

PROCEEDINGS

RCI INTERNATIONAL CONVENTION AND TRADE SHOW

**SEEKING SOLUTIONS
TO COST-EFFECTIVELY INSULATE
AN EXISTING WALL ASSEMBLY**

ANDRÉ DESJARLAIS, FASTM;

AND

KAUSHIK BISWAS

OAK RIDGE NATIONAL LABORATORY

P.O. Box 2008, MS-6070, Oak Ridge, TN 37831

Phone: 865-574-0022 • E-mail: desjarlaisa@ornl.gov

DOUGLAS SMITH

NANOPORE INC.



RCI, Inc.

800-828-1902

WWW.RCI-ONLINE.ORG

ABSTRACT

Retrofitting an existing wall assembly to make it more energy efficient is a difficult technical challenge. Common approaches include cavity fill techniques, adding continuous foam or fibrous insulation, or adding an insulated cladding or siding product.

Filling wall cavities with loose-fill insulation is the most common practice, but conventional “drill-and-fill” techniques result in damage to interior gypsum board. Performing the task from the exterior side requires the removal and replacement of the cladding system and adds appreciable cost. Even after completion, the wall system is under-insulated by today’s standards, achieving an R-value of only approximately R-10.

Continuous insulation (ci) can be applied to the outside of the exterior sheathing, but it also adds appreciable cost to the project. The International Energy Conservation Code (IECC) requires ci thicknesses of 1 or 2 in. in building walls with traditional 2 x 4 framing. Additional ci would be required if the existing wall cavities were uninsulated. The addition of this amount of ci requires that all of the architectural details be retrimmed.

Insulated siding—vinyl siding with manufacturer-installed rigid expanded polystyrene foam plastic insulation permanently adhered to it—forms a layer of ci around a home. The international standard for insulated vinyl siding (ASTM D7793) requires a minimum thermal resistance rating of R-2. The added amount of R-value currently available in insulated vinyl siding on the market is very small.

This presentation will report on a research project to produce vacuum-insulated vinyl siding that would represent at least a five-fold thermal improvement from currently available insulated siding products. It has sufficient R-value to meet the ci requirements of the IECC in all climate zones and has a much thinner profile that will facilitate its application to existing homes without the need for expensive retrimming of the architectural details.

SPEAKER

ANDRÉ DESJARLAIS, FASTM – OAK RIDGE NATIONAL LABORATORY – OAK RIDGE, TN



ANDRÉ DESJARLAIS is the program manager for the Building Envelope and Urban Systems Research Program at ORNL. He has been involved in building envelope and materials research for over 45 years, first as a consultant and, for the last 25 years, at ORNL. Desjarlais has been a member of ASTM since 1987 and serves on Committees C16 on Thermal Insulation and D08 on Roofing, of which he was past chairman. He was awarded the title of ASTM Fellow in 2011. He has served as the chair of ASTM’s Committee on Technical Committee Operations (COTCO). A member of ASHRAE since 1991, he serves on Technical Committees TC 4.4 on Thermal Insulation and Building Systems, TC

1.8 on Mechanical Insulation Systems, and TC 1.12 on Moisture Control in Buildings, and is past chair of TC 4.4. He is also a director of the RCI Foundation.

SEEKING SOLUTIONS TO COST-EFFECTIVELY INSULATE AN EXISTING WALL ASSEMBLY

INTRODUCTION

Developing high R/inch insulation systems for building envelopes is a high-priority research area for the Buildings Technology Office (BTO) of the Department of Energy (DOE). With an average age of almost 40 years old, a major portion of our housing stock has poorly insulated walls and is also in need of exterior cladding replacement. The objective of this project is to target that market and transition to scaled-up manufacturing of an insulated vinyl siding finished prototype that achieves R-10 (hr-ft²-°F/Btu) or more within a 1-in. total thickness for existing housing. The proposed vacuum-insulated siding represents a four- to five-fold thermal improvement from currently available insulated siding products.

The BTO Emerging Technologies (ET) Program has the aim of supporting the development of cost-effective technologies that can reduce aggregate building energy use intensity by 30% by 2020, and 45% by 2030, relative to the consumption of 2010 energy-efficient technologies (DOE 2014). The ET Program strives to meet this goal by researching and developing cost-effective, energy-efficient technologies to be introduced into the marketplace. The DOE seeks to undertake research and test through field validation the feasibility of upgrading existing wall systems. This project is responsive to those objectives; it seeks to build on the popularity and cost competitiveness of vinyl siding by developing and demonstrating a version that would increase the R-value of wall systems by R-10. It offers the best economic path forward to address the retrofit of existing residential walls that are under-insulated by today's standards.

