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Development of a Low Heat Loss, Non-CFC-Based Thermal Insulation: Gas-Filled Panels

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High-Performance, Non-CFC–Based Thermal Insulation: Gas-Filled Panels

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HIGH-PERFORMANCE, NON-CFC–BASED THERMAL INSULATION:

GAS-FILLED PANELS

Prepared for the

CALIFORNIA INSTITUTE FOR ENERGY EFFICIENCY

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Windows and Daylighting Group
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TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

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SUMMARY

This report presents the results of a California Institute for Energy Efficiency (CIEE) exploratory project to develop a new high-performance insulating material, gas-filled panels (GFPs), that is not based on chlorofluorocarbons (CFCs). Applications for GFPs are widespread, with a primary focus on refrigerator/freezer appliances and building walls. While this project has proven the thermal performance potential of GFPs, further development is necessary to optimize designs for cost, manufacturing, and performance.

GFPs were developed by applying approaches that were successful in manufacturing highly insulating windows to the production of an opaque insulation. The use of low-emissivity surfaces and multiple, low-conductivity, gas-filled cavities resulted in a highly insulating panel fabricated with existing materials and technologies. A GFP is not made from a homogeneous insulating material, such as fiberglass or foam, but is rather an assembly of two specialized components. The first component is a barrier envelope that contains a gas, or gas mixture, at atmospheric pressure. Placed inside the envelope is the second component, a baffle consisting of multiple, low-emissivity, coated, impermeable layers. The baffle effectively eliminates radiative and convective heat transfer, allowing conductive heat transfer through the gas and the baffle. Panel geometries and physical properties can be tailored to specific applications. GFPs can be constructed with mechanical properties ranging from flexible but self-supporting to stiff and supportive.

The thermal performance of GFPs was independently tested (per American Society for Testing and Materials [ASTM] test C 518) at Oak Ridge National Laboratory (ORNL), and predicted thermal performance values were supported. *R-value* refers to an insulation's performance per unit of thickness. (Fiberglass has an R-value of R-2.5 to R-3.7, and CFC-blown foams have an R-value of R-7.2.) Measurements of first-generation prototypes yielded R-values of 36 m-K/W (5.2 hr-ft^2-°F/Btu-in.) for air-filled panels, 49.3 m-K/W (7.1 hr-ft^2-°F/Btu-in.) for argon-filled panels, and 86.8 m-K/W (12.5 hr-ft^2-°F/Btu-in.) for krypton-filled panels. Thus, air-filled panels perform as well as styrene foam. Argon-filled panels perform as well as CFC-blown foams, or at a level twice that of fiberglass. Krypton-filled panels perform at higher levels than any insulation currently available. Projected performance levels for second-generation prototypes are expected to be (at 0°C [32°F]) 38 m-K/W (5.5 hr-ft^2-°F/Btu-in.) for air GFPs, 55 m-K/W (8 hr-ft^2-°F/Btu-in.) for argon GFPs, and 105 m-K/W (15 hr-ft^2-°F/Btu-in.) for krypton GFPs.

GFPs are an alternative non-CFC, high-performance insulating material for refrigerator/freezer appliance applications. Such potential materials are in high demand due to the phase-out of CFCs and increasingly stringent energy-efficiency standards. In the near term, appliances could be manufactured with composite insulations consisting of GFPs foamed in place with non-CFC foams. This would not require significant changes in manufacturing methods. In the long run, advanced plastics and processing techniques, used in conjunction with GFP technology, may create high-performance appliance components without the use of foam. Current research is aimed at developing GFPs for both of these applications.

GFP technology can also be applied to energy-efficient building walls. Low-cost, flexible GFPs (air- or argon-filled) could be used to improve the walls' overall thermal resistance without increasing their thickness. These high-performance panels could directly replace fiberglass batt insulation. For example, in 2 x 4 in. stud walls, argon-filled GFPs could be used to achieve R-values greater than 125 m^2-K/W (22 hr-ft^2-°F/Btu); air-filled GFPs could be used to achieve R-values of 109 m^2-K/W (19 hr-ft^2-°F/Btu). This would eliminate the need

for 2 x 6 in. construction in moderate climates, such as California's Central Valley.

GFPs are relatively easy to manufacture and can be produced at low cost. For example, costs for flexible argon GFP batts 0.076 m (3 in.) thick are estimated at \$5.90 to \$7.50/m^2 (\$0.55 to \$0.70/ft^2). GFPs can be assembled from roll-stock polymer films on equipment from the packaging industry. Very high production rates are possible without the need to develop new production techniques.

INTRODUCTION AND MATERIAL DESCRIPTION

Because of the forthcoming phase-out of CFCs and to comply with the more stringent building and appliance energy-use standards, researchers in industry and in the public sector are pursuing the development of non-CFC–based, high-performance insulation materials. This report describes the results of research and development of one alternative insulation material: highly insulating GFPs.

GFPs insulate in two ways: by using a gas barrier envelope to encapsulate a low-thermal-conductivity gas or gas mixture (at atmospheric pressure), and by using low-emissivity baffles to effectively eliminate convective and radiative heat transfer. This approach has been used successfully to produce superinsulated windows (Arasteh 1989). A schematic of one possible GFP is shown in Figure 1. Unlike foams or fibrous insulations, GFPs are not a homogeneous material but rather an assembly of specialized components. The wide range of potential applications of GFPs (appliances, manufactured housing, site-built buildings, refrigerated transport, and so on) leads to several alternative embodiments. While the materials used for prototype GFPs are commercially available, further development of components may be necessary for commercial products. With the exception of a description of the panels that were independently tested, specific information concerning panel designs and materials is omitted for patent reasons; this material is the subject of a patent application by Lawrence Berkeley Laboratory.

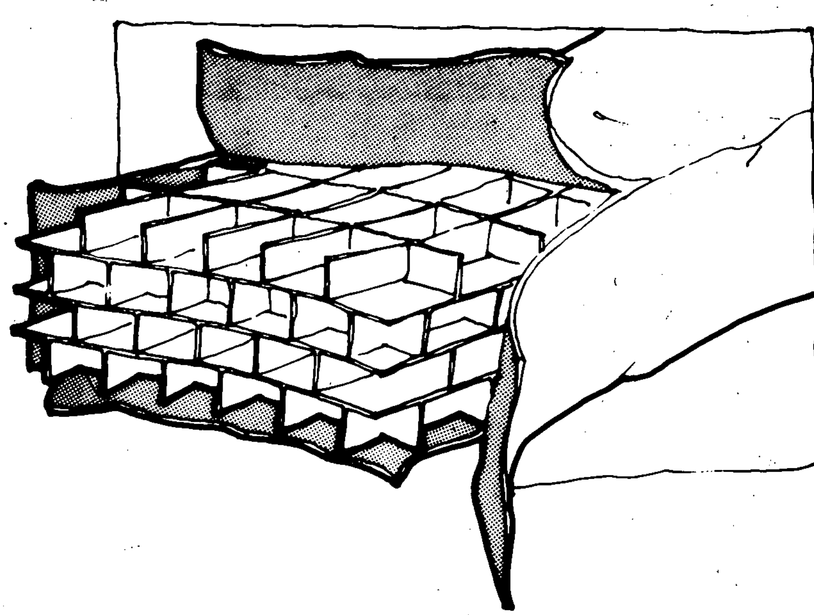

Figure 1. Gas-filled panel schematic cross-section. This figure shows a random orientation of baffle layers; other configurations are possible.

