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Development of Ultra High-R Envelope Using Vacuum Panel Technology

Final Report

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Development of Ultra High-R Envelope Using Vacuum Panel Technology

Final Report

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Acknowledgments

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Acronyms and Abbreviations

FSK	Foil-Scrim-Kraft
IMP	Insulated Metal Panel
MBMA	Metal Buildings Manufacturers Association
MCA	Metal Construction Association
MAI	Modified Atmosphere Insulation
NYSERDA	New York State Energy Research and Development Authority
ORNL	Oak Ridge National Laboratory
PIR	Polyisocyanurate Rigid Board Insulation
RGHB	Rotatable Guarded Hot Box
sq ft	Square Feet
VIP	Vacuum Insulation Panel
IECC	International Energy Construction Code

Executive Summary

Newport Ventures; Oak Ridge National Laboratory (ORNL); Nanopore, Incorporated; and ATAS International partnered to design, fabricate, and test a prototype insulated metal panel (IMP) incorporating Nanopore's Modified Atmosphere Insulation (MAI). MAI is a vacuum insulation with center-of-panel values R-values approaching R-30 to R-35 per inch. Because of increased manufacturing efficiencies, it can be produced at significantly lower cost compared to other vacuum insulation materials. Although currently used in a number of refrigeration applications requiring exceptionally high insulating properties, this project was one of the first to explore its use in the building technology area.

Because the thermal performance of MAI will degrade if punctured, it was necessary to design the insulating core so as to protect it during handling and fastening in real-world applications. Rigid polyisocyanurate insulation was selected due to its comparably high R-value of R-5.5 to R-6.0 per inch relative to other readily available insulating materials. With respect to panel thickness, a 2-inch panel was chosen for two reasons:

- A 2-inch panel is commonly used in the current IMP market.
- Finite element modeling indicated that it was reasonable to expect an overall R-value for the 2-inch panel in the range of R-20 to R-25. This is about the maximum thermal performance for a wall that is panel currently marketable from both a practical and cost effectiveness standpoint.

The overall dimensions of the prototype pane were 8 feet × 8 feet because that is the largest wall section that the hot box (used to measuring the thermal resistance (R-value) and thermal transmittance (U-factor) of wall and window assemblies) at ORNL could accommodate. Three 32-inch × 96-inch, 24-gauge metal panels were used for the exterior skin.

In addition to the 24-gauge metal layer, the insulation core was comprised of two layers: the first comprised of 1-inch MAI panels surrounded by 1-inch strips of polyisocyanurate around the perimeter and at the mid-point of each of the three 32-inch × 96-inch panels and the second layer, 1-inch polyisocyanurate overlaid the first layer for protection. No interior face was added for the prototype because it would have no significant impact on the tested R-value, but would increase project costs.

During the design phase, ORNL performed finite element modeling and analysis to estimate R-value for the 2-inch panel. Modeling for the 2-inch panel with and without fasteners indicated R-23.8 and R-26.8, respectively.

Subsequent hot box testing results for the 2-inch MAI insulated panel were R-22.2. At the equivalent of R-11.1 per inch, this value is 50% to 80% higher than what is currently on the market. As energy codes for both commercial and residential buildings become more stringent, a building product or system that offers twice the insulating value per given thickness will not only provide higher building performance but also greater ease in achieving full code compliance. At this stage in its commercial development, it is premature to accurately predict ultimate retail costs of a MAI IMP. However, with the promising results of this project, further research will be explored for the MAI technology with respect to commercial and residential building applications

1 Background

1.1 Modified Atmosphere Insulation Technology

NanoPore's Modified Atmosphere Insulation (MAI) panels[1] have similar thermal performance to conventional vacuum insulation panels (VIP) that are made with nanoporous silica and infrared opacifiers and have center-of-panel R-values reaching R-35 per inch. However, MAI has several significant advantages:

- It can be manufactured at substantially lower cost compared to regular VIPs due to a 50% reduction in manufacturing steps including the elimination of the expensive and time-consuming drying and evacuation steps.
- It can be readily produced in non-rectilinear cross-sections with minimal tooling costs.
- It does not require the production of a precursor rigid board containing fibers which necessitates subsequent pressing and cutting.

In addition, like nanoporous silica VIPs, MAI maintains relatively high thermal performance (approximately R8-9 per inch) at atmospheric pressure. In other words, its insulating performance is still higher than conventional foam insulations even if punctured. MAI panels contain a high surface-area-fumed silica and infrared opacifier core. This design consists of a mixture of very tiny particles (<10 nanometers) that are formed into micrometer-sized aggregates, intimately blended with compounds including carbon, titania, and silicon carbide, which result in a material having high infrared extinction. For conventional VIPs, the silica/opacifier mixture is pressed into boards, cut to the desired size, dried, shrink-wrapped, encased in a metallized plastic or polymer barrier film, and then sealed under a vacuum.

In contrast, a MAI panel is created by bagging the powder mix in a porous bag that is sealed during processing to encapsulate the product into an impermeable outer barrier film. The condensation of steam (which replaces the air in the porous core) then creates the final vacuum. The porous silica core is filled with steam. As the steam condenses, the liquid takes up significantly less space, thereby creating a vacuum. The superior insulation characteristics of MAI are due to the unique shape and small size of the

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[1] U.S. and foreign patents pending

large number of pores in the core material. Heat transfer via convection is virtually eliminated and conductivity is significantly reduced. Proprietary infrared opacifiers reduce radiant heat transfer. Figure 1 compares the MAI's thermal performance and Figure 2 compares the MAI's conductivity to that of conventional insulation materials.

Figure 1. Thermal Resistance by Insulation Type

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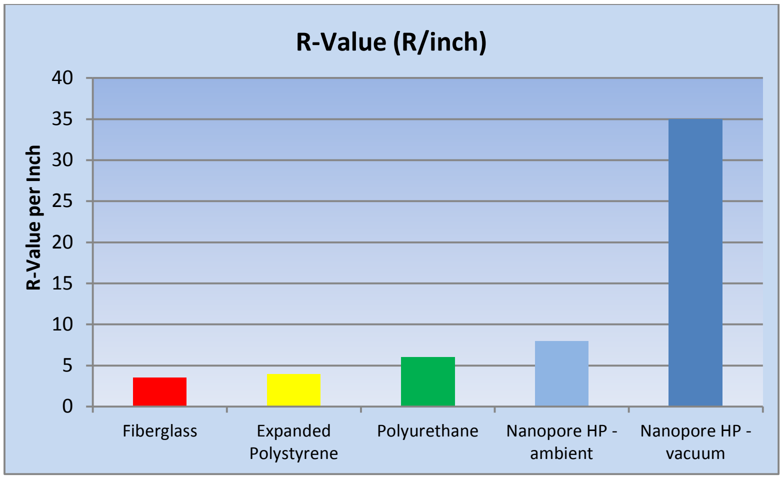

Figure 2. Conductivity by Insulation Type

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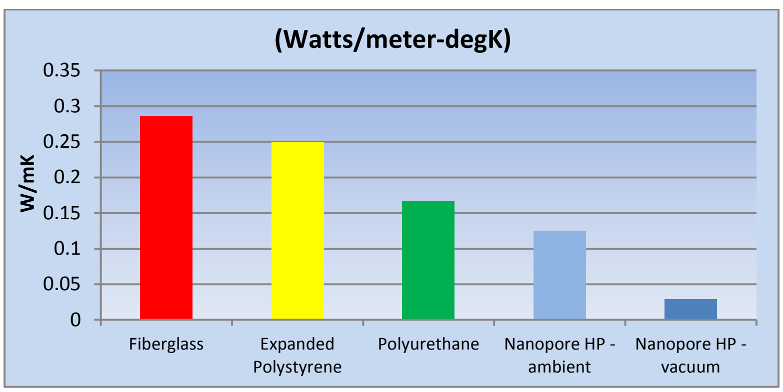

Because the MAI manufacturing process requires about half the steps compared to regular VIP and MAI is sealed at atmospheric pressure using standard packaging equipment at a much faster rate, it can be produced at a lower cost than typical VIPs. Existing research and current applications indicate that the insulation material itself can be produced and distributed to a first tier of purchasers at a cost of $0.15/square foot/R-value. If one assumes an additional 30% markup as the material is passed further along the distribution chain, one might anticipate a future retail cost of approximately $0.20/square foot/R-value. As a comparison, Home Depot pricing of polyisocyanurate rigid insulation (PIR) ranges from $0.11-$0.145/square foot/R-value. Although this price indicates a possible 50%-80% higher price tag for the MAI material alone, a substantially higher R-value per inch (R-11.1 vs. R6-6.5), affords opportunity for other cost savings in the construction process. Examples include:

- Lower costs of interior and exterior trim due to thinner profile.
- Greater ease of fastening adjacent materials such as cladding or interior gypsum.
- Lower costs for shipping and storage.
- Energy savings resulting from superior thermal performance per inch thickness.

