VIP Technology Review and Cost Study for Building Retrofits in Northern US Locations

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ABSTRACT

Vacuum insulation panel (VIP) is an emerging insulation technology that is slowly finding applications in buildings due to its energy saving potential. VIP consists of an evacuated nanoporous core material that is sealed off with an impermeable enclosure. Nanoporous structure of core in conjunction with reduced air pressure results in an ultra-low thermal conductivity of VIP that is almost 5–10 times smaller than the conventional insulations such as foams and fibers. In this paper, we first provide a brief discussion on heat transfer mechanisms that are responsible for reduced thermal conductivity of VIP. Next, we investigated the cost performance of VIP technology when implemented in the deep energy building retrofits in cold climate regions of the northern US. Deep energy retrofits in cold climate regions generally require higher target R-value envelopes. VIPs with significantly higher R-value per unit thickness than the conventional insulations save considerably on the cost associated with the loss of living space caused by the installation itself. In deep energy retrofits, thinner VIP installations may also eliminate the cost associated with alteration of window and door openings, which is otherwise necessary for thicker layers of conventional insulations. We compare the VIP retrofit method against a number of thermally equivalent conventional wall insulation techniques using foam sheathing, sprayed foam, fiber insulations, etc. The cost analysis indicates that for lower priced VIPs, the proposed method of VIP wall retrofit may become cost competitive with current deep retrofit strategies that employ foam insulations. We predict that in the near future, further advancements in VIP manufacturing technology, larger volume production, and higher reliability through quality control of cores and films will enhance VIP cost effectiveness as a retrofit option for providing local insulation and mitigating thermal bridging effects in building envelopes.

INTRODUCTION

Building share of primary energy consumption has increased from 33.7% (26.3 Quads) in year 1980 to 42.1% (40.4 Quads) in year 2010 (EERE 2010). The share is expected to rise in the future (EERE 2010), potentially causing strain on our energy resources and an increase in green house gas emissions. There is a need for more energy efficient buildings that exchange less thermal energy with the exterior environment. A simple way to realize this goal is to add thermal insulation to the building envelope, thereby retarding the energy flow through the envelope. Vacuum insulation panel (VIP) is an emerging insulation technology that holds huge promise in reducing building energy consumption due to its far superior insulation properties than the conventional foam and fiber based insulations (ECBCS 2005; Simmler et al. 2005a). In retrofit building applications, VIP technology becomes even more attractive because high thermal resistivity of VIP allows for application of thinner retrofit solutions, thus saving on usable space. Future success of VIP technology depends on its cost effectiveness in addition to thermal performance and durability as compared to existing conventional technologies.

VIP consists of a nanoporous core that is evacuated and enclosed in a container that is highly impervious to air and water vapor transmission. Typically, silica in pressed fumed, precipitated, or powder form is used as the core material, while a thin metal or a metalized polymer film is used to surround

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and seal the core. Thermal conductivity, λ, of a typical VIP is ~0.004 W/m·K (0.0023 Btu/h·ft·°F), a factor of 5–10 lower than the conventional insulation such as extruded polystyrene (XPS, λ = 0.029 W/m·K or 0.0168 Btu/h·ft·°F), expanded polystyrene (EPS, λ = 0.036 W/m·K or 0.0208 Btu/h·ft·°F), polyisocyanurate (PIC, λ = 0.022 W/m·K or 0.0127 Btu/h·ft·°F), and polyurethane (PU, λ = 0.024 W/m·K or 0.0139 Btu/h·ft·°F).

In this paper, we will first discuss heat transport mechanisms behind the ultra-low thermal conductivity of VIP. Next, we will discuss cost competitiveness of VIP technology in a specific building retrofit application.

HEAT TRANSPORT IN VIP

Thermal conductivity, λ_T, of a porous material, such as conventional insulation and VIP, is a combination of following four heat transfer mechanisms (ECBCS 2005; Caps et al. 2001; Aegerter et al. 2011; Kwon et al. 2009): thermal conduction through the solid network, λ_S, thermal conduction through the entrapped gas, λ_G, convection of the gas component, λ_C, and radiation through the solid and pores, λ_R, i.e.,

$$\lambda_T = \lambda_S + \lambda_G + \lambda_C + \lambda_R \quad (1)$$

Typical pore size in these insulating materials is on the order of nanometer and micrometer. Brownian motion of the gas molecules is completely suppressed; convective heat transport, λ_C, can be safely assumed to be negligible (Aegerter et al. 2011). The porous structure of insulation materials offers only limited channels for heat conduction. This fact, combined with strong scattering of heat carriers (mainly phonons in case of silica core) in the amorphous structure of the core material, results in a significantly reduced solid thermal conductivity, λ_S (Fricke et al. 1989; Scheuerpflug et al. 1991). Lack of gas convection and minimization of solid conductivity are mainly responsible for low thermal conductivity of the conventional insulation, which typically ranges between 0.035 and 0.060 W/m·K (0.02 and 0.035 Btu/h·ft·°F).