INTERIOR BAFFLES

GFPs use interior baffles to minimize heat transfer and provide structure. Convection is suppressed by constructing baffles from multiple impermeable layers. Baffles are constructed to create interior cavities optimized in thickness (according to the direction of heat flow) for the specific gas and application. Typical thicknesses range from 5 to 12 mm (0.2 to 0.5 in.). Baffle surfaces are precoated with a low-emissivity material, typically a layer of aluminum 200 to 500 angstroms thick, to minimize radiative heat transfer across the cavities. To limit solid conduction, baffles are constructed of low-conductivity materials, such as thin plastics or paper, and are arranged to create long, solid conduction paths. For most GFP embodiments, the baffle is self-supporting and helps define the shape of the panel. The baffles can be made with stiff materials to create a strong, supportive structure, or they can be made flexible and resilient. Depending on the application, a continuous variation between structural panels and self-supporting panels is possible. While refrigerator and freezer applications require structural panels, building-wall cavity applications are best served with nonsupportive panels that can collapse for transport. Attempts to quantify and optimize the physical properties of structural GFPs are the subject of future research.

Given an effective baffle, solid conduction through the gas is the only remaining mode of heat transfer within GFPs. Air is a good insulator, and low-cost air GFPs are expected to have many uses in building applications. Other gases, such as argon, carbon dioxide, sulfur hexafluoride, krypton, and xenon, have significantly lower thermal conductivities. These gases are all nontoxic and either nonreactive or inert. The focus of this research was the use of argon and krypton in GFPs because these gases are inert (and thus safe) and appear to be cost-effective. While xenon offers the potential for superior thermal performance, it is currently too costly for such applications. Air-separation improvements over the past two decades have caused the prices of specialty gases to drop, and continued improvements might make krypton and xenon GFPs cost-effective in a wider range of applications.

Exterior barriers, which surround both the interior baffle and the gas, are the final, critical component of GFPs. Multilayer polymer films developed for the food-packaging industry have been used successfully as exterior barriers in prototypes. Such films, which use the gas-barrier resins ethylene vinyl alcohol and polyvinyl alcohol, are durable and puncture-resistant, have very low gas-transmission rates, and are heat-sealable. Other barrier materials under investigation include aluminum and silicon oxide coatings, acrylonitrile copolymers, and vinylidene chloride. In addition to the main gas-barrier component, the multilayer barrier films have an inner layer that is heat-sealable and an outer layer that is durable and puncture-resistant. Materials such as nylon and cross-linked, high-density polyethylene protect the gas barrier and make the panels strong and puncture-resistant. Product lifetimes are a function of barrier material gas-transmission rates and sealing quality. Barrier materials used in prototypes to date have oxygen (O_2) transmission rates of 0.79 cc/m^2-day-atm (0.05 cc/100 in.^{2}-day-atm) at 296 K (73.4 °F) and 0% relative humidity. Further development of barrier materials is expected to produce barriers that are acceptable for use in GFPs, with transmission rates an order of magnitude lower than the current barriers and life expectancies of 20 to 50 years.

While the gas-barrier requirements for GFPs are more stringent than for any food-packaging application, the barrier problems are not as severe for GFPs as for other advanced insulations relying on vacuums for high performance. However, gas transmission is driven by partial pressure differences, so the advantage over a vacuum approach is not as great as it might appear on first analysis. The driving force for oxygen diffusing into a totally inert GFP is the same as for oxygen diffusing into a vacuum panel. In a GFP, however, trace gases such as helium (a small molecule with high diffusion) are not a problem, while helium diffusion for hard vacuum systems is a serious problem. Though a 10% gain of air over 20 years will degrade a krypton panel's performance by less than 10%, it will lead to serious deterioration in the performance of a soft vacuum panel.

The geometry of the panels will vary depending on the intended application. Thin (approximately 25 mm [1 in.]) modular panels of a convenient area could be used in conjunction with non-CFC foams for refrigerator/freezer applications in the near term. In the future, GFPs could take on the geometry, as well as the function, of entire refrigerator/ freezer panels. For building applications, the GFPs can be sized to fit snugly into stud-wall cavities, possibly with sealing flanges extending over studs for fastening, similar to those used in fiberglass insulation. Multiple layers of individual panels can be used for greater flexibility in sizing thickness and for greater insurance against punctures. Panel shape, sizes, and stiffness can be adjusted for numerous other applications, including heating, ventilating, and air conditioning (HVAC) insulation, hot-water-heater insulation, swimming-pool and spa covers, refrigerated-transport walls, and airplane walls.

The density of GFPs can vary widely among embodiments. Typical flexible GFP prototypes have a density of about 8 kg/m3 (0.5 lb/ft^3). The minimum density feasible for barrier panels is probably 4 kg/m^3 (0.25 lb/ft^3). Such low densities make these panels ideal for refrigerated-transport applications (Feldman 1991). Structural baffles have densities of 30 to 80 kg/m^3 (2 to 5 lb/ft^3) or higher.

PROJECTED COST AND PERFORMANCE

Maximum theoretical performance levels for GFPs are based on eliminating convection, minimizing infrared (IR) radiation and solid conduction, and leaving only conductive heat transfer through the still gas. GFP performance levels are thus limited by the thermal conductivity of the still gases inside the panels. Still-gas conductivities, at atmospheric pressure and 273 K (32°F), are 0.0241 W/m-K (0.0139 Btu/hr-ft-°F) for air, 0.0164 W/m-K (0.0095 Btu/hr-ft-°F) for argon, and 0.0087 W/m-K (0.0050 Btu/hr-ft-°F) for krypton (Liley 1968). Table 1 presents theoretical maximum R-values based on these numbers and also on conductivities at 300 K (80°F). These values indicate the temperature dependence of the panels' performance. A temperature of 273 K (32°F) is representative of the temperature of a typical GFP in a refrigerator/freezer or building wall. The higher temperature, 300 K (80°F), is closer to that of a GFP in an HVAC or hot-water application and is also the mean temperature under ASTM C 518 test conditions. While convection may be effectively eliminated, heat transfer by solid conduction and minimal radiation will degrade these theoretical values slightly in real panels. Values given for projected performance are estimates based on testing and computer simulations.

Cost and performance projections for various GFP embodiments are shown in Table 2. The costs vary substantially depending on the materials used to construct the panels and the fill gases used. Costs include materials and manufacturing and do not include distribution, installation, or profit. For purposes of comparison, costs for other insulations are also included. (Note that costs for non-CFC–blown foams are generally higher, and performance generally lower, than for CFC-blown foams.) Costs for GFPs are preliminary and do not reflect a detailed analysis of manufacturing and materials economies, nor can final GFP designs be assessed. Costs for krypton GFPs are based on a current cost of \$0.50/liter.