1.2 Current Industry Status of MAI

MAI products are currently being commercialized in several applications. Because of its thin profile and ability to perform across a very wide range of temperatures (from -330 ºF to over 1,000 ºF), MAI products have been tested for use in refrigeration, shipping, insulation of exhaust systems and thermal batteries, insulation of liquid nitrogen and liquefied natural gas, pipe and pipeline insulation, and isolation of sensitive electronic components. The first large commercial application is controlled temperature packaging for shipment of temperature sensitive drugs, vaccines and diagnostics. Application in the construction and renovation of buildings would offer substantial improvement in thermal performance and concurrent reduction in energy demand and infrastructure development.

1.3 Previous Research and Testing of MAI

Nanopore has been researching the VIP and MAI technologies since 1993 and has steadily improved both the thermal performance and efficiency of the manufacturing process. Throughout the technical development process, Nanopore has partnered with ORNL to provide research support and testing capability. Testing of small panel samples prior to this project, showed center-of-panel R-values approaching R-35 per inch. Earlier funding by the Department of Energy Building Technologies Office provided strong indication that a composite panel comprised of PIR and MAI panels could achieve R-values almost double of what is available on the market today. Dr. Kaushik Biswas, one of ORNL's lead researchers on advanced insulation systems, noted that such a composite could reduce wall-generated heating and cooling loads in buildings by 30-50% and potentially save homeowners approximately $150/year in energy costs.[2]

[2] Oak Ridge National Laboratory. January 13, 2015. "Materials-Next Generation Insulation," https://www.ornl.gov/news/materials-%E2%80%94-next-generation-insulation-%C2%83.

2 Project Scope

2.1 Description of Research Effort

The project scope entailed three components. The first component was constructing a prototype insulated metal panel (IMP) using the MAI technology to demonstrate viability for application in the residential and commercial building industry and to test/verify whole panel thermal performance via hot box testing. Initial project partners were Nanopore, ORNL, and Newport Ventures. However, a key project component was to enlist the participation of a metal panel manufacturer. This participant would not only offer an important market perspective in guiding the design of the MAI IMP, but would also help to lay the groundwork for potential industry and business development of a MAI metal sandwich panel in future stages. ATAS International, Inc. came on board in May 2015 and provided the additional benefit of offering the perspective of an existing metal panel manufacturer in the process of moving into the insulated metal panel industry.

The second component was the design and fabrication of an 8-foot × 8-foot metal panel incorporating MAI composite insulation panels, initial modeling and finite element analysis to estimate anticipated R-value, and whole panel testing in the hot box to capture the impacts of fasteners, edge effects, etc. to provide an overall R-value. Short of measurement and testing on an actual building, this approach offered an excellent basis for projecting real-world performance and estimated potential cost and energy savings.

The third component entailed industry research regarding market penetration of metal panels and Insulated Metal Panels in New York State and projections of estimated energy savings and benefit to the New York State once a MAI sandwich panel became readily available at a competitive price.

2.2 Rationale for Focusing on Metal Panels

The first and foremost reason for a focus on metal sandwich panels pertains to the characteristics of the MAI panels themselves. MAI is more resilient than many conventional VIPs due in large part to its robust exterior barrier film. In contrast to metalized polyethylene barriers, the MAI's ethylene vinyl alcohol (EVOH) barrier is less prone to cracking, thereby reducing air and water vapor permeation that degrades the evacuated core and thus, R-value, over time. Moreover, the thermal performance of MAI does not degrade as significantly if punctured or if the vacuum seal is broken. At atmospheric pressure, the R-value is reduced to about an R-8 to R-9 per inch versus the full center-of-panel R-value that approaches R-35 per inch. With fabrication in the factory, the manufacturing process of a metal sandwich panel can be more tightly controlled. The insulation panels themselves can be designed or placed such that fasteners will not damage the MAI product. Furthermore, the exterior and interior skins of the panel will protect the insulation during shipping, handling, and installation on site.

The metal panel industry is also a prime candidate to introduce the MAI product to the construction industry because of the preponderance of metal building[3] construction in low-rise (one to five stories), non-residential buildings. Although metal panels can certainly be used on wood or light steel frame buildings, Jeff Henry of the Metal Construction Association noted in an interview for this report, "Metal roof panels are used on virtually all metal buildings and the majority of metal buildings have at least a portion clad with metal wall panels."

Metal buildings comprise approximately 40% of low-rise, non-residential buildings across the U.S. In addition, metal wall and roof cladding are used for a significant percentage of exterior and interior building skins. In 2013, the Metal Buildings Manufacturers Association (MBMA) conducted a review of industry trends with respect to metal buildings.[4] They reported that MBMA members comprised a 52% share of low-rise commercial buildings on a square footage basis (floor area) in 2012 (Figure 3 and Figure 4). Figure 3 also shows metal buildings attaining an increased percentage of total low-rise commercial buildings constructed between 2010 and 2012 compared to earlier years.

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3 Metal buildings are defined as those using a structural steel system for the building skeleton. The exterior skin may be brick, stone, reinforced concrete, architectural glass, or metal panels.

4 http://www.mbma.com/Industry_Trends.asp. Data updated annually.

Figure 3. New Low-Rise Non-Residential Construction (Square Feet)

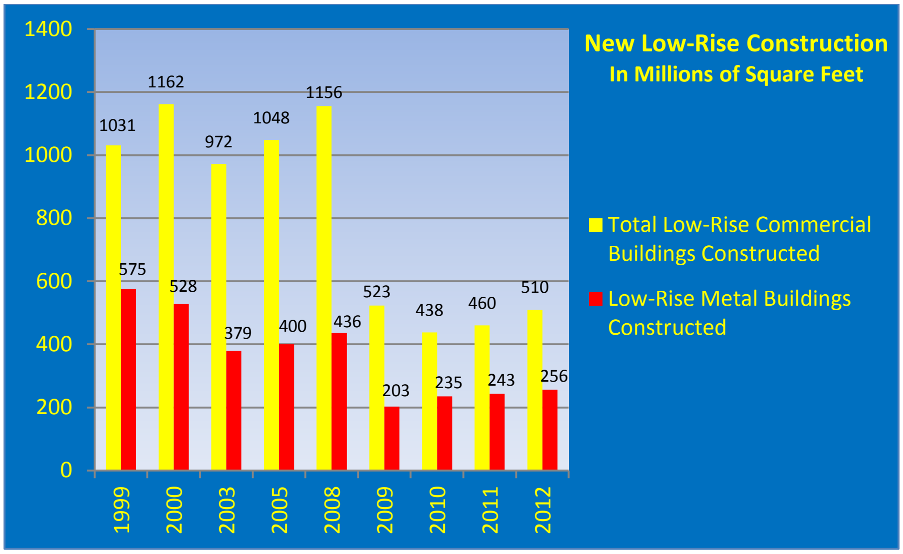
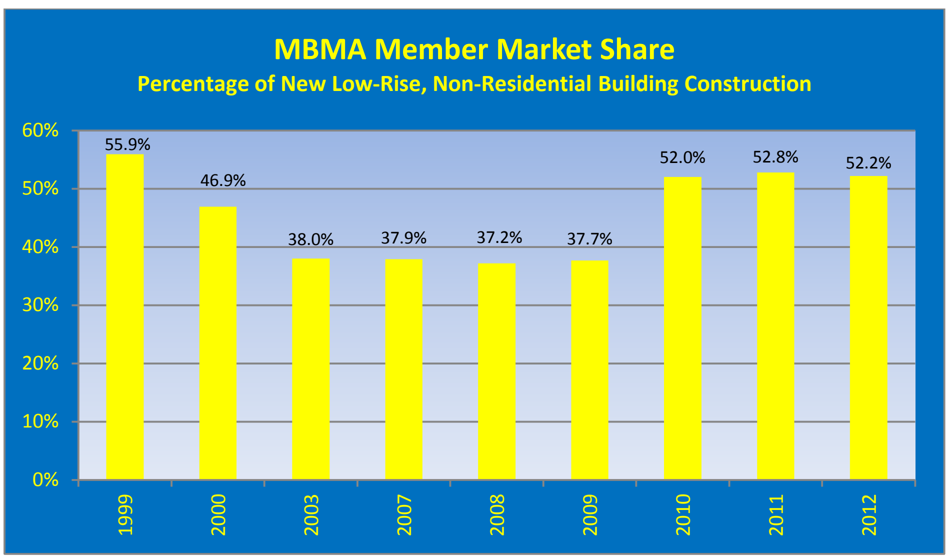


Figure 4. MBMA Member Market Share (Percentage)



With respect to metal panels specifically, a 2014 study by McGraw Hill[5] found that metal roof panels averaged a 41% market share[6] and metal wall panels held a 30% share across agricultural, commercial, industrial, and institutional buildings.[7] Data from the U.S. Energy Information Administration also indicates the strong position that metal panels hold in the commercial buildings sector. Metal was the predominant roof covering material for non-residential buildings in 2012 having a 30% market share; metal wall panels comprised the exterior cladding on approximately 17% of commercial buildings. Although brick, stone, or stucco constituted the largest share of exterior wall covering, approximately 1 million commercial buildings were clad with metal panels.[8]

Market research conducted by ATAS International corroborates these figures, indicating that metal panels comprised 41% (873 million square feet) of roof cladding and 21.5% (389 million square feet) of wall cladding in low-rise commercial buildings.

