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Cold Climate Building Enclosure Solutions

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Fraunhofer CSE

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Cold Climate Building Enclosure Solutions

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Definitions

APD	Atmospheric pressure drying
EIFS	External insulation finishing system
EPS	Expanded polystyrene
PIC	Polyisocyanurate
PU	Polyurethane
U.S. DOE	U.S. Department of Energy
VIP	Vacuum insulation panel
XPS	Extruded polystyrene

Executive Summary

The main goal of this project is to investigate the energy performance and cost effectiveness of several state-of-the-art retrofit strategies that could be used in residential houses in the Boston and New England area. To realize this goal, Fraunhofer CSE evaluated the application of several emerging building enclosure technologies, including high performance (i.e., high R-value) aerogel and vacuum insulations, in forms that would be energy efficient, flexible for different retrofit scenarios, durable, and potentially cost competitive for deep energy retrofits. Historically, high performance thermal insulation has been an expensive material. With recent advancements in the fields of material processing and production technology, however, their prices have been falling, making them a more attractive option for building insulation. In this project, the team focused on the following building enclosure technologies: (i) R-30 vacuum insulation panels (VIP)-based exterior insulation finishing system (EIFS) system technology, (ii) aerogel exterior and interior wall surface insulations, and (iii) R-8 blown-cavity aerogel insulation. A detailed cost analysis was performed for each case.

In the first phase of the project, the team developed detailed cost data that included material costs, labor costs, equivalent cost reductions from space savings and elimination of construction tasks, etc. The cost analysis indicates that the proposed method for VIP wall retrofit could be cost competitive with current deep energy retrofit strategies for walls using foam insulations. 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 superior retrofit option for providing thermal insulation and mitigating thermal bridging effects in building envelopes.

Next, we evaluated aerogel insulation application on the interior and exterior surfaces of the building envelope. Aerogel nanoinsulations are gels whose liquid component is completely removed and replaced with air or gas. They are highly porous materials with pore sizes on the order of nanometers, resulting in high thermal resistivity, about R-10 per inch. As-produced aerogels are fragile and unsuitable for use in most building applications; therefore, they are produced in blanket form by reinforcing them with a mechanically stronger material such as fiberglass. The team found that wall insulation retrofits using aerogel blankets could become cost competitive in certain scenarios, such as interior thermal insulation installation.

Further, the team proposed a novel concept of blown-in aerogel technology. Although this technology does not exist today, it might improve the thermal performance of typical wood-framed walls, vaulted ceilings, and attics in the future. The preliminary cost estimates for this blown-cavity aerogel method show that this could become a cost-competitive option in niche areas of building thermal insulation, such as wall cavity insulation. The team conducted initial thermal testing on samples consisting of shredded aerogel blanket pieces to understand the insulation behavior of proposed blown-in aerogel technology. Thermal testing reveals that the R-value of these shredded aerogel samples increases as the effective packing density of aerogel pieces increases. This testing result shows a pathway for future development of blown-in aerogel technology by optimizing the processing method and packing density of the aerogel.

1 Introduction

This Building America project performed by Fraunhofer CSE investigates the performance of state-of-the-art, high R-value, deep energy retrofit strategies that could be applied to triple-deckers[1] and similar historic houses in the Boston and the New England area [1]. These strategies are based on high performance insulation materials such as vacuum insulation panels (VIPs) and aerogels, enabling achievement of high R-value in retrofits of walls with a very minimal loss of the living space caused by the installation itself. In deep energy retrofit projects, target R-values for building envelopes are usually about R-30 for walls (R-value units in $h \cdot ft^2 \cdot °F/Btu$). This research project has been devised under the assumption that the target market is "deep" energy retrofits that aim to reduce envelope-related energy consumption by at least 50%.[2,3]

The team investigated the potential integration of several high performing building enclosure technologies in forms that are expected to be energy efficient, flexible for different retrofit scenarios, durable, and cost competitive for deep energy retrofits. The focus was on three building enclosure technologies:

- R-35 VIP-based external insulation finishing system (EIFS) system technology
- Aerogel-based wall insulation
- R-8 blown-in aerogel insulation

During the first phase of the project, the team developed detailed cost data for these technologies, including material costs, labor costs, potential time savings, equivalent cost reductions caused by space savings and elimination of construction tasks. In addition, Fraunhofer CSE, in collaboration with local government institutions, utilities, design offices, and contractors, is actively exploring different methods of cost reduction in residential retrofit projects performed in the Greater Boston area.

The blown-in aerogel insulation technology is a new concept proposed in this report. Although this technology has potential for deep energy retrofit applications, it is at an early development stage. This initial analysis of R-8 blown cavity aerogel insulation indicated that, if fully developed, this method could be one of the easiest to apply and most labor-saving approaches to improve the thermal performance of typical wood-framed walls using a drill-and-fill technique.

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[1] 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.

[2] National Grid. Super Insulation Upgrades.
See https://www1.nationalgridus.com/DeepEnergyRetrofit-MA-RES for more information.

3 Castle Square. Deep Energy Retrofit.
See http://www.castledeepenergy.com/?page_id=185 for more information.

2 Insulation Technologies

Emerging insulation technologies are slowly finding their way into buildings. VIP and aerogels are among the most promising of these building insulation technologies. Future success of these two technologies depends on their cost effectiveness in addition to their thermal performance and durability as compared to existing conventional technologies.

In this report, the team analyzed the cost attributes of these two high R-value insulation technologies in combination with novel labor-saving installation techniques. Both technologies offer thermal conductivities several times lower than the conventional fiber and plastic foam insulations, which allows for the application of significantly thinner retrofit solutions, thus saving on space. In addition, thinner retrofit installations reduce costs for altering window and door openings, which is often necessary when using thick layers of conventional insulations for deep energy retrofit projects. Another advantage of these technologies is that both are nonflammable; 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 [2−6].

2.1 Deep Energy Wall Retrofit

The target R-value of framed wall assemblies for deep energy retrofits in colder climates is typically R-30 or greater [7]. High R-value building envelopes reduce energy consumption for space heating and cooling, in addition to enhancing thermal comfort for the occupants. Advanced framing and exterior insulating sheathings can significantly improve thermal continuity to achieve high R-value walls [8]. There are space constraints for wall cavities or exterior installations of insulations, however, particularly in retrofit projects. In addition, very thick building envelopes are not desirable for several reasons: reduction of internal floor area for internal insulation retrofit, zoning regulations in cases of the exterior foam sheathing, a common need for alteration of window and door openings, architectural restrictions, and material use [9].

