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Next Generation Wall Retrofit Panels With Integrated VIPS

PHASE 1 TECHNICAL REPORT

Prepared For

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EXECUTIVE SUMMARY

The *Next Generation Wall Retrofit Panels with Integrated VIPs* project has been focused on developing an ultra-high R-value wall panel solution that can be fabricated offsite in a manufacturing plant for retrofit building projects. These innovative wall panels are intended to complement a whole building retrofit solution like Energiesprong (https://energiesprong.org/about/) – a Dutch remodeling approach where substantial improvements to building enclosures are combined with the use of low-capacity, right-sized equipment. For our project, the research and development objectives are to develop a next generation building envelope retrofit solution that achieves deep operational and embodied energy savings, while being faster to implement, less disruptive to building occupants, more affordable, and more desirable.

During Phase I, the team developed four retrofit wall panel configurations – Exterior Insulation Finish Systems (EIFS); Retrofit Insulated Panels (RIPs); Insulated Concrete Panels, and Insulated Metal Panels – that incorporated Vacuum Insulated Panels (VIPs) to deliver lighter, thinner, fully complete wall panels with ultra-high R-value at a comparable or lower cost than existing wall retrofit solutions. Each wall panel configuration was analyzed and optimized with respect to thermal performance, ease of manufacturing (to determine how easy it would be to incorporate VIPs), moisture resistance, durability, installation, and cost.

Based on modeling, simulations, and a practical evaluation of the concepts, the team selected three retrofit wall panel configurations – EIFS, RIPs using polyisocyanurate, and RIPs with expanded polystyrene (EPS) – to make physical prototypes. After close review of the concepts and prototypes with the Structural Insulated Panel Association (SIPA), the RIPs with EPS were selected for constructability and installation testing. This decision was largely based on the prevalence of EPS being used in 85% of the RIPs products currently in the marketplace, although polyisocyanurate offers higher R-value compared to EPS. Manufacturing preference was another major consideration in selecting the EPS version of RIPs products to enhance.

The final panel design – RIPs with embedded VIPs, which we call "V-RIP" – includes features that make it easy to install without damaging the VIP. We have included additional quality assurance procedures to protect the VIP during 1) manufacturing, 2) assembly, and 3) installation of the V-RIP. The physical testing focused on thermal performance, air leakage, and water penetration. We did not focus on structural testing because the new V-RIP will be installed just like convention RIPs products, which are supported by 2x4 members. The test results are in Table 1.

Table 1: Test Results for Prototype Retrofit Insulated Panels with VIPs (Various Configurations)

Test Method	Results	Comments
ASTM C518 – (R-Value)	47	Core of Panel
ASTM C1363 – (R-Value)	Indeterminant	Not Enough Samples
ASTM E283 – (Air Leakage)	4CFM	Baseline was 11 CFM
ASTM E331 – (Water Leakage)	None Observed	No Leakage

The team referenced existing guidance from the *Retrofit Insulated Wall & Roof Panel Installation Guide*[1] on how to 1) evaluate a candidate building for retrofit, 2) install the panels, and 3) design to prevent moisture issues when installing the product. By leveraging and building on existing guidance, the team believes that adoption of the V-RIP will be much easier than other options because the improvement in R-value can be realized without major changes to how the conventional product is installed; a hallmark of practical innovation. Equally important, we provide design layout guidance for how to arrange the V-RIP product on an existing building to ensure maximum R-value is realized.

In conclusion, we believe that V-RIP has a strong potential for success when it is part of a comprehensive building envelope retrofit strategy that includes improvements in air tightness, windows, doors, and roof insulation. When coupled with heating, cooling, and water heating upgrades, we are confident we can achieve the target improvement of 75% EUI for multifamily building types.

During Phase 2, we propose to demonstrate the target performance with a field study in New York State where the RetrofitNY Program[2] is one of the first programs recognized by the Energiesprong for its approach to deep energy retrofit improvements. The candidate multifamily buildings (Type 4 and Type 6) we have identified represent up to 25% of the multifamily buildings in New York State based on the *NYSERDA RetrofitNY Market Characterization Study: Building Stock Assessment and Architectural Profiles of Predominanate New York State Multifamily Building Types*[3]. The conditions of these buildings are ideal for the whole-building retrofit program given the projected wall and roof R-values.

INTRODUCTION

With over 100 million existing housing units in the United States, the potential for improving energy efficiency and reducing the energy demand on the grid is substantial and remains largely untapped. One of the promising retrofit business models currently being evaluated by various stakeholders, including DOE, is based on the European Energiesprong strategy where substantial, wholesale improvements to enclosures are combined with the use of low-capacity, right-sized equipment. Nail-based Retrofit Insulated Panels (RIPs) are the conventional product in the United States that remodelers use to achieve a significant increase in the building envelope R-value by installing the product on the exterior wall. This product has the benefit of improving the R-value without disrupting building occupants.

Problem Statement

One major barrier to adoption of nail-based retrofit insulated panels is the excessive thickness of the wall panels when standard foam insulation products are utilized. To achieve an R35 panel using conventional foam products, you need a panel that ranges in thickness from 7.75 to 9.75 in. In practical terms, this can be very difficult to accommodate for many existing buildings. A promising alternative technology is Vacuum Insulated Panels (VIPs) integrated into existing wall insulating products. Since VIPs

[1] https://www.sips.org/documents/Retrofit-Insulated-Wall-Roof-Panel-Installation-Guide.pdf

[2] https://energiesprong.org/?country=new-york

[3] https://www.nyserda.ny.gov/-/media/Files/Programs/RetrofitNY/20-20-NYSERDA-Market-Characterization-Report-SU-Pratt.pdf (see Table 1 on page 2 and Appendix B on page B-1).

have an R-value that is approximately R35 per inch, successfully integrating them into conventional insulating products could be a game-changer in façade retrofits.

Objectives of The Study

Our project explores the integration of VIPs with off-site fabrication of high R-value retrofit panels. Factory fabrication combined with the idea of embedding VIPs within existing wall insulating panels will provide the protection needed to avoid risk of damage from handling and installing the VIP insulation at the construction site, and will allow for an effective R-value in the range of R35 to R40, at a thickness ranging from 3.0 to 3.5 in. due to the high R-value the VIP technology provides.

VIPs are a next generation material with thermal characteristics unmatched by any commercially-sold insulation materials in building construction today. Compared to 20 years ago, when HUD studied VIPs as part of the Partnership for Advancing Technology in Housing (PATH) Program[4], VIP manufacturing technology has continued to improve and now has a wide range of applications (e.g., refrigeration, packaging for medical and pharmaceuticals, automotive, trains, ships, and construction)[5]. In addition, because the primary component in VIPs is silica, its fire performance characteristics should be superior to other standard foam-based sheathing materials.

The main objective of our project is to develop a final VIPs-enhanced wall retrofit product that provides lighter, thinner, fully complete wall panels with ultra-high R-value at comparable or lower cost compared to existing wall retrofit solutions. The final panel design must be easy to install without damaging the embedded VIP product. We must define quality assurance procedures to protect the VIP during 1) manufacturing, 2) assembly, and 3) installation at the construction site. The final design must also demonstrate acceptable performance and be ready for commercialization, as judged by potential manufacturers and builders.

Research Questions

We intend to answer the following research questions:

1. **Are there viable concepts?** Develop 3 to 4 product concepts that offer a solution of integrating VIPs with off-site panel fabrication, which may pave the way for VIP technology to be adopted into mainstream construction.

2. **Which concepts should we prototype?** Evaluate the product concepts and determine whether they require new methods of fabrication, assembly, connection, and/or structural support to replace existing products.

3. **Can thermal bridging be reduced to maximize the use of VIPs within the panel and increase the total system R-value?** Develop thermal models to determine if the high R-value in the range of R35-40 can be achieved.

4. Develop a panel configuration that lends itself to rapid factory assembly process.

[4] https://www.huduser.gov/Publications/pdf/VIP_Final_Project_Report.pdf

[5] https://vipa-international.org/vip-applications/

5. **Can any existing fabrication techniques be leveraged to make VIPs implementation more straightforward?** Develop a panel configuration that minimizes or nearly eliminates the risk of damage to the VIPs during both factory assembly and on-site installation. Determine necessary quality assurance procedures.

6. **Can any existing installation and panel connection techniques be utilized?** Develop a method for interlocking and connecting the panels to various substrates that substantially minimizes the number of attachment points.

7. **Can we provide a wide range of factory-installed cladding and/or finish options for broad market acceptance?**

Literature Review / Previous Work

In the field of whole-house energy performance improvements, Home Innovation (HI) has led multiple research projects over the last 20 years for HUD, DOE, NAHB, the American Chemistry Council, Forest Products Laboratory, and other industry clients that led to changes in the building codes and provided the basis for developing industry guidance. Our research included the study of VIPs for HUD's PATH Program with a final report (2002) entitled, *Accelerating the Adoption of Vacuum Insulation Technology in Home Construction, Renovation, and Remodeling*[6], where we identified future potential for VIPs provided they were adequately protected during installation.

Our previous Building America project with DOE "High Performance Building Envelope Assemblies" (DE-EE0007054, 2015-2017) spanned four related topics:

1. Moisture Performance of High-R Wall Systems[7], with the goal of facilitating a broader adoption of high-performance envelopes by reducing the perceived and actual risks to transitioning to high-R walls

2. Extended Plate and Beam (EP&B)[8], an innovative wall system incorporating rigid foam interior to sheathing, which was intended to boost market adoption of high-R walls featuring foam sheathing that could be installed while preserving traditional framing techniques, thereby enhancing constructability

3. Attic Retrofits Using Nail-Base Insulated Panels[9], which developed and demonstrated a value-added roof/attic retrofit solution for a range of older homes where traditional attic insulation approaches are not effective or feasible

4. Using Retrofit Nail-Based Panels to Expand the Market for Wall Upgrades[10], which evaluated the thermal performance and ease of installation of RIPs and included the publication of the *Retrofit Insulated Wall & Roof Panel Installation Guide*

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[6] https://www.huduser.gov/Publications/pdf/VIP_Final_Project_Report.pdf

[7] https://www.energy.gov/eere/buildings/articles/building-america-success-story-moisture-performance-high-r-wall-systems

[8] https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/1439541.pdf

[9] https://www.homeinnovation.com/-/media/Files/Reports/Attic-Retrofits-Using-Nail-Base-Insulated-Panels.pdf

[10] https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/65183.pdf

Oak Ridge National Laboratory (ORNL) is home to the Building Technologies Research and Integration Center (BTRIC), a premier national laboratory, and has frequently teamed with HI. Over the last 3+ decades BTRIC has developed several innovative technologies for improving energy efficiency in buildings. BTRIC is equipped with multiple large-scale thermal performance test beds for building components and assemblies, HVAC equipment, appliances, and natural exposure test facilities for performance evaluation at natural operating conditions. The physical resources and technical capabilities of BTRIC provide strong technical support to achieve the goals of this project.

BTRIC has been involved in researching VIPs since the mid-1980s. Driven by an interest to improve the thermal performance of appliance shells without changing the geometry, VIPs attracted DOE's attention at that time. ORNL, working with key industry partners, studied improved barrier materials, encapsulation techniques, and lower-cost fill materials, and developed test protocols for thermal performance of VIPs and a means of measuring panel internal gas pressure remotely without disturbing the vacuum seal. ORNL staff also authored the ASTM Standard Specification on VIPs (ASTM C1484).

In 2013, ORNL teamed with NanoPore to develop MAI, a low-cost variant of vacuum panels, by substantially modifying the manufacturing process and significantly reducing the cost of this technology. In 2014, ORNL teamed with NanoPore and Firestone Building Products to develop an R25 polyisocyanurate/MAI composite insulation board that has twice the thermal resistance of a traditional polyiso foam product. In 2016, ORNL once again teamed with NanoPore and Royal Building Products to develop an insulated vinyl siding that is less than 1-in. thick and has a thermal resistance of approximately R10. Unfortunately, the inventor of MAI technology passed away in 2020 and his company (NanoPore), the sole manufacturer of the technology, went out of business. The MAI inventor was in the process of licensing the technology to at least one other manufacturer, but the process was never completed. As a result, our project did not explore the MAI VIP option.

METHODOLOGY

Concept Designs

To facilitate the development and fabrication of low-cost, high R-value retrofit panels, several commercially available retrofit systems were explored: 1) EIFS; 2) nail-based structural insulated panels, herein referred to as retrofit panels or RIPs; 3) precast insulated concrete panels; and (4) metal insulated panels. These systems were selected because they are commercially available have well-established infrastructure for fabrication and installation.

The technical concept is relatively simple – replace the core insulation material in these systems, which is typically a rigid plastic foam insulation, with a composite insulation that encapsulates VIPs in rigid plastic foam. This work uses composite systems based on polyisocyanurate and expanded polystyrene insulation. The VIPs have a fumed silica core with a multilayer metalized polymer barrier film.

Exterior Insulation Finish Systems (EIFS)

There are several benefits offered by EIFS making them easy to install while providing high thermal insulation values compared to systems that are installed on site such as fiberglass batt and blown in cellulose. Since they are prefabricated, EIFS are relatively quick and easy to install provided the panels do not require on-site modifications. Since the panels are constructed using rigid plastic foam and installed exterior to the sheathing, they effectively reduce or eliminate thermal bridging that results from structural framing. The use of expanded polystyrene as the core insulation material offers the opportunity to easily incorporate VIPs. The encapsulation of VIPs in the expanded polystyrene core can effectively reduce the thickness while significantly increasing the insulation value. This may offer benefits regarding installation and integration with existing fenestrations and service penetrations. More importantly, it leverages the same manufacturing process and installation practice of the traditional EIFS product making it more acceptable to the industry. Figure 1 shows a schematic of the exterior insulation finish system.

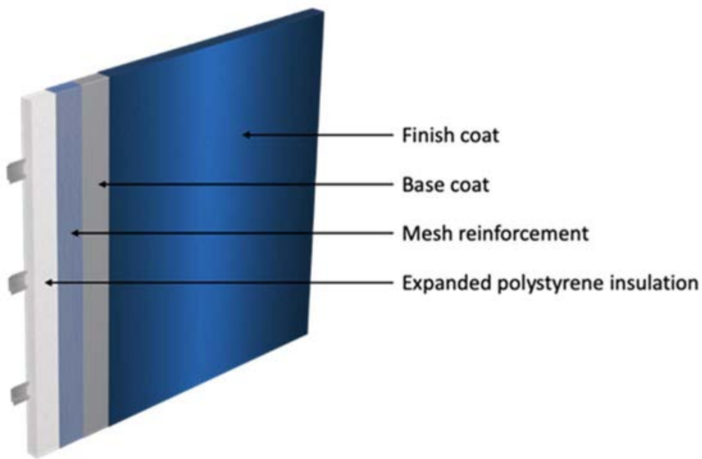


Figure 1: Schematic of exterior insulation finish system retrofit panel
(Source: Dryvit, Fenderlite retrofit panels)

Retrofit Insulated Panels (RIPs)

Nail-based structural insulated panels, which we refer to as retrofit insulated panels (RIPs), offer similar benefits to EIFS, with the exception that the cladding or finished surface is not incorporated into the panel. This offers homeowners more flexibility in selecting cladding material. Figure 2 shows a schematic of a RIPs panel. The core insulation material is expanded polystyrene that is adhered to OSB exterior sheathing. Similar to EIFS, the VIPs can be encapsulated in the expanded polystyrene (EPS) creating a core composite insulation with a much higher R-value. For fabricators of these types of panels, the process remains the same. They will be supplied VIP/EPS composite panels that will then be used to adhere OSB exterior sheathing. The installation of RIPs panels will be different from EIFS installation. Installers will have to utilize spacing at the perimeter and internal gaps between VIPs to ensure that fasteners do not penetrate the VIPs.

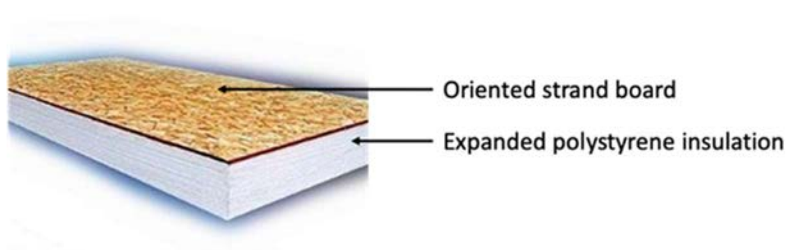


Figure 2: Nail Based Structural Insulate Panel with EPS and OSB

Insulated Concrete Panels

Precast insulated concrete panels were also considered as a possible option. The interesting feature of these types of panels is the flexibility and ease of construction compared to the EIFS and RIPs panels. In this case, the rigid plastic foam insulation is used as the mold in which the concrete is cast. These panels use both EPS and expanded polystyrene (EPS) insulation to fabricate the molds. As with the previously mentioned systems, the core insulation material would be replaced with a VIP/rigid plastic foam composite insulation core. The benefit of using or casting concrete adjacent to the VIP composite core insulation is that it provides superior protection of the VIPs from metal fasteners. The only way to penetrate the barrier film on the VIPs is to drill through the exterior concrete wall. Similar to the previous systems, the manufacturing and installation process are the same for the new and traditional versions of this option. Installers simply need to be made aware that penetration of the exterior concrete wall to the interior must be avoided so as not to damage the VIPs. On the interior, the design of the wall element provides a cavity that should prevent the VIPs from being damaged from fasteners through drywall. Figure 3 shows a wall section with XPS insulation in the cavity between the studs and EPS insulation protecting the studs. The purpose of the EPS is to reduce thermal bridging from the metal framing used as part of the reinforcement.

