Demonstration of the Hygrothermal Performance of a Next-Generation Insulation Material in a Cold Climate

Kaushik Biswas, Andre Desjarlais and Timothy Jiang*
Oak Ridge National Laboratory - Oak Ridge, TN, USA
** Vanderbilt University, Nashville TN (2016 Science Undergraduate Laboratory Intern at Oak Ridge National Laboratory)*

Tapan Patel and Andrew Nelson
U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory - Champaign, IL, USA

Douglas Smith
Nanopore, Inc. – Albuquerque, NM, USA

ABSTRACT: Energy loss through building walls is estimated to cost the department of defense (DOD) about $200m/year, accounting for 5% of the total energy cost in DOD facilities. This article describes the demonstration of a high-performance insulation material, called modified atmosphere insulation (MAI), to reduce wall-related heat losses in a DOD building located in Ft. Drum, New York, in a cold climate. MAI has been demonstrated to achieve R32/inch (hr-ft^2-°F/Btu-in) or greater and its use can significantly increase the thermal resistance of walls with a marginal increase in wall thickness, making it an ideal candidate for retrofit application. MAI is a variant of vacuum insulation panels (VIP), produced at a substantially reduced cost resulting from a change in the evacuation process.

By retrofitting walls and increasing thermal resistance, as measured by R-value, by R10-20 (h-ft^2-°F/Btu), reductions of 30% or more over baseline wall-generated space conditioning loads are possible. Further, with targeted applications for older or more poorly insulated facilities, greater energy savings can be achieved. In this article, the installation of MAI panels in an existing building at Ft. Drum and the resulting energy benefits will be described. Like VIPs, MAI panels consist of an evacuated nanoporous core that is encapsulated within air and vapor impermeable barrier films. Addition of these impermeable barrier films can have implications on the moisture storage and movement within the wall systems. Therefore, in addition to the thermal performance evaluation, measurements and modeling will be used to determine the hygric behavior of the retrofitted walls.

INTRODUCTION

The department of energy (DOE) estimates that in 2010, 15.6 quads of primary energy consumption was attributable to fenestration and building envelope components of all U.S. buildings, including DOD Facilities; the wall-related primary energy consumption was about 21%, or 3.3 quads [1]. For commercial facilities, primary energy consumption attributed to walls during heating cycles was 1.48

quads, or ~30% of the total energy consumption due to fenestration and building envelope components. Heat loss through walls during a heating cycle is a critical component of overall facility energy use and mitigation measures are important in order to reduce total facility energy consumption.

In Department of Defence (DOD) buildings, space conditioning due to the heat transfer through walls is estimated to cost about $200M/year, accounting for 5% of the total energy cost in DOD facilities. This article describes the demonstration the use of modified atmosphere insulation (MAI) to reduce wall-related heat losses in DOD facilities. Modified atmosphere insulation is a lower cost version of vacuum insulation panels [2]. The use of MAI can significantly increase the thermal resistance of walls with a marginal increase in wall thickness, making it an ideal candidate for retrofit installation.

MAI represents a new generation of advanced thermal insulation with the performance of silica-based vacuum insulation panels (VIPs) and significantly reduced cost. MAI consists of an evacuated core composed of fumed silica that is encapsulated in multi-layered barrier films. Advanced insulation materials promise a step-change in performance from current materials that provide R6-7/inch to R40/inch in advanced materials. MAI has been demonstrated to achieve >R32/inch, and can be produced at significantly reduced cost when compared to VIPs ($0.12/ft^2/R vs. $0.25/ft^2/R) [2]; for comparison, the cost of 1 inch thick foam boards is about $0.06-0.10/ft^2/R. The high-cost of VIPs can be attributed to processing that includes pressing fine powders into a board, cutting, drying, and then evacuating and sealing in a vacuum. MAI is produced at a reduced cost by replacing the air in a fluidized powder with a low molecular weight, low conductivity compound, resulting in fewer process steps and lower cost. Biswas et al. [3] have described the development of a R12/inch composite foam insulation board containing MAI panels.

This article describes the installation of MAI panels in an existing building at Ft. Drum and the resulting energy benefits. Since MAI panels consist of an evacuated nanoporous core that is encapsulated within air and vapor impermeable barrier films which can act as air/vapor barriers, addition of MAI panels implications on the moisture storage and movement within the wall systems. Therefore, in addition to the thermal performance evaluation, hygrothermal modeling has been used to determine the hygric behavior of the retrofitted walls.

TEST BUILDINGS AND INSTRUMENTATION

This project proposes to retrofit a classroom building (shown in Figure 1) at Ft. Drum with MAI panels and evaluate the energy benefits. The retrofit using MAI panels will be done on all walls of the target building. The target buildings are approximately 35 ft. by 55 ft., with 10 ft. high walls. They consist of 2x6 wood-frame construction with exterior metal siding, plywood sheathing and R19 fiberglass insulation in the cavities. There are multiple buildings of identical design located close to one another. All buildings have control systems for their HVAC and the project team has access to occupancy, internal load schedule, lighting and miscellaneous electric loads, set points, and runtimes for the HVAC system in the buildings. Two buildings will be monitored throughout the project period: one building will have its walls retrofitted with MAI panels and the other building in its original condition. This enables a side-by-side comparison of two buildings, one in its current (baseline) configuration and another with the external walls retrofitted with MAI panels (test building).