To achieve the highest possible thermal insulation resistance with existing space limitations of retrofit projects, new thermal insulation materials with low thermal conductivity, such as VIPs and aerogels, are reasonable alternatives to conventional insulation materials. As mentioned before, the main barrier to the application of these new materials is low production volume and high cost.

2.2 Vacuum Insulation Panel

VIPs are promising candidates for building thermal insulation because of their ultra-low thermal conductivity. Their thermal conductivity is four to eight times less than foam insulation materials, resulting in a substantially thinner solution to the building envelope relative to conventional insulation [10]. A VIP consists of a core panel enclosed in an air-tight envelope, to which a vacuum is applied. The common core materials are fumed and precipitated silica, open cell polyurethane (PU), and several types of fiberglass. The core is wrapped in a metallic or mylar foil, and then a vacuum is applied. The metallic film is sealed to maintain the vacuum for a long period of time; there may be some loss of insulation value as the panel ages, depending on the design of the installation [10].

Unfortunately, during the last two decades, high cost has been a major barrier to wide-scale adoption of silica-based VIPs. Currently, the price remains dominated by the typical dynamics of the product introduction phase. Furthermore, the products themselves are still being developed and continually improved.

2.3 Aerogel

Aerogel was invented in 1931 by Samuel Stephens Kistle. It is made up of a gel that has had its liquid component replaced by air—in fact, the material is 99% air by volume. Aerogels have considerably higher thermal resistivity values of about *R*-10/in. compared to the commonly used plastic foams such as extruded polystyrene (XPS, R-5/in.), expanded polystyrene (EPS, R-4/in.), polyisocyanurate (PIC, R-6.5/in.), and PU (R-6/in.).[4,5,6] Therefore, in building retrofit applications where thickness of the envelope matters, they are considered a promising candidate for replacing conventional building thermal insulations. In addition, they are low flammable, lightweight, nontoxic, and water repellent, all highly desirable properties for a building thermal insulating material.

Aerogels have found application as thermal insulation material in subsea pipelines, shipping vessels, and the space exploration industry.[7,8,9] Unfortunately, because of relatively low production volumes, this material is still expensive. Currently two U.S. companies, Aspen Aerogels Inc. and Cabot, have commercial products available in the market, and their production volumes are increasing as demand for aerogels grows. Meanwhile, ongoing research seeks to achieve a 50% decrease in the cost of this high performance insulation.[10] Another market research report indicates that emerging insulation technologies such as aerogels will find small but profitable niches in the thermal envelope market, with 2020 market sizes of $230 million and $130 million, respectively.[11]

The thermal and cost analysis of the aerogel insulation presented in this report was prepared in collaboration with Aspen Aerogels, a member of the Fraunhofer CSE Building America team.

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[4] Lawrence Berkley National Lab. Environmental Energy Technologies Division. See http://eetd.lbl.gov/ECS/aerogels/kistler-desert.html for more information.

[5] Lawrence Berkley National Lab. Environmental Energy Technologies Division. See http://eetd.lbl.gov/ecs/aerogels/sa-thermal.html for more information.

[6] TAASI Corporation. Insulation Properties of Aerogels. http://www.taasi.com/pdf/insul.pdf?token=5353a86ccb6eef3136ec51964fea78a49c67a75a|1317301391#PDFP

[7] Aspen Aerogels. See http://www.aerogel.com/ for more information.

[8] NASA. Jet Propulsion Laboratory. California Institute of Technology. Preventing Heat Escape Through Insulation Called "Aerogel". See http://marsrover.nasa.gov/mission/sc_rover_temp_aerogel.html for more information.

[9] Woods, T. NASA (2011). Aerogels: Thinner, Lighter, Stronger. See http://www.nasa.gov/topics/technology/features/aerogels.html for more information

[10] Kanellos, M. Green Tech Media (2011). Aerogel Prices to Drop by 90%?. See http://www.greentechmedia.com/articles/read/aerogels-to-drop-by-90-percent-in-price/ for more information.

[11] McCutcheon, M. (2011). Opening the Thermal Envelope: Emerging Innovation in Dynamic Windows and Advanced Insulation. State of the Market Report. https://portal.luxresearchinc.com/research/report_excerpt/8469

2.4 Relevance to Building America's Goals

The overall goal of the U.S. Department of Energy's (DOE) Building America program is to "reduce home energy use by 30–50% (compared to 2009 energy codes for new homes and pre-retrofit energy use for existing homes)".[12] To this end, the team conducted research to "develop market-ready energy solutions that improve efficiency of new and existing homes in each U.S. climate zone, while increasing comfort, safety, and durability".[12]

This research investigates the need for deep energy retrofits of residential walls in cold climates of the Northeast.

[12] US DOE (2012). Energy Efficiency and Renewable Energy. Building America – Resources for Energy Efficient Homes. http://www1.eere.energy.gov/buildings/building_america/program_goals.html.

3 Cost-Effectiveness Analysis

This project aims to develop and demonstrate advanced building enclosure strategies (based on VIP, aerogel, etc.) that improve energy savings, flexibility for different retrofit scenarios, speed of work, and cost competiveness for deep energy retrofits. We anticipate that the high R-value technologies for retrofitting residential walls and flat roofs could be used on thousands of historical triple-decker and colonial houses in the Boston and New England area.

Affordability is a key aspect of high performance wall cavity insulations and sheathing insulation systems, because it helps ensure large-scale deployment of the systems. The design of the high R-value retrofit strategies focuses on simplicity, easy installation, and high performance materials. The team designed candidate systems and then performed an economic feasibility study to ensure that the design is competitive with the price of existing deep energy retrofit approaches. As part of the economic analysis, the team consulted with contractors to obtain estimates of the installation process and a bill of material to itemize the costs of the materials used in installation of the roof and wall retrofit systems.

It is important to mention here that the main focus of this report is to assess the economic feasibility of certain retrofit strategies that employ advanced insulation technologies. Therefore, hygrothermal performance of these advanced retrofit strategies, which is a key design parameter, is not investigated in this report. In fact, hygrothermal performance is beyond the scope of this cost study. To advance understanding of this topic, Fraunhofer CSE is partnering with Dow Corning Inc. and Dryvit Inc. on a DOE-funded project and with Aspen Aerogel Inc. on a Department of Defense funded project to investigate the hygrothermal behavior of high performance materials such as VIPs and aerogel.[13,14]

3.1 VIP Cost Analysis

This study compares the current cost of wall retrofit projects using VIPs to that of conventional foam applications. Foam insulations were chosen for comparison because they are most commonly used in exterior wall retrofits and provide higher thermal resistance per unit thickness than fiber insulations.