With respect to the market penetration of IMPs as wall or roof cladding in the U.S., widely disseminated information was more difficult to find. Again, research done by ATAS International shows that annual industry sales of IMPs are more than 80 million square feet at a value of more than $700 million. Typical thickness for insulated wall panels is 2 to 2.5 inches, according to ATAS. Colin Osborne, CEO of Vicwest, a building exteriors manufacturer based in Canada, indicated IMP market penetration in North America to be “less than 10%” – substantially less than the 50% share held in Europe. However, he also noted the rapid growth in the company’s sales since they introduced IMPs in the 1960s and 1970s. The company’s IMP sales increased from $8.2 million annually in 1970 to approximately $75 million in 2013.[9]

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5 Metal Construction Association, 2014. Prepared by McGraw Hill. Data sourced from U.S. Departments of Commerce and Energy, Bureau of Economic Analysis, Reed construction Data and FW Dodge Industry proprietary databases.

6 Agricultural buildings constituted the largest percentage in this group with 86% of buildings in this sector having metal roofs.

7 Op. cit. Metal Construction Association, 2014. Prepared by McGraw Hill.

8 www.eia.gov/consumption/commercial/data/2012

9 Arnold, Steve. “All Weather Insulated Metal Panels called a Game-Changer for North America.” *The Hamilton Spectator,* September 14, 2013.

While most of these sales were in Canada, a similar growth pattern can be envisioned in the U.S. given increasingly more stringent energy code requirements, increasing/uncertain energy costs, and continued interest on the part of building owners to reduce operating costs. The previously mentioned McGraw Hill study cited insulated metal panels as the fastest growing segment of the U.S. metal construction industry. ATAS International estimates growth of IMPs within the non-residential buildings sector to be between 6.7% and 12.6% by 2019. The rather broad range is due to the uncertainty of how quickly this sector will recover from the recession that began in 2008.

2.3 Product Development Challenges

Sensitivity of MAI. As previously described, Nanopore's MAI panels are sensitive to damage, and punctures significantly decrease their insulating value. Although using these materials in residential and commercial construction could have an enormous impact on reducing energy consumption, it is challenging to identify products that resist damage during transport and/or do not require extensive, expensive packaging; require minimal handling or cutting on site; and can be predictably fastened according to a pre-set schedule. Thus, a metal sandwich panel seemed to be a best-fit candidate for a first step into the building industry.

Panel design/fabrication. Several questions needed to be addressed with respect to the design and fabrication of the MAI prototype metal panel:

1. What size metal panels should be used to comprise the full 8-foot × 8-foot panel that would fit into the hot box?
2. What is the best metal panel profile to use for the prototype giving consideration to maximum coverage, adhesion, and marketability?
3. What is the optimum type of "other" insulating material to use for the composite insulation core?
4. What is the appropriate thickness for the prototype panel given current market demand, targeted R-value, and relative ease of transportation, handling, and installation?
5. Given the maximum size of MAI panels is 24-inch × 24-inch, how should the insulating core be configured? How should the panels be laid out for optimizing thermal performance, cost, and protection from damage?
6. What is a realistic method of fabrication of the prototype given project budget, available facilities and equipment, and stage of technical development?
7. Are there issues with certain adhesives that might corrode or damage the insulating core or the metal panels?

2.3.1 Eliminate/Minimize Thermal Bridging

At this stage in the development of a prototype MAI metal panel, the primary questions centered on panel connection or abutment along the long edge of the panels. Given the selected profile of the metal panels, how can the insulating core be designed so that there is little, if any, gap in insulation where the panels join? Is it possible to achieve full insulation thickness across the entire 8-foot × 8-foot panel? Where there are seams, how can these best be sealed once the panels are loaded in the hot box?

2.3.2 Potential Barriers

Although metal panels and/or IMPs are impermeable to air flow and water penetration, the seams between panels and intersection with other building components are the weak links in the cladding system. If not properly detailed in the factory and in the field, the cladding assembly will be subject to potential infiltration and water leakage. Manufacturers recommend several key measures to mitigate air leakage, water penetration, and thermal bridging:

1. Assure proper sizing of structural members and purlins to adequately support cladding and prevent buckling which will break seals.
2. Ensure that purlins are accurately spaced as specified.
3. For built-up cladding systems, (components installed in the field), the liner panels (interior) serve as the air barrier and sealant should be applied at seams as they are installed (Figure 5 and Figure 6). The exterior panels are the weather resistant barrier and the sealing method depends on the profile. For overlapping panels, flexible sealants applied with gun or sealant tape may be used, running the length of the panels. For interlocking panels, factory-installed compression gaskets are frequently used and must be fitted tightly in the field.

Figure 5. Built-Up Cladding System

www.steelconstruction.info/thermal_performance

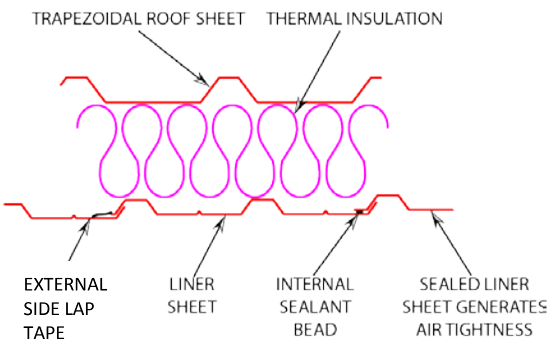
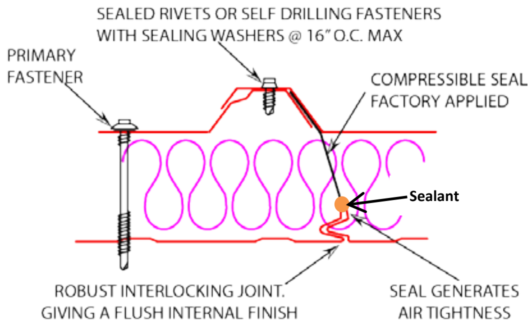


Figure 6. Factory Insulated Panel

www.steelconstruction.info/thermal_performance

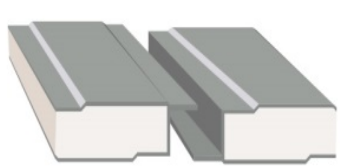


4. For insulated metal panels, compression fittings are installed at the factory. Often these will be installed at the interlocking joint on the liner panel. As the panels are installed in the field, they are butted tightly, thereby compressing the fitting attached to the liner panel. A sealant or sealant tape is applied in the field at joints on the exterior facing panel as the IMPs are installed. Sealants should be flexible and non-skinning and the bead should be of adequate thickness. About 0.25-inch in height is recommended. The interlocking joints, compression fittings, and sealants create a very tight joint between panels that minimize air infiltration and bulk water penetration. Because the metal skin does not wrap the edges of the panel, there is no metal-to-metal contact which would contribute to thermal bridging.

   Although the majority of insulated metal panels have a single- or double-tongue and groove interlocking profile, some manufacturers use a channel-and-panel system or a square-edge system similar to the ones shown in Figure 7 and Figure 8. Although such joints are effective at preventing bulk water penetration, the continuous metal joint does not provide a thermal break.

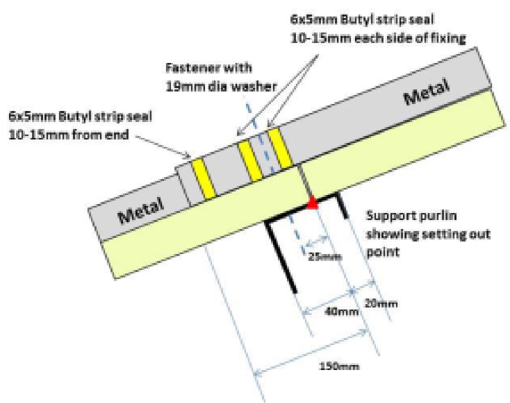
Figure 7. Utilodor Square-Edge Joint

Figure 8. Utilodor Lap Joint



5. End laps must also be adequately fastened and sealed – especially for metal roof panels which are more prone to wind-driven rain (Figure 9). Ideally, three beads of sealant are recommended: one near the bottom edge of the top panel and one bead on either side of the row of fasteners that are typically placed about 4 to 5 inches from the bottom of the overlapping panel. The fasteners should be evenly spaced and located in the valley of the panel.