Table 1. Theoretical and projected thermal performance of gas-filled panels—R-values in m-K/W (hr-ft^2-°F/Btu-in.).

	Theoretical				Projected	
Fill Gas	273 K	(32°F)	300 K	(80°F)	273 K	(32°F)
Air	41	(6.0)	38	(5.5)	38	(5.5)
Argon	61	(8.8)	56	(8.1)	55	(8)
Krypton	155	(16.6)	106	(15.3)	105	(15)

Table 2. Projected performance and costs.[1]

Panel Type		Thickness[2] m (in.)	R-values m^2-K/W (hr-ft^2-°F/Btu)	Costs \$/m^2 (\$/ft^2)
Building Insulations	Fiberglass	0.089 (3.5)	62 (11)	1.50 – 1.90 (0.14 – 0.18)
	Styrene	0.089 (3.5)	99 (18)	2.70 – 3.75 (0.25 – 0.35)
	Air GFP	0.089 (3.5)	109 (19)	3.75 – 5.40 (0.35 – 0.50)
	Argon GFP	0.076 (3.0)	125 (22)	5.90 – 7.50 (0.55 – 0.70)
	Argon/krypton GFP	0.076 (3.0)	176 (31)	24.70 – 26.90 (2.30 – 2.50)
	Krypton GFP	0.076 (3.0)	230 (41)	45.20 – 47.30 (4.20 – 4.40)
Appliance Insulations	CFC-blown foam	0.025 (1.0)	41 (7.2)	2.15 – 5.40 (0.20 – 0.50)
	Argon GFP	0.025 (1.0)	41 (7.2)	5.40 – 10.80 (0.50 – 1.00)
	Krypton GFP	0.025 (1.0)	77 (13.5)	19.40 – 23.70 (1.80 – 2.20)
	Aerogel evacuated	0.025 (1.0)	114 (20)	14.30 – 28.60 (1.33 – 2.66)
	Powder vacuum	0.025 (1.0)	114 (20)	10.80 – 43.00 (1.00 – 4.00)
	Compact vacuum	0.0025 (0.1)	57 (10)	10.80 – 43.00 (1.00 – 4.00)

1 Rocky Mountain Institute (1990).
2 Insulation thickness varies based on typical use.

PROTOTYPE EVALUATION

In 1990, more than 100 prototypes were built and their thermal performances evaluated using an IR imaging system. Prototype samples, typically 200 or 300 mm² (8 or 12 in.²), were placed in a rigid foam board of a recognized thermal resistance. A temperature difference was generated across the insulation by placing the sample between ambient temperature and a cold chamber. The IR imaging system was then used to compare warm-side surface temperatures of the prototype to those of the surrounding foam. This setup is shown schematically in Figure 2. Warm-side temperatures are directly correlated with thermal resistances: the warmer the room-side surface temperature, the better the insulator. Such side-by-side testing allowed for quick, accurate visual evaluation of prototype samples.

A versatile post-processing system provided a quantitative evaluation of the thermographic information for the prototypes. Figures 3 through 6 present samples of this post-processed data. They show that air-filled panels perform as well as rigid styrene foam board (assumed to perform at R-35 m-K/W [R-5 hr-ft²-°F/Btu-in.]), argon panels perform slightly better than CFC-blown polyiso-cyanurate foam board (assumed to perform at R-50 m-K/W [R-7.2 hr-ft²-°F/Btu-in.]), argon-filled panels perform significantly better than fiberglass batt insulation (assumed to perform at R-22 m-K/W [R-3.2 hr-ft²-°F/Btu/in.]), and krypton-filled panels perform significantly better than CFC-blown polyiso-cyanurate foam board. Figures 3, 4, and 6 show that temperatures are roughly the same for different areas and prove that the new insulation performs equivalently to the old.

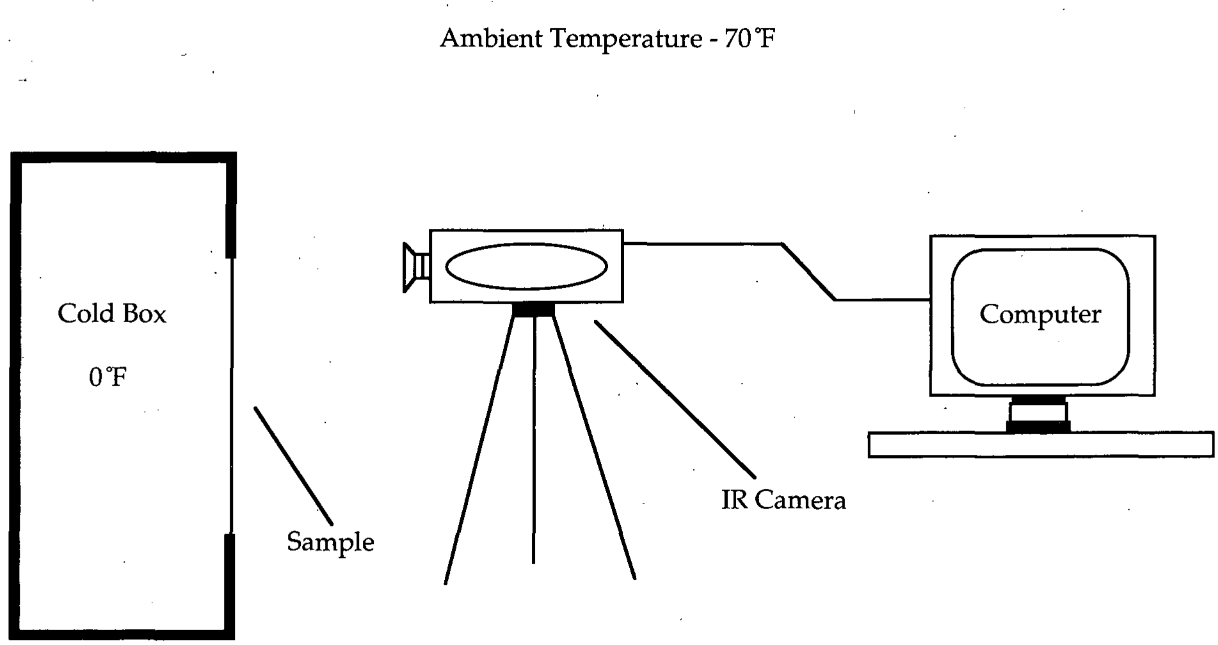

Figure 2. Schematic cross-section of IR radiometer and cold-box facility. The IR camera records the warm-side temperature distribution of a sample placed between the cold box and ambient temperature. The closer all or part of the sample's warm-side temperature is to the ambient temperature, the better the insulator. A computer, attached to the IR radiometer, allows quick and versatile post-processing.