3.1.1 Installed Cost Estimation

We estimated and compared the total cost[15] to deep energy wall retrofitting of a baseline house[16] using conventional foam insulations [11].[17] The conventional foam insulations include rigid board (XPS, EPS, and PIC foams) and spray-applied (closed-cell PU foam) options. The team assumed 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.

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[13] See http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/ns/plenary_2_emerging_tech.pdf for more information.

[14] See http://www.sbir.gov/sbirsearch/detail/12181 for more information.

[15] The total cost is the sum of the bare material cost, the bare labor cost, the bare equipment cost plus 10% for profit.

[16] The baseline house is a two-story average class residential house with 2,000 ft^2 floor surface area and 2,700 ft^2 wall surface area (RSMeans Residential Cost Data 2011, page 29).

[17] The main source of cost data to estimate total cost is RSMeans Construction Cost Data (2011) and RSMeans Residential Cost Data (2011).

Although retrofit applications can apply combined cavity and exterior insulations to reach R-35 thermal resistance, this study considers only exterior installation as compared to VIPs. This is because for the cases considered in this study, the installed cost of combined cavity and exterior installation is higher than the installed cost of just exterior insulation. Table 1 shows an example comparison.

This report considers 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 1 in. thick VIP is encapsulated between two layers of 1-in. XPS layers (Figure 1). Then the 3 in. thick VIP-based EIFS is installed on the exterior sheathing using adhesives. For deep retrofit projects, VIP-based EIFS provides several advantages over 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 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 insulations such as VIPs, these tasks are not necessary.

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

1. A target R-value is estimated.
2. An equivalent thickness is calculated to achieve the target R-value.
3. 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.
4. 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. Furthermore, as mentioned previously, the hygrothermal aspects of VIPs are not considered in this report. As stated previously, VIP-based panels are usually sandwiched within protective layers of foam insulation. The cost of this foam was included in the total cost of the VIP application. Table 1 lists more details.

3.1.2 Target R-Value

VIPs in the market have thermal resistance in the range of R-25 to R-50/in. depending on the core material type and thickness. For the purpose of this study, the team assumed that the VIP has a nominal center-of-the-panel thermal resistance of R-40.[18] HEATING 7.3 software modeled 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 R-35 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 (Figure 2).

For this study, only the effective thermal resistance of R-35 was considered, and cases with R-value losses from aging and puncturing were not included. It is reported that R-value of VIPs with fumed silica core at atmospheric pressure is about R-12 [10], and therefore it is estimated that the punctured VIPs sandwiched between two layers of XPS will have effective thermal resistance of minimum R-22. (Note: Two layers of XPS foam provide R-10.)

It should be noted that to accurately simulate VIPs' R-value, a 3-D heat transfer computer program is required to take into account all the complexity of heat transfer phenomena. The HEATING 7.3 computer code was used in this project. It is a dynamic 3-D heat transfer, finite-difference program that has been extensively validated by ORNL and is capable of solving steady-state and transient heat conduction problems in one-, two-, or three-dimensional Cartesian, cylindrical, or spherical coordinates.

In this report, R-35 is taken as the target R-value to find equivalent thickness of other insulations.

3.1.3 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 3 in. For thermally equivalent conventional insulations, however, the thickness can vary between 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 4 and). Figure 3 shows the equivalent thickness that is required to achieve R-35 for different insulations.

3.1.4 Retrofit Tasks

A VIP-based EIFS can be quickly and easily installed. Because VIPs are sandwiched between foam, the overall installation and drainage system for this technology are almost identical to those of conventional EIFS applications (exterior insulation and finish system). 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 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 (refer to Figure 1).

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[18] Nonaged condition.

3.1.5 Discussion

In this 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 3 in. of foam insulation. There is a large variation in VIP prices among manufacturers and references.

Figure 3 shows cost estimates for wall retrofit strategies with VIP and foam insulations.[19] VIP retrofit cost is the installed cost and not just the material cost. Wall retrofits with foam insulation costs between \$14 and \$17/ft^2, while VIP retrofits vary between \$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, an R-35 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.

3.2 Aerogel Cost Analysis

This section describes the results of examining the economic feasibility of applying aerogels to supplement existing building thermal insulation materials for specific retrofit scenarios. To evaluate the potential cost effectiveness of aerogels as thermal insulation for wall retrofit applications, the team first estimated and compared the cost of applying the aerogel to that of installing conventional building insulations for residential retrofit projects.[20] Next, several approaches to lower the production costs to make aerogel technology more cost effective are proposed.

To estimate the cost of wall retrofit projects using aerogel, different aerogel configurations, both interior and exterior installations are considered. In addition, the team proposes a novel, quick, and simple application of aerogel into the stud cavity for retrofit projects and estimate a price that might make this new application of aerogel cost competitive with conventional insulations.

Because of the relatively limited availability of referenced research, engineering, and cost data to conduct a broader study on this subject, this report includes data from websites and technical publications that might not have established scientific standing. The team encourages readers to use their discretion.

3.2.1 Retrofit Cost Estimation

The total costs[21] to retrofit the wall of a baseline house[22] with conventional insulations and aerogels were estimated and compared using RS Means Cost Data [11]. The aerogel blanket cost

[19] Exterior cladding installation cost is not included in the cost estimation.
[20] R-value was used to indicate performance criteria of foam insulations and aerogel in this report. Future reports need to employ energy performance to account for more comprehensive performance aspects of these insulations.
[21] The total cost is the sum of the bare material cost, the bare labor cost, the bare equipment cost plus 10% for profit.
[22] The baseline house is a two story average class residential house with 2,000 ft^2 floor surface area, 135 ft perimeter, and 2,700 ft^2 wall surface area as defined by RS Means Residential Cost Data (2011, page 42).

is based on the current cost of commercially available aerogel in the U.S. market and short-term cost reduction predictions. Based on communications with Aspen Aerogels, in the United States the cost of an aerogel blanket with R-4 per 10 mm will be between \$2.50 and \$3.00/ft^2 in the near future (considering coming improvements in the production method and production volume increase). This evaluation used a price level of \$2.75/ft^2, which might be slightly lower from the current U.S. market prices.

