood, 2x12 rafters 24" o.c., 1 1/2" air gap, 1/2" gypsum board	R-30 fiber	34.4	(6.1)	30.4	(5.4)
	Argon GFP	75.8	(13.3)	56.8	(10.0)

Notes: o.c. = on center, XEPS = extruded expanded polystyrene

BUILDING THERMAL ENVELOPE APPLICATIONS

Gas-Filled Panel insulation systems offer an opportunity to achieve high levels of thermal resistance in building thermal envelopes. However, as of this writing, there has not been significant effort to develop the technology for such applications. Hence, the panel designs, characteristics, and installation methods discussed here are merely suggestions (based on experience) and should be considered examples rather than a description of a final product. There are many possible embodiments of GFP technology as a building insulation.

Figure 1 shows a cut-away view of a GFP as installed in a wood-frame wall assembly. In this example, panels are fastened to studs with staples through panel flaps. Adhesive backed tape is used to seal adjacent panels across the stud, so the insulation also becomes an air-barrier/moisture-retarder component of the building wall. The far face of the panel is intended to adhere to the exterior sheathing to provide added air sealing and to keep the panel expanded in thickness. This expansion is important in the event of a barrier puncture or other failure because, as long the panel does not collapse in thickness, there is only a 30% reduction in R-value if argon is replaced with air fill.

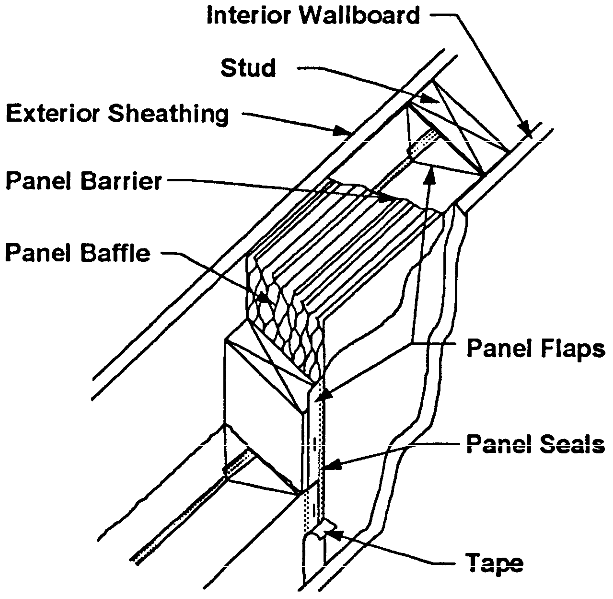

Figure 1. Gas-Filled Panel Installation in Stud Wall

Projected Component Costs

Comprehensive manufacturing and business analysis of GFPs has not been performed, so the expected price of GFP products is not available. However, the material components required to manufacture GFPs for building insulation are fairly well understood, so it is possible to characterize the quantity and costs of the material components required to assemble GFPs. Table 4 lists these projections for prototype building insulation panels. This analysis is based on panels with a length of 48 inches (1.2 m). The panel designs of Table 4 (cost projections) are the same as those for Table 3 (in-situ performance projections). These material components are commercially available; costs listed in Table 4 were gathered from suppliers and include supplier profit.

TABLE 4. GFP Material Component Quantity and Cost Estimates
per Unit Area of Insulation

Panel Type	Baffle Film		Barrier Film		Gas Fill		Adhesive		Total cost
cavity type, gas fill, thickness	lb/ft^2 (g/m^2)	\$/ft^2 (\$/m^2)	lb/ft^2 (g/m^2)	\$/ft^2 (\$/m^2)	l/ft^2 (l/m^2)	\$/ft^2 (\$/m^2)	in^3/ft^2 (cm^3/m^2)	\$/ft^2 (\$/m^2)	\$/ft^2 (\$/m^2)
2x4-16"o.c., Argon, 3.5 in. (89 mm)	0.17 (7)	0.46 (4.9)	0.060 (2.54)	0.18 (1.95)	8.4 (90)	0.02 (0.18)	0.39 (70)	0.03 (0.29)	0.69 (7.43)
2x6-16"o.c., Argon, 5.5 in. (140 mm)	0.24 (lo)	0.66 (7.1)	0.069 (2.9)	0.21 (2.22)	13.2 (142)	0.03 (0.28)	0.58 (102)	0.04 (0.42)	0.94 (10.10)
2x8-24"o.c., Argon, 7.5 in. (190 mm)	0.30 (13)	0.84 (9.0)	0.067 (2.8)	0.20 (2.16)	18.0 (194)	0.04 (0.39)	0.73 (129)	0.05 (0.54)	1.13 (12.16)
2x12-24"o.c., Argon, 10 in. (254 mm)	0.40 (17)	1.11 (12)	0.075 (3.2)	0.23 (2.43)	24 (258)	0.05 (0.52)	0.98 (172)	0.07 (0.72)	1.46 (15.72)

Panel Characteristics

The overall weight of GFPs is comparable to or less than the weight of traditional building insulations. Panel densities are usually about 0.6-0.9 lb/ft^3 (10-14 kg/ins). Density varies with panel size as the ratio of barrier film to panel volume changes with thickness and area. Stiffer kraft-based baffle materials will raise the density to about 3.0 lb/ft^3 (48 kg/m^3).