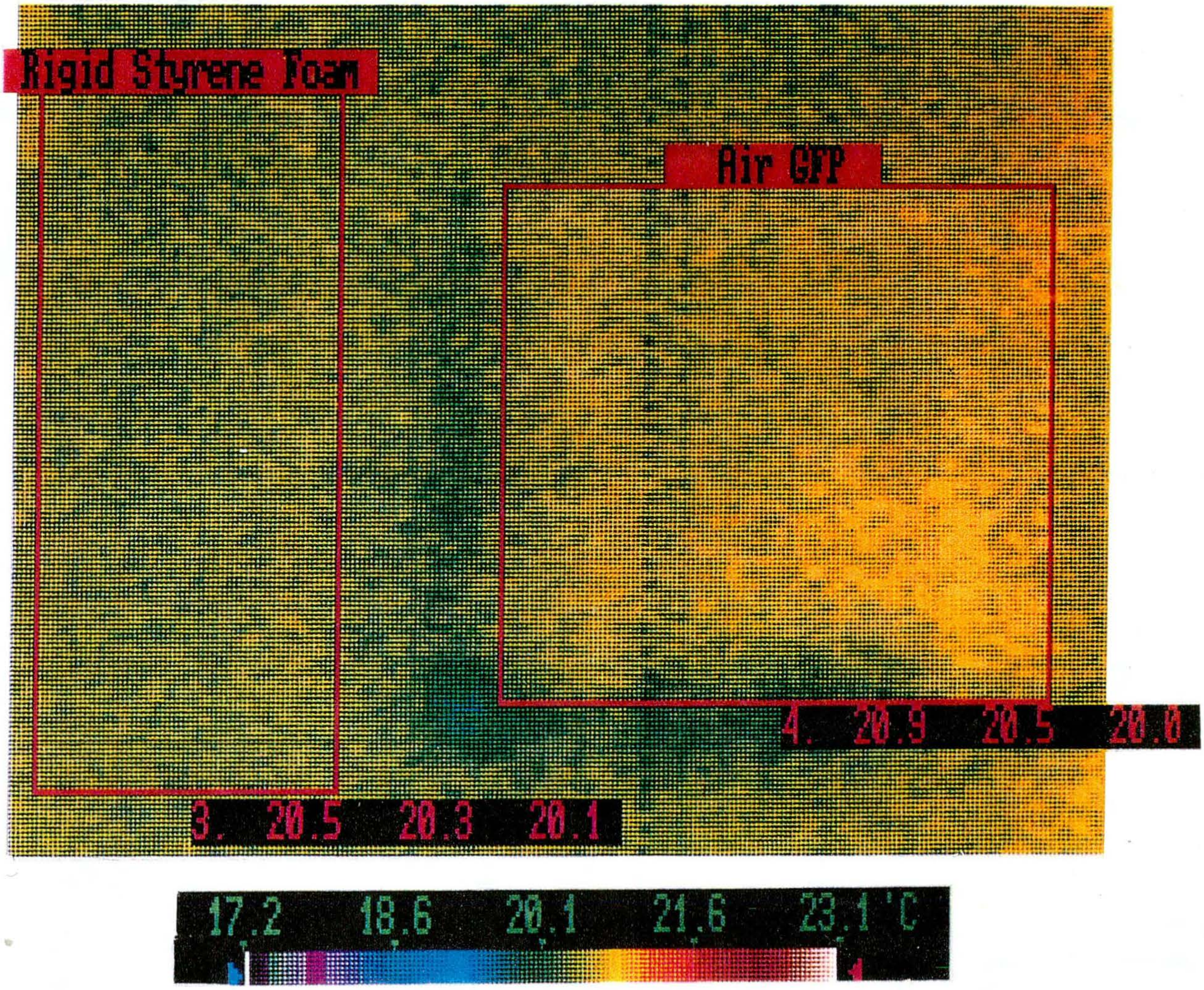

Figure 3. IR image of the warm side of a 5.1 cm (2 in.) thick rigid styrene board with an insert containing a 5.1 cm (2 in.) thick prototype air GFP. The back of the panel faces a cold box at -12.1°C (10.1°F); the ambient temperature is 22.5°C (72.5°F). The warm-side temperature of the styrene board averages 20.3°C (68.5°F) with a maximum of 20.6°C (69.1°F) and a minimum of 20.1°C (68.2°F), while the warm side of the air GFP insulation averages 20.5°C (68.9°F) with a maximum of 20.9°C (69.6°F) and a minimum of 19.8°C (67.6°F). The lack of contrast in this thermograph indicates uniform temperatures. A corresponding temperature scale is shown at the bottom of the figure. Since surface temperatures correspond to heat-loss rates, a higher warm-side temperature implies a lower heat-loss rate. Given an R-value of 35 m-K/W (R-5 hr-ft^2-°F/Btu-in.) for styrene, the R-value for the air GFP is calculated at 37 m-K/W (R-5.4 hr-ft^2-°F/Btu-in.).