Conventional insulations considered in this analysis include cellulose, fiberglass, rigid foam products (XPS, EPS, and PIC), and spray-applied foam (open or closed-cell PU). Aerogel is applied as blankets or using the proposed blown-in application.

To estimate the total cost of each retrofit strategy, the team followed the steps described in section 3.1.1.

In this study, the following aerogel insulating retrofit strategies are proposed:

Aerogel blankets installed on the exterior side of the existing exterior wall sheathing: A relatively thick insulation system made of conventional foam is replaced with a thermally equivalent aerogel material with approximately half the total thickness. In this case, the aerogel insulation adheres directly to the existing wall sheathing and does not require several costly installation tasks that are normally required in retrofits with thicker layers of conventional insulations (long connectors, alteration of window and door openings, extension of roof overhangs, and so on). To assess the cost effectiveness of this proposed retrofit strategy, the total (installed) cost for this approach is compared to that of the thermally equivalent wall retrofit strategies where conventional insulation is installed on the exterior wall surface. For the purpose of the cost estimation, we used three target R-values: R-4, R-20, and R-35. The three levels of insulation reflect a typical re-siding project, a high efficiency solution, and a deep energy retrofit approach. Knowledge of the target R-value and the equivalent thicknesses of the conventional foam insulations (see Figure 6) allowed for an estimation of the associated costs, as shown in Table 2-.

Aerogel blankets installed on the interior side of the existing gypsum board: Because aerogel is nontoxic, low flammable, and air permeable, and provides high R-value in thinner layers, it is a good candidate for interior installation. Three target R-values were assessed: R-4, R-8, and R-12. These were selected as practical and potentially cost-effective approaches for an interior retrofit. The three R-value targets reflect one, two, and three layers of an aerogel blanket, respectively (each 10 mm thick with thermal resistance of R-4 per layer). This is a quick retrofit method that requires limited alteration of the interior space (corners, electrical, heating unit relocation, and window and door openings) and minimizes occupant disruption. This method could also be a solution for internal retrofits of vaulted ceilings, cathedralized attics, knee walls, and exterior walls when exterior insulation is more costly or is not possible because of technical or code reasons. To evaluate the cost effectiveness of this retrofit method, the team compared its cost to that of the conventional insulation installed on the interior wall surface. The conventional insulations considered were fiberglass batt, spray-applied foam, and foam board insulations. Fiberglass batt available in the market has a minimum thickness of 3 ½ in.; however, for the sake of comparison, 1 ½ in. batts were also evaluated. With the exception of the latter fiberglass case, other materials require a new internal frame wall build-up. Additionally, we also compared the cost of adding conventional insulation installed on the exterior wall surface for R-12. Figure 7 shows the calculated equivalent thicknesses for conventional insulations; Table 5 through Table 8 show the estimated and compared costs. At present, there is a limited understanding of the hygrothermal behavior of the wall system where aerogel blankets are installed on the interior side. To further understanding on this topic, Fraunhofer CSE is conducting a long-term moisture measurement and durability study on a wall that is retrofitted with aerogel.[23]

Blown-cavity aerogel: At present, residential retrofit applications use cavity insulations as low-cost insulation techniques. The R-value of these applications, however, is limited because of the cavity space restrictions. Typically, blown-in cellulose is the most common option; however, it is not the best-performing one. Other alternatives involve foam cavity injections. These applications can damage cavities (expanding foams) or create undesired air voids (shrinking in time, so-called nonexpanding foams). In that light, blown-in aerogel insulation can be considered an attractive potential alternative. Blown aerogel for existing 2 × 4 stud wall cavity using a drill-and-fill technique is not yet commercially available. Fraunhofer CSE has worked with its Building America partners to evaluate this technique as a potential wall retrofit measure.

At this stage of technology development, the team assumes that the blown aerogel is produced from chopped aerogel blankets. In the future, it is anticipated that a new formulation of aerogel will be developed specifically for this application. In addition, using the cost reducing approaches outlined later in this report would reduce material costs by 30% to 50%. Moreover, the blown aerogel insulation could be easily blended with other fiber insulations—bringing low-cost alternatives to the U.S. building insulation market.

Estimating conservatively that thermal conductivity will increase by about 20% both during the synthesis of a new blown aerogel formula and while blowing it into the wall cavity, we assumed that the blown aerogel has a thermal resistivity of R-8/in.. This yields an effective thermal resistance of R-20 installed in a 2 × 4 at 16 in. o.c. stud wall cavity, assuming the existing stud cavity is completely empty. Note that R-20 is an effective thermal resistance and takes into account the thermal bridging effects in a 2 × 4 at 16 in. stud wall.

It is very common, however, that old walls are partially insulated in home retrofit projects; therefore, stud cavities already contain existing insulation. For cost comparison with exterior foam sheathing insulations or sprayed foam applications, the team considered the following thermal insulation cases:

- Blown-in aerogel applied in a 2 × 4 stud cavity with R-5 existing insulation compared with the case of the exterior XPS insulation. The team assumed the existing R-5 took approximately 1.5 in. thickness of the cavity and the remaining 2 in. is filled with the blown-in aerogel insulation. Using finite difference thermal modeling, the team determined an equivalent thermal resistance of R-16 for this configuration (see Figure 8). This is an effective thermal resistance of the cavity filled partially with R-5 and remaining with aerogel and takes into account thermal bridging effect due to studs.

[23] See http://cse.fraunhofer.org/5cc/project-overview/ for more information.

Exterior XPS insulation was considered as the only comparative case because other conventional insulations filled into remaining 2 in. cavity cannot reach the target of R-16.

Figure 8 and 9 show the equivalent thicknesses and estimated costs. Table 9 lists the retrofit tasks and cost estimation details.

Blown-in aerogel applied in an empty 2 × 4 stud cavity compared with the case of the blown fiber and sprayed applied foam insulation into the stud cavity. As mentioned, blown-in aerogel into an empty 2 × 4 stud cavity yields an effective thermal resistance of R-20. For comparative cases, the team considered filling a 3.5 in. stud cavity with blown-in fiber, sprayed applied foam, or aerogel insulations. Figure 10 and 11 show the equivalent thicknesses and estimated costs. Table 10 lists the retrofit tasks and cost estimation details.