Figure 9. Panel End Lap Joint, Fastener, and Sealant Details



Because there are no air leakage test requirements for new buildings in the U.S. other than those built to U.S. Army Corps of Engineers standards, it is difficult to know exactly how leaky new commercial buildings are or whether metal clad buildings have substantially higher envelope leakage rates than those with other types of cladding. Typically, the external cladding does not serve as the air barrier layer even though it may contribute to the entire air barrier system. Even where IMPs are used, the air barrier system probably should be located on the warm-in-winter side of the envelope to minimize the potential for condensation in the wall cavity. This location might vary depending on climate zone and use/design of the building.

With respect to water penetration, best practice recommends and code requires a rain screen behind the exterior veneer to shed any water that may make it behind the cladding down and away from the building. In addition to panel-to-panel connections and gaskets, manufacturers also provide an array of trim pieces to correspond to each panel profile. These include interior and exterior corners, starting strips, eave trim, window trim, and flashings.

As with all exterior claddings, the primary problem areas for air and water leakage occur at junctures of different components or assemblies, such as wall/roof junctures, around windows and doors, and at penetrations such as vents. Careful detailing, proper flashing, and high quality sealants are the main methods of mitigation.

3 Description of Project Activities

3.1 Recruitment of Panel Manufacturer

Prior to contacting a potential industry partner, Newport performed some background research on the IMP industry in the U.S., as well as in other countries such as Canada and the U.K. where IMPs have had a longer history and are used more widely. In addition to ATAS, major manufacturers that are leaders in the industry include NCI Building Systems, Kingspan, Vicwest, Metl-Span, MBCI, Green Span Profiles, and Centria. Although Kingspan and Vicwest have established a presence in the U.S., their headquarters are located in the United Kingdom and Canada, respectively. Metl-Span and MBCI are located in Texas and are owned by the same company, NCI Building Systems. Both Green Span Profiles and Centria are located in Pennsylvania. Centria was also recently acquired by NCI.

Newport began recruitment efforts by reaching out to several of our contacts at two of the major metal industry associations in the U.S. – the Metal Construction Association (MCA) and the Metal Building Manufacturers Association (MBMA). Although they expressed a great deal of interest in the project, both were somewhat reluctant to point to any one member, preferring that we might work with a consortium of their members. The authors contacted several association members who were already manufacturing insulated panels. The members indicated particular interest in the project especially because it included the three most significant components: an insulation manufacturer, a testing facility, and an R&D agency. Despite expressing interest, it was difficult to obtain timely approval for participation from the appropriate authority within the companies.

Several "lessons learned" became apparent during the recruiting effort:

- Technical, sales, and/or others at a somewhat lower level in the companies contacted were interested, but not able to make a commitment to such a project without approval from a more senior officer or owner;
- With their understandable primary focus on meeting their own responsibilities within the company, the follow-through on obtaining such approval frequently seemed to hit a dead end;
- Attempts to contact presidents or vice presidents directly also proved difficult as most were extremely hard to reach by phone; and
- Companies with an established business in manufacturing insulated metal sandwich panels may be less interested in such research and prefer to wait and see initial outcomes first.

While the latter is more speculation than fact, it is interesting, but perhaps not surprising that the company which ultimately proved to be most interested and willing to participate was a metal panel manufacturer who is in the process of moving into the insulated panel industry. ATAS International, headquartered in Allentown, PA, had recently partnered with another manufacturer and was taking steps to set up a new division alongside its already successful architectural wall and roof panel business. Three other factors also may have been a part of the relative ease and speed with which ATAS International agreed to partner on this project:

1. They are a third-generation; family-owned business having been established in 1963.
2. They are a somewhat smaller company than Metl-Span or MBCI with approximately 120 employees and thus, it may be easier to engage in new efforts.
3. They have a history of maintaining a focus on innovation and improvement.

ATAS International, Inc. manufactures metal wall and roof panels, metal ceilings and metal accessories, trim, and molding. In addition to its Pennsylvania headquarters, ATAS also has manufacturing facilities in Mesa, AZ, and Maryville, TN. Its sister company, Brightsmith Coil Coaters, is located in Morrisville, PA and provides a variety of finishes and coatings for the finished metal products. ATAS operations have been certified to the ISO 9001:2008 with design International Quality System Standard in all locations.

Selling panels for both residential and commercial applications, ATAS currently manufactures over 20 different profiles of wall panels and 26 styles of roofing products that include panels, metal shingles, and metal tiles. Depending on the profile, panels are either interlocking, overlapping, battened, or seams joined in the field. Fasteners also may be exposed or concealed according to the style of the panel. Panel material may be either steel, galvanized steel, or aluminum, but steel constitutes the majority of sales. With a strong commitment to sustainability and energy conservation, ATAS has also developed two integrated solar roofing products.

Driven by more stringent building and energy codes and customer interest in lowering operating costs, ATAS International has recognized the demand and need for a different type of building product. Its move to add insulated metal panels to its product offerings has been in the planning stages for several years. The company believes that the insulated sandwich panels not only offer enhanced building performance to its customers but also added efficiency in the construction process itself by combining the insulation, cladding, and perhaps interior finish phases into a single step.

3.2 Panel Design and Fabrication

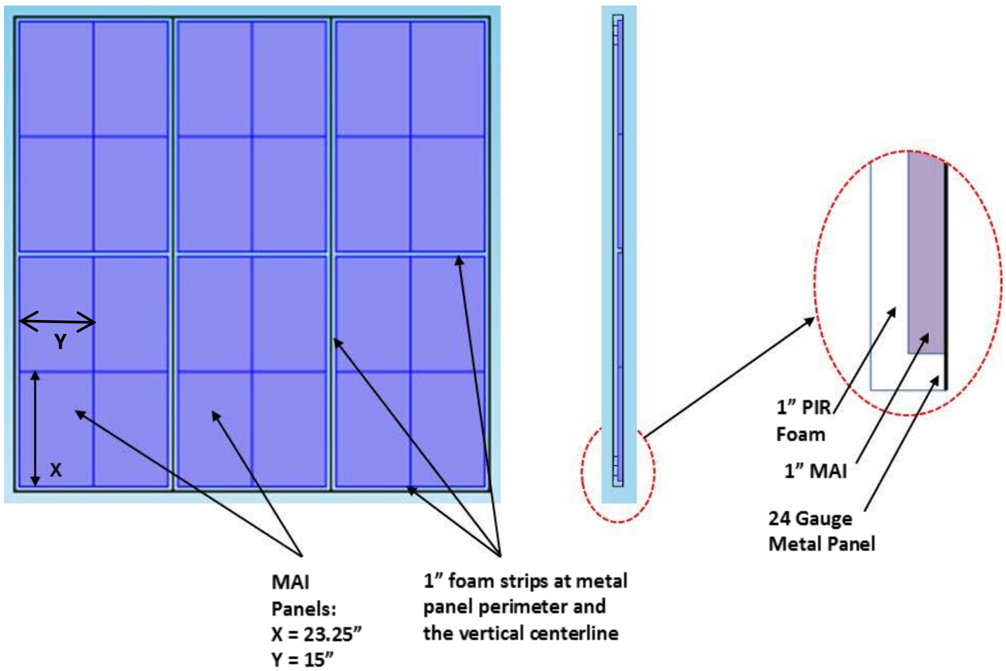
In designing the panel, four main factors were considered:

- Protection of the MAI during handling and installation.
- Balance of thermal performance (R-value) and cost.
- Thickness of panel that is commonly requested.
- Profile of panel that will facilitate adhesion of insulation with minimal thermal bridging.

ATAS International recommended a 2-inch thickness for the prototype panel because it is common in the industry and relatively easy to handle and transport. A flat 24-gauge aluminum panel was chosen because it would provide a smooth profile to facilitate adhesion of the insulation and full insulation coverage. The 8-foot × 8-foot panel would be comprised of three 32-inch × 96-inch panels. A total R-value of 25 was targeted for the 2-inch composite MAI panel. Insulating value exceeding R-25 for exterior wall assemblies has been shown to have diminishing returns for performance relative to energy savings and thus, cost savings. (See Appendix A for analysis). The prototype test panel had only one metal face because it reduced the weight and had no impact on the thermal performance test results (Figure 10).