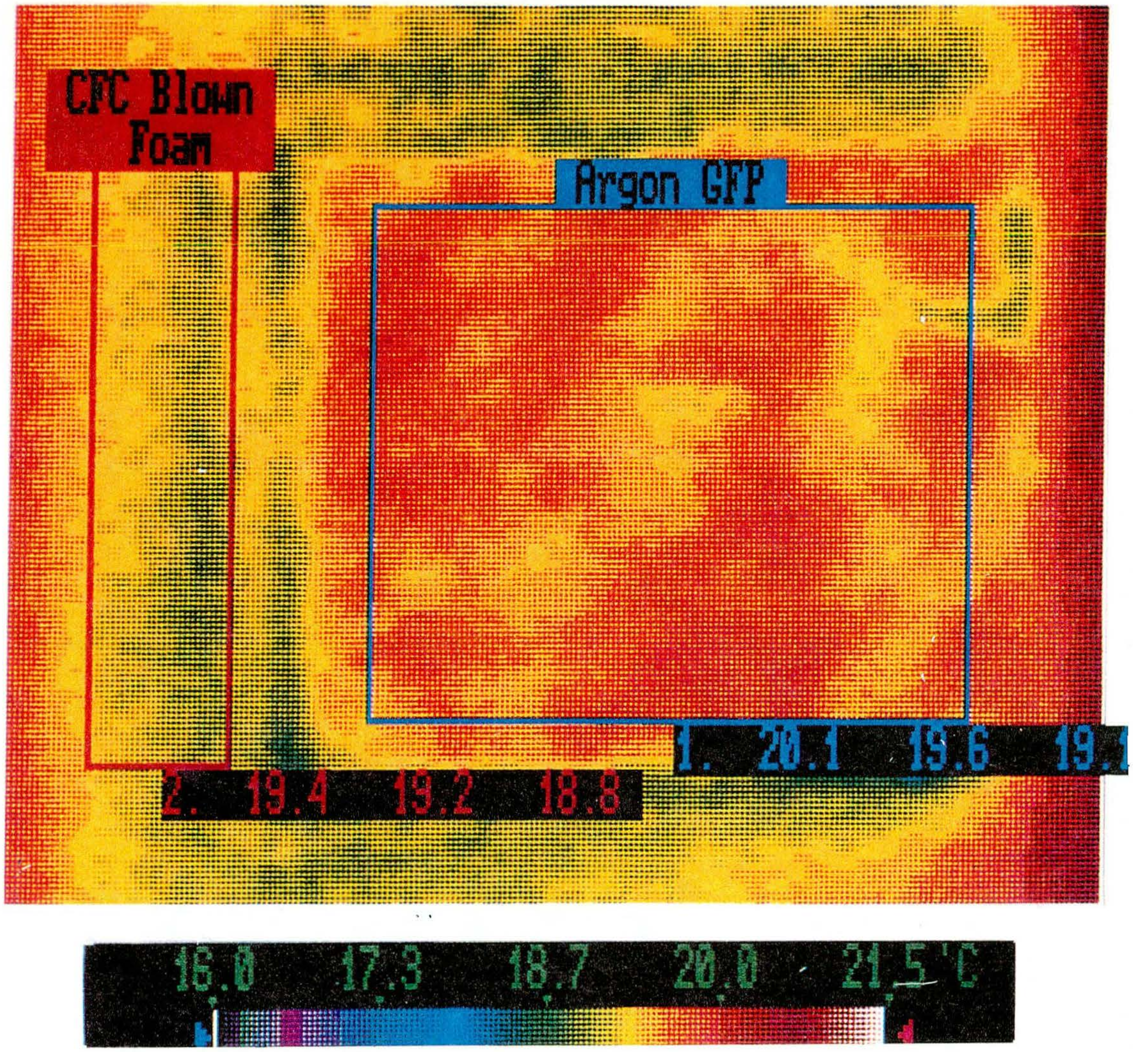

Figure 4. IR image of the warm side of a 2.6 cm (1 in.) thick sample of CFC-blown foam with an insert containing a 2.6 cm (1 in.) thick prototype argon GFP. The back of this assembly faces a cold box at approximately -18.6°C (-1.5°F); the ambient temperature is approximately 22°C (71.6°F). The warm-side temperature of the CFC-blown foam averages 19.2°C (66.6°F) with a maximum of 19.4°C (66.9°F) and a minimum of 18.9°C (66.0°F), while the warm side of the GFP insulation averages 19.6°C (67.3°F) with a maximum of 20.1°C (68.2°F) and a minimum of 19.1°C (66.4°F). In this figure, warmer areas are lighter and colder areas are darker. A corresponding temperature scale is shown at the bottom of the figure. Since surface temperatures correspond to heat-loss rates, a higher warm-side temperature implies a lower heat-loss rate. If the R-value of the CFC-blown foam is taken as R-50 m-K/W (R-7.2 hr-ft^2-°F/Btu-in.), the R-value of this GFP is calculated at R-55 m-K/W (R-7.9 hr-ft^2-°F/Btu-in.).

GFP development progressed rapidly based on quick visual assessments of performance using IR thermography. The primary experiments involved the assessment of which materials and geometries performed poorly. It was quickly learned that frame elements and spacer units are poor thermal performers and should be avoided. Solid elements extending through the thickness of the panel need long conduction paths. Metal foils are poor components due to solid conduction in the plane of the insulation. Thus, the use of thin, metallized plastic films evolved. A more subtle lesson was learned by analyzing the effects of internal convection. It was found that performance can be improved using cavities that do not extend in two dimensions in the plane the panel faces. Preliminary IR thermography has indicated that cavity extensions in one dimension do not significantly alter performance and that the orientation of the cavities is not important.

While IR thermography is excellent for a quick comparison of the thermal performance of different specimens, it is not yet a fully developed technique for determining R-values. For this reason, several samples were fabricated and sent to ORNL for independent testing. The GFP specimens were tested in the ORNL Advanced R-matic Apparatus, which was designed to meet ASTM C 518, Configuration B (two transducers, both faces) (ASTM 1990). Vertical heat-flow conditions were tested with heat flow up and heat flow down. The mean temperature was approximately 24°C (75°F), with a temperature difference of approximately 22.2°C (72°F). The apparatus, calibrated as specified by ASTM C 518, had an estimated uncertainty of ±3% for homogeneous specimens. The specimens measured 40.6 x 40.6 x 2.5 cm (16 x 16 x 1 in.), with a metering area of 25.4 x 25.4 cm (10 x 10 in.) to ensure one-dimensional heat-transfer measurement and minimal edge effects. Note that this standard advises against its being used for measuring inhomogeneous and/or anisotropic material. Although the nature of the baffle used in these samples could cause them to be considered inhomogeneous, IR thermography and finite-element modeling indicate one-dimensional heat transfer. Given this and the smaller metering area, the heat-flux measurements should be an appropriate evaluation of thermal resistance.

The specimens tested at ORNL were intended to demonstrate the effectiveness of the gas-filled-panel approach and were not optimized or designed for mass production. The one-inch-thick specimens were encased in a rigid styrene foam bivalve for a total test thickness of two inches. "Blank" styrene was also measured at ORNL and the effect of the mask accounted for to arrive at the final results. The GFPs were constructed with one primary barrier composed of two films sealed around the perimeter. The inside was split into two cavities by a heat-sealed layer that limited mass transfer but was not hermetically sealed. Each cavity was filled with a baffle pile that consisted of three layers of 13-micron (0.5-mil), two-sided metallized polyester film and two layers of "clear" 13-micron (0.5-mil) polyester film. The clear film was oversized (60 x 60 cm [24 x 24 in.]) and crumpled up in an even but random fashion to create alternating clear and metallized layers. This produced a panel with eleven layers in one inch, with an average cavity size of less than 2.5 mm (0.1 in.). Due to the nature of the crumpling, it is difficult to quantify cavity scale exactly. The intent with these panels was to effectively eliminate convective and radiative heat transfer. Except for the use of ultrathin films, no attempts were made to minimize solid conduction.

Results from ORNL (McElroy and Graves 1990) are summarized in Table 3 and indicate prototype performance levels close to predicted levels. (Note that the predicted R-values given in Table 3 assume a 0°C [32°F] mean sample temperature representative of building and refrigerator/freezer operating temperatures, while the ORNL-measured R-values are based on a mean temperature of 24°C [75°F]. Table 1 indicates that performance is roughly 10% better at the lower temperature.) These tests showed that the difference between heat flow up and heat flow down was less than 1%, which is within the 2% reproducibility of the R-matic. This finding indicates that the contribution of convection to heat transfer has been effectively eliminated. The differences between measured