Gas conduction, λ_G, in a porous media with an average pore size, d, is given by the following relation (Kennard 1938):

$$\lambda_G = \frac{\lambda_{G0}\Pi}{1 + 2\beta\frac{l}{d}} \quad (2)$$

where λ_{G0} is thermal conductivity of the free air, Π is the porosity, β is a constant that depends on the type of gas and temperature, and l is mean free path (MFP) of air molecules. MFP is inversely proportional to gas pressure, P_G, (Kennard 1938)

$$l \propto \frac{1}{P_G} \quad (3)$$

At atmospheric pressure and room temperature conditions, λ_{G0} = 0.026 W/m·K (0.015 Btu/h·ft·°F); a significant but unavoidable contributor to the heat transport in the conventional insulations. According to Equation 2, thermal conductivity will decrease with reduced gas pressure, offering a route for further minimization of thermal conductivity in porous materials. This may be achieved via evacuating and sealing off the porous material, and this concept is at the heart of VIP technology. According to Equation 2, a perfect vacuum condition will be required to eliminate the gas conduction; however, for highly porous and nanostructured VIP core, an order of magnitude reduction in gas conduction may be achieved even at a weak vacuum levels of 0.01–0.5 Pa (1.45e-6-72.5e-6 psi) (Simmler et al. 2005b).

For optically thick silica core, the thermal radiation propagates via diffusion (Aegerter et al. 2011), and radiative part of the thermal conductivity may be given by the following equation:

$$\lambda_R = \frac{16}{3}\frac{n^2\sigma T^3}{E} \quad (4)$$

where n is the index of refraction, T is the temperature, E is the extinction coefficient defined as the inverse of mean free path of photons or the ratio of optical thickness and geometrical thickness, and σ is the Stephen-Boltzman constant. In general, core materials such as fumed silica are transparent for a major part of the IR wavelength spectrum at room temperature (i.e., the extinction coefficient is low, leading to a large radiation contribution). To reduce the radiative component, optically contrasting materials known as opacifiers that absorb or scatter photons in IR spectrum are added to the core material. Carbon black, titanium oxide, iron oxide, and silicon carbide are some of the commonly used opacifiers.

To summarize, nanoporous structure of the core in conjunction with reduced air pressure is responsible for ultra-low thermal conductivity of VIP. Adding small amounts of opacifiers to the core material may further reduce the thermal conductivity to as low as 0.004 W/m·K (0.0023 Btu/h·ft·°F).

VIP COST ANALYSIS

Currently, higher cost of VIP has been a major barrier to its wide-scale adoption in the buildings. In retrofit projects where living space is valuable, VIP technology becomes a very cost attractive alternative because it provides significantly higher R-value per unit thickness, minimizing loss of the living space caused by the installation itself. For "deep" energy retrofit projects that aim to reduce building envelope-related energy consumption by at least 50%,[1] thinner VIP installations may avoid cost associated with alteration of window and door openings, which is otherwise necessary for thicker layers of conventional insulations. Installation of thinner VIP may be achieved by performing only minor adjustments to the window and door opening without causing any major structural changes to the envelope itself. On the other hand, conventional insulation due to its thickness may require

1. See National Grid (2013) for more information and Castle Square (2010) for an example.

special attachment methods (long nails or additional furring) and roof overhang adjustments. Another advantage of VIP is that it is nonflammable and may be packed between nonflammable protective layers to provide a nonflammable thermal insulation solution in buildings; this could be important if the United States adopts more restrictive building fire codes in the future, such as those that are already adopted in Europe, Japan, and China (ISO 2002a, 2002b, 2002c, 2002d, 2002e).