This paper reports on a technology that would address a key opportunity to achieve energy savings in the existing housing stock. It is typically very difficult to increase the R-value of the thermal envelope in existing housing, as doing so from the inside is disruptive and can be cost prohibitive. Also, there have not been good solutions to increase thermal envelope performance from the exterior through adding continu-

ous insulation due to the additional work required to fit existing architectural features to the new wall thickness. A high-R-value-per-in. product that can be used in these applications offers an excellent solution.

"Drill-and-fill" techniques cost approximately \$3/ft² but are limited to R-values of approximately R-10. Meeting existing codes is not possible using this technique exclusively. The cost of insulated vinyl siding is approximately \$5/ft² but includes new siding and an additional R-value of R-2 to R-3 of continuous insulation. Adding additional R-value is possible through adding 2 in. of foam but creates considerable expense in architectural detailing and a less-than-desirable appearance. The cost of this approach depends on the home but is estimated to be at least \$6/ft². Our target is to provide this product for \$5 to \$6/ft², which will give the homeowner a good return on investment and better options than currently exist in the market. We believe that this product has enormous market potential. Even after being punctured, the R-value of the vacuum insulation remains at R-8, a level higher than conventional insulations.

THE TECHNOLOGY

The technology being developed is an insulated vinyl siding product that has an R-10 (hr-ft²-°F/Btu) or more. The proposed technology combines a low-cost vacuum panel with traditional vinyl siding in a manner that the overall thickness of the composite totals approximately 1 in. A thin section of traditional foam insulation is also used on the exterior or sheathing side of the insulated siding to protect the

vacuum panels. The vacuum panels will be approximately 16 to 24 in. long by the width of the vinyl siding. If cutting of the vinyl siding is required, the vacuum for only that section will be compromised. Note that the R-value of a 1-in. air-filled vacuum panel is still R-8 due to the nanoporous structure of the fill material.

A vacuum insulation panel (VIP) offers a very low thermal conductivity (or high R/in.) compared to conventional insulation materials (Alam et al. 2011). It is the only technology that can enable the development of composite insulation materials with R-values of 12 per in. or greater. This paper describes the development and evaluation of a composite insulated siding material consisting of vacuum insulation cores attached to vinyl siding. VIPs have existed for more than two decades, but their adoption in buildings has been limited, their high cost being one of the major hindrances. A newly developed, lower-cost variant of vacuum insulation, called modified atmosphere insulation (MAI), was used in this research. MAI is created using a different processing method compared to VIPs, which leads to significant cost reductions. However, to achieve the stated R/in. of the composite insulated siding, it was critical that MAI

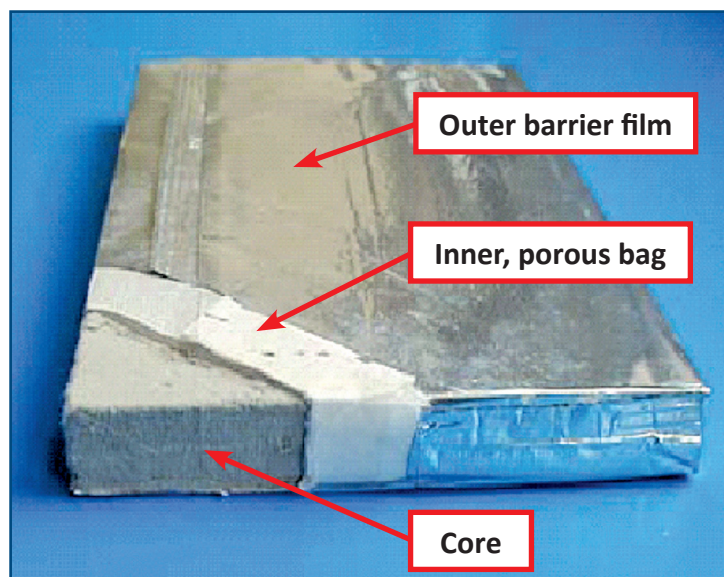


Figure 1 – VIP (http://www.iea-ebc.org/Data/publications/EBC_Annex_39_PSR.pdf).