3.2.2 Cost Comparisons

For the three retrofit strategies described, the cost model yields the following cost values:

The exterior installation using aerogel to achieve a target of R-4 is close to the price range of the conventional insulations. The cost of wall retrofit project using aerogel to achieve R-20 and R-35 is, however, 1.5–2 times more expensive than retrofit with conventional fiber and foam insulations (see Figure 6).

If conventional insulation is installed from the interior side of a retrofitted wall, interior installation of aerogel to achieve a target R-value of R-4 or R-8 is cost competitive or within the current price range of conventional insulations (see Figure 7). The cost of a wall retrofit project to achieve R-12 using aerogel is, however, 1.5–2 times more expensive than retrofit with fiber and foam insulations (see Figure 7).

If conventional insulation is installed from the exterior side of a retrofitted wall, interior installation of aerogel to achieve target of R-12 is cost competitive (see Figure 7).

Blown-in aerogel installed into 3.5 in. empty space of a 2 × 4 stud cavity would become cost competitive with blown-in fiber and spray-applied foam insulation into the stud cavity if the cost is below or in the range of \$12 to \$14/ft^2.

Blown-in aerogel installed into an R-5 partially insulated 2 × 4 stud cavity would be cost competitive compared with the case of the blown fiber and spray-applied foam insulation if the cost is less than about \$12 /ft^2.

Although both 2 × 4 stud wall cases have very close price ranges, the latter case where blown aerogel is filled into a 2 in. stud cavity thickness is more cost effective than the case of filling aerogel into an empty 3.5 in. stud cavity.

Therefore, based on the current cost of the aerogel, the wall insulation retrofit using aerogel is cost competitive for a target of R-4 for both the interior and the exterior installation cases. R-8 aerogel interior insulation is within the range of current conventional insulation prices; however, for the other interior and exterior wall retrofit applications considered here, aerogels seem to be 1.5−2 times more expensive than the current conventional fiber and foam insulation. The proposed blown-in aerogel into a 2 × 4 stud cavity would be cost competitive if its price were lower than $\$12/ft^2$ in cases with a partially insulated cavity and within the range of $\$12–\$14/ft^2$ for the empty cavity case. All aerogel insulating techniques do not require additional furrings or wall opening alterations, and they seem to be more suitable than conventional insulations for confined spaces.

3.2.3 Future Cost Comparisons

Several current publications report the possible reduction of aerogel cost. These reports predict that the manufacturing cost could be reduced by as much as 50% in the near future by modifying the production process. Such reductions would make aerogel a cost-effective solution for a larger portion of retrofit projects. Based on a 50% reduction in the current price of the aerogel (as shown in Figure 6 and), the future cost of the blanket and blown-in installations could be well below the current cost of conventional retrofit strategies. Moreover, blown-in aerogel is the only retrofit method that provides a high R-value with a single application into stud cavities. The existing competing retrofit methods require a combination of stud cavity and exterior sheeting insulation to achieve similar R-values, which adds to retrofit project cost, duration, and subtasks.

3.2.4 Aerogel Production Cost

Aerogel production has remained costly mainly because of high costs of raw materials and relatively smaller production volumes.

Usually, aerogel synthesis involves the following three steps [12]:

Sol-Gel preparation. The gel is prepared using silicon precursors such as tetramethylorthosilicate, tetraethylorthosilicate, polyethoxydisiloxane, methyltriethoxysilane, and silicon alkaoxide.

Gel aging. The gel prepared in step 1 is aged in a solvent for long periods of time to improve the mechanical and permeability properties of the gel network. The concentration, aging time, temperature, pH, and polarity have a strong influence on the strength and porosity of the aerogel.

In laboratory settings, a batch process is adopted for the aging step, which is inherently a slow process. When scaling to the production phase, the batch processing step could increase product cost because of increased process line downtime and frequent stopping/starting of the production line. A continuous process is desirable because it helps increase the output. As with any multistep process, however, the individual step only adds time to the overall process if it is the bottleneck. Because aging is not the capitally intensive part of the process, more aging vessels can be used to reduce the aging time.

Gel drying. In this step, the liquid inside the gel network is removed using a liquid to gas phase change process. Because of the surface tension of the liquid in contact with the solid, however, the liquid changing phase tends to pull the gel network along with it. This causes gel network to shrink and collapse. To retain the integrity of the gel structure during the drying process, the aged gel is brought to the supercritical condition. Under the supercritical condition, surface tension vanishes because there is no distinct liquid-vapor phase boundary. The supercritical condition can be realized at either low or high temperatures, depending on the liquid (e.g., CO2, ethanol), but high pressures are always required.

As-produced aerogels are fragile and unsuitable for use in any practical application unless they are reinforced with some other material such as glass fiber, mineral fiber, and carbon fiber, or cross-linked with polymers.[24] Although the reinforcement process gives mechanical strength and flexibility to the aerogel, it can result in an undesirable increase in the thermal conductivity and density of the resulting aerogel composite [13].[25] This thermal conductivity increase can be minimized by using lower volume fractions of inferior, thermally conductive fibers as long as the mechanical requirements for the areogel application are satisfied. IR opacifiers such as carbon black, titanium oxide, and iron oxide with suitable fiber diameters can also be added during the sol-gel process to reduce the radiative part of the thermal conductivity [14]. The radiative contribution can be further reduced by using IR opacified fibers such as PET fibers coated with carbon black.

3.2.5 Approaches to Lower Production Cost

The expensive raw materials used in step 1 and the large amounts of energy consumed to create high pressures in step 3 lead to high costs of production. In each of the synthesis steps, however, there is considerable potential to lower the cost:

Step 1: Use cheaper, more abundant raw materials such as rice husk, clay, and oil shale ash, and recycle process materials.

The market prices for silicon precursors are exorbitant; for example, tetraethylorthosilicate costs \$1.8−3.0/kg.[26] Rice husk is an inexpensive precursor source that is rich in silica; e.g., its ash can contain up to 92−97% of amorphous silica [15]. Clay is another less costly and more plentiful substitute. Clay aerogel is produced using a freeze-drying process [16] and consists of stacked sheets of clay with occasional struts connecting these sheets. The thermal resistivity values have been reported to vary between R-4 and R-6/in. depending on the orientation of the stacked layers [17]. Oil shale ash, a waste product from the oil shale refinement process, is another low-cost alternative that contains large quantities of silica (~50%) [18].

Although these options have potential, they require additional steps to arrive at the final product. For example, ash needs to be converted and then processed through more steps than currently required. This could add to the cost rather than reduce it. Aspen Aerogel has developed an approach to reduce the cost of raw material sand process by recycling the two main process chemicals that are used in a supercritical drying process for aerogel: alcohol and CO_2. Aspen reclaims and recycles 100% of the alcohol and approximately 97% of the CO_2 [19].