The panel was comprised of 1-inch Firestone Building Products PIR and 1-inch MAI panels. The PIR board had a fiberglass facing on both sides; the MAI panels were encased in an ethylene vinyl alcohol and polyethylene film. One-inch strips of PIR framed each panel and were also placed at the midpoint of each 8-foot panel. The PIR strips provide areas where the panels would typically be fastened to the structure and also facilitate handling so as not to puncture or damage the MAI panels. Eight 1-inch thick MAI panels were cut to fit between the PIR strips and were then adhered to the metal panel. A solid 1-inch thick PIR panel overlaid the MAI-PIR layer. This combination contributed about an R-5.5 (after aging) to the panel and functioned to protect the MAI panels.

Figure 10. Prototype Panel Design



Gorilla Heavy Duty Construction Adhesive was used to adhere the insulation to the metal panel and the insulation layers to one another. After trials and comparison to several other adhesives, the Gorilla adhesive bonded the best to the outer surface of the MAI panels, the metal panel surface with no preconditioning or cleaning required, and the fiberglass facing of the PIR board.

To ensure that the metal stayed flat during processing, the metal was supported by an 8-foot × 4-foot ×2-inch PIR board throughout processing and shipment. 24 MAI panels with dimensions of 23.25-inch × 15 -inch × 1-inch were produced and the flaps were heat-tacked to the panel surface. A series of clamps and weights were used to minimize gaps between the MAI panels and the PIR strips in the x-y direction and enhance compression in the z direction. MAI coverage was 90.8% of the total area of the 8-foot × 8-foot panel.

For shipping, each composite panel was supported by a 2-inch PIR board and the entire stack was encased in 1-inch insulation boards. That combination was encased in plastic and strapped to a wooden pallet. The composite panel fabrication process from beginning through packaging for shipment to ORNL are shown sequentially in Figures 11 through 19.

Figure 11. Metal sheet on 2-inch polyisocyanurate support

Figure 12. Adhesive being applied to MAI panels that are encased in membrane to minimize loss of vacuum

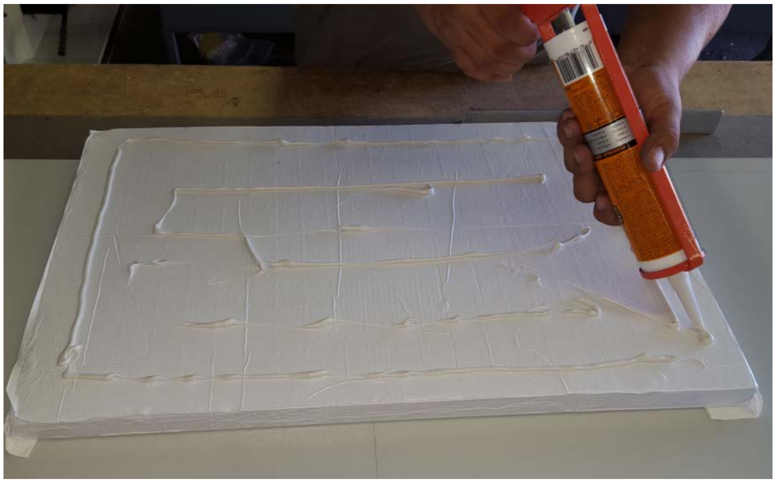


Figure 13. Four MAI panels clamped for x-y compression

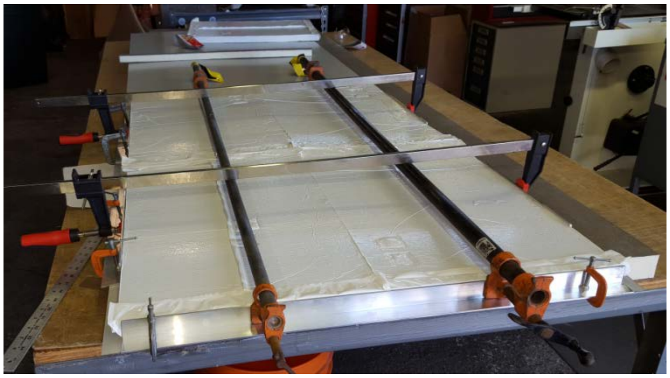


Figure 14. Weights added for z compression

Figure 15. 2nd MAI-panel section with 1-inch polyisocyanurate spacer jigged

Figure 16. Completed first layer with 1-inch polyisocyanurate at perimeter

Figure 17. Adhesive applied to top 1-inch polyisocyanurate board

Figure 18. Finished composite panel

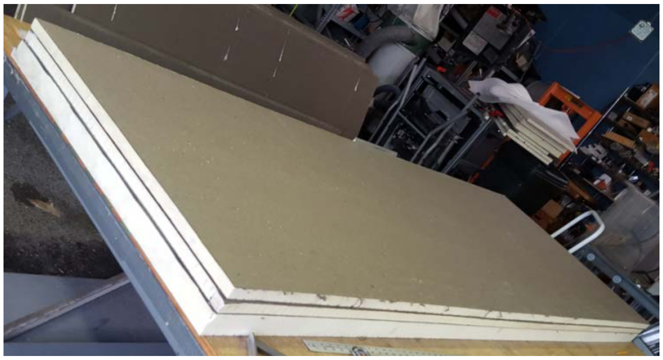


Figure 19. Three composite metal-MAI-polyisocyanurate panels on a pallet and ready for shipping to ORNL

3.3 Finite Element Modeling and Analysis

During the design phase of the project, Oak Ridge National Lab performed finite element modeling and analysis to estimate the R-value of the prototype IMP with the MAI composite core. The simulations were done using the Heat Transfer Module of COMSOL Multiphysics.[10] The calculation incorporated 24-gauge metal sheets, the proportional amounts of PIR insulation and the requisite MAI panels in the 2-inch core for a total panel thickness of 2.025-inch. The individual 8-foot × 32-inch × 2-inch composite MAI-foam-metal panels were assumed to be seamlessly joined along their 8-foot interfaces. To eliminate modeling complexities, the joint details (sealants, etc.) were eliminated because they would be captured in the hot box testing. Two simulations were performed: one with no fasteners included and one with fasteners spaced 15.5 inches apart along the short edge of the panels and 19 inches apart on the long edge of the panels. (A somewhat greater than usual spacing was assumed because oversized fasteners were required to facilitate modeling.)

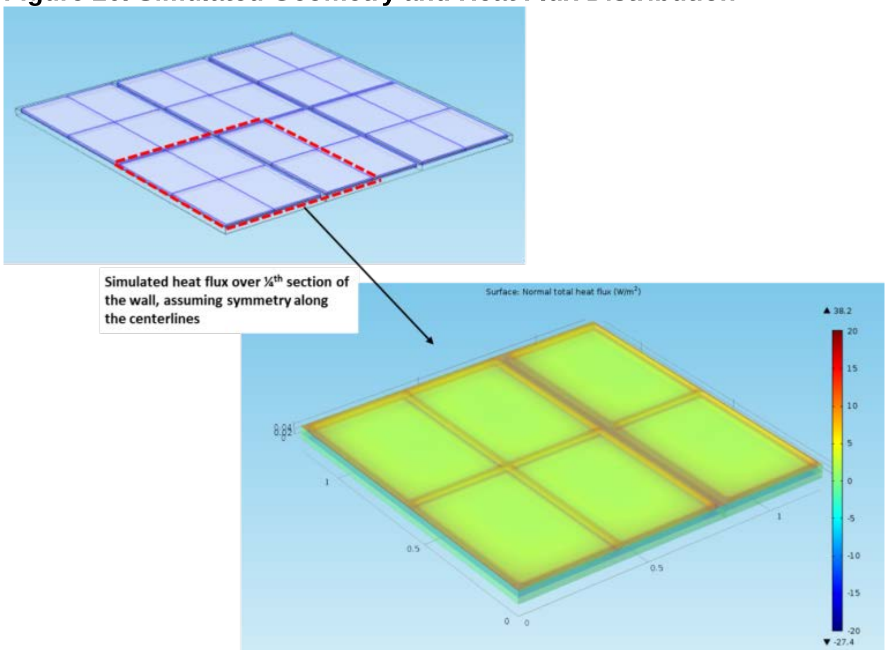
Figure 20 shows the modeled geometry and the simulated heat flux distribution across the wall. Given the inherent symmetry of the composite wall, only one quarter of the wall was simulated, as indicated by the dashed red lines. The model geometry was based on the actual dimensions of the metal sheets, MAI panels, and PIR. Material properties of the thermal conductivity, density, and specific heat of the different components were obtained from literature and prior measurements. The boundary conditions were selected based on the test conditions described in the following sections. The air temperatures on the hot and cold surfaces of the modeled wall were assumed to be 100 ºF and 50 ºF. A heat transfer coefficient of 8.29 $W/m^2/K$ was assumed for non-reflective vertical surfaces, following the ASHRAE Handbook of Fundamentals.[11] The lateral edges of the wall were assumed to be adiabatic (insulated, as in the tests).