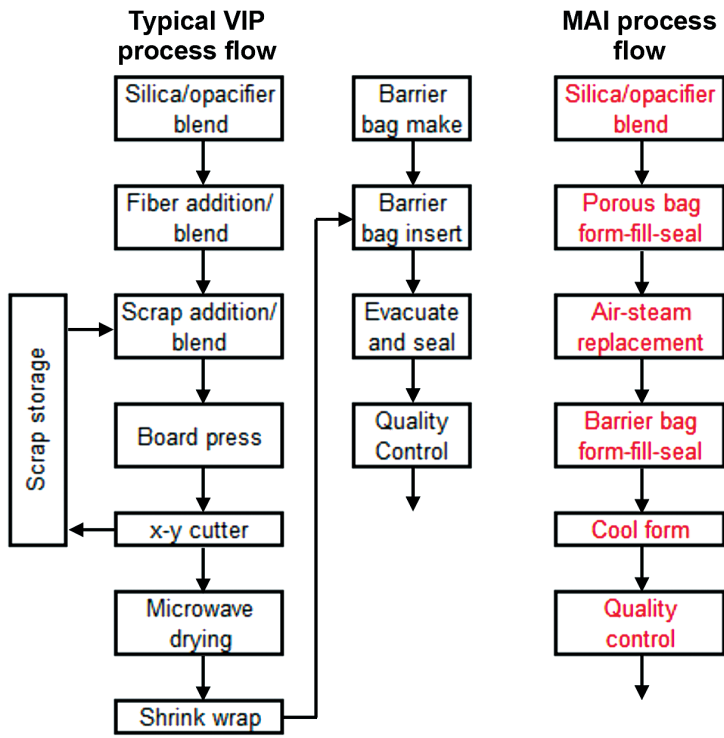


Figure 2 – Differences in MAI and VIP manufacturing (Biswas et al. 2018).

possess the same thermal performance as regular VIPs. In this paper, some background information on the MAI technology, its distinguishing features, and its thermal performance are also provided.

VIPs contain an evacuated nano/microporous core that is sealed with multilayered barrier films (Figure 1). Two major issues that have hindered the widespread use of VIPs in buildings are cost and integration into the building envelope.

Protecting the VIPs during transportation and handling, as well as when they are installed in the envelope, are also issues that need to be mitigated to successfully deploy VIPs in building envelopes. The newly developed composite insulated siding contains VIPs that are adhered to the vinyl siding. The composite siding can be used as a surrogate for continuous insulation (ci) and regular siding, with little or no change in handling and installation methods.

intensive, includes pressing fine powders into boards, which must then be cut, dried, evacuated, and sealed in a vacuum. MAI avoids these process steps by replacing the air in the fluidized powder core with a low-conductivity vapor (steam, for example). Once the core is sealed within the barrier films and cool-formed to its final shape, the vapor condenses and creates the vacuum. On a commercial scale, MAI cost is projected to be \$0.10–0.13/ft² per R, versus about \$0.25/ft² per R for regular VIPs. In comparison, the cost of 1-in. foam insulation boards is about \$0.06–0.10/ft² per R

(RS Means 2014). The cost of VIPs is primarily driven by the manufacturing process (up to 75% of the total cost). The composite siding contains vacuum insulation cores that are manufactured in a different manner compared to traditional VIPs. MAI is processed at ambient pressure, using standard vertical form-fill-seal machines of the type used to package potato chips. Regular VIP processing, which is expensive and energy

(RS Means 2014). Figure 2 illustrates the differences in processing of VIP and MAI. The MAI technology is protected by several patents, which are listed in Appendix A.

THERMAL CHARACTERIZATION OF THE MAI PANELS

Laboratory tests of small- and full-scale composite boards were performed according to ASTM International test standards. The small-scale samples were 12 in. square by 1 in. thick. The tests measured the overall thermal conductance (and resistance) of the samples. These tests were done in a heat flow meter (HFM) that operates according to ASTM C518 (ASTM 2017a), which measures the steady-state thermal transmission properties of materials. In a nutshell, an HFM consists of two plates that sandwich the test specimen. The temperature of each plate can be independently controlled, and each plate is equipped with a heat flux transducer (HFT) to measure the heat flow entering or exiting the plates. By measuring the temperature difference across the sample, the heat flow, and the sample thickness, the thermal resistance of the sample can be determined following Fourier’s law, assuming one-dimensional heat flow.