In this section, we investigate cost performance of VIP technology when implemented in the favorable scenario of deep energy building retrofits in cold climate regions. In deep energy retrofit projects in cold climate regions, target R-values for walls are usually higher (i.e., around 5.28 $m^2 \cdot K/W$ [R-30 $h \cdot ft^2 \cdot °F/Btu$]). The higher target R-value results in increased living space or savings for VIP technology. Triple-deckers[2] and similar historic houses in New England region (Krim 1977) offer a large market potential for such deep retrofit applications. In fact, city of Boston alone has almost 9000 triple decker houses (City of Boston 2013). The primary goal of the study is to estimate and compare the cost of wall retrofit projects using current state-of-the-art VIP technology to that of the conventional foam applications. Foam insulations have been chosen for comparison because they are most commonly used in exterior wall retrofits and provide higher thermal resistance per unit thickness than fiber insulations.

Installed Cost Estimation

We estimate and compare the total cost[3] to deep energy wall retrofitting of a baseline house[4] using the conventional foam insulations (Waier et al. 2011).[5] The conventional foam insulations considered are rigid board (XPS, EPS, and PIC foams) and spray-applied (closed-cell PU foam) options. We assume that the rigid boards are installed in the form of an exterior sheathing, and the foam is sprayed either in between added studs or between exterior furrings. Although retrofit applications can apply combined cavity and exterior insulations to reach 6.16 $m^2 \cdot K/W$ (R-35 $h \cdot ft^2 \cdot °F/Btu$) thermal resistance, the cost analysis considers only exterior installation as compared to VIPs. This is because for the cases considered in the study, the installed cost of combined cavity and exterior installation is higher than the installed cost of exterior insulation alone. Table 1 shows an example comparison.

2. The triple-decker (or three-decker) is a unique housing type characteristic of New England cities in early 20th century. Generally defined, the triple-decker is a free standing, wood frame structure on its own narrow lot, three stories high and one family unit at each floor.
3. The total cost is the sum of the bare material cost, the bare labor cost, and the bare equipment cost plus 10% for profit.
4. The baseline house is a two-story average class residential house with 2000 ft^2 floor surface area and 2700 ft^2 wall surface area (Waier et al. [2011], p. 29).
5. The main source of cost data to estimate total cost is the 2011 RSMeans Construction Cost Data and RSMeans Residential Cost Data.

We consider a new retrofit method of installing VIPs insulation that takes advantage of exterior cladding of a wall assembly to achieve continuity of thermal insulation in addition to the convenience of quick and easy installations. In this method, a 2.5 cm (1 in.) thick VIP is encapsulated between two layers of 2.5 cm (1 in.) XPS layers. Next, a 3 in. thick VIP-based EIFS is installed on the exterior sheathing using adhesives. For deep retrofit projects, VIP-based EIFS offers several advantages over the conventional foam based EIFS: higher R-value per unit thickness, improved thermal continuity, and avoidance of numerous added thickness-related costly tasks such as window alteration because it directly adheres to the existing wall. For example, in deep retrofits of walls using conventional foam insulations, adding thick layers of thermal insulation is necessary (often 15−25 cm and 6−10 in.). Thick layers of insulation usually require special attachment methods (long screws or additional furring). In addition, window and door openings need to be altered to allow window replacements closer to the exterior surface, reduce local thermal bridging, and improve water drainage, for example. Further work is very often necessary to adjust roof overhangs because the original wall surface moves notably toward the outside when the thick foam layers are installed. When using significantly thinner high performance VIPs, these tasks are not necessary.

We used the following approach to estimate the total cost of each retrofit strategy:

- A target R-value is estimated.
- An equivalent thickness is calculated to achieve the target R-value.
- A list of required retrofit tasks is determined. The retrofit work depending on insulation type and equivalent thickness includes a series of tasks from altering the existing walls and roof to installing the insulation and exterior cladding.
- The cost of each retrofit task and the installed cost are estimated.

It is important to recognize that the market for the VIP technology is immature, and the prices are expected to decrease as demand grows. Therefore, it is more appropriate to compare this technology with conventional insulation methods assuming thermal performance or target R-value as the criterion rather than finding an optimum balance between R-value and cost/savings.

Target R-Value

VIPs in the market have thermal resistance in the range of 4.4 to 8.8 $m^2 \cdot K/W$ (R-25 to R-50 $h \cdot ft^2 \cdot °F/Btu$) for a 2.5 cm (1 in.) thick, panel depending on the core material type. For the purpose of this study, we assumed that the VIP has a nominal center-of-the-panel thermal resistance of R-40.[6]

6. Non-aged condition.

Table 1. Installed Cost Estimates for Conventional and Emerging Insulation Techniques to Retrofit the Wall of a Baseline House

VIP Retrofit Techniques Do Not Require All Retrofit Tasks because of Low Thickness. Costs of the Exterior Wall Finishes Are Not Included in Analysis for all Considered Cases of Deep Energy Retrofits; Only the Insulation Part of the Retrofit Strategy is Analyzed.