Results of the simulation with no fasteners indicated an overall R-value of 26.2 $hr\text{-}ft^2\text{-}°F/Btu$ (or R12.9/inch) for the 2.025-inch thick 8-footx8-foot MAI-metal composite wall; with fasteners included, the overall R-value was 23.8 or R-11.8/inch. Of course, details of construction such as interface with different materials, sealing around openings, detailing at trim pieces, and fasteners will impact the wall R-value.

[10] http://www.comsol.com/heat-transfer-module

[11] https://www.ashrae.org/resources--publications/handbook

Figure 20. Simulated Geometry and Heat Flux Distribution



3.4 Hot Box Testing

3.4.1 Description of Guarded Hot Box

ORNL's Rotatable Guarded Hot Box (RGHB) is capable of measuring the thermal resistance (R-value) and thermal transmittance (U-factor) of full size (8-foot × 8-foot) wall and window assemblies. Test assemblies are installed in a frame mounted on a moveable dolly. The frame/test assembly is inserted between two "clam-shell" chambers of identical cross-section. This design allows the chamber temperatures to be independently controlled, thus creating a temperature difference across the test assembly. Figure 21 shows a typical wall specimen installed in the test frame.

Figure 21. Rotatable Guarded Hot Box

The climate chamber (cold side) is equipped with blowers and an air-conditioning system capable of producing stable environmental conditions to the extremes of 10°F and 15 miles per hour wind velocity. The hot side consists of two similarly shaped chambers, which are essentially a guard chamber surrounding a smaller metering chamber. The metering chamber has heaters and fans capable of producing stable environmental conditions to the extremes of 100 °F and 2.0 miles per hour wind velocity. A series of temperature and relative humidity sensors and pressure transducers measure conditions across the wall assembly throughout the test period. The hot box operates under the requirements of ASTM C 1363.[12]

3.4.2 MAI Panel Test Procedure

The three composite MAI-foam-metal panels 8-foot × 32-inch × 2-inch were assembled and tested at ORNL following ASTM C1363. The temperature conditions were 100 °F and 50 °F in the metering and climate chambers, respectively. The test wall was installed so that the metal sheets (exterior) were facing the climate chamber and the foam surface of the wall (interior) faced the metering chamber. The perimeter of the test frame surrounding the specimen wall was filled with foam strips of the same depth as the test wall to eliminate edge heat losses (Figure 22).

The perimeter of the test wall and the joints between the 8-foot × 32-inch panels were caulked and taped to prevent air leakage. The test wall was instrumented with 30 pairs of thermocouples distributed over the 8-foot × 8-foot foot test area. The average temperature differences of the hot and cold wall surfaces were determined by averaging all thermocouples attached to the individual components. Figure 23 shows the meter- and climate-facing surfaces of the test wall, with the thermocouples installed.

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[12] ASTM C 1363: Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot-Box Apparatus.

Figure 22. Schematic of a typical test wall within the hot-box test frame

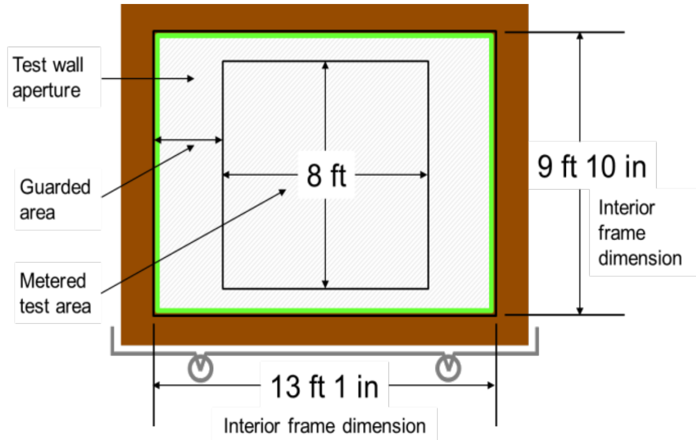

Figure 23. Meter-facing (left) and climate-facing (right) surfaces of the MAI composite test wall

Once the test is started, it takes between 24 and 48 hours to reach stable temperature and heat flow conditions. The current test ran for about 166 hours to allow sufficient time for the hot box and test specimen to reach steady-state conditions. Data from the final 12 hours were used for analysis, following ASTM C1363 procedures.

3.4.3 Results of Hot Box Testing

The hot box test was initiated on October 28, 2015, and terminated on November 4, 2015. The overall wall R-value was calculated based on the heat input to the meter chamber (less heat loss to the surroundings) and the measured surface temperatures on the hot and cold sides of the test wall. The air temperatures in the climate and meter chambers were maintained at 50 °F and 100 °F, respectively.

The overall R-value of the prototype 8-foot × 8-foot test wall comprised of the 2-inch thick MAI-foam-metal composite panel was 22.2 hr-ft^2-°F/Btu (or R-11.1 per inch). It is not surprising that the hot box test results were somewhat lower than the previously discussed modeling results. The test captures the effects of seams between the MAI and PIR panels as well as the fact that the three insulated metal panels were abutted to one another in the hot box. The impact of such seams is difficult to capture in a modeling analysis. Previous testing and modeling by ORNL of MAI alone and MAI composite foam panels have shown results in the following range:

- 1-inch MAI center-of-panel R-value: as high as R-37
- 1-inch MAI surrounded by PIR foam: approximately R-20
- 2-inch panel: 1-inch MAI/polyiso layer, 2nd layer polyiso: approximately R-28

Although the R-value of the MAI itself is very high, it drops when it is incorporated into a building system that will be suitable for real-world applications.

3.5 Possible Panel Improvements

The overall tested R-value of the 2-inch panel at R-22.2 is very good, especially in light of what is currently available on the market (approximately R-13 to R-14 for a 2-inch polyisocyanurate metal sandwich panel). Boosting the R-value of a 2-inch panel to R-25 would be advantageous from the standpoint that this would meet ASHRAE 90.1-2013 prescriptive above-grade wall requirements for metal and metal-framed buildings in all climate zones in the U.S., including Group R buildings in Climate Zones 7 and 8. Of course, lesser thicknesses could meet New York's requirements in Climate Zones 4 through 6, especially when combined with cavity insulation, offering advantages in both cost and constructability. Increasing MAI coverage by slightly reducing the width of the PIR strips could achieve the goal of R-25 per 2-inch panel.

A second improvement would be to identify a metal panel with a ribbed interlocking profile and develop a prototype process for creating a composite MAI core where the voids are filled and the composite cores of adjacent panels butt tightly when installed. Jim Bus, vice president of ATAS International, noted that the latter has already been achieved for conventional IMPs and depends on an exacting fabrication process. The equipment used and the process in the factory are key to achieving an IMP system in the field in which panels interlock tightly and eliminate thermal bridging. A low-rise foam might be used to fill the voids in a ribbed panel with the composite MAI core built from there. Such an improvement would offer enhanced marketability via an additional profile as well as enhanced sealing against air infiltration and water penetration due to the interlocking seams.

A third improvement would be to develop a more automated and efficient panel fabrication process. Current commercialized IMP fabrication processes entail either a “batch process” or a “continuous production line/roll form process.” The latter is more efficient, but significantly more expensive to set up and presumes production of very large quantities of 40,000 sf or more. A realistic step forward from the manual, mechanical process used for the prototype in the current project would be to develop a more efficient fabrication process along the lines of the batch process.

3.6 Project Findings

3.6.1 Results of Finite Element Modeling and Hot Box Testing on Prototype MAI Panel

Table 1 summarizes the modeling and hot box test results for the prototype MAI-foam metal panel. Based on the approximate 9% reduction in R-value in the modeling results with fasteners included versus no fasteners, a similar impact on thermal performance could be assumed for hot box test results had the panels been fastened to a structural frame as they would be in real-world applications.