Figure 3: Precast Insulated Concrete Panel
(Source: Superior Walls, https://www.superiorwalls.com/superior-walls-products/)

Insulated Metal Panels

The last concept that was considered was insulated metal panels. The overall theme was the same – to encapsulate VIPs into the rigid plastic foam insulation that forms the core of the metal insulated panel. The result would be a significant increase in insulation value compared to conventional rigid plastic foams, such as polyisocyanurate and polyurethane. Like the other approaches, no changes in the fabrication and installation process would be needed in order to substitute the core with a VIP composite core insulation. Figure 4 shows a schematic of an insulated metal panel. Unfortunately, it was not possible to partner with fabricators of these systems, so this option was not evaluated further but could be revisited if the opportunity presents itself in the future.

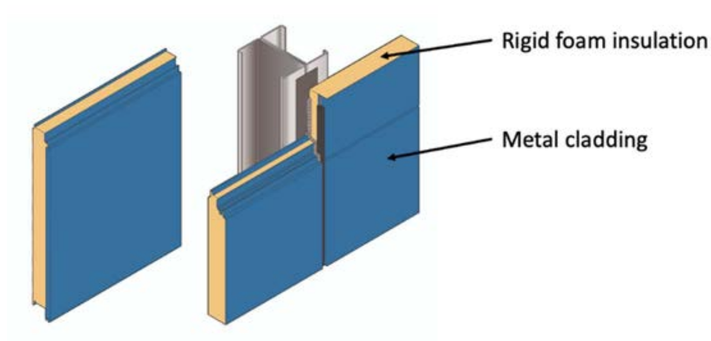


Figure 4: Insulated Metal Panel with Rigid Foam Insulation Core Protected by Metal Cladding

Analyze and Optimize Each VIP Retrofit Wall Configuration with Modeling

The fundamental feature that all retrofit options have in common is that they use rigid plastic foam to encapsulate vacuum insulation panels. The benefit of doing this is that it protects the VIP from hazards normally encountered during transport and handling on the job site. Previous work at ORNL demonstrated that vacuum insulation panels could be encapsulated in polyisocyanurate foam using standard manufacturing processes.[11] Figure 5 highlights the steps used to encapsulate VIPs in polyisocyanurate insulation board. The fabrication was carried out on a commercial manufacturing line used to produce paper-faced polyisocyanurate insulation board. A 3x4 array of VIPs was placed on a 4 ft. x 8 ft. polyisocyanurate insulation board, ½-in. thick. The spacing between panels was approximately one inch. This provided a space for installers to cut and/or fasten the boards to exterior sheathing using mechanical fastening methods. The board was then passed through a foaming step, followed by a lamination step, and then cut to size. The work demonstrated that VIP/polyisocyanurate insulation boards could be fabricated in a continuous process.

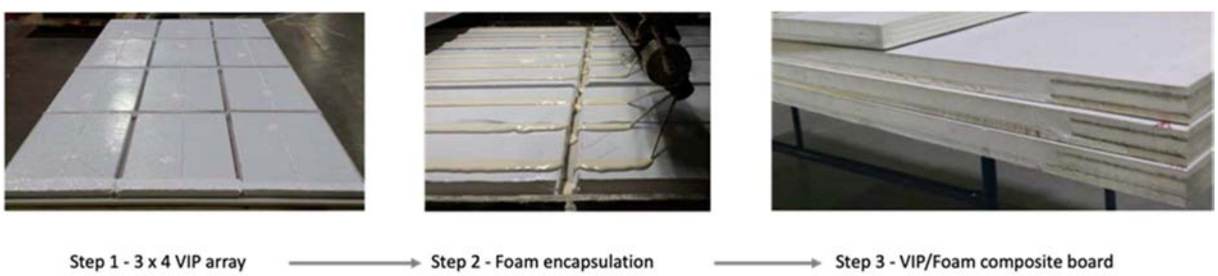


Figure 5: The process used to fabricate a composite rigid insulation panel[12]

In this work an analysis was first carried out to determine the insulation value of VIP/rigid plastic foam systems for the different retrofit options. The target performance value for the composite insulation was R30 or greater. The size of the panel, area and thickness of VIPs, and coverage were evaluated. Also, two insulations were evaluated – expanded polystyrene and polyisocyanurate foams. Simple isothermal planes method and THERM simulations were carried out to calculate insulation values.

[11] https://www.energy.gov/sites/prod/files/2017/04/f34/5_31395_Biswas_031617-1100.pdf

[12] The panel is comprised of an array of vacuum insulation panels encapsulated in polyisocyanurate foam insulation to produce a standard 4 ft x 8 ft board, 2 in. thick. The measured insulation value of the panels in this construction were approximately R 25.

As a first step, the size of VIPs was selected based on the criteria of maximizing coverage, and preserving a perimeter and spacing between panels of one inch. Also, sizes were selected from panels that were commercially available and that would provide the greatest flexibility in customizing sizes on the job site.

Precast Insulated Concrete Panels

To determine the feasibility of using precast insulated concrete panels, the insulation value was calculated using the isothermal planes method and THERM.[13] THERM is a two-dimensional heat transfer model developed by Lawrence Berkeley Lab's Windows and Daylighting group. Originally developed to study the thermal performance of windows, the flexibility of the tool in the construction of complicated shapes and the ability to import material properties makes is a very powerful tool to study the heat transfer of any building component and/or system such as wall assemblies. It's ideally suited to calculate insulation values of composite systems such as the retrofit options in this study.

Calculations were carried out for precast insulated concrete walls as a function of insulation materials and thickness. Several options were evaluated to improve thermal performance of the retrofit assembly. The thickness of VIPs was evaluated in accordance with the values listed in Table 2. These are commercially available thicknesses. The addition of fiberglass batt and mineral wool insulation were used to fill the remainder of the wall cavity to improve thermal performance. To decrease heat transfer further, the density of the concrete was reduced.

Table 2: The measured insulation values as reported by the manufacturer for the panels as a function of thickness. Center of panel insulation values and edge effect reductions are reported. The units for R value are ft^2 hr ^{o}F/BTU.

Thickness	Center of panel	Calc'd with edge
inches	R	R
0.79	26	22
0.98	32	28
1.18	37	33
1.57	49	46
1.97	60	57

Figure 6 shows the cross-section of the precast insulated concrete panel. The nominal concrete thickness is 1.75 in. The extruded polystyrene insulation between the metal studs is 2.5 in. thick. The steel reinforced concrete studs are surrounded by 1 in. of expanded polystyrene insulation. The arrangement of the insulation forms a mold that is used to cast the concrete.

Using isothermal planes method, the insulation value of the wall was calculated using the configuration in Figure 6 and then compared to the same configuration replacing the expanded polystyrene with VIPs. In this case, the insulation thickness is 2 in. The thermal conductivity of the VIPs used in the calculation is 0.0364 Btu in/h ft^2 °F. The thermal conductivity of the materials is listed in Table 3. The results are shown in Figure 7. Even though the insulation value of two inches of VIPs has an R-value of almost 60 (see Table 2), the R-value for the wall system is 19, significantly lower than the target value of R30. Polyisocyanurate board is also shown for comparison. The problem is the thermal bridging of the concrete both perpendicular to and parallel to the wall.

[13] https://windows.lbl.gov/software/therm

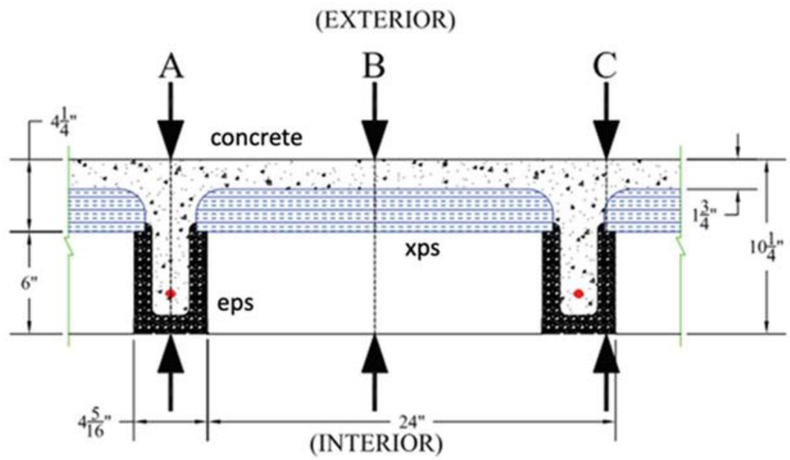


Figure 6: Precast insulated panel, cross-section. The wall panel is shown with the stud sections insulted with approximately 1 in. of expanded polystyrene. The cavity between the stud members is insulated with extruded polystyrene, a thickness of 2 in.

Table 3: Thermal conductivity for materials used in isothermal plane calculations of insulation value for precast insulated concrete panels. The letters refer to thickness along the lines identified in Figure 6.

Material	Conductivity, BTU in/h ft^2 °F	Thickness, [inches]
Concrete	3.699	[A, B], [9.25, 1.75]
Extruded polystyrene	0.201	[B], [2.0] *
Expanded polystyrene	0.250	[A, C], [1.0, 6.0]
Vacuum insulation panels	0.036	[B], [2.0]

To optimize the system's thermal performance, additional calculations were carried out using THERM. This study investigated the effect of concrete density, the addition of insulation in the cavity between the studs, and the thickness of the VIPs. Figure 8 shows the different configurations and insulation materials used. The concrete density varied between 20 and 160 pcf (lbs/ft^3). The thickness of the VIPs varied in accordance with the thicknesses in Table 2. Fiberglass and mineral wool insulation was used to fill the remaining wall cavity to flush with the studs, comparable to the installation of batt insulation in wood-frame construction.

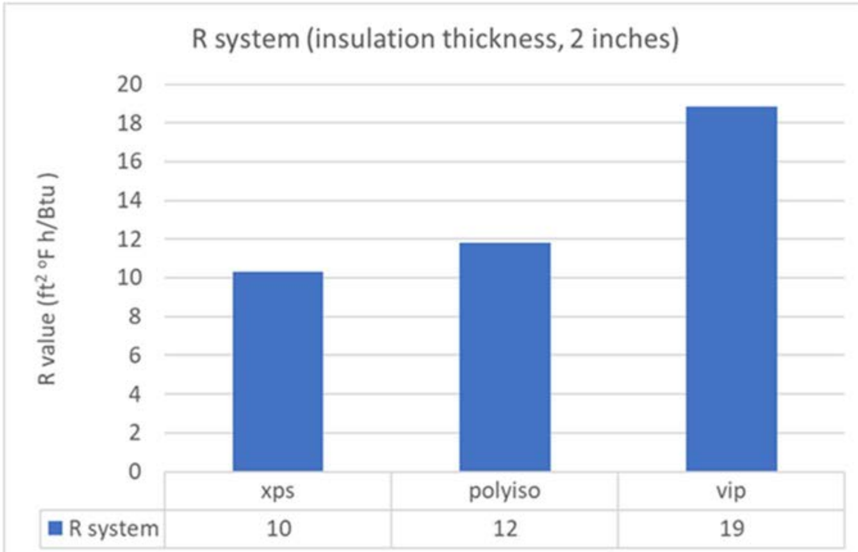


Figure 7: The insulation value for the configuration in Figure 6

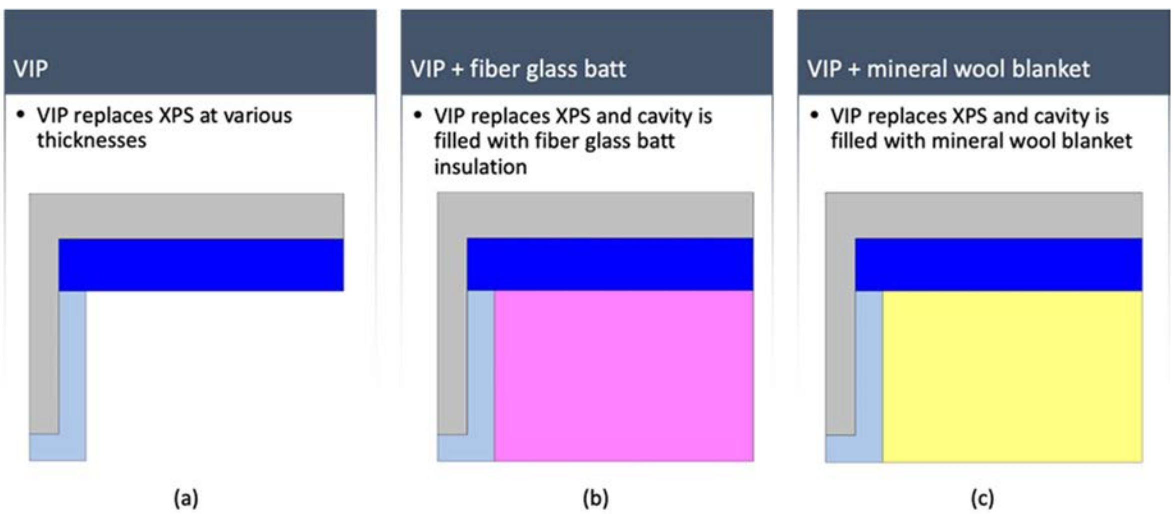


Figure 8: The different geometries used for the THERM simulations. Geometry (a) is the precast panel with the extruded polystyrene insulation replaced with vacuum insulation panels of different thicknesses given in Table 2 Geometries (b) and (c) are the same as (a) except in these cases fiber glass batt and mineral wool are used to fill the empty space to the level of the expanded polystyrene that insulates the stud sections.

The unit weight and moisture dependence on thermal conductivity of concrete was determined in accordance with *ACI/TMS 122-R14 Guide to Thermal Properties of Concrete and Masonry Systems*. The thermal conductivity for the concrete in the precast panel was calculated using equation 3.2 from Table 4. A correction factor was used to account for the dependence on moisture content. These correction factors are based on an internal relative humidity between 60 and 80% and obtained from Table 5. The results, corrected and uncorrected for moisture content, are shown in Figure 9 as a function of concrete density. These values were then used as the conductivity in the THERM calculations. The thermal properties used in the THERM simulations are given in Table 6.

Table 4: The thermal conductivity of oven-dry lightweight concrete, mortar, and brick. The table was obtained from ACI 122R-14, Table 3.2a.

Thermal conductivity k_c, Btu·in./(h·ft²·°F)																
Material, type of aggregate in concrete or data source	Oven-dry density, lb/ft³															
	15	20	25	30	40	50	60	70	80	90	100	110	120	130	140	150
Equation (3.2) $k_c = 0.5e^{0.02\rho}$	0.67	0.75	0.82	0.91	1.11	1.36	1.66	2.03	2.48	3.02	3.69	4.51	5.51	6.75	8.22	10.04
Neat cement paste and foam concrete	0.54	0.64	0.75	0.87	1.11	1.39	1.69	2.03	2.41	2.82	3.29	3.80	4.36	—	—	—
Autoclaved aerated (cellular) concrete	0.47	0.57	0.67	0.79	1.05	1.34	1.68	2.06	—	—	—	—	—	—	—	—
Autoclaved microporous silica	0.41	0.51	0.61	0.72	0.96	1.25	1.58	1.95	2.38	—	—	—	—	—	—	—
Expanded polystyrene beads	0.50	0.62	0.74	0.88	1.18	1.53	1.94	—	—	—	—	—	—	—	—	—
Expanded perlite	0.46	0.57	0.69	0.83	1.13	1.48	1.90	—	—	—	—	—	—	—	—	—
Exfoliated vermiculite	0.53	0.63	0.74	0.86	1.10	1.38	1.69	—	—	—	—	—	—	—	—	—
Natural pumice	—	—	—	0.74	1.02	1.35	1.73	2.19	2.71	3.32	4.03	—	—	—	—	—
Sintered fly ash and coal cinders	—	—	—	—	—	—	1.17	2.11	2.56	3.06	3.64	4.28	—	—	—	—
Volcanic slag and scoria	—	—	—	—	—	—	1.67	2.06	2.50	2.99	3.56	—	—	—	—	—
Expanded slag	—	—	—	—	—	—	1.51	1.84	2.21	2.63	3.10	3.62	4.19	—	—	—
Expanded and sintered clay, shale, and slate	—	—	—	0.87	1.16	1.49	1.88	2.23	2.83	3.40	4.05	4.78	—	—	—	—
Sanded expanded clay, shale, and slate	—	—	—	—	—	1.70	2.21	2.81	3.51	4.32	5.26	6.35	7.60	—	—	—
No-fines pumice, and expanded and sintered clay, shale, and slate	—	—	—	0.97	1.27	1.60	1.98	2.40	2.88	3.41	—	—	—	—	—	—
Limestone	—	—	—	—	—	—	—	2.57	3.20	3.94	4.79	5.76	6.88	8.16	9.62	11.27
Cement-sand mortar and foam concrete	—	—	—	—	—	—	2.35	2.98	3.72	4.58	5.58	6.73	8.05	—	—	—
Fired clay bricks	—	—	—	—	—	—	—	2.19	2.62	3.09	3.63	4.22	4.87	5.58	6.39	7.26

*Obtained from density/thermal conductivity linear equations.