Insulation Type		Retrofit Tasks and Cost, ($/ft^2) *(Note numbers are included in brackets.)*																		Total Cost, ($/ft^2)
		Removal of Exterior Cladding (vinyl siding)	Furring	Framing (2x4; OC 16)	Framing (2x6; OC 16)	Window Relocation for deep window wells	Insulation Installation (material and labor)	Insulation protection layers (2 XPS layers)	EIFS with 1/2 in. cement board sheathing and 2.5#/S.Y metal lath substrate	Removal of shingles (two layers)	Removal of OSB Deck	Rafter extension (4 feet)	Fascia Boards Installation	Soffit Nailer	Replace-ment of OSB Deck	Replacement of shingles	Rake Overhang	Building Kraft Paper	Strapping Screws	Installation of exterior cladding (vinyl siding)	
Rigid Insulation		*[1]*	*[2]*			*[2]*	*[3]*			*[8]*	*[9]*	*[10]*	*[9]*	*[4]*	*[9]*	*[9]*	*[5]*	*[1]*	*[11]*	*[1]*	
	XPS (7 in.)	$0.59	$0.92	—	—	$0.52	$5.81	—	—	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.22	$0.39	$7.79	$16.98
	EPS (9 in.)	$0.59	$0.92	—	—	$0.52	$5.04	—	—	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.22	$0.39	$7.79	$16.21
	PIC (6.0 in.)	$0.59	$0.92	—	—	$0.52	$4.51	—	—	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.22	$0.25	$7.79	$15.54
Sprayed Applied Foam Insulation		*[1]*	*[1]*	*[4]*	*[4]*	*[2]*	*[3]*			*[8]*	*[9]*	*[10]*	*[4]*	*[4]*	*[9]*	*[9]*	*[5]*	*[1]*	*[11]*	*[1]*	
	PU[1] (7.5 in.)	$0.59	—	—	$1.91	$0.52	$5.39	—	—	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.22	$0.39	$7.79	$16.34
	PU[2] (7.0 in.)	$0.59	—	$1.50	—	$0.52	$5.78	—	—	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.22	$0.39	$7.79	$16.32
	PU[3] (6.0 in.)	$0.59	$0.92	—	—	$0.52	$4.62	—	—	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.22	$0.25	$7.79	$14.59
Combined Cavity and Exterior Insulations		*[1]*	*[1]*	*[4]*	*[4]*		*[12]*			*[8]*	*[9]*	*[10]*	*[4]*	*[4]*	*[9]*	*[9]*	*[5]*	*[1]*	*[11]*	*[1]*	
	Blown Cellulose (5 3/16 in.) *[1]*	$0.59		—	—	—	$1.88	—	—	—	—	—	—	—	—	—	—	—	—	—	
	XPS (3 in.)	—	$0.92			—	$2.30	—	—	—	—	—	—	—	—	—	—	—	—	$7.79	$13.48

Table 1. *(Continued)* **Installed Cost Estimates for Conventional and Emerging Insulation Techniques to Retrofit the Wall of a Baseline House**

VIP Retrofit Techniques Do Not Require All Retrofit Tasks because of Low Thickness. Costs of the Exterior Wall Finishes Are Not Included in Analysis for all Considered Cases of Deep Energy Retrofits; Only the Insulation Part of the Retrofit Strategy is Analyzed.