Figure 1: Northwest (left) and southwest (right) corner views of a target building at Ft. Drum

Both the baseline and test buildings were instrumented with an array of thermocouples, relative humidity (RH) probes and heat flux transducers (HFT). Figure 2 shows the sensors attached to the walls, ceiling and floor of the two buildings. A weather station is also installed to obtain the onsite weather data (solar, wind, outdoor temperature and RH, etc.).

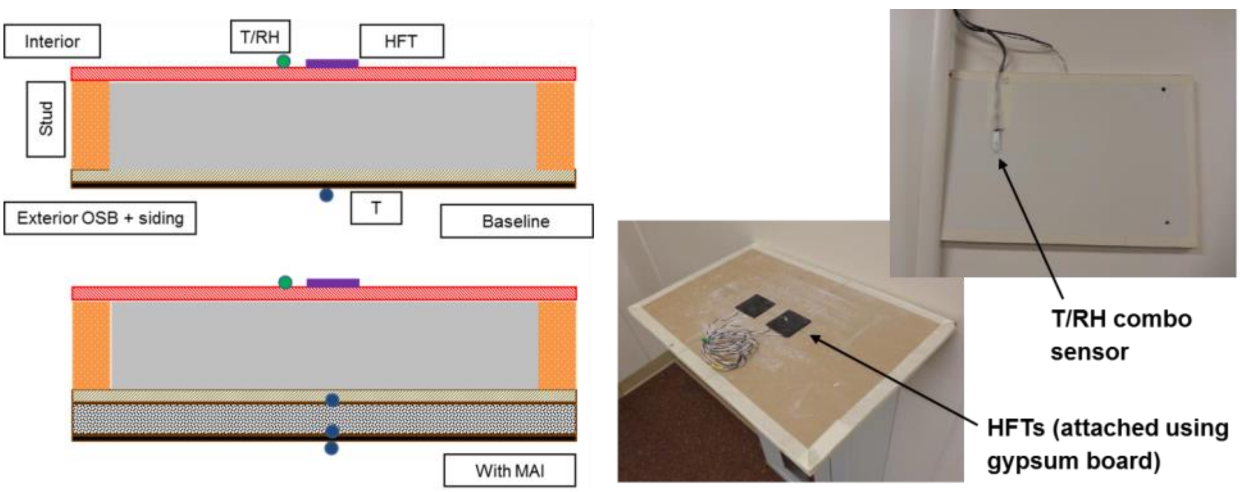

Figure 2: Suite of sensor attached to the walls of the test and baseline building walls

BUILDING RETROFIT

The retrofit work was performed in November 2015. The MAI panel dimensions were chosen to optimize the variation in dimensions and overall coverage of the walls that can be achieved with MAI panels. It is desirable to use as few different panel dimensions as possible, since fewer sizes result in lower manufacturing costs. Table 1 lists the four different panel dimensions that were used; all panels were 1 inch thick. Total of 331 panels were used, yielding an average coverage of 76% of MAI panels. The gaps between MAI panels were filled with 1 inch thick polyisocyanurate (PIR) insulation boards.

Table 1. MAI panel dimensions

Description	Length (inch)	Width (inch)	No. of panels
A	28.00	19.95	87
B	28.00	21.29	83
C	25.50	19.17	26
D	25.50	20.58	135

The MAI panels were attached using adhesives after removing the metal siding. The interfaces between the MAI panels and the polyiso foam strips were sealed using adhesive tape. Figure 3 shows some images of the wall retrofit using the MAI panels.

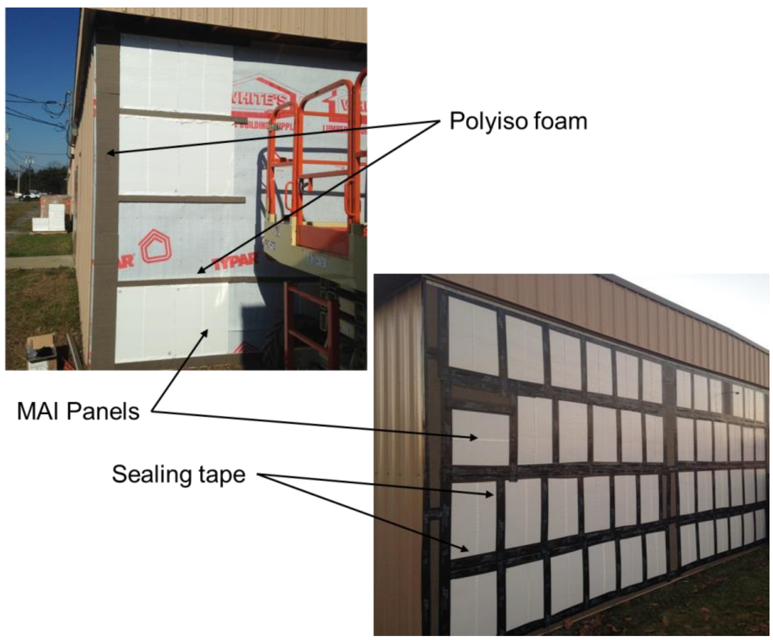

Figure 3: Wall retrofit using MAI panels

RESULTS AND DISCUSSION

Temperature, Heat Flux and Power Consumption Data

The data monitoring started in August 2015, to gather some initial data from both the baseline and test buildings. However, troubleshooting of some sensors and the remote data acquisition were performed during November 2015 and April 2016. Here, data from a winter month (January 2016) are shown. Figure 4 shows the temperature distribution across the north wall of the test building.