Table 5: Correction factors as a function of the different materials used in concrete mix designs. The average multiplier is 1.23 with a standard deviation of 0.067.

Material or type of aggregate in concrete	Type of exposure	Relative humidity mean, %	Moisture content, percent by weight	Thermal conductivity moisture correction factor, percent increase in thermal conductivity per 1 percent moisture content	Practical thermal conductivity multiplier
Neat cement paste and foam concrete; expanded polystyrene bead concrete	Pr†	80	8.0	3.0	1.25
Autoclaved aerated (cellular) concrete	Pr	80	4.5	4.5	1.20
Expanded perlite and exfoliated vermiculite	Pr	80	6.5	4.5	1.30
Natural pumice	Pr Uh‡	80 80	5.5 7.0	4.25 4.25	1.22 1.30
Sintered fly ash, scoria, and coal cinders	Pr Uh	60 80	3.75 5.0	6.0 6.0	1.22 1.30
Expanded slag	Pr Uh	80 80	3.5 5.5	5.5 5.5	1.20 1.30
Expanded and sintered clay, shale, slate (no natural sand); sanded expanded slag	Pr Uh	80 80	3.5 5.5	4.0 4.0	1.14 1.22
Sanded expanded and sintered clay, shale, and slate	Pr Uh	60 80	3.0 5.0	5.0 5.0	1.15 1.25
Limestone	Pr Uh	60 80	2.0 3.0	7.0 7.0	1.15 1.22
Sand gravel, < 50 percent quartz or quartzite	Pr Uh	60 80	2.0 3.0	7.0 7.0	1.15 1.22
Sand gravel, > 50 percent quartz or quartzite	Pr Uh	60 80	2.0 3.0	9.0 9.0	1.18 1.27
Cement mortar, sanded	Pr	60	2.0	9.0	1.20
Foam concrete	Uh	80	3.0	9.0	1.30
Clay bricks	Pr Uh	60 80	0.5 2.0	30.0 20.0	1.15 1.40

*For converting thermal conductivity of oven-dry concretes and clay bricks to practical design values.

†Pr = protected exposure: exterior wall stuccoed or coated with cement base, texture, or latex paint; interior wythe or cavity wall or of composite wall with full collar joint.

‡Uh = unprotected: exterior wall surface uncoated, or treated with water repellent or thin, clear polymeric sealer only.

Note: Reproduced by permission from Valore (1988).

Table 6: The thermal conductivity of the materials used in the THERM simulations and representative of the materials used to construct the precast insulated concrete panels.

Materials	Thermal conductivity, BTU in/h ft^2 °F
Vacuum insulation panels	0.036
Fiber glass batt	0.300
Mineral wool	0.200
Concrete, 20 pcf	0.750
Concrete, 80 pcf	2.450
Concrete, 160 pcf	12.670

Tables 7 - 9 show the results from the THERM calculations for the different geometries in Figure 8. Each table shows a region highlighted in yellow that corresponds to the concrete density and vacuum insulation panel thicknesses that meet the target insulation value of R 30. Table 7 presents the results for a precast insulated concrete wall panel that utilizes only VIPs. In Table 7, only one cell is highlighted in yellow – a concrete density of 20 pcf and VIP thickness of 1.97 in. For this assembly, this is the only configuration that can achieve an insulation of R30 or greater. Table 8 shows the results from simulations carried out on a precast insulated concrete wall panel with the wall cavity filled with fiberglass batt insulation to the level of the studs. The depth of the wall cavity is 8.5 in. The addition of fiberglass insulation is equivalent to the depth of the wall cavity minus the thickness of the VIPs. Table 3 shows the thicknesses of VIPs and cavity insulation used in the simulations. If the wall cavity is filled with fiberglass insulation, the thermal performance improves and enables the use of higher density concrete. When fiberglass insulation is added to the wall cavity, the range of thermal performance covers all VIP thicknesses up to a concrete density of 60 pcf. At a concrete density of 80 pcf, only the VIP thickness of 1.97 in. results in an insulation value for the wall assembly greater than R30. If the fiberglass insulation is replaced with mineral wool, the region expands further to cover all vacuum insulation thicknesses at a concrete density of 80 pcf. The results for mineral insulation are given in Table 9.

Table 7: The insulation value for precast insulated concrete panel as a function of concrete density and the thickness of vacuum insulation panels.

	Concrete Unit Weight (lbs/ft^3)							
VIP thickness, in	**20**	**40**	**60**	**80**	**100**	**120**	**140**	**160**
0.98	20.6	17.9	15.5	13.4	11.6	10.1	9.0	8.1
1.18	23.1	19.9	17.1	14.6	12.5	10.9	9.6	8.6
1.57	27.6	23.5	19.8	16.7	14.1	12.1	10.6	9.4
1.97	31.8	26.8	22.3	18.6	15.6	13.2	11.5	10.2

Table 8: The insulation value of precast insulated concrete panel as a function of concrete density and the thickness of vacuum insulation panels with fiber glass batt insulation in the wall cavity between the studs.

	Concrete Unit Weight (lbs/ft^3)							
VIP thickness, in	**20**	**40**	**60**	**80**	**100**	**120**	**140**	**160**
0.98	40.0	35.4	31.1	27.4	24.2	21.8	19.9	18.5
1.18	41.9	36.8	32.2	28.1	24.8	22.2	20.2	18.8
1.57	45.1	39.2	33.9	29.4	25.7	22.9	20.8	19.3
1.97	48.2	41.5	35.6	30.6	26.6	23.6	21.3	19.7

Table 9: The insulation value of precast insulated concrete panel as a function of concrete density and the thickness of vacuum insulation panels with mineral wool insulation in the wall cavity between the studs.

	Concrete Unit Weight (lbs/ft^3)							
VIP thickness, in	**20**	**40**	**60**	**80**	**100**	**120**	**140**	**160**
0.98	46.3	40.7	35.6	31.1	27.5	24.7	22.6	21.1
1.18	47.8	41.8	36.4	31.7	27.9	25.0	22.9	21.3
1.57	50.6	43.9	37.9	32.8	28.7	25.6	23.3	21.7
1.97	53.3	45.8	39.2	33.7	29.4	26.1	23.8	22.0

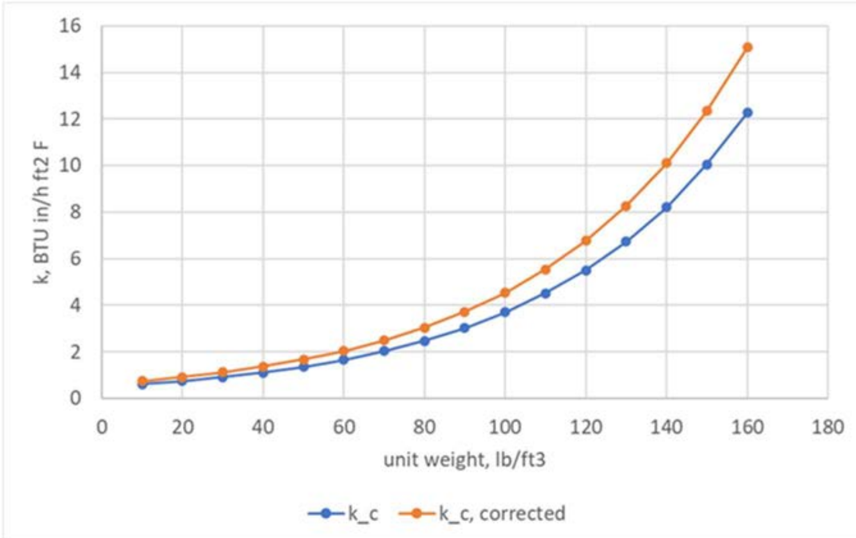


Figure 9: The thermal conductivity of concrete as a function of unit weight (density) uncorrected and corrected for moisture content. The calculations were based on ACI/TMS 122R-14, Guide to Thermal Properties of Concrete and Masonry Systems.

In summary, the only way to achieve the target insulation value of R30 or greater is to reduce the density of concrete from approximately 150 pcf to 80 pcf or less. With only one exception, the addition of insulation in the wall cavity is required as well. This requires modifications to the concrete mix design and fabrication process. It also requires more insulation material in addition to the VIPs. These modifications, unfortunately, will not lower the cost of the precast insulated concrete panels, and will increase the level of complexity in the manufacturing process. For these reasons, this option was eliminated as a possible retrofit option.

Exterior Insulation Finish System and Retrofit Insulated Panels

The benefit or advantage of the EIFS and RIPs retrofit options is that they are built on similar core insulation materials – expanded polystyrene and polyisocyanurate – with expanded polystyrene being the predominant insulation in both. The encapsulation of VIPs in expanded polystyrene and polyisocyanurate insulation offers the most flexibility in the construction of the retrofit panels that meet the target value of R30 with no modifications to the fabrication and installation of the retrofit panels.

For this study, VIPs were encapsulated into expanded polystyrene and polyisocyanurate foam. The initial plan was to construct panels using both types of insulation with the dimensions given in Figure 10. The configuration in Figure 10 was optimized for thermal performance. The coverage of VIPs in this configuration is 85.8%. The VIP coverage is defined as the ratio of VIP surface area to the total panel area. Table 10 shows the results from THERM simulations as a function of VIP thickness. The total panel thickness was maintained at a constant value of 2.5 in., as shown in Figure 11. The thicknesses are listed in Table 2. Results show that an R-value of approximately 30 or greater can be achieved for all VIP thicknesses. For VIP thickness of 0.98 in. with EPS insulation, the insulation value was just below R30. However, the addition of a ½-in. of OSB sheathing is expected to increase the insulation value to over 30. The thermal properties of the materials used in the THERM simulations are given in Table 11.

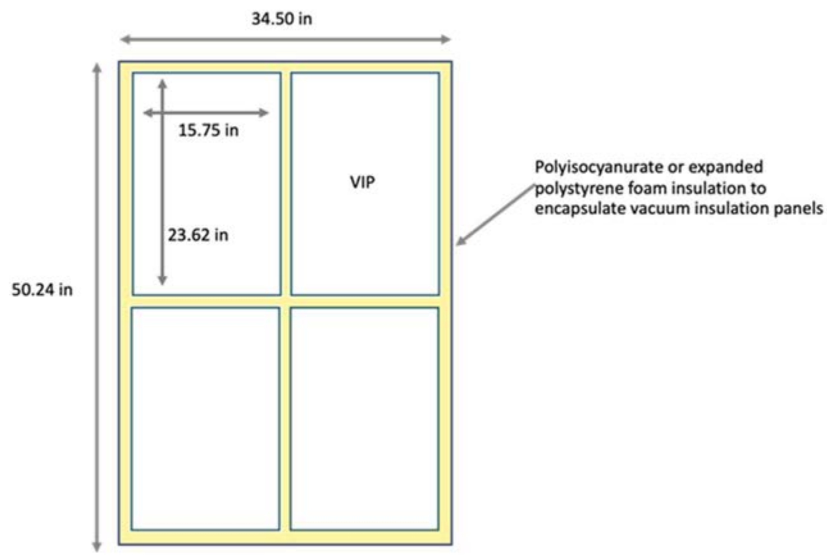


Figure 10: The first prototype panel construction. The initial plan was to produce panels that were 34.50 in. x 50.24 in., the thickness would be governed by the thickness of the vacuum insulation panels. The coverage of VIP is 85.8%.

Table 10: The insulation value for panel configuration defined in Figures 11 and 12 for two different VIP thicknesses, 0.98 and 1.18 in., and two different insulation materials used to encapsulate the vacuum insulation panels, expanded polystyrene and polyisocyanurate.

VIP thickness, in	VIP R-assembly	Foam substrate	Faom R value	Btm thickness, in.	Top thickness, in.	Total board thickness, in. (also total thickness at ribs and selvage)	Rigid foam total thickness at VIP depth	Retrofit panel R value, h*sf*F/Btu
0.98	28	EPS	4	2	0.5	2.5	1.52	29.2
1.18	33	EPS	4	2	0.5	2.5	1.32	33.6
0.98	28	Polyiso	6	2	0.5	2.5	1.52	33.7
1.18	33	Polyiso	6	2	0.5	2.5	1.32	37.1

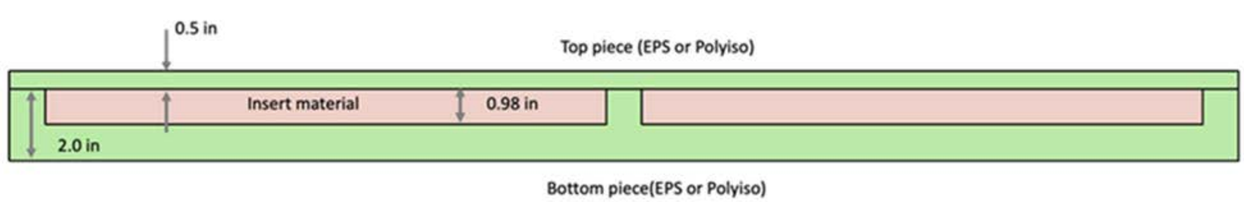


Figure 11: The cross section of the composite core insulation defined above shows a vacuum insulation panel with a thickness of 0.98 in. encapsulated in plastic rigid foam, expanded polystyrene or polyisocyanurate.

Table 11: The thermal conductivity of materials at 75F used in the THERM simulations for the retrofit panels.

Materials	Thermal conductivity, ft^2 hr °F/BTU
Expanded polystyrene insulation	0.26
Polyisocyanurate insulation	0.19
Vacuum insulation panels	0.08

Based on these results, the objective was to fabricate core insulations comprised of VIPs that are 15.75 in. x 23.62 in. x 0.98 in. in a 2x2 array to produce the panel in Figure 10. The spacing between VIPs would be 1 in. and there would be 1 in. of perimeter insulation to protect the VIP and provide a surface for installers to mechanically fasten panels to the wall.

Unfortunately, the manufacturer was unable to supply the VIPs in Figure 10. In addition, we also encountered issues with the insulation manufacturers and suppliers. The net result was a constraint on manufacturing due to shortages of raw materials, increased demand for construction materials and VIPs, and bottlenecks in the supply chain – most of this was attributable to a spike in demand for VIPs needed for COVID-19 vaccine refrigeration requirements.

The manufacturer did have an inventory of older VIPs that were made available to us. The sizes and quantities are listed in Figure 12. In parallel, we reached out to contract manufacturers to fabricate shells of expanded polystyrene insulation that we could use to insert VIPs to build a composite core. For the cores made of polyisocyanurate insulation, we out reached to building material suppliers to obtain any available stock of material. We were able to acquire several 4 ft. x 8 ft. boards between 0.5 and 1.5 in. thick that we could use to construct wall panels. HI took the lead to fabricate two panel types made using expanded polystyrene – a RIPs panel and an EIFS panel. ORNL manually constructed composite insulation panels using polyisocyanurate board and OSB as exterior sheathing.

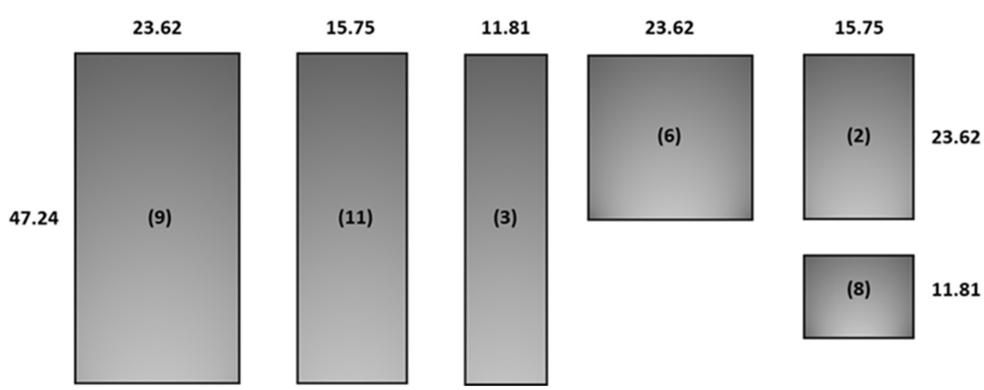


Figure 12: The following figure shows the VIP configurations or geometries used to construct the panels. The numbers on the outside are the dimensions measured in inches and the numbers in the panels within quotes are the number of panels that were supplied by the manufacturer.

Using the panel sizes and quantities in Figure 12, five different configurations were produced and listed in Table 12. The configurations and cross-sections are in Figures 13 and 14, respectively. The thicknesses of all the VIPs are 1.18 in. The calculated coverage of VIPs in these panels is 87.3% for panels a, b, c, and e. The coverage for panel d is less, 78.6%. THERM was used to calculate the insulation value of the composite insulations based on the geometries in Figure 15.