Table 1. Prototype MAI Panel Modeling and Test Results Table

	2-inch MAI-Foam Metal Panel W/O Fasteners (R-Value)	2-inch MAI-Foam Metal Panel With Fasteners (R-Value)
Finite Element Modeling	R-26.2	R-23.8
Hot Box Test Results	R-22.2	R-20.2 (assumed)

3.6.2 Expectations for Installed R-Value

The current project designed, fabricated, and tested a prototype metal panel with a composite MAI-PIR core. As an initial proof-of-concept effort to demonstrate the viability and estimated thermal performance of the MAI vacuum insulation technology in a residential or commercial building component, many simplifications were made compared to an eventual real-world application. Although these issues were discussed in Section 3.5, several important factors impacting installed R-value are the panel profile and the trim pieces that are used to finish building details such as corners, starting strips, eave details, and where panels abut to openings or different surfaces. Undoubtedly, a real-world panel system would either have interlocking seams or joints covered and sealed by battens – rather than simply flat panels butted together and sealed with a bead of silicone. Interlocking joints would be tighter with continuous insulation to eliminate thermal bridging. Trim pieces would be designed for the specific profile with insulation incorporated and specifications for sealing. With careful design and fabrication in the factory, the installed R-value of the MAI IMP system should be the same as the hot box test results, (in the R-20 to R-22 range for a 2-inch panel).

3.6.3 Implications of MAI IMPs for Meeting New York State Energy Code

New York State will be adopting the 2015 International Energy Conservation Code for residential and commercial buildings during the summer of 2016. Two methods for meeting above-grade wall and roof requirements for commercial buildings include the prescriptive R-value and U-factor tables, which lay out minimum and maximum insulating values for different assembly types. Above-grade wall types for commercial buildings include metal buildings, steel-framed buildings, and wood-framed buildings. Insulated metal panels could be used on any of these structural assemblies. For roofs, the assembly type most applicable to insulated panels is “insulation entirely above deck.” Such an assembly would most likely be a sloped roof consisting of structural steel members and purlins, steel framing, or wood trusses with the insulation or IMPs placed on top of the structural frame.

For all of the previously described assemblies, MAI IMPs offer considerable advantage over the current most commonly used polyisocyanurate-core IMPs in that they meet minimum prescriptive code requirements with a profile that is approximately half the thickness. This result holds true across all three of New York’s climate zones. For example, for above-grade walls in metal buildings, a MAI IMP could meet the prescriptive requirement with a 2-inch panel while the PIR panel would need to be 4 inches. For steel- and wood-framed buildings, a MAI 2-inch panel would comply whereas the code-compliant PIR panel would be 3 inches. Likewise, for roofs with insulation entirely above the deck, a MAI IMP could meet the prescriptive requirement with a 3-inch panel; a 6-inch PIR panel would be required to meet the minimum prescriptive threshold. Appendix A outlines these differences.

Engineering, transportation, and installation costs increase substantially as the thickness of IMPs increase – especially as they reach profiles of 4-6 inches. The cost of the panel itself may not increase dramatically, but related costs will. As one New York State metal building contractor noted:

> The transportation costs are very high for IMPs. For instance, freight costs for panels 58' long are likely to be at least several thousand dollars. Plus, maximum height for a load is typically 14'. If you could reduce the panel thickness by half and carry twice as many IMPs on a load, this would decrease transportation costs substantially.[13]

Interviews with other metal building contractors in New York State also pointed to complications regarding fastening panels that are 4 inches or more in thickness. It is not only the practical issue with respect to the possibility of screws bending or breaking but also the likely need for engineering with respect to size and spacing of fasteners. In addition, simply setting and holding the panels in place during installation can be more difficult as panel thickness increases. The fact that a MAI IMP can provide equivalent thermal performance with approximately 50% of the panel thickness helps move the market to adopt an insulation and cladding system that is higher performing than current systems and provide a path to actual full compliance with the Energy Code.

Other advantages and savings also accrue from using MAI IMPs including:

- Reduced construction costs by achieving equivalent or higher R-value with a thinner profile exterior insulated cladding.
- Reduced construction costs and time by utilizing an integrated insulation, air sealing, and cladding component.
- Reduced material use and maintenance/repair costs realized by using an exterior cladding that is long-lived and durable.

3.6.4 Nontechnical Project Findings

As previously mentioned, metal panels comprise an approximate 40% market share of non-residential roof cladding and 20% share of non-residential wall cladding nationwide. The combination totals about 1,260 million square feet of metal panels sold annually. In residential buildings, metal roofing is gaining an increasing share of the market especially in the large re-roofing market where it comprises

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13 Fingerlakes Construction, Clyde, NY.

about 13% of roofing material installed. Currently, in the U.S., about 80 million square feet of insulated metal panels are sold annually. This amount represents about 2% of total nonresidential wall and roof cladding.[14] A McGraw Hill study completed for the Metal Construction Association indicated a specification rate for insulated metal panels at 7% in 2013, a substantial increase since the middle of 2012 (Figure 24).[15]

Figure 24. Specification Rate for Insulated Metal Panels

Reproduced from McGraw Hill Study for the Metal Construction Association

3.6.5 Anticipated Growth Rate of IMPs

Regardless of the exact market share of IMPs in the U.S., it is fairly certain that their use is on the rise, particularly in low-rise, non-residential buildings. As energy codes become more stringent and more uniformly enforced, uninsulated metal panel claddings may be replaced by IMPs at an increased rate. One source from the Metal Construction Association surmised that uneven code enforcement is one of the largest market barriers to the growth of the IMP industry in the U.S. IMPs offer a way to provide a range of insulating values for the building envelope. Especially in exterior walls where the thickness of the cavity may limit practical amounts of insulation, the IMP affords a way to achieve higher thermal performance, improve air tightness, and provide weather-resistant finished cladding at the same time.

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14 ATAS International.

15 Op. Cit., McGraw Hill Study.

Labor savings can be realized by installing a single system that serves multiple functions served in one step compared to having each function performed with a distinct system. Furthermore, as codes move toward requirements for continuous wall insulation for both residential and commercial buildings, IMPs offer an attractive and efficient option. The 2015 International Energy Construction Code (IECC) (soon to be adopted in New York State) requires continuous insulation on above grade walls in commercial and Group R buildings for all construction types except wood frame buildings in all New York State climate zones. In Climate Zone 6, wood frame buildings must also have continuous insulation. A thinner continuous insulation profile not only eases installation and detailing of finishes, but also reduces construction costs.

Jim Bus, Vice President of ATAS International highlighted changes in energy codes and the resulting changes in the way buildings are being constructed as the two major drivers behind his company's recent decision to move into the IMP manufacturing industry. They see strong growth in this industry but believe it will be essential to offer insulated panels to remain a strong metal panel manufacturer in U.S. markets.

3.6.6 New York State Market and Industry Indicators for Insulated Metal Panels

Very little information specifically related to the New York State market for metal panels or insulated metal panels appears to exist. It remains unclear whether related research has been done at all or whether some information exists, but remains proprietary.

NYSERDA published a somewhat general, but NYS-focused, report for a market characterization study.[16] This report provided an assessment of the new commercial building construction market for NYSERDA's New Construction Program. In 2012, new construction project starts totaled just under 7,000 buildings comprising about 46 million square feet. The largest sectors included wholesale and retail commercial buildings (3,000 projects), apartments (2,500 projects), and schools, libraries, and labs (500 projects). Certainly, wholesale and retail commercial building sector and schools, libraries, and labs are likely
to be low-rise buildings that are conditioned and therefore, good potential candidates for use of insulated metal panels.

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[16] NYSERDA. 2015. "Phase One Process Evaluation and Market Evaluation of the NYSERDA New Construction Program." Prepared by Navigant Consulting, nyserda.ny.gov/about/publications

Another positive factor for expansion of the market for insulated metal panels in the State is the greater awareness of and demand for energy efficiency on the part of end-users. The report cited an increase in the focus on energy efficiency amongst building owners and tenants over the three-year period from 2011 to 2014. On the down-side, interviewees noted financing as a continuing barrier to installing more energy saving measures. Although lenders can readily include and analyze higher efficiency equipment in their calculations, they have a much more difficult time incorporating whole building measures in their debt-to-income ratios.

3.6.7 Market Barriers, Incentives, and Advantages for Ultra-High R-Value Metal Sandwich Panels

As noted by the IMP manager at ATAS International, perhaps the greatest barrier to increased use of insulated metal sandwich panels is “old IMP thinking.” Historically, metal panels have been viewed as the cheapest and the lowest quality of wall and/or roof cladding options. Limited choices were available with respect to profile and color. Metal buildings as well as metal cladding were viewed as primarily suited for agricultural buildings or warehouses, but not for commercial or residential buildings where a higher aesthetic or improved performance is desired. Because they were deemed to be of inferior quality, they were also perceived to be energy inefficient and prone to significant air and water leakage. However, even a brief glance at several metal manufacturers’ websites proves the perceptions regarding aesthetics incorrect. As Figures 25 to 28 illustrate, metal panels can be used to create unique and attractive exteriors for both residential and commercial buildings.