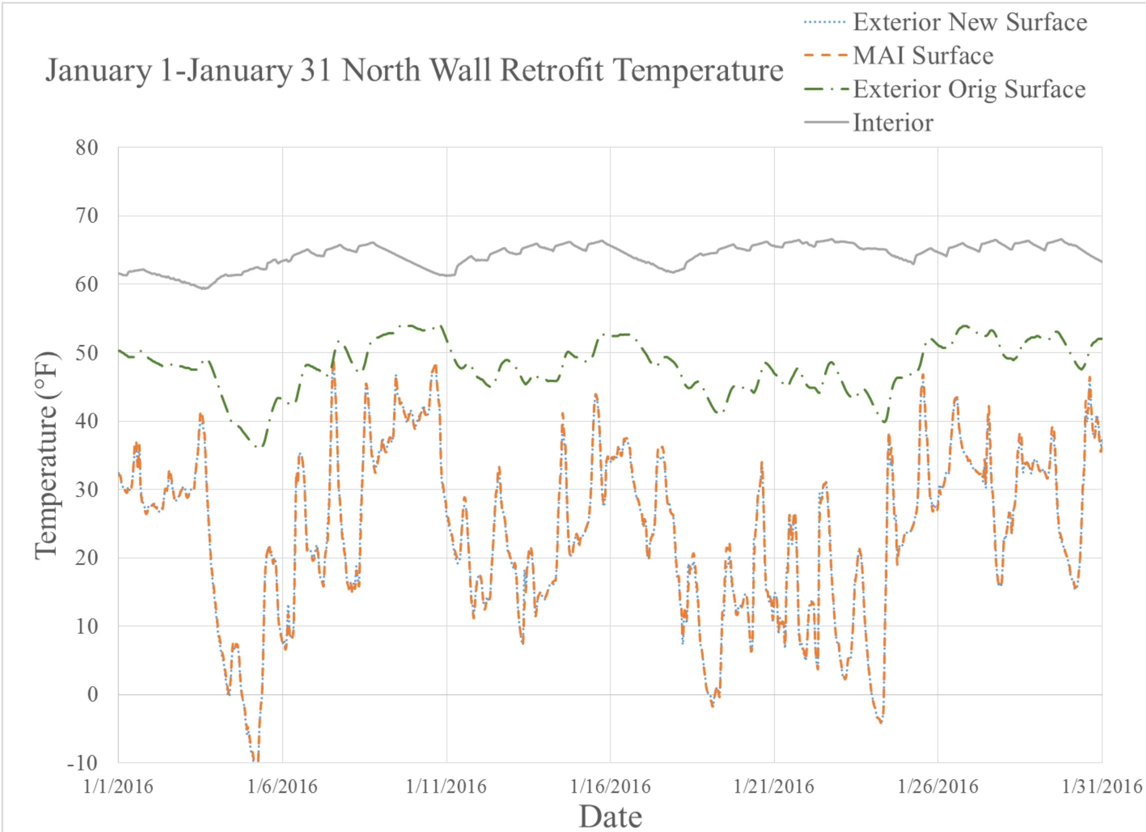

Figure 4: Measured temperatures across the north wall of the test building during January 2016.

Figure 5 compares the heat flows through the east wall of the baseline and test (retrofit) buildings. Some reductions in the peak heat losses were observed due to the addition of the MAI panels. It should be noted that the both the test and baseline buildings were newly constructed with a high level of wall insulation as the default construction. In older, poorly insulated buildings, much greater reductions in heat flows with addition of MAI panels can be expected.

In addition to the wall sensors, natural gas flow meters and watt-meters were installed in both buildings to measure the overall energy consumption. During January 2016, the natural gas usage for space heating in the baseline and retrofit buildings were 11596 and 9949 cubic feet, respectively; thus a reduction of 14.2% was observed in the retrofit building. The normalization of the energy consumption based on occupancy needs to be performed to get a better savings estimate. Data collection, analysis and energy modeling are ongoing to thoroughly evaluate the energy benefits of retrofitting one of the buildings with MAI panels.