Table 12: Panel sizes, combinations, and numbers used to construct composite panels with the area of VIPs equal to 42.37 in. x 50.24 in. The exception was panel e where the number and combination resulted in a VIP area of 35.43 in. x 47.24 in. The thickness of the VIPs used was 1.18 in. Using the panel configurations or supplied panels, a total of 15 panels were constructed and then used to fabricate different retrofit panels.

	number of panel sizes (in. x in.) used to construct a composite panel						
panel	11.81 x 15.75	23.62 x 15.75	11.81 x 11.81	23.62 x 23.62	47.24 x 11.81	47.24 x 15.75	47.24 x 23.62
a	4	0	0	2	0	0	0
b	0	0	0	0	0	1	1
c	0	0	0	2	0	1	0
d	0	2	0	2	0	0	0
e	0	0	0	0	3	0	0

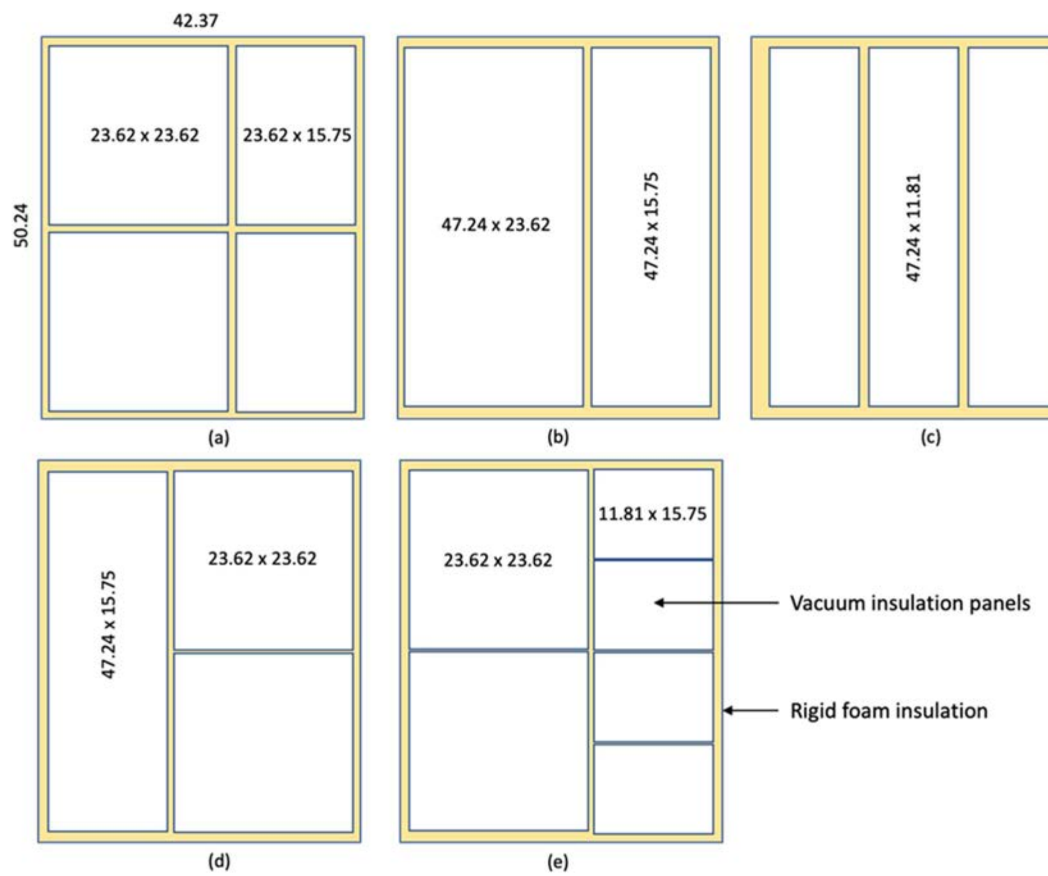


Figure 13: The configuration or layout and sizes of vacuum insulation panels used to construct the panels listed in Table 12. The thickness of the vacuum insulation panels is 1.18 in. and the sizes listed if figures (a) thru (e) are in inches. The thickness of the rigid foam insulation around the perimeter is one inch or greater. The gap between panels is nominally one inch or less.

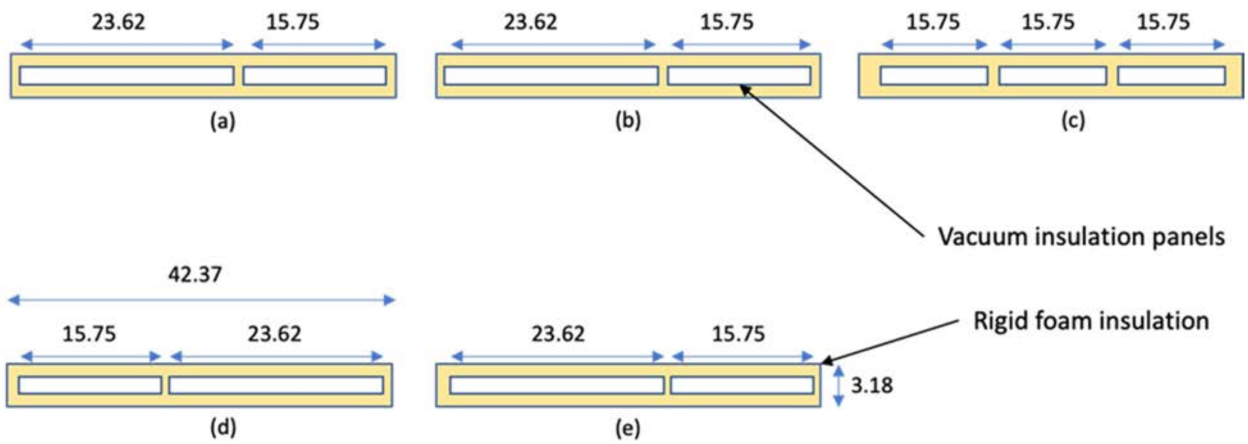


Figure 14: A cross-section of the panels showing the overall thickness of the panels and cover of rigid foam insulation surrounding the vacuum insulation panels. The thickness of the vacuum insulation panels is 1.18 in., and the cover of rigid foam insulation is 1 in. These represent the same panels in Figure 13. All the dimensions are measured in inches.

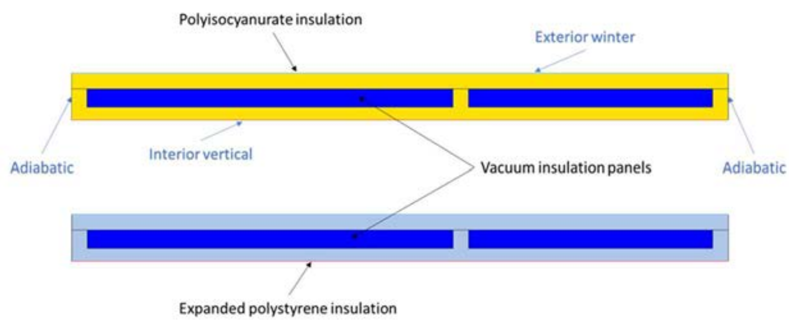


Figure 15: The THERM models used to calculate the insulation values. The geometries are representative of panels (a) thru (e) in Figure 14.

The effect of insulation material and the thickness of VIPs on the thermal value of the composite was studied. The insulation materials used to encapsulate the VIPs are expanded polystyrene or polyisocyanurate. The expanded polystyrene insulation is the preferred insulation for EIFS panels. Polyisocyanurate insulation board is used in RIPs panels, however, the predominant insulation is also expanded polystyrene. The advantage of expanded polystyrene over polyisocyanurate is cost and the ability to be modified on the construction site. The thickness of the expanded polystyrene panel can be adjusted by rasping. Polyisocyanurate insulation offers performance benefits over expanded polystyrene. The R-value of polyisocyanurate is about 25% greater than expanded polystyrene.

THERM calculations were carried out for the cross-section in Figure 14, which represents panels (a) thru (e) in Figure 13. The THERM models are shown in Figure 15. The insulation value was calculated using the exterior winter and interior vertical surface boundary conditions. The temperature, heat transfer coefficients, and emissivity's are given in Table 13. The boundary conditions were the same for all THERM simulations including the analysis for the precast insulated concrete panels. For the case of the VIP/rigid plastic foam composite insulations, the boundary conditions, including adiabatic boundaries, are given in Figure 15. The results are summarized in Table 14. Unlike the concrete panels, there is only one thickness where the target value of R30 is not met – 0.79 in. for the case of expanded polystyrene.

Table 13: The boundary conditions used for the THERM simulations of the retrofit panels.

Boundary	Temperature, °F	Heat transfer coefficient, BTU/ft^2 hr °F	Emissivity
Exterior winter	0	1.46	0.90
Interior vertical	70	5.99	0.90

Table 14: The total insulation value of the panel systems calculated using THERM. The panel dimensions including the VIPs are given in Figure 14. The total panel thickness is 3 in. The percent VIP coverage is 87.3%.

VIP thickness	Insulation shell	
inches	EPS	Polyiso
0.79	27.5	36.1
0.97	30.8	39.2
1.18	34.0	42.5
1.57	40.1	48.6
1.97	46.1	54.8

Analyze Thermal, Air, and Moisture of VIP Prototypes

Panel Construction and GHB Testing

Based on the results from the THERM analysis and the constraints regarding raw materials, VIP composite panel prototypes were constructed using the inventory of VIPs supplied by the manufacturer and listed in Figure 12. The configurations in Figure 8 were fabricated, with uniform thickness of 1.18 in. for all VIPs.

Three sets of panels were fabricated – two retrofit insulated panels; one EIFS retrofit panels. One of the retrofit insulated panels was manufactured using polyisocyanurate insulation as the shell. The remaining panels were constructed using expanded polystyrene insulation as the shell.

Panels manufactured using VIPs encapsulated in EPS were produced by Foard Panel using EPS fabricated by Plastec Profiles, Inc. The prototype production was managed by Home Innovation. ORNL manufactured the panel systems that encapsulated VIPs in polyisocyanurate insulation. Due to manufacturing and material constraints, ORNL manufactured those panels by hand.

A guarded hot box (GHB) operated according to ASTM C1363 (ASTM, 2019) was used to measure the steady-state thermal resistance of the full-scale retrofit panels. Figure 16 shows the hot box that was used to characterize full-scale walls and 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 x 10 ft. high. Typical test specimen dimensions, however, are 8 ft. square with the remainder of the aperture filled with 6-in. rigid EPS insulation with a thermal resistance of at least 24 hr-ft^2°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 defines the test area. The climate chamber can achieve a low temperature of 10°F, and the metering chamber can achieve a high temperature of 110°F. The walls of the metering chamber are constructed with 3-in.-thick aged, XPS foam with a thermal resistance of 14.8 hr ft^2°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 is allowed to attain 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 a steady-state is established, data from the last 12 hours of the steady-state period are used for analyses.

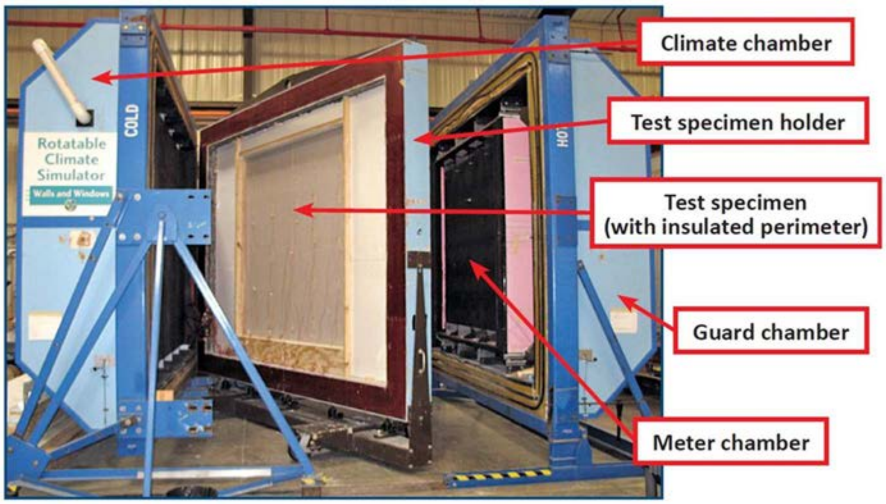


Figure 16: Guarded hot box used for evaluating the VIP panel assemblies

A base test wall comprised of 0.5-in. OSB, 2x4 studs with empty cavities, and 0.5-in. interior sheathing (gypsum board) was constructed, and the retrofit panels were added to this assembly. The retrofit panels were facing the cold (climate) side of the hot box that was maintained at 50˚F; the gypsum board was facing the warm (metering) side of the hot box that was maintained at 100˚F.

The first retrofit panel was identified as the polyisocyanurate/vacuum insulation panel retrofit panel (PIR/VIP RIP). The retrofit panel was comprised of 0.5-in. OSB, 0.5-in. PIR, 1.2-in. VIPs, and 1.0-in. PIR. Four panels 42.5 x 50.25 in. high were constructed using two VIPs dimensioned 47.25 x 15.75 in. and 47.25 x 23.5 in., respectively. The VIPs were surrounded and separated with a 1-in. wide section of PIR (see Figure 17). The overall panel area was 14.7 ft^2 with the VIPs covering 87.4%, or 12.9 ft^2, of the surface area. The exterior surface of the retrofit panel was covered with a spun-bonded polyolefin membrane and vinyl siding to complete the construction.

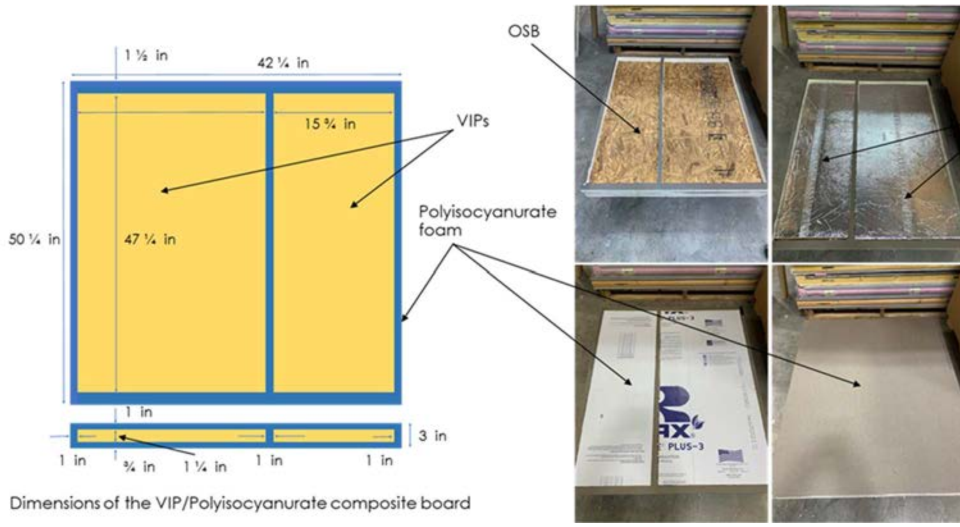


Figure 17: Construction details of the polyisocyanurate/vacuum insulation panel retrofit panel (PIR/VIP RIP).

The second retrofit panel was identified as the exterior insulation finish system/vacuum insulation panel retrofit panel (EIFS/VIP). This retrofit panel was comprised of a 0.25-in. stucco finish, 0.5-in. EPS, 1.2-in. VIPs, and 1.0-in. EPS. Prior to the application of the traditional stucco finish, aluminum C-channels were embedded and adhered into the 1-in. EPS layer. These C-channels would extend slightly beyond the edge of the panels and be used to mechanically attach the panels to the existing wall system. Three panels 42.5 in. wide x 50.25 in. high were constructed using two VIPs dimensioned 47.25 x 15.75 in. and 47.25 x 23.5 in., respectively. The VIPs were surrounded and separated with a 1-in. wide section of PIR (see Figure 18). The overall panel area was 14.7 ft^2 with the VIPs covering 87.4%, or 12.9 ft^2, of the surface area.

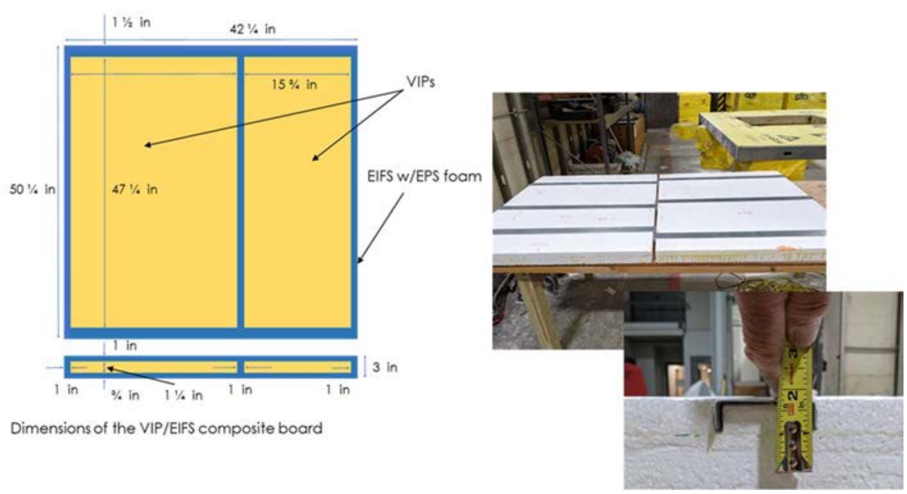


Figure 18: Construction details of the exterior insulation finish system/VIP retrofit panel (EIFS/VIP).