		Removal of Exterior Cladding (vinyl siding)	Furring	Framing (2x4; OC 16)	Framing (2x6; OC 16)	Window Relocation for deep window wells	VIP Insulation	Insulation protection layers for VIPs (2 XPS layers)	Installed cost of EIFS with 1/2 in. cement board sheathing and 2.5#/S.Y metal lath substrate (material and labor); cost of foam insulation not included	Removal of shingles (two layers)	Removal of OSB Deck	Rafter extension (4 feet)	Fascia Boards Installation	Soffit Nailer	Replacement of OSB Deck	Replacement of shingles	Rake Overhang	Building Kraft Paper	Strapping Screws	Installation of exterior cladding (vinyl siding)	
		[1]						*[6]*	*[7]*												
VIP Insulation	VIP1 (3.0 in.)	$0.59	—	—	—	—	$30.00	$2.42	$8.44	—	—	—	—	—	—	—	—	—	—	—	$41.45
	VIP2 (3.0 in.)	$0.59	—	—	—	—	$11.43	$2.42	$8.44	—	—	—	—	—	—	—	—	—	—	—	$22.88
	VIP3 (3.0 in.)	$0.59	—	—	—	—	$7.00	$2.42	$8.44	—	—	—	—	—	—	—	—	—	—	—	$18.45
	VIP4 (3.0 in.)	$0.59	—	—	—	—	$4.27	$2.42	$8.44	—	—	—	—	—	—	—	—	—	—	—	$15.72
	VIP5 (3.0 in.)	$0.59	—	—	—	—	$3.50	$2.42	$8.44	—	—	—	—	—	—	—	—	—	—	—	$14.95
	VIP6 (3.0 in.)	$0.59	—	—	—	—	$3.00	$2.42	$8.44	—	—	—	—	—	—	—	—	—	—	—	$14.45
	VIP7 (3.0 in.)	$0.59	—	—	—	—	$1.23	$2.42	$8.44	—	—	—	—	—	—	—	—	—	—	—	$12.68
	VIP8 (3.0 in.)	$0.59	—	—	—	—	$1.15	$2.42	$8.44	—	—	—	—	—	—	—	—	—	—	—	$12.60
	VIP9 (3.0 in.)	$0.59	—	—	—	—	$4.25	$2.42	$8.44	—	—	—	—	—	—	—	—	—	—	—	$15.70
	VIP10 (3.0 in.)	$0.59	—	—	—	—	$3.25	$2.42	$8.44	—	—	—	—	—	—	—	—	—	—	—	$14.70
	VIP11 (3.0 in.)	$0.59	—	—	—	—	$2.78	$2.42	$8.44	—	—	—	—	—	—	—	—	—	—	—	$14.23
	VIP12 (3.0 in.)	$0.59	—	—	—	—	$5.18	$2.42	$8.44	—	—	—	—	—	—	—	—	—	—	—	$16.63

Table 1. *(Continued)* **Installed Cost Estimates for Conventional and Emerging Insulation Techniques to Retrofit the Wall of a Baseline House**

VIP Retrofit Techniques Do Not Require All Retrofit Tasks because of Low Thickness. Costs of the Exterior Wall Finishes Are Not Included in Analysis for all Considered Cases of Deep Energy Retrofits; Only the Insulation Part of the Retrofit Strategy is Analyzed.

Notes:

PU[1]: Closed cell polyurethane foam was applied inside of 2 × 4 wood studs.
PU[2]: Closed cell polyurethane foam was applied inside of 2 × 6 wood studs.
Both cases: the added stud is installed from inside and standing off a few inches from existing stud.
PU[3]: Closed cell polyurethane foam was applied in exterior furring.

VIP1: Glacier Bay (according to website in 2011: http://passivehousetoronto.blogspot.com/2011/03/vacuum-insulated-panels-and-prices.html).
VIP2: Dow Corning - Silica Core (based on price quotations obtained from Dow Corning's in 2011).
VIP3: Popular Mechanics (according to Popular Mechanics magazine, Oct 2009). (See www.popularmechanics.com/home/improvement/3455301 for more information.)
VIP4: Richard T. Bynum (according to Richard T. Bynum, Technology and Engineering obtained in 2011).
VIP5: Dow Corning - Mineral Wool Core (according to Dow Corning's quoting obtained in 2011).
VIP6: University of Chicago (personal communication with Dr. Alan Feinerman, Associate Professor, University of Illinois at Chicago in 2011).
VIP7: Thermal Vision (according to Thermal Vision company's quoting obtained in 2011).
VIP8: Dow Corning Future price (estimated by Dow Corning in 2011).
VIP9 – Based on the following paper: Alam, M., Singh, H., and Limbachiya, M. C. (2011). Vacuum Insulation Panels (VIPs) for building construction industry - A review of the contemporary developments and future directions. Applied Energy, 88(11), 3592–3602.
VIP10 - Qingdao Kerui New Environmental Materials Co. (according to company's quoting for R-30 VIP obtained in 2011).
VIP11 - Sinoarch Shanghai Co. (according to company's quoting obtained in 2011); http://www.alibaba.com/showroom/vip-insulation.html.
VIP12 - Hangzhou Sanyou Dior Insulation Materials MFG Co.,Ltd (according to company's price quotation obtained in 2011).