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[24] Strong and Flexible Aerogels. See http://www.aerogel.org/?p=1058 for more information.
[25] Aspen Aerogels. 2012. Pyrogel XT. See http://www.aerogel.com/products/pdf/Pyrogel_XT_DS.pdf for more information.
[26] Anhui Huishang International Ltd. Tetraethyl Orthosilicate TEOS. See http://ahhs.en.alibaba.com/product/475123281-0/tetraethyl_orthosilicate_TEOS.html for more information.

Step 2: Use low vapor pressure solvents.

The commonly used solvents such as siloaxane, H_2O/ethanol, tetraethylorthosilicate /ethanol, and polyethoxydisiloxane evaporate during the aging process, adding to the cost of the product. The evaporation also causes a slight shrinkage in the gel network, hence compromising the mechanical integrity of the final aerogel product. To address these issues, solvents with low vapor pressure such as ionic liquids should be considered in the future. These solvents will not be lost during the aging process, and can be recycled, resulting in a cost reduction. Ionic liquids, however, suffer from stability and corrosion issues and a detailed R&D effort will be needed to find a suitable type of ionic solvent for silica aerogel processing.

Water, an abundant and cheap resource, has also been considered an aging solvent that improves the mechanical stability of the aerogel [20]. Another direction to reduce the cost is to minimize the aging time, which can be achieved by aging in a simulated pore solvent [21] or increasing the solvent temperature.

Step 3: Use atmospheric pressure drying.

There are alternative cost-effective routes to achieve drying without resorting to high pressures: freeze drying and atmospheric pressure drying (APD). In freeze drying, the gel is frozen and subsequently sublimated. The freeze-drying process produces cracked and powder-like products, rendering this process unsuitable for large-scale mass production. APD is the most promising alternative to replace supercritical drying. It is a subcritical method where the capillary force between the pore liquid and the pore walls is minimized by modifying the surface chemistry of the pore walls. The surface is functionalized in such a manner that it becomes hydrophobic, and in the process expels water out of the pores. Because APD is an atmospheric pressure method, it consumes significantly less energy. In addition, APD does not require the expensive autoclave system used in supercritical drying, thus saving greatly on capital equipment cost [22]. At this time, an APD process cannot be fully employed for the large-scale production of powdered aerogels because fine aerogel particles will be lost to the open atmosphere. To avoid the mass loss and make the production process a continuous one, a closed type of drying process, such as a fluidized bed drying technique, can be a possible solution [23].

The fibers used in the reinforcement steps add to the aerogel production cost. Depending on the reinforcement material and the fraction content, the thermal conductivity can increase slightly or significantly. The same applies to the mechanical strength. For many building thermal insulation applications, however (e.g., blown-cavity or attic floor insulation), the thermal performance is the main performance criterion rather than the mechanical stiffness. The team believes that incorporating relatively mechanically weaker yet cheaper and low conductivity alternatives such as organic and biological fibers and using less fiber content will appreciably reduce the cost while achieving the thermal performance required for typical building insulations.

3.2.6 Discussion

For this project, Fraunhofer CSE partnered with Aspen Aerogel. Aspen holds significant knowledge and technical expertise in optimizing the process parameters for aerogel production in order to decrease the production cost. According to Aspen, there is further potential to lower the cost of aerogel products by as much as 50% through approaches such as APD and implementing their strategic programs.

There are claims of developing a rice husk-based aerogel processing method that will decrease aerogel production cost by 80% [24]. The team believes that such dramatic cost reduction can be achieved primarily from the cheaper cost of rice husks and using a subcritical drying method. The team is unable, however, to find any new development on this product since 2010, suggesting serious production and cost challenges might be associated with the realization of this product.

Svenska Aerogel Inc. recently claimed to have discovered a method that would reduce the price of their aerogels by 90% compared to their current baseline cost [10]. The company is highly secretive about their technology and it is not clear how such a high cost reduction has been achieved. Their current baseline cost is not available in the literature. Because their current baseline is not based on a production process, their baseline cost could be much higher compared to the production cost of U.S. aerogel manufacturers. The company plans to launch its products in 2012.[27]

Clay aerogels are also an attractive option because they are prepared from cheap and abundant clay material, although the process requires a potentially expensive freeze drying process. The thermal resistivity value of R-4–R-6/in. for clay aerogel is relatively inferior compared to R-8–R-10/in. for current silica-based aerogels;[28] however, their production cost is expected to be significantly lower than the current high-end aerogels available on the market.

Although claims made by these aerogel manufacturers are encouraging, they lack scientific veracity and credible demonstration of the performance benefits and cost reductions.

Considering this fact along with the fluctuating market demands, it is unlikely that aerogels will become a commonplace thermal insulation material for the U.S. building envelope industry in the near future. The team believes, however, that even today, aerogels may become a cost-effective option for local insulation and for mitigation of thermal bridging effects in building envelopes such as in window and steel frames, and complex architectural details.

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[27] CleanTech Investor (2011). Svenska Aerogel – Low cost aerogel solutions. See http://www.cleantechinvestor.com/portal/mainmenucomp/companiesa/2813-aerogel/9446-aerogelprofile1june11.html for more information.

[28] Cabot Aerogel, Inc. See http://www.cabot-corp.com/ for more information.

4 Blown-In Aerogel Technology

Today, aerogel blankets are the most common application of aerogel insulation. The team anticipates that R-8 or even R-10 blown-cavity insulation based on aerogel has the potential to become one of the most effective methods to improve the thermal performance of typical wood-framed walls, vaulted ceilings, and attics. The blown-in aerogel technology does not exist yet, but this concept has the potential for deep retrofit applications. If successfully developed, this technology might be an entirely new application of aerogel insulation. When the application space is very limited, small aerogel particles or aerogel blended with other fiber insulation would be blown into the wall cavity or into the vaulted ceiling instead of using significantly less thermally efficient conventional insulations. This application will not require strong fiber reinforcement unlike aerogel blankets.

The team proposes to mix cheaper and renewable fibers such as cellulose during the sol-gel process, and then carry out atmospheric condition drying. Here, the production process might be continuous because the reinforcement step will become an inherent part of the aerogel preparation process. The expected thermal conductivity of aerogels strengthened with cellulose will be only slightly higher than the thermal conductivity of silica aerogels [25]. This approach could bring cost savings by reducing processing costs and using less expensive fiber reinforcement and drying steps.