The third retrofit panel was identified as the expanded polystyrene/vacuum insulation panel retrofit panel (EPS/VIP RIP). This retrofit panel was constructed in an identical manner to the PIR/VIP RIP with the exception that EPS was substituted wherever PIR had been used in the initial panel. Three of these panels were constructed but were never tested for thermal performance as we did not have enough material to build a full four-panel assembly. Figures 19-23 depict various images of the test panels used for the guarded hot box testing.

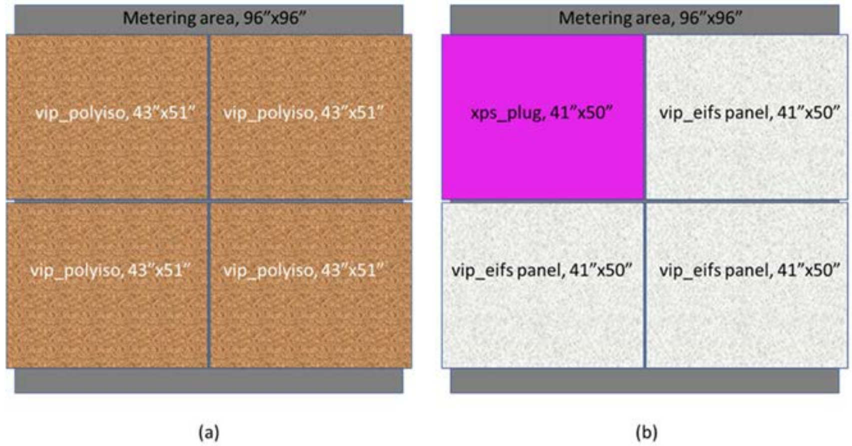


Figure 19: Test Set-Up with 4 Panels (PIR/VIP RIP) compared to 3 Panels (EIFS/VIP)

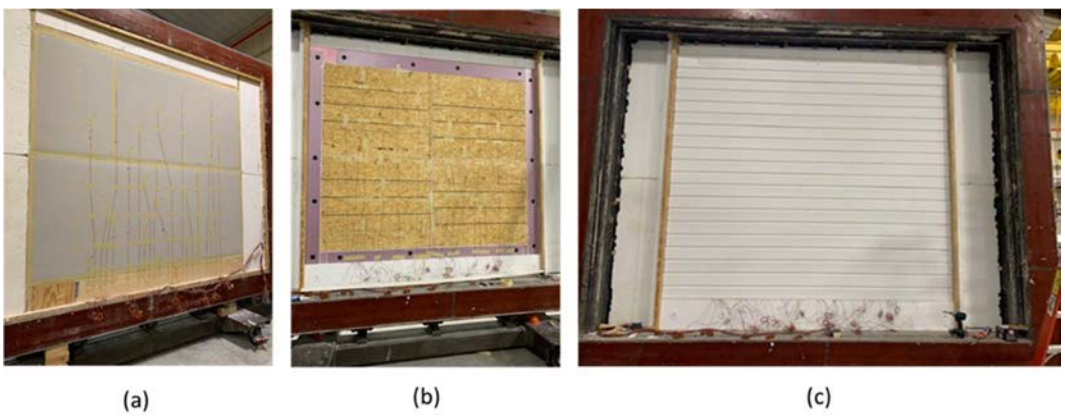


Figure 20: The figures show the construction of the panel used for the guarded hot box measurements. (a) is the interior wall section or the metering side. (b) is the construction of 4 VIP/PIR composite panels to form a complete wall section on the climate side. (c) is a finished wall with vinyl siding on the climate side.

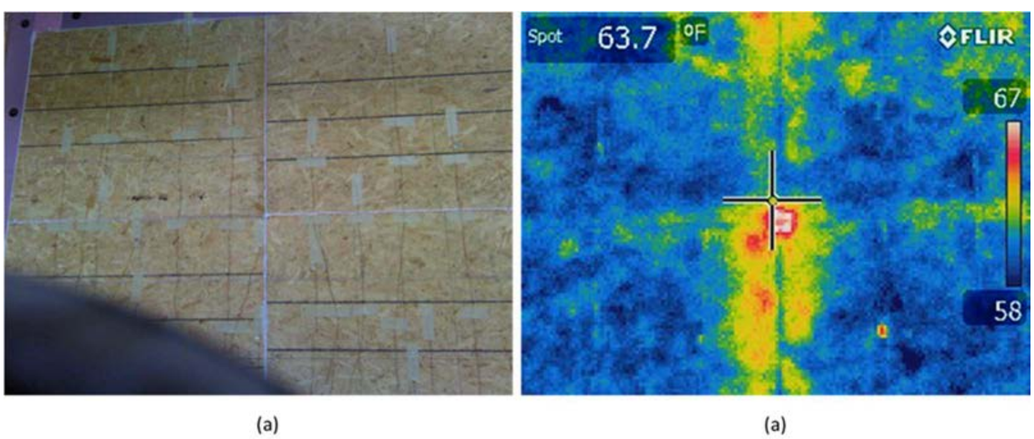
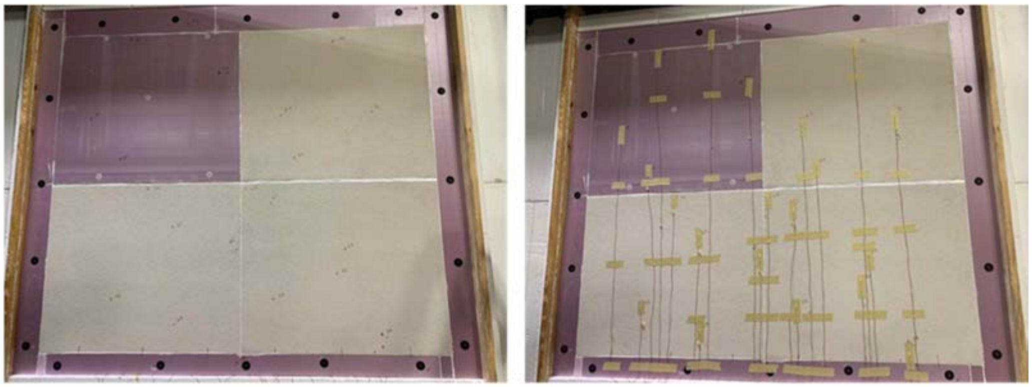


Figure 21: A thermal or infrared image of the VIP/PIR composite sample after the guarded hot box test. The vinyl siding was removed, and a thermal image was acquired showing the temperature distribution from the climate side. Higher temperatures were observed at the joints.



(a) (b)

Figure22: VIP/EIFs panel installed on the climate side of the guarded hot box. (b) shows placement of the thermocouple.

(a) (b) (c)

Figure 23: (a) Wall panel constructed of polyiso insulation board, (b) VIP/EIFS insulation board insert, (c) cutout of polyiso reinserted into original polyiso board.

The metering area of the guarded hot box is 8 feet by 8 feet in cross-section. Since the retrofit panels were too small to cover the entire metering area, the balance of the metering area was filled with XPS foam with a thickness matching that of the retrofit panels. Separate temperature sensors were installed on the XPS foam to monitor its temperature difference. ASTM C518 heat flow meter tests were performed on the different thicknesses of the XPS foam so that an energy correction could be applied to the measurement to account for the heat flow through that portion of the metering area not covered by the retrofit panels.

Three arrays of 20 thermocouples were placed on the exterior OSB surface, the interface between retrofit panel 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 the calculation of the temperature differences across the surfaces. With instrumentation installed at critical locations, the R-value of different portions of the test wall can be derived separately. Knowing the temperature differences across the entire assembly and the stud cavity (OSB/gypsum), their individual R-values can be calculated.

Prior to any testing on the retrofit panels, all the voltmeters, power transmitters, and precision resistors used in the guarded hot box were calibrated using ORNL's internal metrology capabilities. Testing was performed on an EPS standard reference wall that ORNL has maintained for the past 25 years. Periodically, this test wall is retested to verify the performance of the guarded hot box. Over the past 25 years, this wall assembly, which is comprised of 5 in. of expanded polystyrene foam faced with a protective PVC facer, has yielded thermal resistance values of R20.5 +/- R1. Our repeat test yielded results within the margin of error.

Obtain panel results of the magnitude shown in Table 15 implies that the performance of the VIPs in the prototype panels must be compromised. To verify this claim, we disassembled one of the PIR/VIP RIP panels to access the VIPs. Since the VIPs had been adhered to the PIR foam, we were unable to separate the VIP from all the panel components but were able to examine the VIP and perform heat flow meter apparatus test on the VIP adhered to the 0.5-in. PIR layer. This test yielded an R-value of approximately 45 hr ft^2F/Btu.

Table 15: Guarded hot box results for two VIP retrofit insulation panels.

Test	Temperature, °F					
	Climate Panel Surface	Climate XPS Panel	OSB Panel Surface	OSB XPS Panel	Meter Panel Surface	Meter XPS Panel
PIR/VIP RIP	51.8	51.9	92.1	95.7	98.9	98.1
EPS EIFS/VIP	50.7	51.3	89.5	91.9	97.8	98.3

Test	Area, ft^2		Energy Input, Btu/hr		Panel R-value, hr ft^2F/Btu	
	Meter	Panel	Wall	Panel	Wall	Panel
PIR/VIP RIP	64.0	57.0	142.9	125.3	21.1	18.3
EPS EIFS/VIP	64.0	41.0	184.6	119.8	16.4	13.3

This result and the visual inspection indicated that this VIP was intact. While the heat flow meter apparatus test was being performed, we retested the EPS standard reference wall and obtained results consistent with our earlier testing. At this juncture, we suspected that there was an issue with the first batch of VIP samples received from our partners. All tests on configurations without VIPs yield results that were within expectations.

A second possible explanation for the test results is that as the thermal performance of the test assembly increases, the overall energy input becomes much smaller. Uncertainties in the experimental results begin to become magnified. For example, if the apparatus has a systematic bias of 100 Btu/hr, this has a 10% impact on an experiment where you are metering 1,000 Btu/hr energy input, but has a 50% impact if your energy input is 200 Btu/hr.

We are left with an indeterminant test result using to ASTM C1363 (ASTM, 2019) because we did not have a full wall assembly, which could lead to added measurement uncertainty or perhaps the VIPs were potentially damaged, or both.

GHB Apparatus Validation

To validate the operation of the guarded hot box, a test wall comprised of three layers of polyisocyanurate foam (PIR) was fabricated from full-size 4 ft. x 8 ft. sheets of material. The joints of the boards were offset so that a solid section 10 ft. x 10 ft. square could be produced. Samples of each layer of the PIR 24 in. square were stacked together in a manner like the wall construction. This stack of PIR was measured in a heat flow meter apparatus in accordance with ASTM C518 at a mean temperature of 75°F and a temperature difference of 50°F. The measured R-value from the heat flow meter test was 19.5 hr ft2 F/Btu.

Three guarded hot box tests were performed. The first experiment was on the solid 3.5-in. PIR wall assembly. When this experiment was complete, an aperture approximately 36 x 60 in. cross-section was cut from the center of the PIR foam wall and an EPS/VIP RIP comprised of 0.5-in. OSB, 1-in. EPS, 1.2-in. VIPs inserted in an EPS frame, and a 0.5-in. EPS layer was inserted in the aperture. The perimeter edges were sealed with backer rod and tape. After completing this experiment, the RIP panel was removed and the PIR section cut from the PIR wall was reinserted, sealed in place, and retested. All three of these experiments were undertaken with the same boundary conditions. The results are summarized in Table 16.

Table 16: Guarded hot box experiments to validate its performance.

Test	**Temperature, °F**				**Area, ft^2**		**Energy Input**	**Panel R-value**
	Climate Surface	**Climate Panel**	**Meter Surface**	**Meter Panel**	**PIR**	**Panel**	**Btu/hr**	**hr ft^{2}F/Btu**
Solid 3.5-in. PIR	50.5	50.8	98.2	98.3	64.0	0	160.4	19.0
EPS/VIP RIP Panel in PIR	50.7	50.9	98.3	97.6	49.2	14.8	170.3	13.6
PIR Cutout in PIR	50.7	50.9	98.5	98.3	49.2	14.8	157.9	19.4

When the data on the solid PIR wall assembly is compared to the heat flow meter results, the data agrees to within 3%. The data on the RIP panel is significantly below expectations; our earlier analyses suggested that this panel should have an R-value of approximately R30. To obtain a thermal performance level as measured would require a failure of the VIPs or some significant thermal bridging due to the metallized barrier material. We theorized that there may be some impact of the perimeter due to a lower thermal performance or air leakage. We tested this hypothesis by retesting the PIR wall assembly by reinserting the PIR cut from the wall assembly to test the panel. We treated the perimeter in a manner identical to the EPS/VIP RIP. The results of this repeat experiment demonstrated that the perimeter loss was not the culprit; we were able to repeat our test result to within 2%. These experiments provided the evidence that the guarded hot box facility is performing well; therefore, the panels produced with the VIPs originally obtained from our partners appeared to have a performance issue.

Air Leakage and Water Penetration tests

Oak Ridge National Laboratory's Heat, Air, and Moisture chamber was used to test air leakage and water penetration across a retrofit installation made up of four panels covering a wall section that is 8 ft. x 8 ft. The HAM chamber as shown in Figure 25 consists of an interior and exterior chamber separated by a test panel. The temperature and relative humidity of each chamber can be controlled. Pressure gradients can be applied across the test panel to measure air leakage. The exterior chamber is configured to apply rain and solar loads. As a result, the HAM chamber has the capability of simulating most climates around the world. Table 19 lists the specifications of the HAM chamber. In addition to these capabilities, the interior and exterior climates together with data acquisition are computer-controlled via a custom program developed using National Instruments LabView suite.

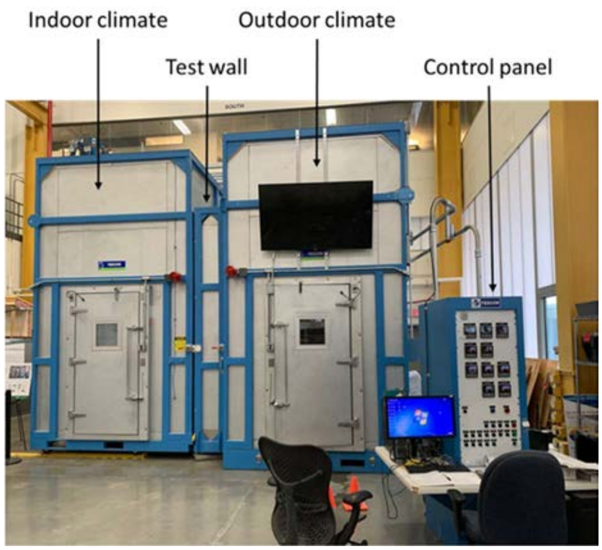


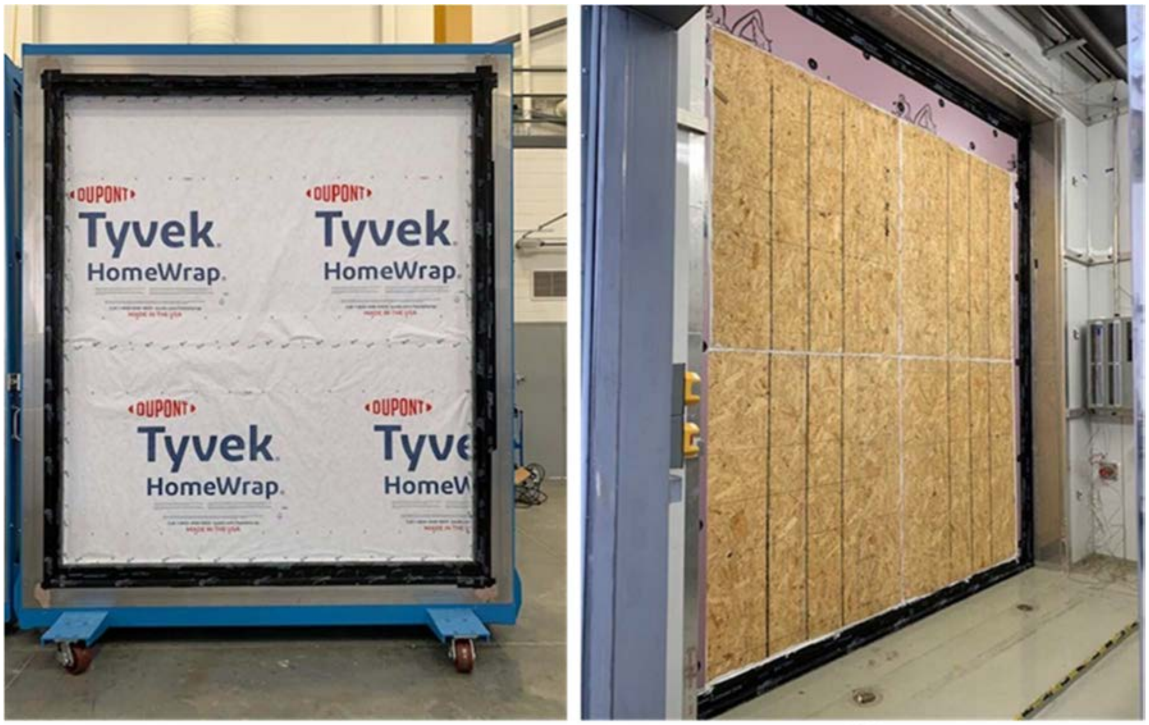
Figure 25: Heat, Air, and Moisture (HAM) chamber at ORNL. The chamber is comprised of two environmental compartments separated by a test frame that accommodates the wall assembly. The temperature and relative humidity can be controlled in both compartments.