Aerogel1: According to Aspen Aerogel in 2011. The unit price is \$2.75/ft^2 with 3/8 in. thickness from Aspen Aerogel.
Aerogel2: Assuming 80% cost drop in future.

[1] According to RSMeans Building Construction Cost Data 2011.
[2] According to Building Science Corporation (BSC). Estimated as \$100/window × 14 windows of base case house / 2,700 (total façade area of the base case house).
[3] According to RSMeans Building Construction Cost Data 2011, which includes material, equipment, and labor costs; the cheapest combination of rigid board insulation thickness was assumed for the cost analysis (e.g., 9 in. was assumed as 3 × 3 in. layer instead of 4 × 2 + 1 in.). For PU, thermal bridging effect was taken into account while calculating required thickness to achieve target R-value.
[4] According to RSMeans Building Residential Cost Data 2011.
[5] According to William A. Zoeller from Steven Winter Associates, Inc., Norwalk, CT.
[6] VIPs are encapsulated between two layers of XPS protection layers to reduce lateral damages. The cost includes material and labor costs.
[7] According to RSMeans Building Construction Cost Data 2011. The cost estimated for EIFS with ½ in. cement board sheathing and 2.5#/S.Y metal lathe substrate (material and labor). The cost of 3 in. EPS foam insulation is not included because in VIP-based EIFS the foam insulation is replaced with 3 in. encapsulated VIPs.
[8] According to RSMeans Building Construction Cost Data 2011. Estimated as 2 × 40 ft (removed area) × 2 (shingle layers) × \$0.35 (removal unit price /ft^2) × 2 (both eave sides) / 2,700 ft^2 (total façade area).
[9] According to RSMeans Building Construction Cost Data 2011. Estimated the same way as [8].
[10] According to RSMeans Building Construction Cost Data 2011. The rafter extension is 4 in.; 2 in. overlap and 2 in. extension from its existing length.
[11] According to http://www.bestmaterials.com/SearchResult.aspx?CategoryID=750.
[12] According to Steven Winter Associates, Inc. (https://www.google.com/search?q=Practical+Residential+Wall+Systems%3A+R-30+and+Beyond&ie=utf-8&oe=utf-8&aq=t&rls=org.mozilla:en-US:official&client=firefox-a). This is the cost of blown cellulose insulation including material and labor into 2 × 6 framing wall (\$1,500 for 100 × 8 ft wall).

HEATING 7.3, a 3D heat transfer computer program, was used to model the effective R-value for the case where the VIP is sandwiched between two layers of XPS insulation layers (1 in. XPS + 1 in. VIP + 1 in. XPS) to protect it from impact and damage. An effective thermal resistance of 6.16 m^2·K/W (R-35 h·ft^2·°F/Btu) was determined by taking into account all thermal bridging effects of XPS and foil layers. This number also includes R-value reduction caused by possible inserts of XPS in the remaining areas where modular dimensions of VIPs do not exactly cover the whole wall. In the cost analysis, 6.16 m^2·K/W (R-35 h·ft^2·°F/Btu) is taken as the target R-value to find equivalent thickness of other insulations.

Equivalent Thickness

The VIP is sandwiched between two layers of XPS rigid board protection layers. The foam-VIP-foam panel considered has a total thickness of 7.5 cm (3 in.) For thermally equivalent conventional insulations, however, the thickness can vary between 15 and 22.5 cm (6 and 9 in.) For foam insulations, the effective R-value was calculated by taking into account the thermal bridging effect of exterior wood studs or furring. Figure 1 shows the equivalent thickness that is required to achieve 6.16 m^2·K/W (R-35 h·ft^2·°F/Btu) for different insulations.

Retrofit Tasks

A VIP-based EIFS can be quickly and easily installed. Because VIPs are sandwiched between foam, the overall installation and drainage systems for this technology are almost identical to those of conventional EIFS (exterior insulation and finish system) applications. In contrast, installing thermally equivalent foam insulation involves several additional costly and labor-intensive retrofit tasks. Moreover, because the equivalent thickness of foam insulation is greater than 15 cm (6 in.), the retrofit tasks are limited to not only the walls but also fenestration openings and roof overhangs that might need to be readjusted or extended. This adds to the cost as well. Table 1 shows the required wall retrofit tasks of a baseline house for VIPs and foam insulations.