Because they are hermetically sealed, GFPs tend to be discrete and modular in size. Their exact volume can vary continuously depending on the amount of gas enclosed. GFPs tend to have anisotropic stiffness with little or no stiffness across the thickness (when point loaded) and some stiffness in the direction of adhesive lines within the baffle. This stiffness in the baffle may be used to friction-fit panels in cavities by sizing such that a small amount of interference exists. This interference fit is also part of the edge design within the panel and is necessary to seal off baffle cells at their edge. The sealed volume of gas is typically much less than the full potential volume of the barrier enclosure. The panel pressure, therefore, remains close to atmospheric pressure. Slight changes in panel volume arise from fluctuations in surrounding barometric pressure as well as in mean temperature. In situations where the panel is loaded from all directions, panel pressure can exceed atmospheric and thus generate substantial, spring-like distributed forces which are limited by the film and seal strength.

The barrier film exterior of the panel offers a nearly impermeable barrier to air and water transmission: in other words, GFPs are essentially waterproof and airtight insulation so their thermal performance should be unaffected by wind wash or water migration. These qualities allow the insulation to be integrated with the air barrier and moisture retarder components of the building envelope.

Environmental problems should be minimal for GFPs because the components are generally clean and benign. Polymer films and adhesives used in prototypes have been developed as food-grade packaging materials and therefore have been evaluated by the Food and Drug Administration. The inert nature of argon and its natural presence in the atmosphere means that it presents no environmental problems other than the remote possibility of simple asphyxiation.

Installation Issues and Recommendations

GFPs can be manufactured in nearly any size or shape. Thus, in principle, the technology could insulate nearly any cavity found in building thermal envelopes without relying on composites with other insulations. In practice, however, the variety of cavity sizes and the problems that result if there are defects or gaps in the end installation make successful use of a hermetically sealed panel insulation very challenging. Installation of GFPs in site-built construction is expected to be more difficult and time consuming than installation of conventional products because GFPs are not as easily cut and shaped to fit odd-shaped cavities. This sort of difficulty maybe alleviated by focusing on specific building applications where cavities are more or less uniform, as in manufactured housing and engineered building systems. Nevertheless, a very versatile combination of panel designs and installation methods will need to be developed in order to allow widespread implementation of the technology.

The need to maintain an intact barrier in the GFP poses special problems because wall cavities are commonly invaded with nails and other hardware that can puncture. Installing around plumbing and wiring poses additional challenges; however, the panels are flexible and it is relatively easy to deflect a panel around an obstruction.

When installing GFPs in closed envelope cavities, builders can completely fill the thickness of a cavity or leave room. Using the full thickness has thermal advantages. However, because the panels can expand and contract with barometric pressure and mean temperature fluctuations, it may be wise to leave an air gap of about 0.5 inches (12 mm) to avoid pressurizing the panel. The puncture resistance of the panel will also be enhanced if there is room for the panel to deflect.

One possible process for the installation of GFPs in building envelopes is suggested. GFPs would be produced at the panel factory in both continuous lengths and modular sizes and then shipped to the building site or factory in a compressed low volume form, i.e., unfilled. The continuous-length panels would be made in different widths and could be cut and sealed to length with ancillary heat sealing tools. Pre-made modular sizes could be selected to fit various niches and common irregularities. Gas would be shipped in high-pressure steel cylinders; one full-sized argon cylinder typically holds enough gas to insulate about two normal sized houses. Panels would be partially filled with gas and then fit into the cavities. Once the far side of a panel is seated at the back of a cavity, more gas can be added to the panel until the panel is flush with the near side of the cavity. Once adjacent cavities are filled with panels, the panels would be sealed across the stud or joist by tape or other suitable air and vapor barrier material.

In a futuristic method of installation, the framed structure to be insulated could be surveyed ahead of time, and flexible automated machinery could produce a set of custom-built panels to fit each part of the structure. Modem digital imaging coupled with computer aided design and manufacturing would be necessary.

Advanced insulations can perhaps be most useful for thermal protection in areas other than clear wall, floor, and ceiling cavities. Anywhere that the thickness available for insulation is lower than elsewhere in the structure, higher resistivity insulation maybe useful in improving overall thermal performance. These areas include architectural features such as headers, interior wall junctions, and the attic perimeter.

Unresolved Issues and Future Work

Technical issues remain to be resolved in evaluating GFP technology for building applications. Flame spread and smoke generation testing needs to be performed. Flammability is a concern because thin polymer films can spread fire quickly. Design modifications to allow a low enough flame spread rating for the intended installation may raise the material costs of GFPs compared to prototype designs presented here. Full-scale wall assembly measurements using a hot-box apparatus need to be performed in order to better demonstrate thermal performance in an actual building installation. The panel's ability to function as both air barriers and moisture retarders also needs experimental verification. Because the waterproof GFP dominates the available volume in the cavity, we need to evaluate possible side effects arising from the lack of a "sink" for moisture in the assembly. Long-term performance of the GFP barrier needs to be explored along with thermal aging characteristics.

Future research at Lawrence Berkeley National Laboratory will focus on making prototype panels available for testing and demonstration projects. A machine is being completed to allow semi-automated assembly of baffles.

SUMMARY AND CONCLUSIONS

Gas-Filled Panels can provide significant improvements over traditional cavity insulations for conventional residential and light commercial construction. The thermal performance of GFPs varies widely with the type of gas fill and the design of the baffle component. Effective apparent thermal conductivities have been measured at 0.194 Btu·in/h·ft^2·°F (0.028 W/m·K) with air fill, 0.138 Btu·in/h·ft^2·°F (0.020 W/m·K) with argon fill, 0.081 Btu·in/h·ft^2·°F (0.012 W/m·K) with krypton fill, and 0.055 Btu·in/h·ft^2·°F (0.008 W/m·K) with xenon fill. Although applications for the building thermal envelope have not been developed, the technology appears versatile enough for widespread use as cavity insulation in traditional wood-frame construction. Installation is expected to be more difficult than for traditional insulations. Important technical issues that need to be resolved include: in-situ thermal performance, flammability, Iong-term barrier performance, and air and moisture barrier performance.

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