The thermal resistivity of blown insulation made of the aerogel blankets will be at least 10% to 25% lower than current products' R-10 to R-11/in. because of current fiber reinforcement levels. In the short term, aerogel blown insulation would be made with significantly fewer fiber reinforcements. This would reduce insulation cost and improve its thermal resistivity with only incremental capital investments. Taken together, this would yield at least a 20% cost reduction.

4.1 Thermal Testing of Shredded Spaceloft Aerogel Blankets

The thermal performance and density of proposed blowable aerogel would need to be optimized for cavity applications so that aerogel can meet thermal and structural requirements. This would require intensive research efforts before implementation in real building applications. As a preliminary step to understand the trends between thermal performance and density for the proposed blown aerogel, the team conducted ASTM C-518 thermal testing on a series of aerogel samples that were created by shredding aerogel blankets into small pieces and then packing these small pieces inside a container. The purpose was to explore the thermal performance of packed aerogel material such as blowable aerogel and shredded aerogel. The shredded aerogel samples do not represent future technology; the final blowable aerogel product and the technology will use different material formulation, density, and much improved performance compared to the shredded aerogel discussed in this section.

To prepare shredded aerogel samples, a large Spaceloft aerogel blanket was chopped into small pieces about 1−2 in. in size using a commercial shredder (see Figure 12). Next, a container with side walls was made out of Styrofoam (outside dimension of 12 × 12 × 1.65 in. with wall thickness of ~1 in.), with the top and bottom sides covered with very thin paper sheets. Three aerogel samples varied in effective packing density, with three different amounts of shredded aerogels in this container. Here, effective packing density is defined as the ratio of aerogel mass placed inside the container to the internal volume of the container. A Lasercomp FOX305 heat flow meter apparatus measured the thermal conductivity of the chopped aerogel samples. The hot and cold plates were set to 37.5°C and 12.5°C, respectively, with an average temperature of 25°C for the experiments.

Table 11 and Figure 13 present R-value/in. as a function of aerogel sample effective packing density. R-value/in. increases as more shredded aerogel pieces are packed inside the given container volume. This trend can be explained using effective medium theory, which implies that adding a lower thermal conductivity material to a medium decreases the overall thermal conductivity of the composite. The Spaceloft aerogel blanket has lower thermal conductivity than air; therefore, packing more shredded aerogel mass in the same volume will yield a reduced overall thermal conductivity (or increase in R-value) of aerogel samples. The R-value for Spaceloft aerogel blanket is about 10/in.,[29] and is included in Figure 13. As effective packing density increases, R-value is predicted to also increase. Following the trend in Figure 13, in order to obtain an R-value of 8/in. for shredded aerogel, density should be approximately 115 kg/m^{-3} (7.18 lb/ft^{-3}). Future blown-in aerogel insulation will have a significantly lower application density.

4.2 Discussion

The thermal testing results on shredded aerogel samples suggest that for blown-cavity applications it is critical to develop an aerogel synthesis process that would produce small-sized aerogel particles and avoid the need to shred aerogel blankets, which results in loss of valuable aerogel material. The strength of the fibers or mesh would be adjusted such that they will break into the desired size during the subsequent processing steps. Thermal testing also underlines the importance of optimizing the size of these aerogel particles to achieve a desired R-value performance.

[29] Aspen Aerogels. Spaceloft 6250. See http://www.aerogel.com/products/pdf/Spaceloft_6250_DS.pdf for more information.

5 Conclusions and Future Work

This report analyzes and compares the cost and performance of emerging high performance insulation technologies with conventional insulation methods in home energy retrofit situations. In particular, the team investigated the economic feasibility of applying VIPs and aerogels as a potential building thermal insulation material for wall retrofit applications. Surprisingly, very little has been done so far to evaluate their cost effectiveness, although this is a crucial factor to determine the potential application and limitation of these technologies.

We evaluated the cost of VIPs as building envelope insulation relative to conventional building foam insulations in wall deep energy retrofit projects. Data from websites, technical publications, and quotes from manufacturers from the United States, Europe, and China show a wide range of prices for VIPs. We find that the proposed method for VIP wall retrofit can be cost competitive with current deep retrofit strategies using foam insulations. Based on this finding, further advancements in VIP manufacturing technology, larger volume production, and higher reliability through quality control of cores and films could enhance VIP cost effectiveness as a retrofit option for local insulation and mitigation of thermal bridging effects in building envelopes.

Wall insulation retrofit using aerogel technology could become cost competitive in certain scenarios such as where a target R-4 is desired for both the interior and the exterior installation. In light of the recent technological advancements in aerogel processing, a novel approach of blown-cavity aerogel insulation, pending significant research and development, has the potential to become a cost-competitive option in niche areas of building thermal insulation, such as in cavity insulation and local insulations in areas of restricted space. Thermal testing on a series of samples consisting of shredded aerogel blanket pieces allowed the team to understand the insulation behavior of proposed blown aerogel technology. These tests showed that the R-value of these shredded aerogel samples increases as the effective packing density of aerogel pieces increases.

This report also gave an overview of the aerogel synthesis process. Currently, aerogel production is an expensive business, mainly because of the high cost associated with process chemicals and the drying procedure. A two-stage effort would reduce the aerogel production cost:

1. Short term: Evaluate different ways to reduce the cost of processing materials. This would involve using less expensive source materials and processing solvents, and using less reinforcement material to reduce production cost.

2. Longer term: Decrease the production process related costs by implementing a continuous production methodology and employing APD.

The rising demand for insulation materials along with tight space limitations will be favorable factors for aerogel industry growth and lowering the production cost.

In the future, the team, plans to apply the insights gained through cost analysis and thermal lab testing to evaluate the in-field performance of aerogel and VIP based retrofit strategies for northern U.S. climates.