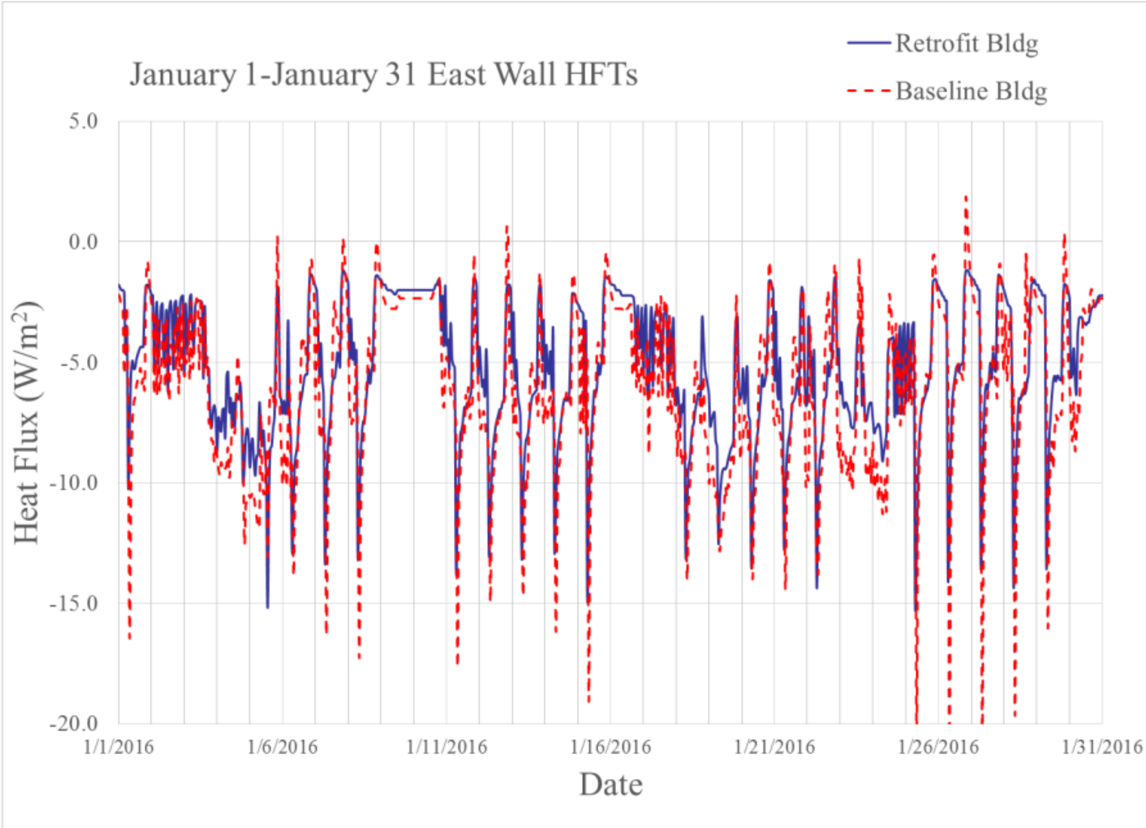

Figure 5: Measured heat fluxes across the different walls of the test building during January 2016.

Hygrothermal Modeling

One-dimensional (1D) calculations were performed to assess how the MAI panels as an additional exterior insulation for a typical residential wall construction influences the hygrothermal performance of the walls of the retrofitted building. The calculations were done using WUFI,[1] which is a software program used for performing realistic transient calculations of coupled, one-dimensional heat and moisture transfer through building envelope systems. In this section, the WUFI modeling of the walls of the Ft. Drum buildings will be presented.

Figure 6 shows the schematic of a modeled test wall consisted of metal siding, a 0.2 inch air layer, a 1 inch thick MAI layer, 0.5 inch thick oriented strand board (OSB) with an exterior weather barrier (0.008 inch polyolefin membrane), 5.5 inch cavity filled with fiberglass insulation and 0.5 inch thick interior gypsum board. An additional model was created with 1 inch thick faced-polyisocyanurate foam insulation replacing the MAI panel, to represent the wall areas between the MAI panels. The baseline wall model was the same as above, but without the MAI/polyisocyanurate layer.

[1] http://web.ornl.gov/sci/buildings/tools/wufi/

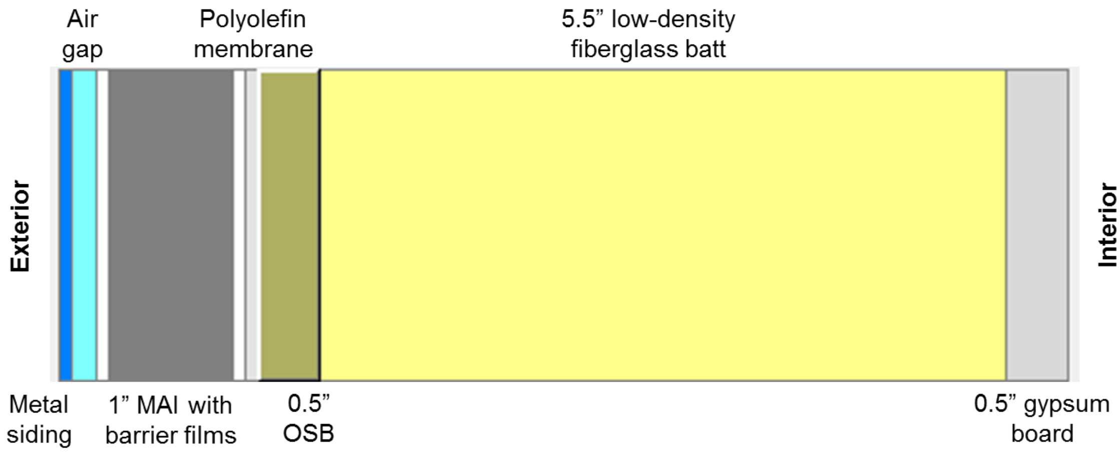

Figure 6: Schematic of the modeled test wall with MAI panels.