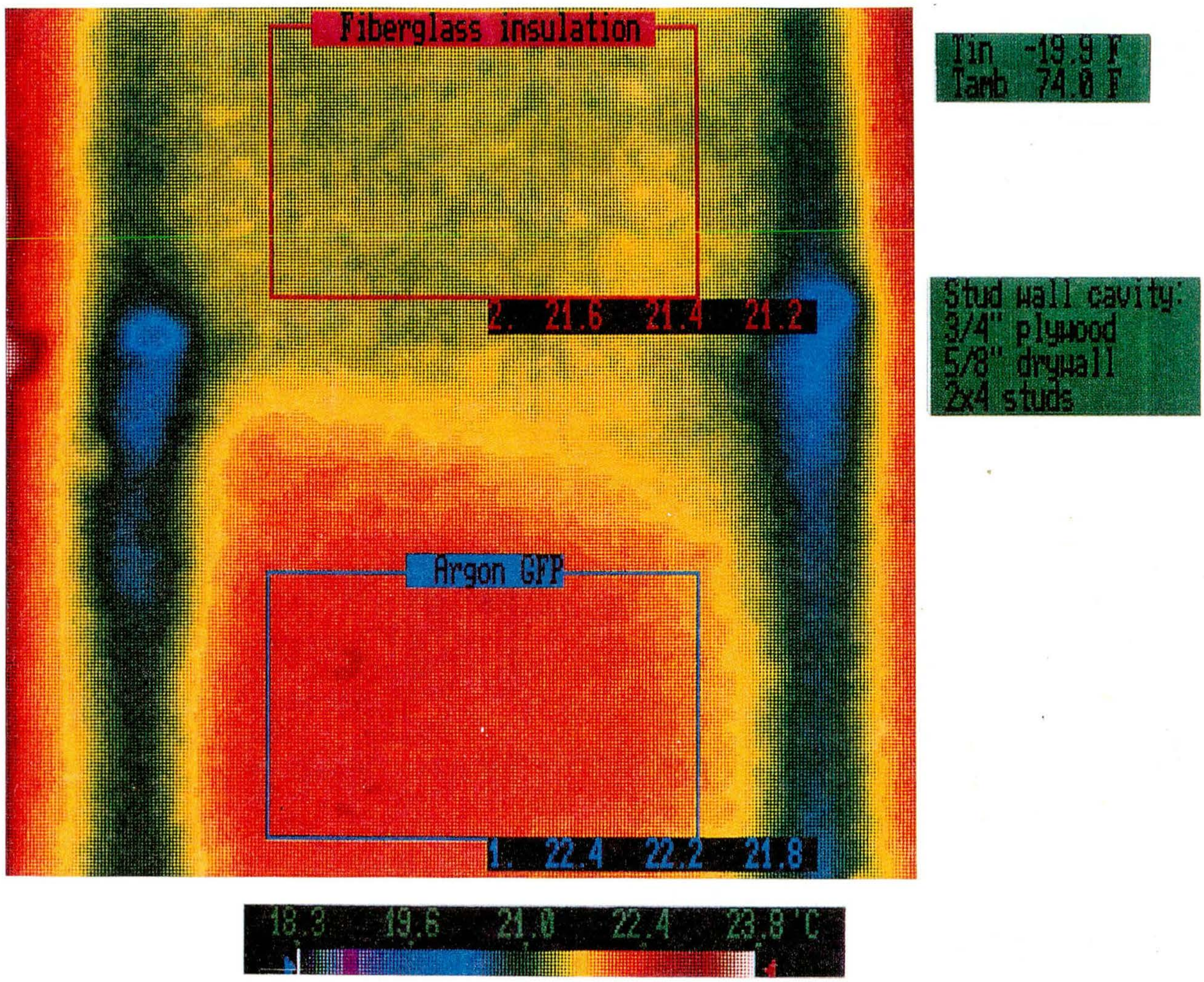

Figure 5. IR image of the warm-side surface of a stud-wall cavity test section. The upper portion of the cavity is insulated with R-62 m^2-K/W (R-11 hr-ft^2-°F/Btu) fiberglass, and the lower portion is insulated with an argon GFP. The wall section is constructed with 1.9 cm (3/4 in.) plywood, 1.6 cm (5/8 in.) drywall, and standard 40.6 cm (16 in.) on-center 2 x 4 in. studs. The back of this assembly faces a cold box at approximately -28.8°C (-19.9°F); the ambient temperature is 23.3°C (74.0°F). The warm-side surface temperature of the fiberglass-insulated section averages 21.4°C (70.4°F), with a maximum of 21.6°C (70.9°F) and a minimum of 21.2°C (70.1°F). The warm-side surface temperature of the argon GFP-insulated section averages 22.1°C (71.9°F), with a maximum of 22.4°C (72.4°F) and a minimum of 21.6°C (71.1°F). A corresponding temperature scale is shown at the bottom of the figure. Since surface temperatures correspond to heat-loss rates, a higher warm-side temperature implies a lower heat-loss rate. Based on this IR temperature data, the argon GFP-insulated wall section has a total R-value 1.7 times that of the fiberglass-insulated wall section of the same thickness.

and projected R-values for the argon and krypton GFPs is primarily attributed to solid conduction through the large numbers of baffle layers. In addition, decreased performance may be attributed to fill concentrations of less than 100%. However, a crude gas-fill measurement (a measurement of the percentage of O_2) indicated that fill concentrations were higher than 98% even four months after filling.

Table 3. Measured and projected R-values from the ORNL R-matic in m-K/W (hr-ft²-°F/Btu-in.).

Fill Gas	ORNL Measured		Projected	
Air	36.1	(5.2)	38	(5.5)
Argon	49.3	(7.1)	55	(8)
Krypton	86.7	(12.5)	105	(15)