Table 19: The specifications for Oak Ridge National Laboratories Heat, Air, and Moisture (HAM) Chamber.

	Interior chamber	**Exterior chamber**
Dry bulb temperature, °F	30 – 90	0 – 110 (ramp rate 1 – 1.5°/min)
Relative humidity, %	10 – 90	10 – 90
Dew point, °F	7 – 80	-5 – 90
Pressure (wrt to ambient), Pa	0 – 75 (sustained)	+/- 1200 (pulsed), 75 (sustained)
Precipitation	-	<= 1 ft^3/min
Precipitation temperature, °F	-	40 – 95
Solar insolation	-	<= 100 W/ft^2

ASTM E283 Test Method for Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors

To test the integrity of joints between retrofit panels, air leakage testing in accordance with ASTM E283, Standard Test Method for Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors, was carried out on an 8 ft. x 8 ft. wall construction as shown in Figure 26.



(a) (b)

Figure 26: (a) Shows the test frame removed from the chamber with the weather resistive barrier installed. The tape between the joints was removed for the test. (b) shows the retrofit insulated panels, 4 installed, over the weather resistive barrier with all the joints sealed with acrylic latex caulk including the perimeter of the assembly.

At first, a measurement was carried out on a base wall constructed with ¼-in. joints or gaps created between sheathing. One horizontal and two vertical joints were created. The exterior sheathing was then covered with a weather resistive barrier (WRB) and the lap between sheets of WRB were not taped. The flow rate across the test assembly was measured as a function of the applied pressure difference up to a pressure difference of 400 Pa. The test was repeated with four retrofit panels installed over the WRB. Four RIP panels were used to complete the assembly. Two were made using VIPs encapsulated in expanded polystyrene foam; the other two had VIPs encapsulated in polyisocyanurate foam. The joints were sealed with acrylic latex caulk. The air leakage test was repeated and the flow rate across the assembly, the volumetric flow rate in cubic feet per minute (CFM), was measured up to a pressure difference of 300 Pa. Figure 27 compares the measurements for the two assemblies. For residential constructions, the air leakage is measured at a pressure difference of 75 Pa. In this case, the flow rate for the retrofit panels at 75 Pa could not be measured. Measurements were compared at a pressure difference of 150 Pa. The base assembly had an air leakage rate of 6 CFM. After the retrofit panels were installed over the WRB, the air leakage rate was reduced to just over 1 CFM.

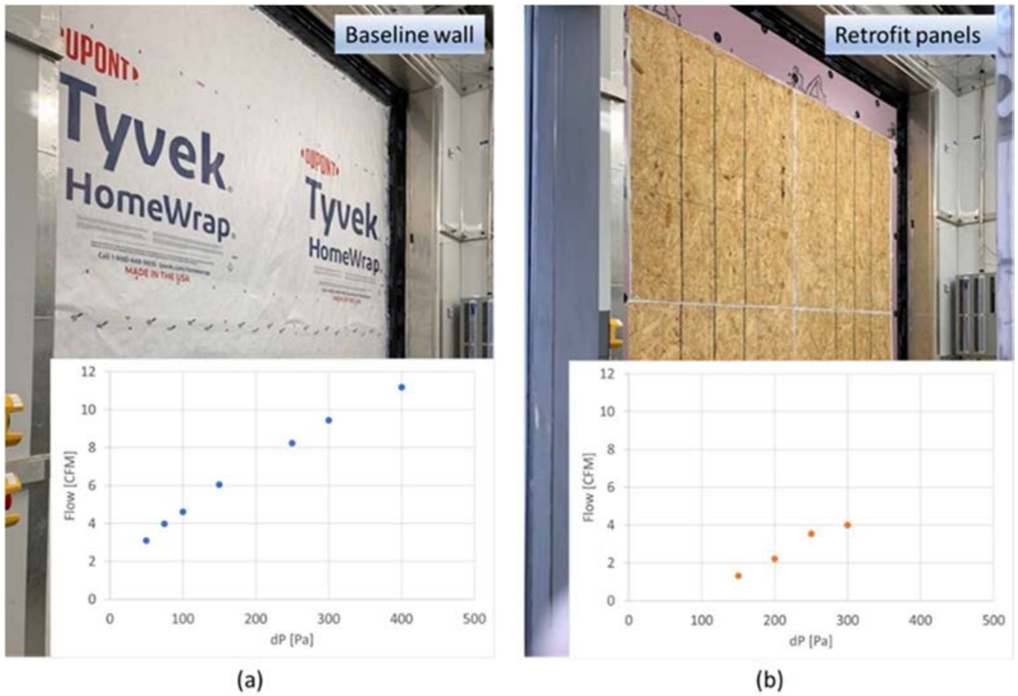


Figure27: Air leakage test of wall assembly using HAM chamber and ASTM E236. (a) is the baseline wall assembly. (b) is the retrofit wall showing significant reduction in air leakage. At 75 Pa, the flow rate could not be measured for the retrofit wall assembly. The flow rate was reduced by more than a factor of three at 200 Pa.

ASTM E331 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference.

The resistance to water penetration was measured in accordance with ASTM E331, Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference. In this case, vinyl siding was applied over the assembly as shown in Figure 28. In accordance with the standard, a differential pressure of 137 Pa was applied and after 15 minutes of water being sprayed onto the surface, there was no water detected on the interior side of the assembly.

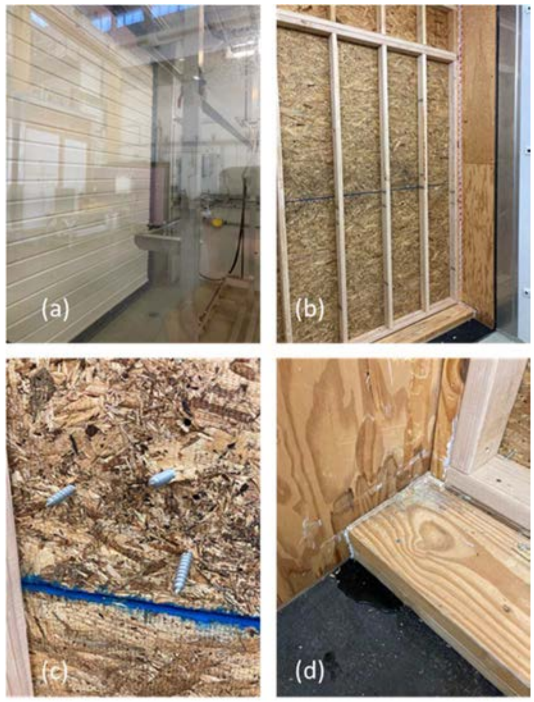


Figure 28: Results from water penetration test. (a) rain load being applied to the exterior cladding of the wall assembly. (b) is the interior of the wall assembly, no water penetration observed. (c) air leakage detected at fasteners. (d) water passing underneath the frame of the test panel. The water was not caused by passage of water behind the retrofit panels.

Hygrothermal Modeling of the Retrofit Assembly

Hygrothermal modeling is used to evaluate the condensation potential, moisture content, drying capacity of the assembly, potential for mold growth, and freeze-thaw damage. During the last two decades, several computer simulation tools have been developed to predict thermal and moisture conditions in buildings and the building envelope. In addition to their use as forensic tools in the investigation of building failures, these computer models are increasingly used to make recommendations for building design in various climates.

WUFI® is one of the commonly used researchers in the building industry. WUFI is an acronym for Wärme Und Feuchte Instationär which, translated, means heat and moisture transiency. The WUFI model is based on a state-of-the-art understanding of the physics regarding sorption and suction isotherms, vapor diffusion, liquid transport, and phase changes. The model is well documented and has been validated by many comparisons between calculated and field performance data.

The purpose of performing the hygrothermal modeling is to verify that the proposed energy-efficiency retrofit measures do not create a durability issue. The use of transient hygrothermal models for moisture control is well established in the building industry in its codes, standards, and building insulation design principles. Building envelopes are designed to naturally shed liquid water and attempt to minimize its entry. Building envelopes should also be constructed to facilitate vapor transport so that moisture doesn't accumulate within the building envelope and lead to moisture accumulation and its subsequent failure mechanisms.

Hygrothermal simulations were carried out using WUFI Pro (Version 6.4). Two types of hygrothermal modeling were undertaken for this project. First, the modeling was performed in the climate zone where the retrofit will take place. Once this was completed, the model was employed to generalize the findings for other climate zones.

A site visit was undertaken to assess the existing construction of the wall assemblies. In the candidate multifamily complex, Nutgrove Garden Apartments[14], we were allowed to create a small hole and examine the interior of the wall assembly. Though not foolproof, this examination allowed us to identify most of the components of the existing wall assembly. The existing assembly was comprised, from the interior outward, of painted 0.5-in. gypsum board, an uninsulated 3.5-in. wood frame cavity, 0.5-in. plywood, 1.75-in. foil-faced polyisocyanurate foam, and off-white vinyl siding.

We were not allowed the luxury of penetrating into the wall assembly at the second candidate multifamily complex, Creighton Storey Homes[15]. Instead, we noted that the interior walls were finished with paints and the exterior cladding was a white wood plank board. Since these units were built in the 1980s, we will assume that existing assembly is comprised, from the interior outwards, of painted 0.5-in. gypsum board, an uninsulated 3.5-in. wood frame cavity, 0.5-in. plywood, building paper, and white wood plank siding.

To model the retrofit, we will assume that the existing claddings will be removed. The retrofit EPS/VIP RIP is made up of, from the interior side outward, 0.5-in. EPS foam, 1.2-in. VIPs in an EPS picture frame covering 90% of the surface area, 1-in. EPS foam, and a 0.5-in. OSB. To finish the wall assembly retrofit, a spun-bonded polyolefin air and water resistive barrier and white vinyl siding will be added to the wall assembly. Descriptions of the wall assemblies modeled for Nutgrove and Creighton Storey Apartments are shown in Figures 29 and 30, respectively. All the simulations followed the recommendations of ASHRAE Standard 160. Interior conditions were computed based on EN 15026, "Hygrothermal Performance of Building Components and Building Elements - Assessment of Moisture Transfer by Numerical Simulation." No water leakage was included in any of the simulations.

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[14] Nutgrove Garden Apartments is a multifamily residential apartment complex in Albany, NY. We visited the property to determine if it could be a good candidate for the field study in Phase 2 of the Retrofit Project.

[15] Creighton Storey Homes is a multifamily residential apartment complex in Albany, NY. We visited the property to determine if it could be a good candidate for the field study in Phase 2 of the Retrofit Project.

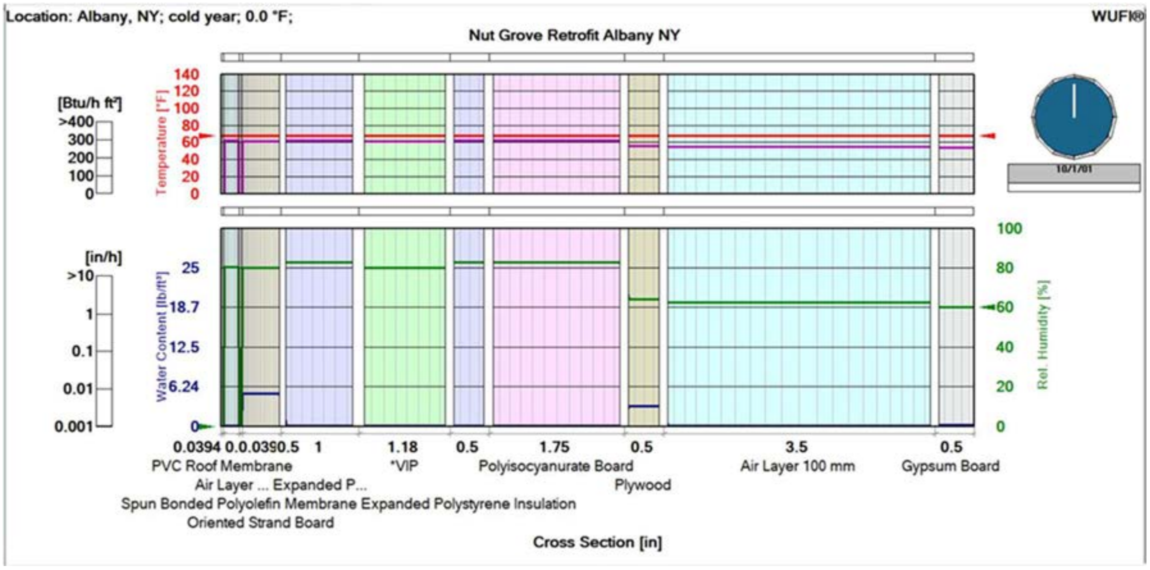

Figure 29: Retrofit wall component assembly schematic for Nut Grove Apartments hygrothermal model input file

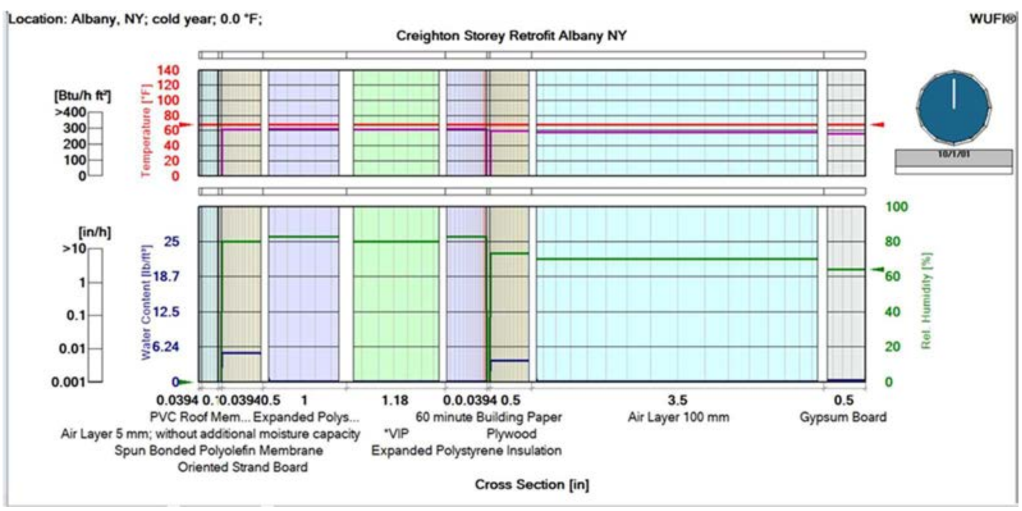

Figure 30: Retrofit wall component assembly schematic for Creighton Storey Homes hygrothermal model input file

After completing the modeling exercise for Albany, N.Y., hygrothermal simulations of all wall assemblies were carried out in the eight DOE Climate Zones to understand the impact of the retrofit systems on moisture performance/durability. The selected cities were Fairbanks, Alaska (subarctic); Duluth, Minn. (very cold); Minneapolis, Minn. (cool humid); Chicago, Ill. (cold); Baltimore, Md. (mixed humid); Atlanta, Ga. (warm humid); Houston, Texas (hot humid); and Miami, Fl. (very hot).

Simulations were carried out for prevalent driving rain direction in accordance with standard ANSI/ASRHAE 160-2016, Criteria for Moisture-Control Design Analysis in Buildings (ASHRAE, 2106). The initial moisture content for each component in the assemblies prior to the retrofit was established by simulating the existing base case wall. Simulation of the base case was run for three years and the moisture content in the base case wall after the three-year simulation was used as the initial moisture content for the same elements in the retrofit construction. The equilibrium moisture content at 80% relative humidity (EMC80) was used for the new retrofit elements. These data, along with the moisture contents of each component after retrofit and three years of performance, are shown in Tables 20 and 21.