The material properties were taken from the existing WUFI databases or obtained from measurements, literature, private communications, etc. In several instances, due to lack of readily available data, materials properties of the assembly components were approximated by existing data for materials with similar properties in the WUFI databases. For example, the facers of the polyisocyanurate insulation were approximated by ‘60 minute Building Paper’ from one of the WUFI databases. The MAI barrier films were approximated by a vapor barrier. The permeability of the metal siding was specified while considering joints between siding panels and mechanical fasteners. Table 2 lists the basic material properties used in the simulation. Other functions such as the moisture storage function (RH dependent), liquid transport coefficient, etc. are not listed here but can be found in the WUFI databases.

Table 2. Material properties used in the WUFI simulations

Material	Density (lb/ft^3)	Specific heat (Btu/lb-°F)	Conductivity (Btu/h-ft-°F)	Permeability (perm-inch)
Metal siding	488.811	0.119	26.174	0.039
Air	0.081	0.239	0.041	176.438
MAI barrier film	8.116	0.549	1.329	0.001
MAI core	10.925	0.201	0.002	2.501[a]
Polyisocyanurate foam insulation	1.654	0.351	0.014	2.501
Insulation facer (60-min building paper)	17.480	0.358	6.933	0.894
Polyolefin membrane	27.968	0.358	1.387	0.392
OSB	40.578	0.449	0.053	0.159
Low-density fiberglass batt	0.5	0.201	0.025	106.446
Gypsum board	39.018	0.208	0.092	18.322

[a] Approximated from polyisocyanurate data

Hourly weather data from Albany, NY was used for the simulations, again due to lack of readily available weather data from Ft. Drum. The weather data include solar, wind, rain, temperature and RH data. 10% cold year weather data was used, i.e. the third coldest out of 30 years, representing a more critical test of the wall assembly in terms of moisture-related vulnerabilities (compared to warmer weather). A 1% rain intrusion into the exterior sheathing (OSB) was assumed following ASHRAE 160 [4]. Interior temperature and RH conditions were based on EN 15026 [5], which are appropriate for a small commercial building like the classroom buildings at Ft. Drum. Figure 7 compares the prescribed interior RH from EN 15026 with limited measured RH from one of the test buildings. The simulations were performed over five years (October, 2016 – Septmeber, 2021). For analysis and discussion, the results of the simulations after the first two years have been utilized

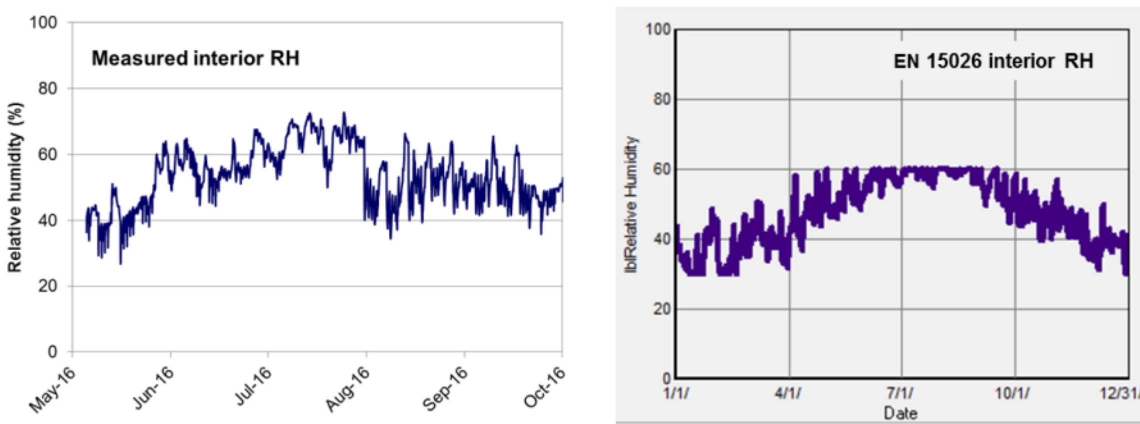

Figure 7: Comparison of measured (left) and EN 15026 prescribed (right) internal RH.

Figure 8: Schematic of the modeled test wall with MAI panels.