Discussion

In the cost analysis, for foam insulation retrofits, the costs of material, installation, and labor were taken from the RSMeans Cost Data 2011 book. For VIP retrofits, the price quotations were obtained from several VIP manufacturers around the world and used as material cost. Data from manufacturers' websites and technical publications were also included. The labor cost for VIP-based EIFS installation was assumed to be the same as the cost of installing 7.5 cm (3 in.)

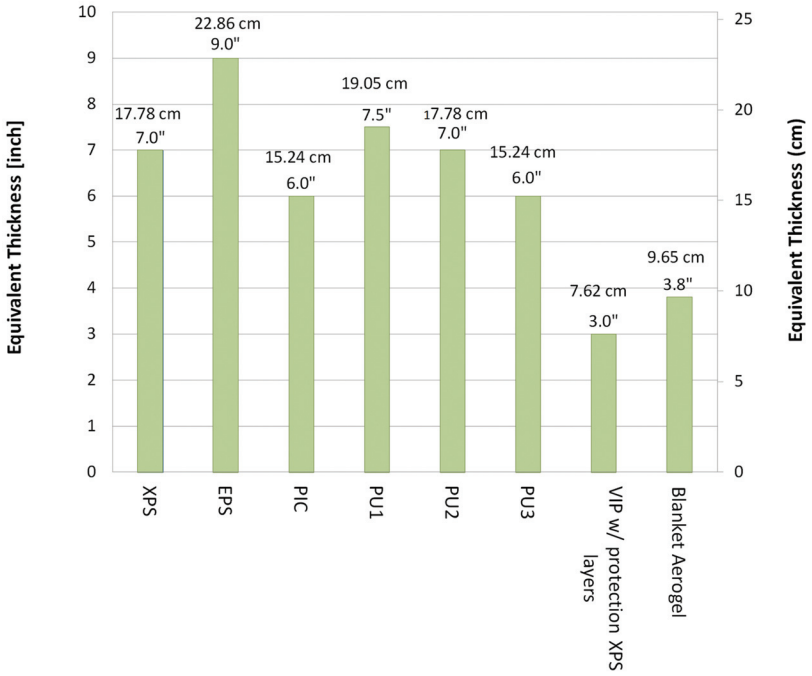

Figure 1 *Equivalent thicknesses of different exterior wall insulation systems to achieve a thermal resistance of 6.16 m^2·K/W (R-35 h·ft^2·°F/Btu). The thicknesses in this figure are rounded from the manufactured thickness (rigid board with at least 2.54 cm or 1 in. thickness and spray foam with at least 1.25 cm or 0.5 in. thickness). The equivalent thickness for PU takes into account the thermal bridging effect of wood studs. VIP encapsulated in XPS insulation has an effective thermal resistance of 6.16 m^2·K/W (R-35 h·ft^2·°F/Btu). The thermal resistivity of EPS, XPS, PU, and PIC insulations have been assumed to be 28, 35, 42, and 46 m·K/W (4, 5, 6, and 6.5 h·ft^2·°F/Btu in.), respectively.*

of foam insulation. There is a large variation in VIP prices among manufacturers and references.

Figure 2 shows cost estimates for wall retrofit methods with VIP and foam insulations.[7] VIP retrofit cost is the installed cost and not just the material cost. Wall retrofits with foam insulation costs between \$151 and \$183/m^2 (\$14 and \$17/ft^2), while VIP retrofits vary between \$129 and \$441/m^2 (\$12 and \$41/ft^2), depending on the manufacturer. This wide range in VIP-based EIFS retrofit cost reflects the large variability in the VIP prices across different manufacturers. Taking the lower range of VIP-based EIFS cost, a 6.16 m^2·K/W (R-35 h·ft^2·°F/Btu) VIP-based wall retrofit costs almost 15% less than that using foam insulation. In fact, it is interesting to note that majority of the VIP-based solutions covered in this study are very cost competitive with foam-based retrofits, and at the same time provide the convenience of easy and quick installation with minimum disruption to the occupants.

VIP is a fragile material and once punctured it may significantly lose its insulating capability due to loss of vacuum (ECBCS 2005). It is important that the VIP element is protected from external damage or impact by enclosing it within a damage-resistant material such as XPS, etc. as described in this paper. We predict that in the near future, further advancements in VIP manufacturing technology, larger volume production, and higher reliability through quality control of cores and films will enhance VIP cost effectiveness as a retrofit option for providing local insulation and mitigating thermal bridging effects in building envelopes.