Figure 3 depicts the thermal resistance per inch thickness of the MAI panels as a function of temperature and pressure. An R per inch of approximately 36 is measured at room temperature. This R-value drops to approximately 32 hr-ft²-°F/Btu at 140°F. If the MAI panels were installed behind a dark-colored vinyl siding, it is anticipated that its temperature might increase to about this level. At approximately 1 mbar, the MAI panels have an R-value

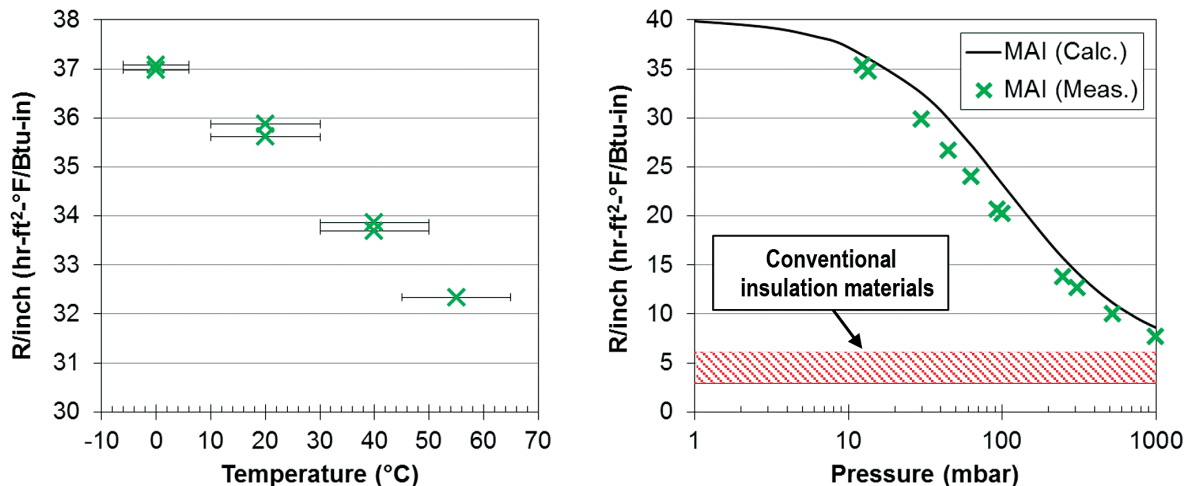


Figure 3 – R-value of MAI panels.

per inch of approximately 40. This R-value drops slightly until approximately 10–15 mbar and then drops quickly until it stabilizes at ambient pressure at an R-value of 8. Note that if the MAI panels are produced with an internal gas pressure of 1 mbar, leakage can occur into the panel and only a modest loss of R-value will be measured. This “plateau” in the R-value vs. pressure curve allows for some panel aging to occur without significant performance loss. Finally, at ambient pressure, the MAI panel still outperforms all traditional insulations because of the nanoporous nature of its core.

THERMAL CHARACTERIZATION OF THE COMPOSITE VINYL SIDING

A guarded hot box (GHB), operated according to ASTM C1363 (ASTM, 2011) was used to measure the steady-state thermal conductance (and resistance) of the full-scale foam-MAI composites. *Figure 4* shows the hot box that is used to characterize full-scale wall and window assemblies. Test assemblies are installed in a specimen frame mounted on a moveable dolly. The specimen frame has an overall aperture of 12 ft. wide by 10 ft. high. However, typical test specimen dimensions are 8 ft. squared, while the remainder of the aperture is filled with 6-in. rigid expanded polystyrene (EPS) insulation with a thermal resistance of at least 24 hr-ft² °F/Btu.

The specimen frame/test assembly is inserted between two “clam-shell” chambers of identical cross sections. These chambers are designated as the climate (cold) and metering/guard (hot) chambers. The metering chamber is 8 ft. squared by 1.3 ft. deep, and its aperture typically defines the test area. The climate chamber can achieve a low temperature of 10°F, and the metering chamber can achieve