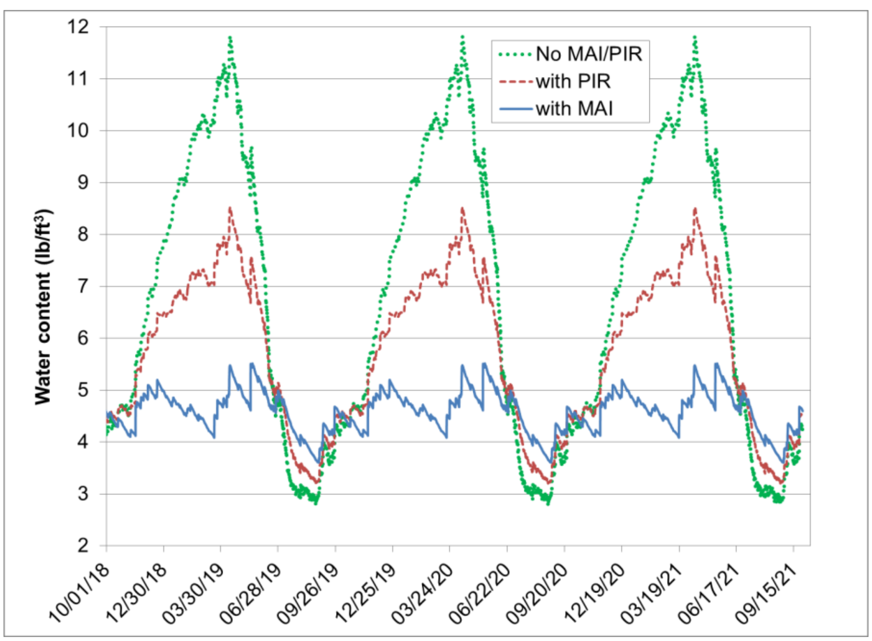

Figure 9: Calculated water content in the OSB layer.

In the remainder of this section, the water content in the OSB and temperature and vapor pressure distributions across the modeled wall assemblies are presented. For the present calculations, the OSB layer is the component of interest from the perspective of moisture-related issues. As seen in Figure 9, highest moisture content was observed in the baseline model ('No MAI/PIR'), followed by the wall model with PIR insulation and finally the wall model with MAI. The results are shown for a north-west facing. Analysis of the weather data for Albany showed that the northwest facing wall gets the highest rainfall and, therefore, this orientation provides the most stringent test of the wall designs. For further assessment, the calculated temperatures and vapor pressure from the different models are presented.

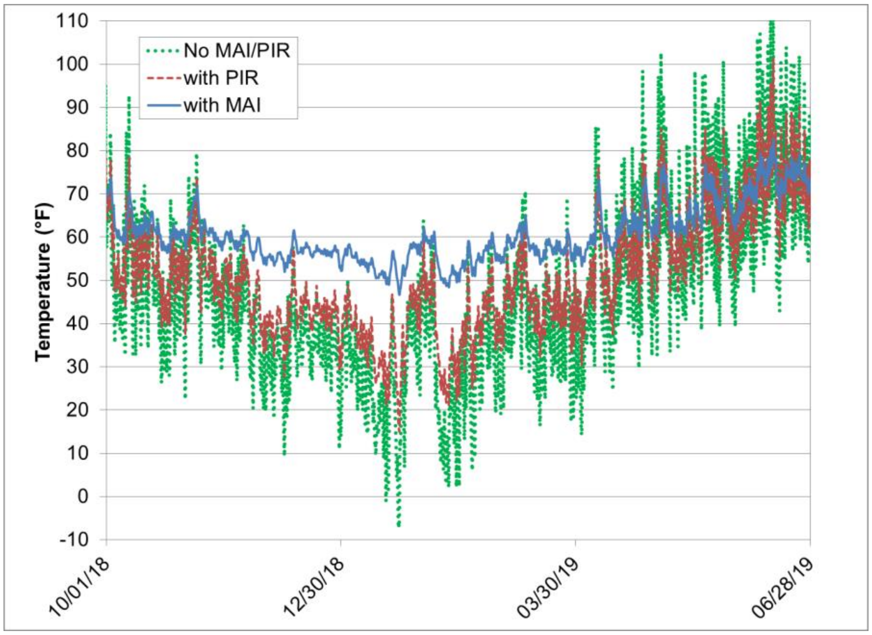

Figure 10: Calculated temperatures at the exterior OSB surface.