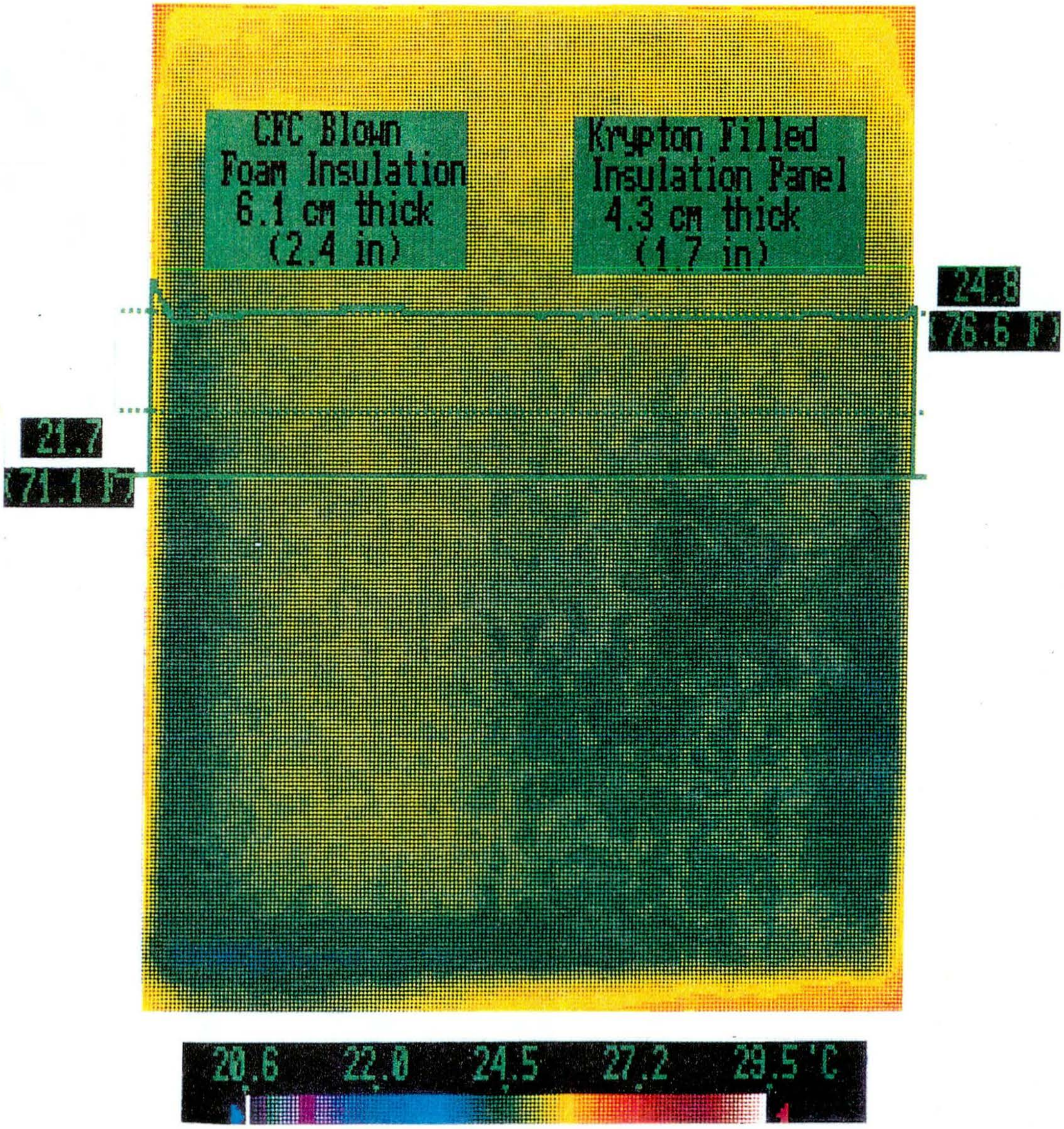

Figure 6. IR image of the door on a real freezer. The freezer is operating at about -20.5°C (-4.9°F), with an ambient temperature of 26.7°C (80°F). Half of the freezer door was left as manufactured (with 6 cm [2.4 in.] of CFC-blown foam); the other half was retrofitted with 4.3 cm (1.7 in.) of krypton GFPs. In this figure, warmer areas are lighter and colder areas are darker. A corresponding temperature scale is shown at the bottom of the figure. Since surface temperatures correspond to heat-loss rates, a higher warm-side temperature implies a lower heat-loss rate. The IR photo shows no significant difference (the resolution of the camera is 0.1°C) between the warm-side temperatures of both sides of the freezer door, indicating that 4.3 cm (1.7 in.) of GFPs insulate as well as 6 cm (2.4 in.) of CFC-blown foam. (The average surface temperature is 24.8°C [76.6°F] across the solid white line. A second line, at a temperature of 21.7°C [71.1°F], is used to define the scale.)

MANUFACTURING

The large-scale manufacture of GFPs will not require the development of any substantially new materials-processing technologies. The primary material components are finished roll-stock plastic films, which are widely produced in a mature industry and make the assembly of the panels relatively simple. Existing machinery from the food-packaging industry, such as thermoformers, impulse heat-sealers, and bag-making and wrapping machines, could be adapted to manufacture GFPs at high line rates. Complete machines (known as *form, fill, and seal* equipment) routinely used in the food-packaging industry can rapidly encapsulate the baffle with a barrier material, flush it with a vacuum, gas-backfill it, and seal the panel into a final product. Custom-built automated GFP production equipment could easily be produced because of the large base of related experience and expertise within the package-machinery industry.

Gas-filling of the assembled panels is also fairly straightforward. Prototypes constructed to date have been filled with a simple apparatus. Fill percentages for flexible panels using this apparatus are generally in the 95% to 98% range with no purging. Flexible GFPs can be filled more easily than structural GFPs because their inside volume can collapse to zero under a vacuum. Flexible panels could be shipped in an evacuated form and easily gas-filled at the point of use. Advanced gas-filling methods using vacuum chambers are expected to yield stiff GFPs with fill percentages of 98% to 100%; these percentages have been achieved in both the window and food industries using vacuum chamber equipment.

APPLICATIONS

GFPs have the potential to be used in practically all "ambient"—temperature thermal—insulation applications. Panel components generally should not be subjected to temperatures greater than 150°C (300°F) or less than -40°C (-40°F). Component properties can be adapted to different physical requirements. GFPs lend themselves best to flexible applications because small baffle-material thicknesses have low costs and high performance. While stiffer GFPs may not be able to reach the same performance or cost levels as flexible GFPs, they still have widespread potential applications due to the high demand for alternative insulations in markets currently using CFC-blown foam.

Flexible panels can be used wherever there is a well-enclosed cavity of a reasonable size and where the insulation need not contribute to structural strength. Flexible GFPs can directly replace fiberglass in building cavities. Air GFP baffles that do not require a barrier material could be cut and installed in the same manner as fiberglass, although such panels would perform 50% better on a unit-thickness basis. Argon panels with barriers cannot be cut to size easily at a standard construction site. One way this could be handled is to make the panels available in different lengths and shapes. Wall cavities of odd shapes and sizes could then be insulated in a manner analogous to masonry work. The manufactured-housing market is well suited to the use of argon or krypton GFPs because of standardized panel sizes and the use of construction jigs and skilled workers. Transportation and storage costs for GFPs should be lower than for conventional insulation because GFPs can be of lower density than fiberglass and can collapse to very small volumes for transportation and storage.

GFPs may help meet the standards of current and emerging building energy codes. They may find applications where builders do not want to change their construction techniques but are required to have R-108 SI (R-19 IP) insulation in walls. For example, in 2 x 4 in. stud-wall construction there is about a 0.089 m (3.5 in.) thick cavity, which is typically insulated to R-62.5 SI (R-11 IP) using fiberglass. A 0.089 m (3.5 in.) thick air GFP could achieve an R-value of R-109 SI (R-19 IP), and a 0.076 m (3.0 in.) thick argon GFP could achieve R-125 SI (R-22 IP). Such performance levels would eliminate the need to replace 2 x 4 in. construction with 2 x 6 in. construction in moderate climates such as California's Central Valley. In cold climates, where 2 x 6 in. construction is used, R-values of R-175 to R-225 SI (R-30 to R-40 IP) could be achieved. Note that we assume argon- and krypton-filled panels used in building applications must be slightly thinner than the cavity to accommodate temperature-driven pressure changes and protrusions into the cavity (nails, plumbing, and wiring).

Refrigerator/freezer appliance insulation is the biggest immediate potential application for GFPs because of the Montreal Protocol's mandated phase-out of CFC-blown foams and higher federal energy-efficiency standards. GFPs for appliances will require strong "structural" panels because existing foam insulations are used for structure in the appliances. Thus, one of the challenges in developing GFPs is to develop a structural baffle that can be substituted for, or used in conjunction with, foam-in-place applications. Initial attempts to develop such a baffle have been encouraging.