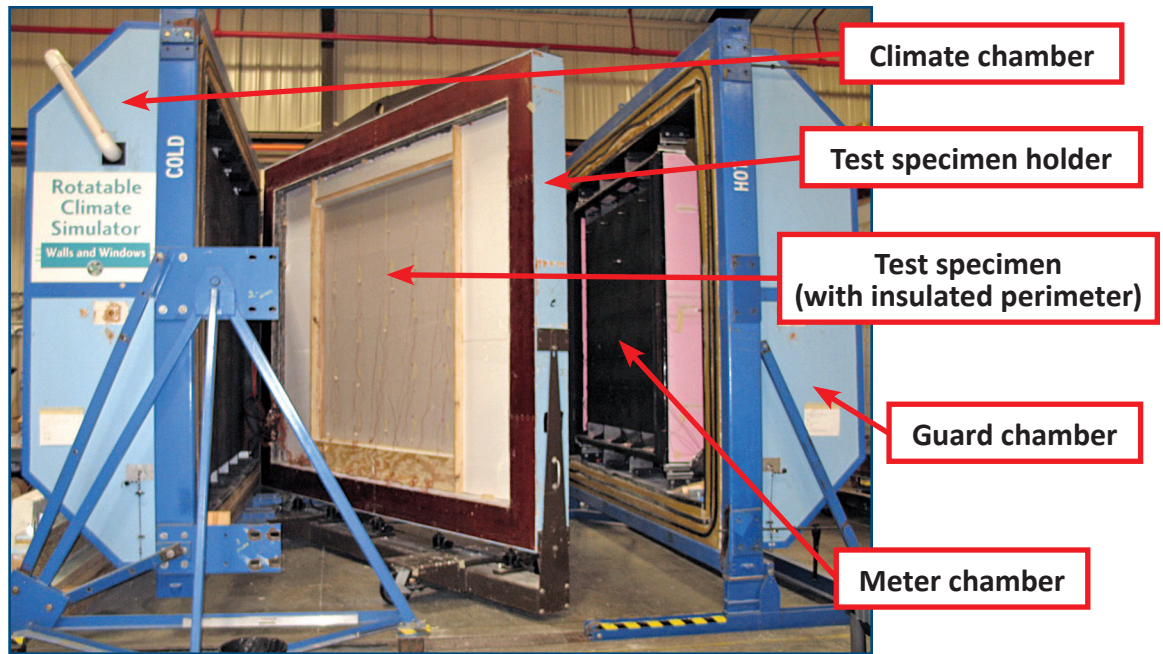


Figure 4 – The guarded hot box.

a high temperature of 110°F. The walls of the metering chamber are constructed with 3-in.-thick aged extruded polystyrene (XPS) foam with a thermal resistance of 14.8 hr ft² °F/Btu. Further, the guard chamber is also equipped with heaters to minimize the temperature difference with the metering chamber. The combination of foam insulation on the metering chamber and the guard chamber heaters essentially eliminates any heat loss from the metering to the guard chamber. During operation, the temperatures of the climate and metering

chambers are set at the desired levels and the system can reach steady state. Steady state is defined by the measured variables staying within the prescribed tolerances of ±0.5°F for temperature and ±1% for power and showing no monotonic changes. During the tests, the data (temperatures, power supply, etc.) are collected every 30 seconds. Once steady state is established, data from the last 12 hours of the steady-state period are used for analyses.

The test wall construction from the exterior side inward was as follows: MAI/vinyl,



Figure 5 – Fabrication of MAI panels and construction of the GHB test specimen.

0.5-in. extruded polystyrene foam (XPS), 0.5-in. oriented strand board (OSB), 2 x 4 studs with empty cavities, and 0.5-in. interior sheathing (gypsum board). See *Figure 5*. The MA/vinyl composite was facing the cold (climate) side of the hot box that was maintained at 50°F; the gypsum board was facing the warm (meter) side of the hot box that was maintained at 100°F.

Three arrays of 20 thermocouples were placed on the vinyl surface, the interface between XPS and OSB, and the gypsum surface. The thermocouples were installed on identical locations on the three surfaces; in other words, at any given location, the thermocouples on the three surfaces were along a straight line to enable calculation of the temperature differences across the surfaces.

Eight pieces of siding were used to construct the wall. Within each piece there were four MAI panels; three were of dimensions 24 x 10.62 in., and one was 22 x 10.62 in. Thus, the overall MAI coverage within the wall was 86.7%. On the cavity side, the area fraction of the frames or studs was 13.7%. Ten thermocouples were placed on MAI sections without joints or studs, while five sensors were attached over the joints between the siding pieces and the stud locations. The area fractions were used to calculate the area-weighted temperature differences between the different surfaces. Area-weighting equations were used (see *Equations 1* and *2*):

It is noted that for the whole wall, the MAI and non-MAI areas will impact the calculated temperature differences. Similarly, for the vinyl-to-XPS section, the thermocouples on the stud locations will have an impact on its weighted-average temperature difference. Thus, there is some uncertainty in calculations of R-value resulting from the uncertainty in the temperature difference

For the whole wall and OSD-cavity-gypsum section:

$$\Delta T_{\text{area-weighted}} = \Delta T_{\text{non-stud}} \cdot \left(1 - \frac{A_{\text{stud}}}{A_{\text{total}}}\right) + \Delta T_{\text{stud}} \cdot \frac{A_{\text{stud}}}{A_{\text{total}}}$$

Equation 1

For the siding-XPS section:

$$\Delta T_{\text{area-weighted}} = \Delta T_{\text{non-MAI}} \cdot \left(1 - \frac{A_{\text{MAI}}}{A_{\text{total}}}\right) + \Delta T_{\text{MAI}} \cdot \frac{A_{\text{MAI}}}{A_{\text{total}}}$$

Equation 2

Power input meter chamber (Btu/hr)	189.7		
Total wall area (ft ²)	64.0		
	Vinyl	XPS/OSB	Gypsum
Average air temperatures (°F)	50.1		100.1
Average surface temperatures (°F)	51.3	89.6	96.8
	Whole wall	Vinyl/XPS	OSB/Gypsum
Area weighted ΔT (°F)	45.5	38.3	7.2
R-value (hr-ft ² -°F/Btu)	15.4	12.9	2.4

Figure 6 – Summary of guarded hot box results.

calculations.