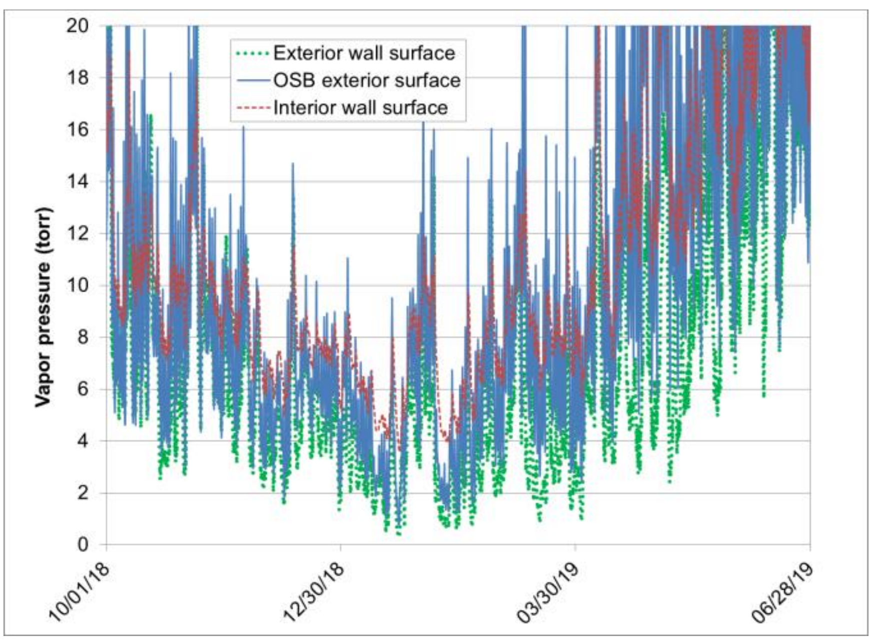

Figure 11: Calculated vapor pressure at different wall surfaces of the baseline model.

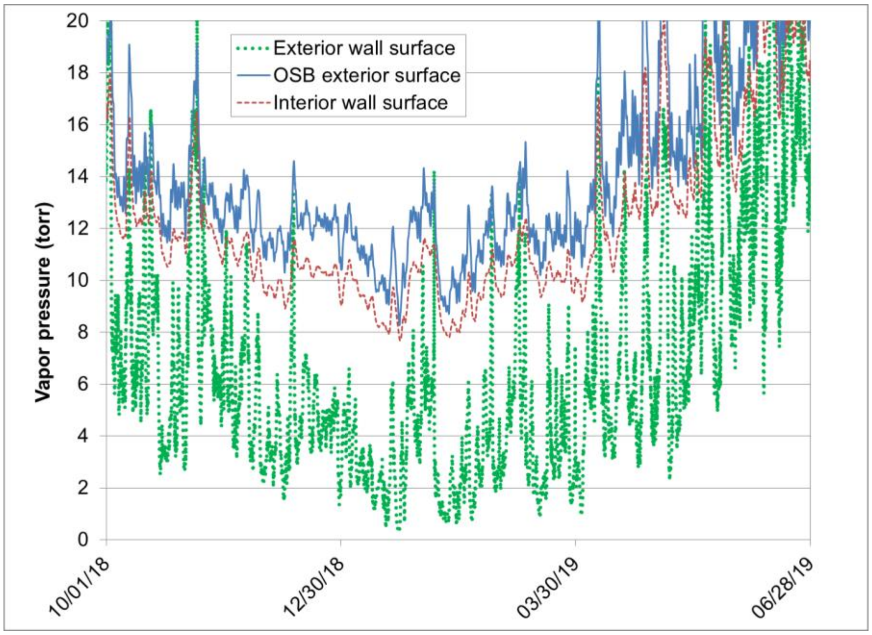

Figure 12: Calculated vapor pressure at different wall surfaces with MAI.

Figure 10 shows the calculated exterior OSB surface temperatures during the winter and spring periods, when the OSB moisture content peaked. As expected, higher temperatures at the exterior OSB surface were observed with higher external thermal resistance (MAI > PIR > baseline). Figure 11 and Figure 12 show the calculated vapor pressure at three surfaces for the baseline model and the wall model with MAI. The vapor pressures at the exterior wall surface, the exterior OSB surface and the interior wall surface are shown. For the baseline model, while there is a lot of overlap between the three plots, a trend of higher vapor pressure on the interior surface, followed by the exterior OSB and finally the exterior wall surface is seen. This indicates a predominantly outward moisture drive. Conversely, for the wall model with MAI, the highest vapor pressure was observed at the exterior OSB surface, followed by the interior wall surface and then the exterior wall surface.

Finally, Figure 13 shows the difference in the calculated vapor pressure at the interior wall surface and the exterior OSB surface. A positive difference indicates moisture drive from the interior to the OSB. The calculated differences from the baseline model show large fluctuations between positive and negative values. For the period shown in Figure 13, the vapor pressure difference in the baseline model was observed to be positive during 4621 hours and negative during 1859 hours. For the wall model with polyisocyanurate, the difference was positive over 3694 hours and negative over 2786 hours. For the model with MAI, the difference was negative at all times. Thus, higher the thermal resistance of the exterior insulation, the lower is the moisture drive from the interior to the OSB.

It is noted that the wall models with MAI and polyisocyanurate do not account for two-dimensional (2D) effects that will be present in the actual retrofitted wall. Here, the 1D simulations assumed only MAI or only polyisocyanurate exterior insulation. A 2D WUFI simulations are required for accurate simulations of the whole wall containing the MAI panels with polyisocyanurate strips filling the gaps. The intent of this article was primarily to determine if adding the MAI as an exterior insulation can lead to moisture-related problems.