Table 20A: Component moisture contents for the pre- and post-retrofit wall assemblies - Nut Grove Apartments

Nut Grove Apartments						
		Moisture content after 3 years, lbs/ft^3				
Condition	Layer	Albany NY	Miami FL	Houston TX	Atlanta GA	Baltimore MD
Pre-retrofit	Vinyl cladding	0.0	0.0	0.0	0.0	0.0
Pre-retrofit	Airspace	0.1	0.1	0.1	0.1	0.1
Pre-retrofit	PIR	0.1	0.1	0.1	0.1	0.1
Pre-retrofit	Plywood	3.1	3.4	3.6	3.2	3.1
Pre-retrofit	Airspace	0.1	0.1	0.1	0.1	0.1
Pre-retrofit	Gypsum board	0.2	0.3	0.3	0.3	0.3
Post-retrofit	Vinyl cladding	0.0	0.0	0.0	0.0	0.0
Post-retrofit	Airspace	0.1	0.1	0.1	0.1	0.1
Post-retrofit	SBP WRB	0.0	0.0	0.0	0.0	0.0
Post-retrofit	OSB	4.3	3.9	4.2	3.7	4.2
Post-retrofit	1-inch EPS	0.0	0.0	0.0	0.0	0.0
Post-retrofit	VIP	0.1	0.1	0.1	0.1	0.1
Post-retrofit	0.5-inch EPS	0.0	0.0	0.0	0.0	0.0
Post-retrofit	PIR	0.1	0.1	0.1	0.1	0.1
Post-retrofit	Plywood	2.9	3.3	3.3	3.2	3.0
Post-retrofit	Airspace	0.0	0.1	0.1	0.1	0.1
Post-retrofit	Gypsum board	0.2	0.3	0.3	0.3	0.2

Table 20B: Component moisture contents for the pre- and post-retrofit wall assemblies Nut Grove Apartments

Nut Grove Apartments					
		Moisture content after 3 years, lbs/ft3			
Condition	Layer	Chicago IL	Minneapolis MN	Duluth MN	Fairbanks AK
Pre-retrofit	Vinyl cladding	0.0	0.0	0.0	0.0
Pre-retrofit	Airspace	0.1	0.1	0.1	0.1
Pre-retrofit	PIR	0.1	0.1	0.1	0.1
Pre-retrofit	Plywood	3.2	2.8	2.8	2.6
Pre-retrofit	Airspace	0.1	0.0	0.0	0.0
Pre-retrofit	Gypsum board	0.3	0.2	0.2	0.2
Post-retrofit	Vinyl cladding	0.0	0.0	0.0	0.0
Post-retrofit	Airspace	0.1	0.1	0.1	0.1
Post-retrofit	SBP WRB	0.0	0.0	0.0	0.0
Post-retrofit	OSB	4.1	3.8	4.1	5.2
Post-retrofit	1-inch EPS	0.0	0.0	0.0	0.0
Post-retrofit	VIP	0.1	0.1	0.1	0.1
Post-retrofit	0.5-inch EPS	0.0	0.0	0.0	0.0
Post-retrofit	PIR	0.1	0.1	0.1	0.0
Post-retrofit	Plywood	3.1	2.8	2.8	2.5
Post-retrofit	Airspace	0.1	0.0	0.0	0.0
Post-retrofit	Gypsum board	0.2	0.2	0.2	0.2

Table 21A: Component moisture contents for the pre- and post-retrofit wall assemblies - Creighton Storey Homes

Creighton Storey Apartments						
		Moisture content after 3 years, lbs/ft^3				
Condition	**Layer**	**Albany NY**	**Miami FL**	**Houston TX**	**Atlanta GA**	**Baltimore MD**
Pre-retrofit	Wood cladding	3.9	5.0	3.8	3.8	3.7
Pre-retrofit	Airspace	0.0	0.0	0.0	0.0	0.0
Pre-retrofit	Building paper	0.0	0.0	0.0	0.0	0.0
Pre-retrofit	Plywood	3.8	3.9	4.2	3.8	3.8
Pre-retrofit	Airspace	0.1	0.1	0.1	0.1	0.1
Pre-retrofit	Gypsum board	0.3	0.3	0.3	0.3	0.3
Post-retrofit	Vinyl cladding	0.0	0.0	0.0	0.0	0.0
Post-retrofit	Airspace	0.0	0.0	0.0	0.0	0.0
Post-retrofit	SBP WRB	0.0	0.0	0.0	0.0	0.0
Post-retrofit	OSB	4.2	3.9	4.2	3.7	4.2
Post-retrofit	1-inch EPS	0.0	0.0	0.0	0.0	0.0
Post-retrofit	VIP	0.1	0.1	0.1	0.1	0.1
Post-retrofit	0.5-inch EPS	0.0	0.0	0.0	0.0	0.0
Post-retrofit	Building paper	0.0	0.0	0.0	0.0	0.0
Post-retrofit	Plywood	2.9	3.2	3.2	3.2	3.1
Post-retrofit	Airspace	0.0	0.1	0.1	0.1	0.1
Post-retrofit	Gypsum board	0.2	0.3	0.3	0.3	0.4

Table 21B: Component moisture contents for the pre- and post-retrofit wall assemblies - Creighton Storey Homes

Creighton Storey Apartments					
		Moisture content after 3 years, lbs/ft3			
Condition	**Layer**	**Chicago IL**	**Minneapolis MN**	**Duluth MN**	**Fairbanks AK**
Pre-retrofit	Wood cladding	3.5	4.8	3.6	2.8
Pre-retrofit	Airspace	0.0	0.0	0.0	0.0
Pre-retrofit	Building paper	0.0	0.0	0.0	0.0
Pre-retrofit	Plywood	3.8	3.5	3.7	3.4
Pre-retrofit	Airspace	0.1	0.1	0.1	0.1
Pre-retrofit	Gypsum board	0.3	0.2	0.2	0.2
Post-retrofit	Vinyl cladding	0.0	0.0	0.0	0.0
Post-retrofit	Airspace	0.0	0.0	0.0	0.0
Post-retrofit	SBP WRB	0.0	0.0	0.0	0.0
Post-retrofit	OSB	4.1	3.8	4.0	3.7
Post-retrofit	1-inch EPS	0.1	0.0	0.0	0.1
Post-retrofit	VIP	0.1	0.0	0.1	0.1
Post-retrofit	0.5-inch EPS	0.0	0.0	0.0	0.0
Post-retrofit	Building paper	0.0	0.0	0.0	0.0
Post-retrofit	Plywood	2.8	2.8	2.9	2.7
Post-retrofit	Airspace	0.0	0.0	0.0	0.0
Post-retrofit	Gypsum board	0.3	0.2	0.2	0.2

The mold index calculated in accordance with ASHRAE 160 was used as an indicator of moisture durability. ASHRAE 160 uses the model developed by Vitanen and Ojanen of VTT Technical Research Centre of Finland (Vitanen, 2007) to calculate a mold index for materials that make up the building envelope. The calculation is based on experimental studies of typical building materials. According to ASHRAE 160: "In order to minimize problems associated with mold growth on the surfaces of components of building envelope assemblies, the mold index shall not exceed a value of three (3.00).” The calculation was carried out for all the wall assemblies in all Climate Zones and a matrix was developed using the classification illustrated in Figure 6. The mold index takes on a value between 1 and 6. In this classification scheme colors are assigned to different ranges. If the mold index is 2 or less, the assembly is given a value of green. If the value is less than 3 or greater than 2, the assembly is assigned the color yellow. Any value greater than 3 is assigned the color red. Mold indices were calculated on each surface of the moisture-susceptible layers within each wall assembly. Plywood, OSB, and gypsum were assumed to fall into this category. An example of this calculation is shown in Figure 31. This data is for the retrofitted wall for the Creighton Storey Apartments. The different color lines in Figure 31 represent the six different surfaces that were being modeled. The maximum mold growth index for any of the modeled surfaces is less than 0.1 over the entire three-year simulation.

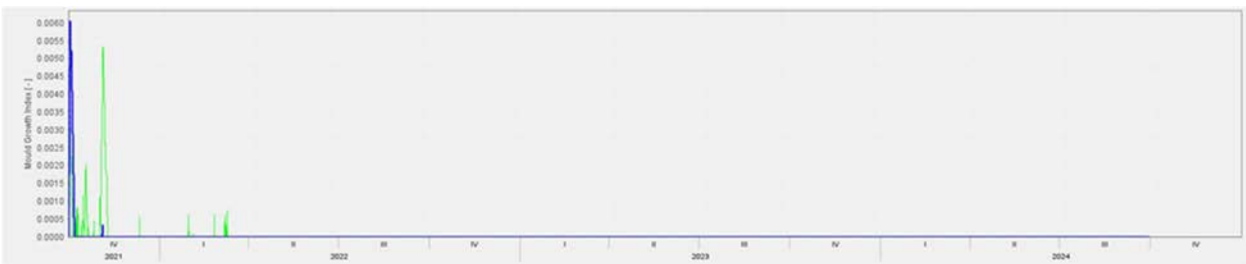

Figure 31: Mold growth index as a function of time for the retrofitted wall assembly for Creighton Storey Homes

The mold index is calculated on all surfaces that are deemed moisture susceptible. The surfaces that are characterized in this manner include the plywood, OSB, and gypsum components and each surface of these components were analyzed.

The surface with the highest value was then used as the representative value for the wall assembly and a color was assigned accordingly. All four wall assemblies (pre- and post-retrofit walls from the two apartment complexes) were modeled in Albany, N.Y., and in a representative city from the DOE Climate Zone map. The maximum mold index computed for all these 360 simulations (4 walls x 9 Climate Zones x 10 locations) was 1.0. Based on the criteria used to assess the mold growth index data, all the modeled wall systems should be moisture durable. These results are consistent with good building science practice. The addition of significant amounts of R-value as continuous insulation isolates the bulk of the moisture sensitive materials and maintains their temperature and absolute humidity conditions to match that of the building interior. Those conditions protect the wood and gypsum layers from moisture accumulation.

Panel Design, Installation Mock-Up, and Quality Assurance

As we considered the physical test results and the prototypes that were fabricated based on the available VIPs and the designs illustrated in Figure 8, the team met with the SIPA and decided to develop a system of V-RIP panels that would meet the requirements to the *Retrofit Insulated Wall & Roof Panel Installation Guide*. As a result, we designed six basic panel types that would be prefabricated in a manufacturer’s plant (i.e., any SIP or RIP panel manufacturer). These panels, illustrated in Figure 32, include a spline feature [green] for connecting the panels, rather than butt-joints like the earlier prototypes. We also include a nailing feature [blue], and the panels are designed to use all of the standard nail-based panel tools and accessories.

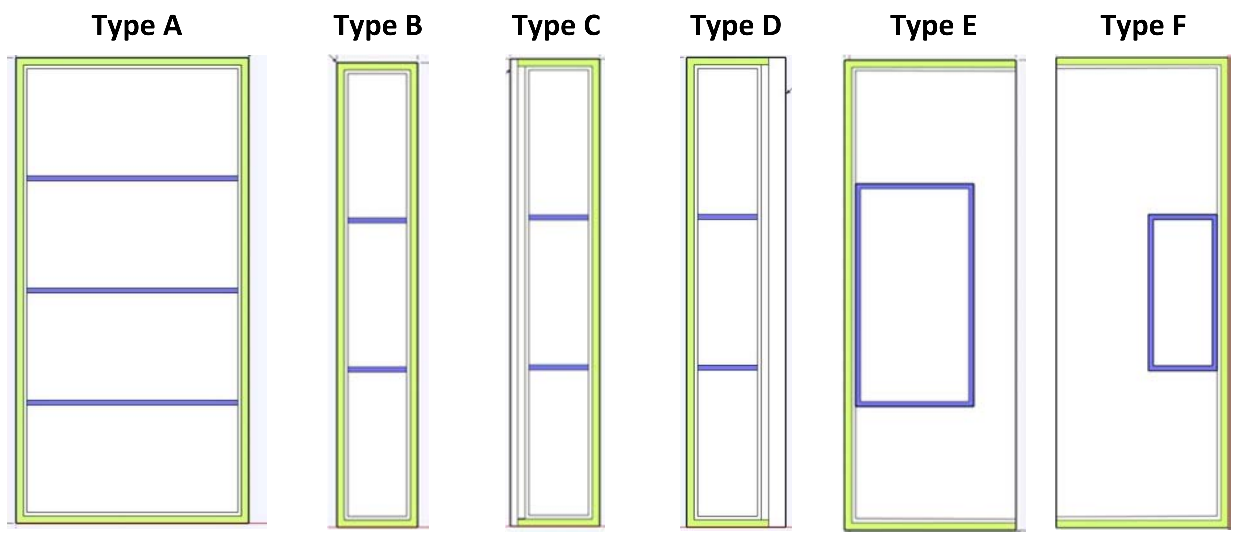

Figure 32: Six Basic V-RIP Panels - Types (A, B, C, D, E, & F) for Wall Layout

Each specific panel type has a specific function based on how it should be installed. The Type A and Type B panels are designed to cover "opaque" clear wall surface, while the Type C and Type D panels are designed to cover corners (they are left and right parts that create a corner). The Type E and Type F panel is a "Filler Panel" that is designed to fill irregular wall surface areas – especially around windows, doors, and other wall features (vents, lights, fixtures, etc.) that are not clear wall surface. The six panels are designed to cover an entire wall.

The challenge for the retrofit wall designer is to maximize the surface area using Type A, B, C, and D panels, while minimizing the foam filler area with Type E and F panels, because using too much "EPS foam filler" material will reduce the effective R-value for the entire wall section. The ideal coverage with the R-VIP would be equal to an R-value of 47. This is based on ASTM C518 testing of Optimum-R at Home Innovation's lab, where the VIPs were provided by Kingspan, and we added 1 in. of EPS foam on the top and bottom of the VIP to increase the R-value from 37 to 47.

If the wall surface has too many irregular areas, resulting in too much EPS foam filler being used, it will not be cost effective to use the V-RIP system. We will develop an effective R-value curve using the actual full-size V-RIP product in various configurations, such that designers can identify the minimum wall surface area that needs to be covered.

Home Innovation completed a full-scale mock-up installation using the six basic V-RIP panel designs in Figure 32. Our 2-story test house was prepared with structural blocking such that the 3.5-in. panels could be installed on the 2x4 framing edge, shown in Figure 33, to ensure better product alignment when installed. Then the panels were installed, joined with splines, and anchored along the blue anchor tape (shown in Figure 34).

Figure 33: Building Preparation

Figure 34: Installation of Mock-Up Panels

The V-RIPs were installed using each panel type and, as part of our Quality Assurance procedure, we inspected every screw joint and nail spline location to ensure there were no nail or screw penetrations into the area of the panel where the VIP would be in an actual panel. The construction crew used the nailing locators to pre-drill the panels on the ground, then they installed each panel in place, according to the design layout. The completed house design is shown in Figure 35.

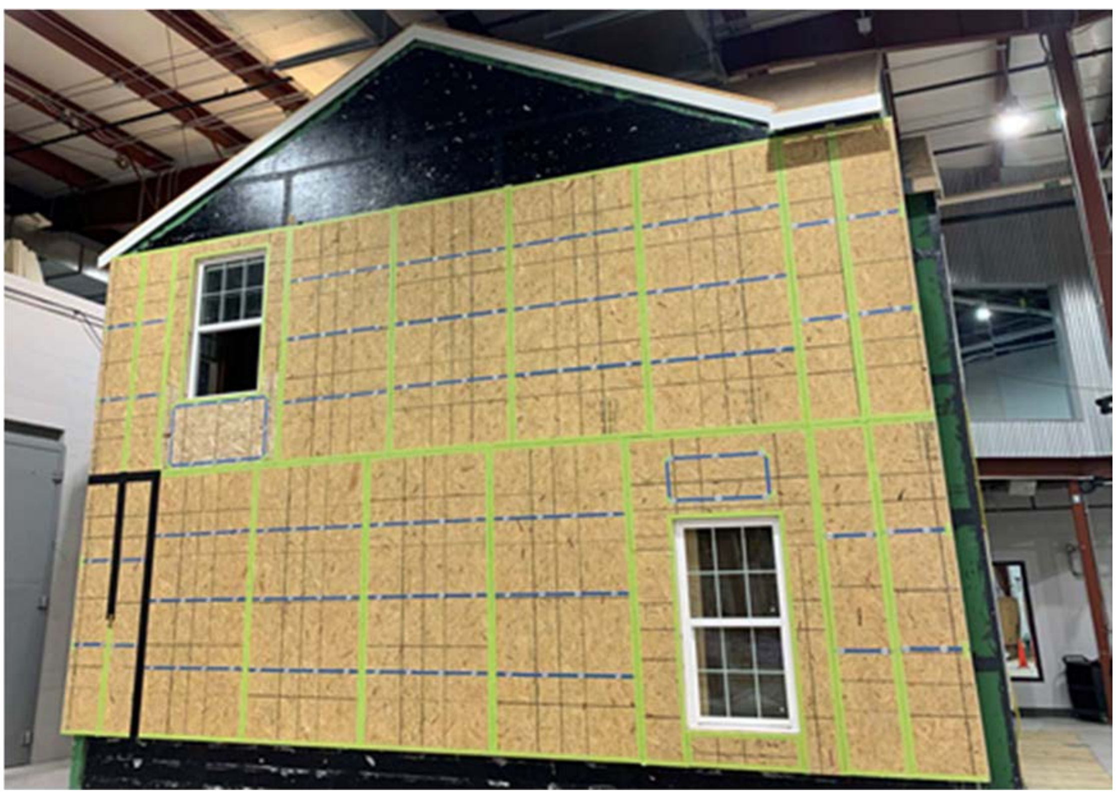

Figure 35: Completed installation of Mock-Up Panels on Test House

Home Innovation's research engineering staff inspected each panel to determine if either the nail or screw locations missed their intended spot. After installing more than 840 fasteners, we determined that all screws were on the blue tape locator, which ensures a good anchor location, and only one of the nailing spline locations missed the mark. Fortunately, the problematic nail did not puncture the VIP location. Note that because the spline area is 2 in. wide, the nails are staggered after the splines are joined together and the groove is sealed with mastic or another EPS-compatible adhesive.