With instrumentation installed at critical locations, the R-value of different portions of the test wall can be derived separately (*Figure 6*). Knowing the temperature differences across the entire assembly and the stud cavity (OSB/gypsum), their individual R-values can be calculated. The measured R-value of the MAI/vinyl and XPS layer was 12.9 hr-ft²-°F/Btu, if taking the difference between the whole wall and the OSB-to-gypsum section. Assuming R-5/in. for XPS, the R-value of the MAI/vinyl portion is in the range 10.4 hr ft² °F/Btu.

DURABILITY OF THE VINYL/MAI PANEL BOND

A potential issue of these composites is the difference in thermal expansion coefficients (CTE) of the MAI panels (core and barrier films) and the vinyl siding. These can vary by a factor of 10 and the thickness between the barrier film and vinyl siding varies by a factor of 200. Experiments were performed in Albuquerque, NM, to subject the test panels to the extreme diurnal solar load cycles that provided as large a temperature difference (ΔT) as the siding would typically experience under virtually any installation conditions. The surface temperature variation from night to day

can vary by over 90°F, which will cause the outer layers to be in compression during the night and tension during the day. These temperature variations cause changes in the lengths of the barrier films and vinyl siding that stress the adhesive bond.

The MAI/vinyl siding was compared to a traditional insulated siding of expanded polystyrene (EPS). Both sets of siding were installed on a south-facing wall, which utilizes the solar irradiance that results in high daytime surface temperatures of the MAI/vinyl and EPS/vinyl composites. Initial experiments utilized hot-melt adhesive to connect the components together. One section of panel was also painted black to enhance the effect of the solar radiation by decreasing its solar reflectance. This first experiment failed within the first week as the increased surface temperatures (over 150°F) allowed the hot-melt adhesive to melt again, causing the vinyl siding to lose rigidity and warp. The panels on the black painted siding completely detached from the siding, leading to extreme warping (*Figure 7*).

A second experiment was undertaken that utilized a polyurethane reactive (PUR) adhesive to mitigate the delamination encountered from solar radiation. Unlike regular hot melt, PUR will solidify through moisture in the air to form a bond that will not re-melt. A PUR applicator gun with an adjustable spray nozzle was used to apply the PUR. This allowed for more coverage area than the extrusion applicator that was used for the first experiment. This kind of application process is dependent on temperature and humidity to ensure the best possible bond. The PUR was applied only to the MAI composite, as we did not have a sufficient quantity to use on the EPS siding at the time. This second experiment did not include the black painted siding; the available solar radiation did not need any enhancing, as it was sufficient to increase



Figure 7 – Initial experiment setup (left); delamination and warping of siding (right).

the vinyl surface temperatures to reasonable mid-afternoon sunlit levels.

The MAI and EPS composites were instrumented with temperature sensors on the front of the vinyl siding and on the support board behind the insulation. This allowed for measurement of the temperature difference across their cross sections. Ambient temperature was recorded directly in front of the test panels. The solar radiation was also monitored using a pyranometer mounted on a cross bar. We collected data from this second experiment for seven months. This time frame provided data in both the winter and summer months, giving valuable information about the durability of the panels and the possible negative side effects from extreme thermal cycling. The test wall was monitored for signs of warping and delamination during this period. During the experiment it was noted that there was minimal

warping of the siding. This observation led to a modification to the experiment at the four-month mark. At that point in time, the top MAI panel was cut in half to test what would happen to the siding with decreased thermal performance if an MAI panel failed. This would provide information for real-world installation where siding would need to be cut around windows and doors.

Visual inspection of the test wall showed some bumps in the siding that would be indicative of areas not being fully adhered. It should be noted that there were more bumps present on the EPS composite, which is due to the use of hot melt instead of PUR adhesive. After taking the test wall apart, it was apparent that certain areas of the EPS had become completely detached. The MAI sections were all strongly adhered to the vinyl, including the MAI panel that had been cut in half (Figure

8). There were still some issues with getting full coverage with the PUR due to the applicator gun. This problem would likely be resolved in an inline process required for mass production as the proper equipment and would likely mitigate the bumps developed in this experiment.