Figure 7 shows a first-generation structural GFP with a density of only 38 kg/m^3 (2.4 lb/ft^3) supporting six bricks. The bricks exert a force of 700 newtons (1 lb/in.^{2} [psi]) on the panel. Under this load, the 50 mm (2 in.) thick panel elastically deflects approximately 0.006 m (0.25 in.). This sample is also exceptionally stiff in torsion. (Note that its construction is different from that of the flexible panels sent to ORNL.) Preliminary IR testing shows slightly lower performance because of increased solid conduction. Development of struc-

[1] *System Internacional* units.
[2] Inch-Pound units.

tural GFPs is continuing with a focus on optimizing the trade-offs between structural and thermal performance. It is envisioned that modular structural GFPs will be used in conjunction with non-CFC–blown foams to yield an insulated cavity with a net thermal performance that is as good as, or better than, the potential performance of the CFC foams currently in use. This "drop-in" approach would not require that appliance manufacturing methods be significantly changed. Future applications could use the structural GFP approach in combination with new plastic-manufacturing processes to produce a new generation of highly insulated durable goods. Rapidly developing production processes such as thermoforming and blow molding will very likely change the design and manufacture of appliances. Incorporating GFPs into the design of such products could eliminate the use of foam insulations. For example, new plastic-manufacturing methods could be used to make highly insulating refrigerator/freezer door panels out of engineering plastics that incorporate gas-barrier resins. The main interior and exterior door panels would then constitute the gas-barrier envelope of a GFP that would contain a structural baffle for added stiffness. Plastic structural building materials and components with exceptional thermal properties (such as whole-wall panels) could be produced in a similar fashion. Significant percentages of recycled plastics could be used to manufacture such durable goods.

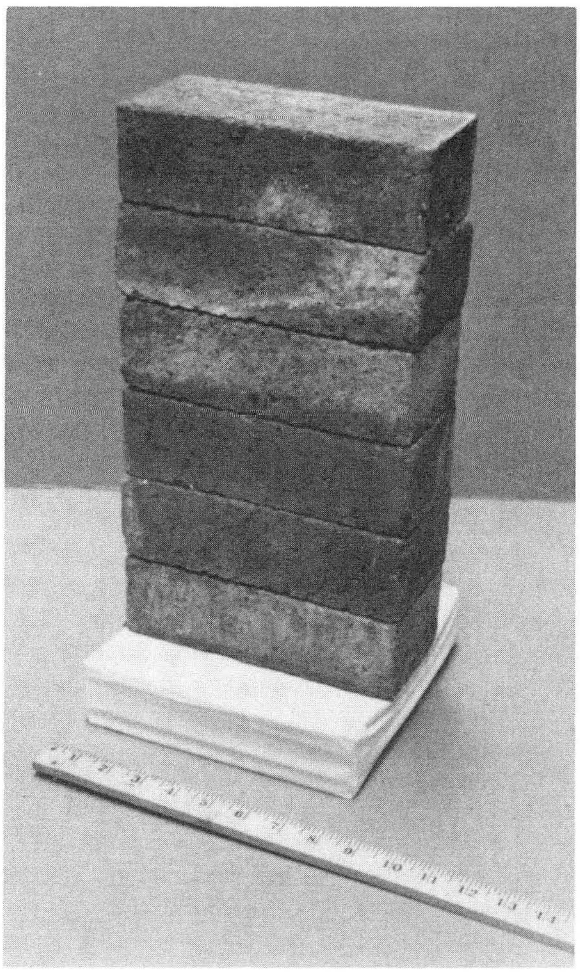

Figure 7. A first-generation structural GFP prototype carrying a load of six standard bricks. The mass of the load is 13 kg (28.6 lb). The panel measures 20 x 20 x 5 cm (8 x 8 x 2 in.) and has a density of approximately 38 kg/m^3 (2.4 lb/ft^3).

CONCLUSIONS AND ADDITIONAL RESEARCH REQUIREMENTS

Prototype GFPs were fabricated using commercially available materials, and their thermal performance was verified through independent tests at ORNL. Measured thermal performances were R-86.7 m-K/W (R-12.5 hr-ft^2-°F/Btu-in.) for krypton-filled panels, R-49.3 m-K/W (R-7.1 hr-ft^2-°F/Btu-in.) for argon-filled panels, and R-36.1 m-K/W (R-5.2 hr-ft^2-°F/Btu-in.) for air-filled panels. Higher thermal performances are expected.

Over the course of this project, numerous contacts were made with component suppliers. While the ideal polymer films for GFPs are not commercially available, it is expected that such films will be in production within one to two years and will be used in a variety of applications. The other potential GFP components, argon and krypton, are commercially available. Argon is relatively inexpensive and abundant, while the price and availability of krypton fluctuate with worldwide demand. Development, testing, and analysis of GFP components and costs will continue with Department of Energy (DOE) funding during 1991. Many existing manufacturing technologies in the food-processing industry can be adapted to the manufacture of GFPs.

Requirements for specific applications, primarily building and refrigerator/freezer walls, were identified. Flexible GFPs have promise for use in manufactured housing. However, several technical and practical issues still need to be resolved before they can be used in site-built construction. At the time of this writing, further research on the application of GFPs to building walls is dependent on additional funding. Structural GFPs are promising for use in appliance walls. Research efforts during the remainder of 1991, funded by DOE, are aimed at building prototype GFPs for use in conjunction with non-CFC–blown foams in an advanced-appliance demonstration project sponsored by the Environmental Protection Agency. For all applications, additional nonthermal testing (flame spread and smoke generation, acoustical resistance, and accelerated aging, for example) is necessary to assess potential end-uses. Finally, application demonstrations of real-life situations require the upscaling of prototype production capabilities.

REFERENCES

Arasteh, D., S. Selkowitz, and J. Wolfe. The design and testing of a highly insulating glazing system for use with conventional window systems. *ASME Journal of Solar Energy Engineering*, Vol. III, February 1989.

ASTM Standard C 518-85. Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the heat flow meter apparatus. *Annual Book of ASTM Standards*, Vol 04.06. Philadelphia: American Society for Testing and Materials, 1990.

Feldman, K.T., and D.A. Lubreche. Advanced vacuum insulation for refrigerated shipping containers. Albuquerque: RE/SPEC Inc., 1991.

Liley, P.E. The thermal conductivity of 46 gases at atmospheric pressure. *Proceedings of the Fourth Symposium on Thermophysical Properties*. College Park, Maryland: American Society of Mechanical Engineers, 1968.

McElroy, D.L., and R.S. Graves. Personal letters dated July 30, September 14, and December 5, 1990. Oak Ridge, Tennessee: Oak Ridge National Laboratory.

Rocky Mountain Institute. *The State of the Art: Appliances*. Snowmass, Colorado: Competitek, 1990.

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