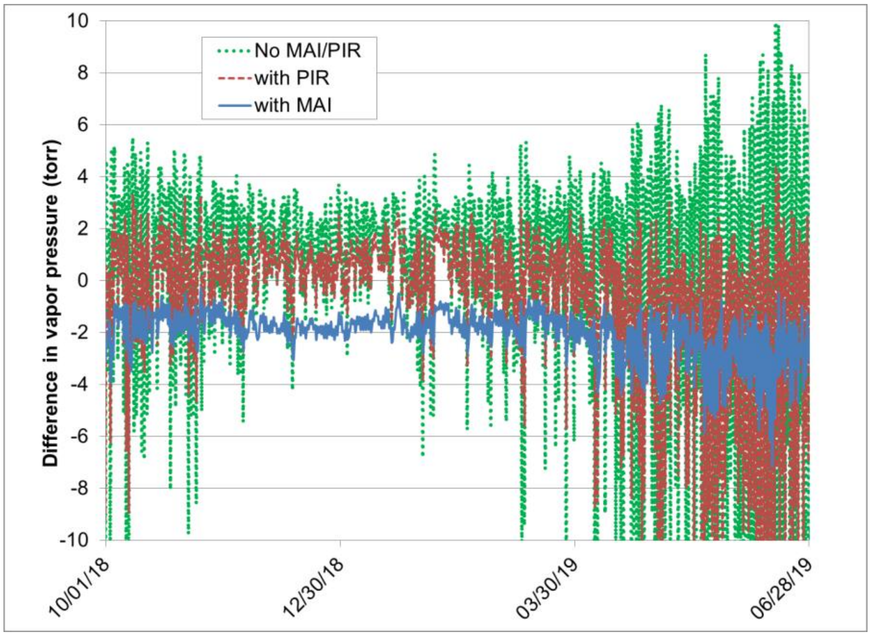

Figure 13: Difference in vapor pressure between the interior wall and exterior OSB surfaces.

SUMMARY AND FUTURE WORK

This is a work-in-progress project to demonstrate the use of MAI in a retrofit application and quantify the effectiveness and cost payback of such an approach at an existing building at Ft. Drum. The monitoring plan includes temperature, heat flux and humidity sensors, gas flow and watt-meters for the HVAC and miscellaneous electrical loads, and an onsite weather station. Energy consumption-related and hygrothermal modeling of the baseline and test buildings are planned.

In this article, preliminary data and analysis results as well as hygrothermal modeling results are presented. Initial analysis indicated heating energy savings of 14.2% in terms of cubic feet of natural gas consumed. One-dimensional hygrothermal modeling using WUFI indicated no adverse moisture implications of adding the MAI panels as exterior wall insulation. In fact, for the current construction and climate conditions, addition of exterior insulation reduced the risk of moisture-related issues in the exterior sheathing.

In addition to continued monitoring and analyses of the experimental data, EnergyPlus whole-building models of the two buildings will be developed. The models will be validated using measured temperature, heat flux and energy consumption data. The validated numerical models will be used for parametric studies of the energy-saving potential of the MAI technology in buildings with different levels of wall insulation in different climate zones. Finally, as more on site data become available, the hygrothermal models can be revisited using local weather data.

ACKNOWLEDGMENTS

The funding for this project has been provided by the Department of Defense's Environmental Security Technology Certification Program (ESTCP). ORNL is supported by the Building Technologies

Office of the U. S. Department of Energy under contract no. DE-AC05-00OR22725 with UT-Battelle, LLC. Thanks to Dr. Johney Green (former Division Director at ORNL) for his support of this project. The contributions of Ron Esparza of NanoPore and Megan Kreiger and Jeffrey Lattimore of CERL in retrofitting one of the buildings with MAI as well as Phil Childs, Bradley Brown and Anthony Gehl of ORNL in instrumenting the test building, data gathering and troubleshooting are gratefully acknowledged. Stephen Rowley, the Ft. Drum Energy Manager, was instrumental in selection, instrumentation and retrofit of the test building, and the authors appreciate his efforts. The help received from Mike Howard (foreman), Dave Huston, Kent Fleming, Tommy Lundy and Tony Ramos (Carpenters) as well as Wayne Ashline and Glen Sarnowski (Electricians) of Ft. Drum was invaluable in the retrofitting and instrumentation tasks. Finally, thanks to Manfred Kehrer (formerly of ORNL) for the WUFI simulations of walls containing MAI-foam composites, which guided the present simulations.

REFERENCES

1. Windows and Building Envelope Research and Development: Roadmap for Emerging Technologies, US DOE Office of Energy Efficiency & Renewable Energy, February 2014, available online at http://energy.gov/eere/buildings/downloads/windows-and-building-envelope-research-and-development-roadmap.
2. Modified Atmosphere Insulation - Scoping Study for Next Generation Building Envelope Materials, 2014 Building Technologies Office Peer Review, U.S. Department of Energy, available online at http://energy.gov/sites/prod/files/2014/07/f17/emt60_Biswas_042314.pdf.
3. Biswas, Kaushik, Desjarlais, Andre Omer, Smith, Douglas, Letts, John, Yao, Jennifer. Development of High Performance Composite Foam Insulation with Vacuum Insulation Cores. Buildings XIII – Thermal Performance of the Exterior Envelope of Whole Buildings Conference, *accepted July 2016*.
4. ANSI/ASHRAE Standard 160-2009. Criteria for Moisture-Control Design Analysis in Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, www.ashrae.org.
5. CEN EN 15026. Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation, European Committee for Standardization, www.cen.eu.