Testing of the thermal cycling of the MAI composites showed that with the proper adhesive (PUR), warping/buckling of the vinyl siding could be avoided. Although the vinyl siding and the MAI panels have different CTEs, the stress of the thermal cycling was not enough to break the adhesive bond between them. It is essential to get full coverage of PUR hot melt, as well as good contact between the MAI panels and vinyl siding to avoid warping. During this experiment it was also shown that the MAI panels were able to maintain the internal vacuum for the duration of the test.



Figure 8 – Siding autopsy. Panels still fully adhered to siding.



Figure 9 – Natural exposure test facility.

FIELD TESTING

A field test has just been initiated in a natural exposure test (NET) facility in Charleston, South Carolina. The NET facility is a single-story, conditioned building, which exposes side-by-side roof/attic and wall assemblies to natural weathering. *Figure 9* shows the southeast and southwest walls of the NET facility; the southeast wall is parallel to the long axis of the building and contains several openings for test walls. This orientation exposes the test walls to a maximum amount of wind-driven rain. These openings can accommodate test walls with state-of-the-art and prototype building envelope technologies for evaluation under real building and weather conditions. Typical test wall dimensions are 9 x 4 ft., and they are usually instrumented with temperature, relative humidity, and heat flow sensors. The data are collected and monitored over several months and even years to evaluate the long-term performance of building envelope systems and technologies.

Two test walls were built for this study: one with the MAI/vinyl composite siding, and the second one with EPS/vinyl siding. The test walls were constructed using interior sheathing (0.5-in. gypsum board), wood

framing (studs), cavity insulation (fiberglass batts), and exterior sheathing (0.5-in. oriented strand board or OSB). The studs were 3.5 in. deep and 1.5 in. thick, and the fiberglass batts had a nominal thermal resistance of R-13. The test walls contained thermistors, combination T/RH sensors, and HFTs at different interfaces and across the cross section. The sensors are scanned at 60-second intervals, and the time-averaged data were recorded at an hourly rate.

Experimental data from this facility were not available at the time of this writing but will be added to the presentation.

WHAT IS THE IMPACT IF THIS PRODUCT IS SUCCESSFUL?

The U.S. Census indicates that there are 135 million houses in the U.S., and that the median age of homes is approximately 40 years (American Community Survey 2015; see *Figure 10*). To estimate the potential energy savings of having an R-10 vinyl siding product, we divided the retrofit market into two segments based on the age of the home. We assumed that those homes built after 1990 (30 percent) had an average performance equal to the International Energy Conservation Code 2006 standard (IECC 2006). Homes built prior to 1990 (70

percent) were assumed to have an average performance based on American Society of Heating, Refrigerating and Air-Conditioning Engineers Standard 90A (ASHRAE 1980). The energy benefits of adding R-10 insulated siding to residential walls were estimated via EnergyPlus simulations of standardized buildings in Climate Zones 2 (Houston, TX) and 5 (Chicago, IL).

Per the DOE BTO Market Definition Calculator, the energy use totals for residential wall-generated heating and cooling loads for new and retrofit houses in climate zones 1-5 total 1600 TBTU for heating and cooling loads. On average, retrofitting the walls in the two climate zones show approximately a 9% reduction in heating and cooling load compared to the IECC 2006 baseline and 28% compared to ASHRAE 90A-1980 baseline. In total, the anticipated energy savings benefits of deploying R-10 MAI/vinyl siding would be approximately 360 TBTUs.

The estimated annual savings were 3.03 MWh of electricity and 79.1 therms of natural gas. If the national costs of 12.64 cents/kWh and \$12.36/1000 ft³ of natural gas (100 ft³=1.03 therms) are used to calculate reductions in energy cost, these yield annual savings of \$0.06/ft² of wall area for Chicago that initially conformed to IECC

2006. If we assume that buildings are insulated per the ASHRAE 1980 standard, the energy cost reduction due to added R-10 MAI/vinyl siding would be \$0.27/ft² of wall area per year. Similar savings were estimated for Houston (CZ2) weather.