Dozens of profiles and styles are available and all have matching trim pieces that not only achieve a finished appearance but also provide a weather barrier that prevents wind-driven rain from getting behind the exterior cladding. Many of the panel profiles for both standard metal panels and IMPs have interlocking edge profiles where they join the adjacent panel, thereby minimizing air infiltration and thermal bridging. Moreover, most manufacturers provide detailed guides on how to install their products properly so that they perform as expected and intended. As with all exterior claddings, the primary problem areas for air and water leakage occur at junctures of different components or assemblies – for instance wall/roof junctures, around windows and doors, and at penetrations such as vents. Careful detailing, proper flashing, high quality sealants, and to some extent, redundancy are the main methods of mitigation.

Figure 25. Single-Family Residence – Wayne County, PA

Figure 26. College Town Apartments – Ithaca, NY

Figure 27. Single-Family Residence – Kempton, PA

Figure 28. Brooklyn Pizza – Hackensack, NJ

Building codes can be viewed as both a barrier to moving toward more energy efficient and higher performing buildings and "the stick" that sets minimum thresholds of performance and requires that certain measures are incorporated in all new buildings and major renovations. Historically, the codes have placed the greatest emphasis on health and safety; energy efficiency has not been a significant focus until more recently. Unlike many European countries and Canada, energy codes in the U.S. have not required any type of testing for envelope air leakage in commercial buildings, careful attention to detailing to prevent thermal bridging, or increased levels of insulation to minimize heat loss. Although there are undoubtedly more complicated reasons for not having these requirements, comparably low energy costs in the U.S. have not encouraged priority on reduction in energy use and thus, building operating costs.

But times are changing. The Navigant study found a greater awareness of and demand for energy efficiency on the part of end users. Over a three-year period between 2011 and 2014, both commercial building owners and tenants expressed an increased focus on energy efficiency.[17] As previously discussed, the 2015 IECC will be implemented in New York State in 2016 requires continuous insulation on most types of structural assemblies. Code changes combined with higher energy costs and more savvy commercial building tenants will help drive interest in attaining better thermal performance while maintaining cavity thickness to reduce both operating and construction costs.

[17] NYSERDA. 2015. "Phase One Process Evaluation and Market Evaluation of the NYSERDA New Construction Program." Prepared by Navigant Consulting, nyserda.ny.gov/about/publications

Cost is usually one of the greatest constraints to increasing market penetration of an ultra-high R-value metal sandwich panel. Interviews with several New York State metal building contractors indicated that the higher first cost of conventional IMPs is one of the biggest barriers to moving toward what they acknowledge is a higher performing insulation and cladding system. Typically, IMPs tend to be used on their higher end residential and commercial buildings rather than for the building owner who is looking for the rock bottom initial cost outlay. However, they pointed out that when considering all related costs, the price difference between an IMP and a fiberglass batt system narrows. In some cases, the IMP is actually more cost effective. By using an IMP, cost savings can be realized for the following:

- Avoided labor and materials for framing.
- Avoided labor and materials for exterior sheathing.
- Avoided labor for insulation, interior wall covering, and exterior cladding.

Furthermore, added value is achieved from the “cleaner” appearance of the interior steel liner panel versus the frequently exposed FSK (Foil-Scrim-Kraft) covering when fiberglass is used; the longevity of the durable steel exterior skin, and the expedited construction schedule due to the faster “drying-in” of the building.

In addition, several cited inconsistent energy code enforcement and approval of non-compliant systems as one of the main reasons for not transitioning to a higher performing system. Often, the energy code requirements for continuous insulation discussed above are not actually met even though the plans are professionally designed and approved. The use of an IMP and especially, a MAI IMP with a thinner profile would not only make it easier, but also more likely, that full code compliance is achieved.

ATAS International provided the following average costs for varied thicknesses of PIR IMPs:

- 2-inch PIR IMP: $7.25/sq ft.
- 4-inch PIR IMP: $10.02/sq ft.
- 6-inch PIR IMP: $12.32/sq ft.

Although it is difficult to accurately predict retail cost of a MAI IMP to the consumer at this stage in its development, Nanopore currently sells small quantities of the MAI material alone for $5.00/sq ft. Of course, commercial application in the building industry as either the composite core in a metal sandwich panel or as rigid board insulation requires the development of an automated manufacturing process.

Nanopore estimates that the cost of a 2-inch MAI IMP might be in the range of $15.00/sq ft once the product is fully commercialized and manufactured in larger quantities. This cost would be about 50% higher than a current conventional 4-inch PIR IMP, but carries the previously discussed advantages regarding equivalent thermal performance with a significantly thinner profile.

The value of the current project lies in the fact that the thermal performance of a prototype MAI IMP now has been tested and verified to be almost double compared to the current IMP technology. At R-11 per inch, an important milestone has been reached that provides incentive to continue with product development via other public or private funding sources. NYSERDA funding has filled an important gap in information that is critical to the development of a new construction system that offers superior performance and greater likelihood of full compliance with the Energy Code for many commercial building assembly types.

4 Conclusion

Given the successful results of the hot box testing of the prototype MAI metal panel, further efforts to research, develop, and commercialize a sandwich panel with a MAI composite core are anticipated. Several directions can be pursued to improve the panels.

The first improvement would be to maximize MAI coverage to boost the R-value of a 2-inch panel to R-25. This increase would facilitate meeting energy code requirements for above-grade walls in all climate zones in the U.S. In retrofit situations, this increase would provide an exterior cladding for older buildings with little or no insulation in exterior walls.

A second improvement would be to identify a metal panel with a ribbed interlocking profile and develop a prototype process for creating a composite MAI core where the voids are filled and the composite cores of adjacent panels butt tightly when installed. Such an improvement would offer enhanced marketability via an additional profile as well as enhanced sealing against air infiltration and water penetration due to the interlocking seams.

Finally, a more automated and efficient fabrication process must be developed to be able to assemble large quantities of panels in production line fashion and reduce manufacturing costs. This process improvement is essential for commercialization of a MAI sandwich panel and to make it a viable and competitive player in the marketplace.

Appendix A: IECC 2015 Prescriptive Envelope Requirements and Insulated Metal Panel (IMP) Types/Thickness

IECC 2015 Code Requirements for Above-Grade Walls - Commercial Buildings							Polyisocyanurate - Thickness (No cavity insulation)[*]		MAI IMP – Thickness (No cavity insulation)[**]
							Code Compliant		Code Compliant
	Climate Zone 4		Climate Zone 5		Climate Zone 6		~3" R-16.8	~4" R-22.4	2" ~R-22.4
	R-Value	U-Factor	R-Value	U-Factor	R-Value	U-Factor	U-Factor	U-Factor	U-Factor
Metal Building	R-13 + R-13 ci	U-0.052	R-13 + R-13 ci	U-0.052	R-13 + R-13 ci	U-0.052	U-0.059	U-0.045	U-0.045
Steel Framed - 24" o.c.	R-13 + R-7.5 ci	U-0.064	R-13 + R-7.5 ci	U-0.064	R-13 + R-7.5 ci	U-0.064	U-0.051	U-0.041	U-0.041
Wood Framed - 24" o.c.	R-13 + R-3.8 ci or R-20	U-0.064	R-13 + R-3.8 ci or R-20 Group R: R-13 + R-7.5 ci or R-20 + R-3.8 ci	U-0.064	R-13 + R-7.5 ci or R-20 + R-3.8 ci	U-0.051	U-0.050	U-.039	U-0.039

[*] From ASHRAE 90.1 Appendix A Table A3.2 Assembly U-Factors for Metal Building Walls, Table 3.3 Assembly U-Factors for Steel-Frame Walls, and Table 3.4 Assembly U-Factors for Wood-Framed Walls

[**] ORNL Hot Box Test Results 2015 and ASHRAE 90.1 Appendix A Table A3.2 Assembly U-Factors for Metal Building Walls, Table 3.3 Assembly U-Factors for Steel-Frame Walls, and Table 3.4 Assembly U-Factors for Wood-Framed Walls

IECC 2015 Code Requirements for Roofs - Commercial Buildings							Polyisocyanurate Thickness (No cavity insulation)*	MAI IMP Thickness (No cavity insulation)**
							Code Compliant	Code Compliant
	Climate Zone 4		Climate Zone 5		Climate Zone 6		~6” R-33.6	3” ~R-33.6
	R-Value	U-Factor	R-Value	U-Factor	R-Value	U-Factor	U-Factor	U-Factor
Insulation Entirely Above Deck	R-30 ci	U-0.032	R-30 ci	U-0.032	R-30 ci	U-0.032	U-.030	U-0.030

* From ASHRAE 90.1 Appendix A Table A2.2 Assembly U-Factors for Roofs w/ Insulation Entirely Above Deck

** ORNL Hot Box Test Results 2015 and From ASHRAE 90.1 Appendix A Table A2.2 Assembly U-Factors for Roofs w/ Insulation Entirely Above Deck

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