7. Exterior cladding installation cost is not included in the cost estimation.

CONCLUSIONS

Vacuum insulation panel (VIP) is an emerging insulation technology that is slowly finding applications in buildings due to its energy saving potential. VIP technology involves evacuating a nanostructured porous material and enclosing it in an impermeable container. The nanoporous structure of core in conjunction with reduced air pressure results in an ultra-low thermal conductivity of VIP that is almost 5–10 times smaller than the conventional insulations such as foams and fibers. In this paper, we first provided a brief discussion on heat transfer mechanisms that are responsible for reduced thermal conductivity of VIP.

Next, we investigated the cost performance of VIP technology when implemented in the deep energy building retrofits in cold climate regions. Deep energy retrofits in cold climate regions generally require higher target R-value envelopes. VIPs with significantly higher R-value per unit thickness than the conventional insulations save considerably on the cost associated with the loss of living space caused by the installation itself. In addition, thinner VIP installations may also avoid cost associated with alteration of window and door openings, which is otherwise necessary for thicker layers of conventional insulations. VIP prices were collected from a variety of sources such as VIP manufacturer websites, techni-

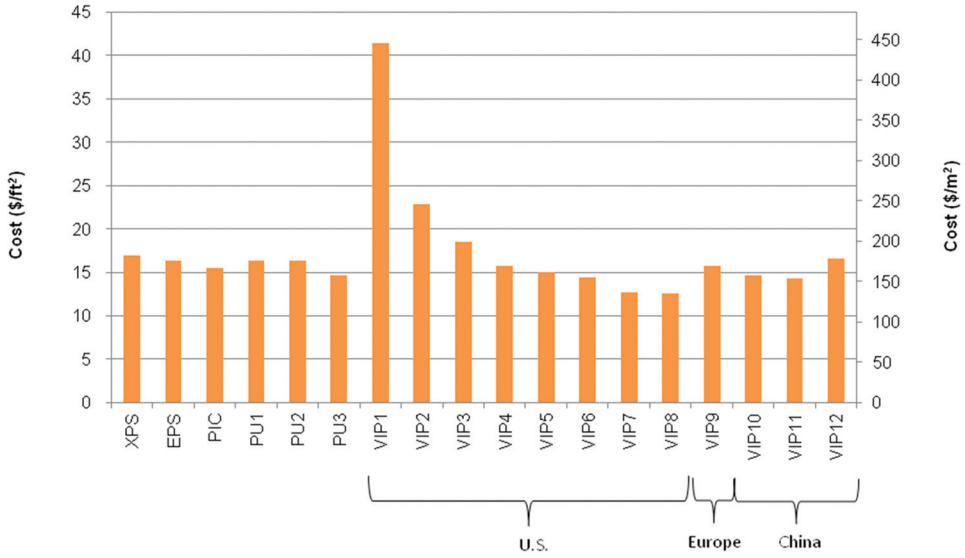

Figure 2 *Installed cost of different exterior wall insulation systems to achieve a thermal resistance of 6.16 m^2·K/W (R-35 h·ft^2·°F/Btu). The equivalent thickness for PU takes into account the thermal bridging effect of wood studs. VIP encapsulated in XPS insulation has an effective thermal resistance of 6.16 m^2·K/W (R-35 h·ft^2·°F/Btu). The thermal resistivity of EPS, XPS, PU, and PIC insulations have been assumed to be 28, 35, 42, and 46 m·K/W (4, 5, 6, and 6.5 h·ft^2·°F/Btu.in), respectively. The VIP cost was collected either directly from manufacturers or from published data on the internet for US, European, and Chinese markets.*

cal publications, and quotes from manufacturers in the United States, Europe, and China. A wide range in VIP prices was observed across these sources. The cost analysis indicated that for lower priced VIPs, the proposed method of VIP wall retrofit may become cost competitive with current deep retrofit strategies that employ foam insulations. In fact, we found that a 6.16 m^2·K/W (R-35 h·ft^2·°F/Btu) VIP-based wall retrofit costs almost 15% less than that using foam insulation considering the lower range of VIP-based EIFS cost.

Further advancements in VIP manufacturing technology, larger volume production, and higher reliability through quality control of cores and films may further improve VIP cost effectiveness as a retrofit option for local insulation and mitigation of thermal bridging effects in buildings envelopes.

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