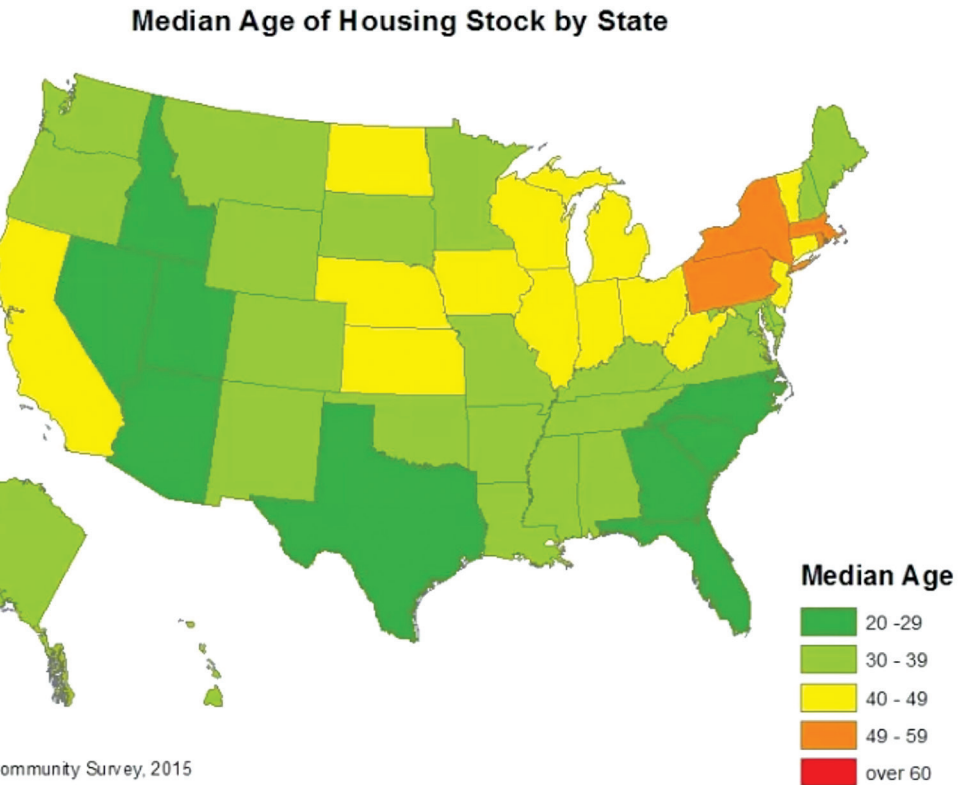
The 2015 U.S. Census data show siding replacement is a popular home improvement measure, with 1.1 million siding replacement projects implemented with revenues of \$6.3 billion. The National Association of Realtors cited siding replacement as one of the best long-term investments for homeowners, with vinyl siding showing an 85% cost recovery or the percent of the investment

that would be recovered due to increased property value (Cost vs. Value, 2016). Thus, cost-effective exterior cladding and insulation retrofit systems not only yield energy savings but also add value in terms of future resale, a critical decision factor for homeowners.

Material and installation cost of MAI/vinyl siding is based on typical insulated vinyl siding and estimated at our price target, which we feel is achievable. Thus, based on calculated energy cost savings, and assuming 85% cost recovery of the MAI/vinyl siding (Cost vs. Value, 2016), the estimated payback periods are 13 and three years for buildings with wall insulation, based on IECC 2006 and ASHRAE 1980, respectively.

SUMMARY AND CONCLUSIONS

This paper comprehensively describes the development, testing, and thermal characterization of novel vinyl siding with attached modified atmosphere insulation (MAI) panels. MAI is a low-cost vacuum insulation technology that can achieve a very high thermal resistance of R-40 per in. of thickness. Initial laboratory tests were done to test and verify the R-value claims of the MAI panels.



Source: American Community Survey, 2015


Figure 10 – Median age of housing stock by state. <http://eyeonhousing.org/2017/01/age-of-housing-stock-by-state/> (American Community Survey, 2015).

Steady-state laboratory tests were done on full-scale prototype siding composite panels. Hot box tests of full-scale samples yielded a thermal resistance of R-10.4; in comparison, current insulated claddings can only achieve about R-2 at the same thickness. The reduction in the R-value of the MAI panel (R-40) to the MAI/vinyl siding composite is due to the thermal bridging created by the incomplete coverage. Work is underway to improve this attribute.

Field tests have been initiated to assess the durability of the insulated cladding system. Small-scale field exposures have been undertaken to help assess various vinyl siding attachment methods to the MAI panels. Based on limited testing and limited durations of exposure, the use of a PUR adhesive appears to be suitable for this purpose.

A simple payback analysis has been undertaken. If an installed cost of \$6.00/ft² can be achieved, the calculated energy cost savings and assumed 85% cost recovery of the MAI/vinyl siding will result in estimated payback periods of between three and 13 years, depending on how well the existing wall systems perform and the type and efficiency of the heating and cooling systems.

ACKNOWLEDGEMENTS

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APPENDIX A – MAI-RELATED PATENTS

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