The mock-up installation allowed Home Innovation to receive constructability feedback from an actual framing subcontractor – including comments about the building wall preparation, the ease of handling the panels, pre-drilling on the ground, installing mastic, the spline, and joining the product.

Quality Assurance Procedures

Vacuum Insulated Panels offer superior thermal insulating performance, but the product must be handled with care, protected, and installed without being damaged. Since we plan to source Kingspan's Optimum-R VIP product for the Phase 2 field study, we have already incorporated some of their Quality Assurance procedures into our fabrication, assembly, and installation process.

Step #1 – Product is shipped from Kingspan to the manufacturer of the V-RIP Panel product. The VIP should remain packaged until it is ready to be assembled into the EPS (or other foam material matrix). Kingspan will assist the manufacturer with setting up the QA program as it relates to protecting Optimum-R and confirming that the product has arrived in excellent condition.

Step #2 – Visual inspection upon opening the box that contains VIPs. Figure 36 includes a visual key that illustrates acceptable surfaces that show the VIP is still under vacuum and in good condition. Notice, the image with the red "X" next to it is considered unacceptable; when the vacuum fails, the surface becomes smooth and less "shrink-wrapped" in appearance.

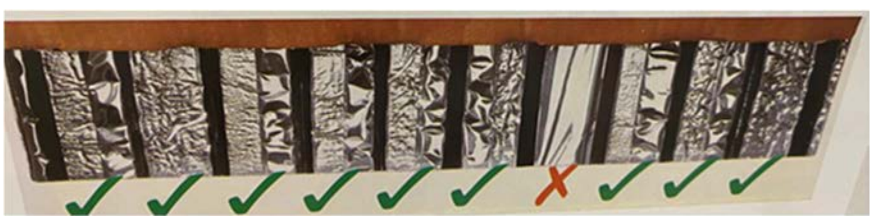

Figure 36: Visual inspection is key to identifying compromised or damaged VIPs

Step #3 – When placing the VIP into the EPS foam tray, handle with care and continue to conduct a visual inspection as well as a physical inspection of the VIP. The product should be rigid when taking it from the box and inserting it into place. Figure 37 illustrates the assembly process.

Figure 37: Visual and physical inspection should be done before the embedding into foam

Step #4 – When installing the product, take care when screwing the product to the wall and nailing the splines to connect the panels.

Step #5 – The final QA step is a thermal imaging check of the installation. In Figure 38, we have installed four VIPs on our outdoor Test Hut.

The V-RIP prototypes were installed without splines and the butt-joints were not sealed. As a result, the heat can be seen between the panels in Figure 39, as well as around the outer perimeter of the VIPs. The VIPs in Figure 39 are intact and the thermal imaging is essentially the same for each VIP. Thermal heat loss between the panels can be greatly reduced by incorporating the features illustrated in the panel design in Figure 32.

Figure 38: Thermal imaging should be the final quality inspection of the installation

Weeks later, we intentionally punctured the VIPs in the lower right-hand corner, as shown in Figure 40. Notice the difference between the intact VIP areas that show blue, while the damaged VIP is greenish-yellow.

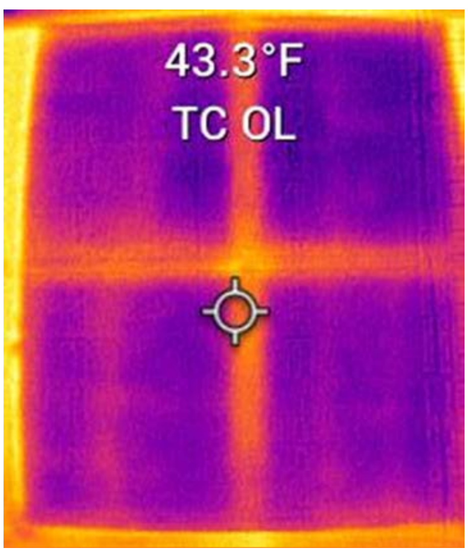

Figure 39: Thermal Image No Puncture

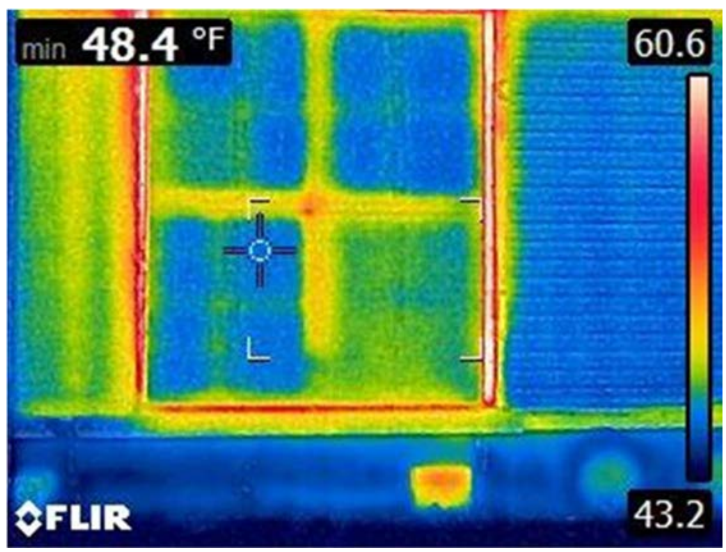

Figure 40: Thermal image with punctured panel lower right

Energy Modeling and Cost Analysis

We are confident that the V-RIP product can be a major component in the overall improvement of existing building envelope performance, comprising approximately 45 - 50% of the overall energy improvement, with the V-RIP product accounting for approximately 20 - 25% of that improvement.

For Phase 2 of this research, we intend to upgrade existing buildings in New York State. We have identified and conducted a preliminary survey of two properties in Albany, N.Y. (Nutgrove Garden Apartments and Creighton Storey Homes); and we have used the *NYSERDA RetrofitNY Market Characterization Study: Building Stock Assessment and Architectural Profiles of Predominant New York State Multifamily Building Types* report to estimate conditions of the building details that are unknown. Using this information, we have created energy models and projected energy savings in Table 22. Given the uncertainty of some details about the buildings, we have developed multiple baselines to consider, and we will select the appropriate baseline based on the condition we confirm. In addition, we have estimated the cost of the V-RIP panel along with the overall cost of the whole building retrofit improvements to achieve a 75% reduction in EUI.

Table 22: Energy Modeling and Cost Savings Results for Creighton Storey Homes and Nutgrove Garden Apartments

	Site Energy: HVAC & Hot Water			Energy Cost
Creighton Storey Homes Configuration	**MMBtu/yr**	**% saving**	**kBtu/sf**	**$/yr**
Baseline 1: R-7 walls, R-7 ceiling, R-0 slab, U-0.65 windows, 12 ach50; 90.5 AFUE gas boiler, 8.5 EER through wall AC, 0.51 EF gas water heater	1014.6		67.5	$27,396
Upgrade 1: R-40 VIP walls, 9 ach50	771.4	24.0%	51.3	$24,423
Upgrade 2: Upgrade 1 + R-60 ceiling, U-0.25 windows, 3 ach50	413.0	59.3%	27.5	$19,611
Upgrade 3: Upgrade 2 + 95 AFUE, 15 CEER, 0.95 UEF WH, 0.65 SRE HRV	330.3	67.4%	22.0	$16,976
Baseline 2: Baseline 1 except 60 AFUE gas boiler	1343.9		89.4	$31,540
Upgrade 1: same as above	998.6	25.7%	66.4	$27,281
Upgrade 2: same as above	494.0	63.2%	32.9	$20,630
Upgrade 3: same as above	330.3	75.4%	22.0	$16,976
Baseline 3: Baseline 2 except R-0 walls	1731.4		115.2	$36,329
Upgrade 1: same as above	1039.1	40.0%	69.1	$27,763
Upgrade 2: same as above	532.0	69.3%	35.4	$21,073
Upgrade 3: same as above	354.2	79.5%	23.6	$17,258
Nutgrove Garden Apartments Configuration	**MMBtu/yr**	**% saving**	**kBtu/sf**	**$/yr**
Baseline 1: R-11 walls, R-19 ceiling, R-0 slab, U-0.50 windows, 10 ach50; 80 AFUE gas furnaces, 10 SEER AC, 0.56 EF gas water heaters	960.1		60.2	$28,330
Upgrade 1: R-40 VIP walls, 8 ach50	760.6	20.8%	47.7	$25,776
Upgrade 2: Upgrade 1 + R-60 ceiling, U-0.25 windows, 3 ach50	479.9	50.0%	30.1	$22,262
Upgrade 3: Upgrade 2 + 95 AFUE, 16 SEER, 0.93 UEF WH, 0.65 SRE HRV	323.7	66.3%	20.3	$18,342
Baseline 2: Baseline 1 except R-7 walls, R-13 ceiling, U-0.65, 12 ach50	1130.5		70.8	$30,984
Upgrade 1: R-40 VIP walls, 9 ach50	868.8	23.1%	54.4	$27,628
Upgrade 2: same as above	490.3	56.6%	30.7	$22,388
Upgrade 3: same as above	330.2	70.8%	20.7	$18,418
Baseline 3: Baseline 2 except R-0 walls, U-0.98 windows	1526.3		95.6	$36,274
Upgrade 1: R-40 VIP walls, 9 ach50	981.7	35.7%	61.5	$29,274
Upgrade 2: same as above	507	66.8%	31.8	$22,591
Upgrade 3: same as above	348.1	77.2%	21.8	$18,640

RESULTS

Depending on the Baseline Energy Models in Tables 22, both properties have the potential to reach and, in some cases, exceed the target 75% EUI reduction. Our preliminary audit identified some discrepancies between what is on historical engineering documents and what is actually in the apartment buildings. Both Creighton Storey Homes and Nutgrove Garden Apartments have multiple buildings and there is some difference between the buildings. One major uncertainty and driver for energy efficiency is the ACH50 (air leakage) within the multifamily buildings, based on the age and condition of the buildings, we suspect the ACH will be in the range of 12-14 (especially at Creighton Storey Homes where all of the units have thru-the-wall air conditioning units). If our Phase 2 proposal is selected, we will conduct air blower door tests to identify the ACH of the buildings. We expect those buildings at Creighton Storey Homes to be very leaky – many of the characteristics match the descriptions in the *NYSERDA RetrofitNY Market Characterization Study*.

Table 23: Overall Cost Projects to achieve the target 75% Reduction in EUI

Estimated Cost of Construction: Rollup Table with Summary of Cost Details Provided in Tables Below, $/building					
Component			**Creighton**		**Nutgrove**
VIP walls			$161,859		$155,892
VIP roofs (Creighton only)			$158,590		na
Ceiling insulation (Nutgrove) & air sealing (both)			$9,803		$39,066
Windows			$90,237		$122,946
Siding (fiber cement at Creighton; vinyl at Nutgrove)			$82,515		$57,168
Heating			$47,403		$119,922
Cooling			$33,891		$115,265
Water heating			$22,213		$86,237
Mechanical Ventilation			$41,301		$49,562
Total per Building			**$647,812**		**$746,059**

Table 23 illustrates that the estimated cost of for Nutgrove is more than Creighton, but note that buildings at Creighton needs new roofs, so there is an opportunity to improve the energy performance of the entire building envelope with VIPs. On the other hand, Nutgrove had all new roofs installed in 2018.

Table 24: Economy of Scale - Unit Cost with Multifamily Buildings

Building	**$ Cost for Retrofit**	**No. of Units**	**$ Cost per Unit**
Creighton Storey Homes	$ 647,812.00	15	$ 43,187.47
Nutgrove Garden Apartments	$ 746,059.00	18	$ 41,447.72
Creighton Storey Homes w/o Roof	$ 489,222.00	15	$ 32,614.80

Consider Table 24, if we only focused on improving the walls with VIPs, the cost per unit decreases; and it is within the range of the $40K incentive for the RetrofitNY Gap Funding Program[16]. The question then becomes can the roof be improved without the VIP retrofit – it will be challenging because the roof designs at Creighton have a very low pitch – there may not be enough space to achieve R-60 insulation in the conventional way.

[16] https://portal.nyserda.ny.gov/CORE_Solicitation_Detail_Page?SolicitationId=a0rt000000MeEPtAAN

Table 25: The Cost of VIP Walls as a Percentage of the Total Retrofit Project

Building	$ Cost for Retrofit	$ VIP Walls	$VIP Roof	$ Everything Else	Wall %
Creighton Storey Homes	$ 647,812.00	$ 161,859.00	$ 158,590.00	$ 327,363.00	**25%**
Nutgrove Garden Apartments	$ 746,059.00	$ 155,892.00	$ -	$ 590,167.00	**21%**
Creighton Storey Homes w/o Roof	$ 489,222.00	$ 161,859.00	$ -	$ 327,363.00	**33%**

If we consider Table 25, the VIP wall improvement as a percentage of the overall cost ranges from 25 to 33% of the total cost at Creighton Storey Homes, but is actually a lower percentage of the total cost at Nutgrove Garden Apartments.

Figure: 41 Nutgrove VIP Wall Cost Distribution

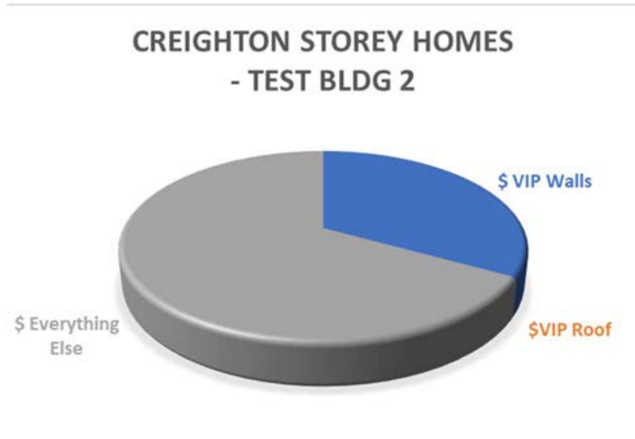

Figure 42: Creighton VIP Wall Cost Distribution

Discussion

The Phase 1 results indicate that the V-RIP product has exceptional insulating attributes, but to realize it the product must be: 1) installed in a manner that maximizes the wall surface area being covered; and 2) coupled with air sealing practices as part of the building envelope improvement retrofit approach.

Our limited small prototype testing indicates that the V-RIP product will perform better with air-sealed joints compared to butt-joints alone. Since we were unable to secure enough VIPs to make full-size V RIP panel assemblies, we were not able to fully demonstrate the critical aspects of the assembly features and details.

In addition to product installation guidance, we believe that design guidance will be equally important, because some building envelopes may not be suitable for maximizing the wall surface area coverage. Given the high R-value of the VIP material, conventional insulation may become the de facto “thermal bridge” that reduces the effectiveness of the product. Clear design guidance and easy-to-use support tools must be provided in Phase 2. In Table 26, we have an overall summary of the test results for the Phase 1 study.

Table 26: Summary of Performance Results

Performance Metric	VIP-Enhanced (RIP)[1] w/EPS Foam and OSB (3.5")
Test Method	**Results**
ASTM C518 - R Value	47 R-Value (Core Material - [1"ESP/VIP-Optim-R/1" ESP] - nominal 3.5")
ASTM C1363 - R Value	Indeterminant (Due to test sample size -or- Perhaps Damaged VIP)
ASTM E283 - Air Leakage	4CFM (The Baseline Wall was 11CFM)
ASTM E331 - Water Leakage	None Observed - **Passes** (no water present)
Thermal Simulation	Therm Modeling Analysis - Complete for Prototypes
Moisture Simulation	WUFI Modeling Analysis - Complete for Nutgrove and Creighton Storey
Energy Simulation	REMRate Energy Modeling Analysis - Complete for Nutgrove and Creighton Storey
Moisture Control Guidance	Yes - Provide with Retrofit Insulation Panel Guide/Buildng Code
Moisture Management Plan	Yes - Provide with Retrofit Insulation Panel Guide/Buildng Code/WUFI
Quality Assurance	Yes - Provided Step by Step QC/QA Procedures
Design Panel Layout	Yes - New System of (6) Panel Types
Installation[1]	Yes - Mock Up Installation Completed
Constructability[2]	Yes - Graphic Layout to Confirm Maximum Wall Area Coverage

[1]The prototype VIP-Enhanced (RIP) design was used for testing (not the final V-RIP Product)
[2]Installation and Constructability Evaluation was completed graphically and then with the mock-up (not the final V-RIP Product)

We believe that New York State and others can greatly benefit from this innovation because they have characterized most of their multifamily housing stock – making it easy to project the overall savings they can achieve. For those Climate Zones that will benefit from greater insulation, this product should be considered and should be easy to launch since it is basically an enhancement of traditional insulation products.

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