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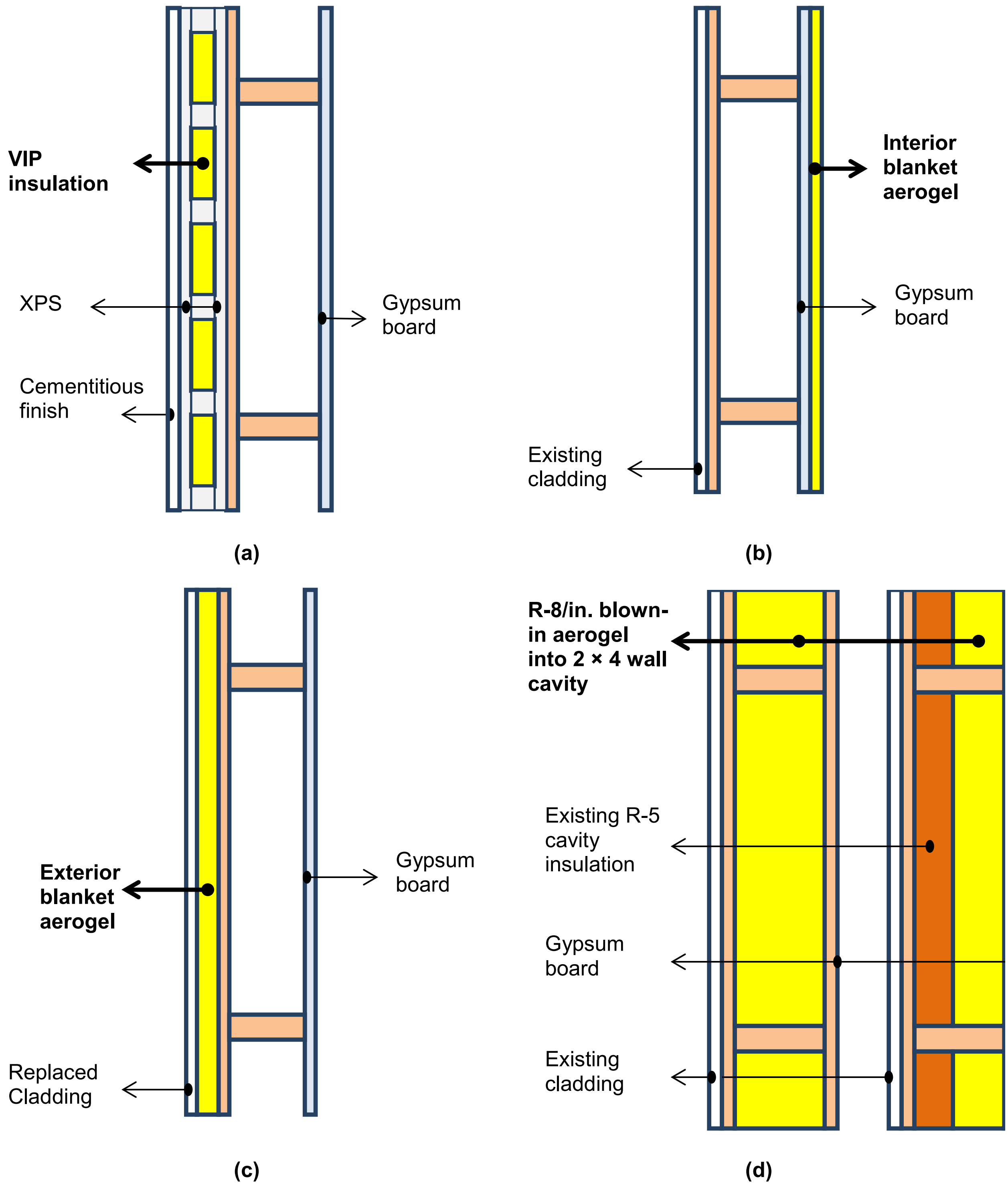
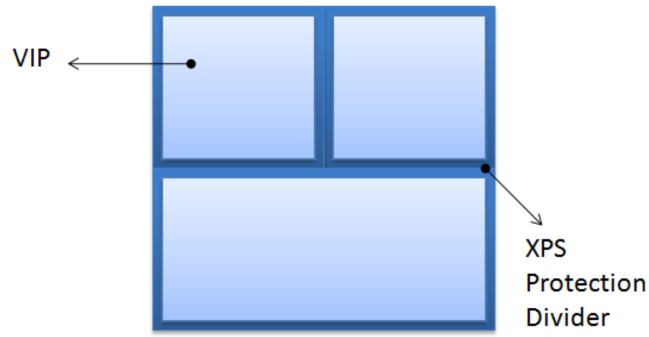
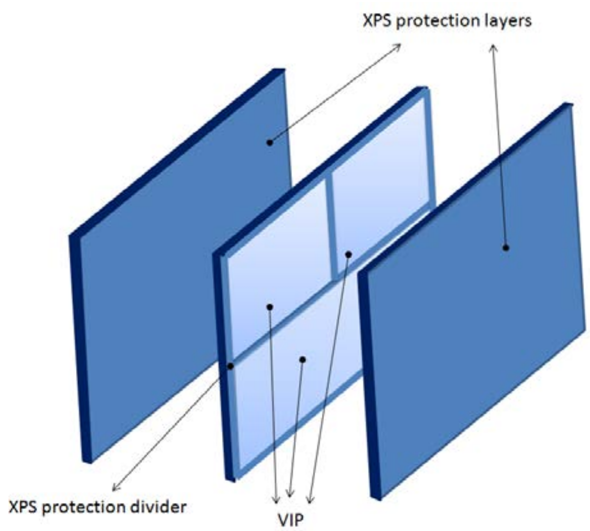


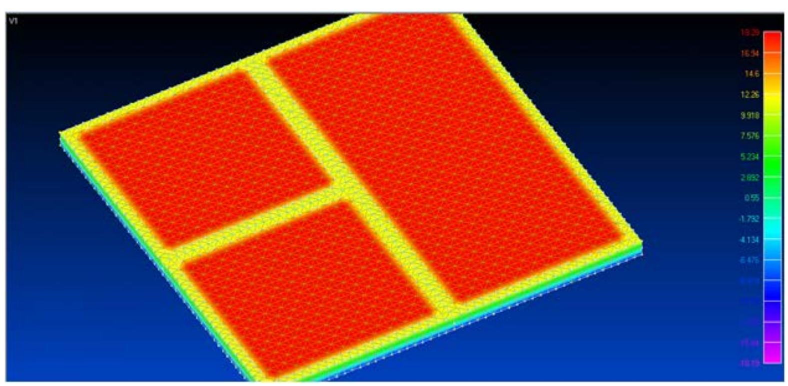
Figure 1. Emerging building insulation technologies considered: (a) VIP-based EIFS, (b) aerogel applied on the interior surface of the wall, (c) aerogel applied on the exterior surface of the wall, (d) blown-in aerogel applied to completely and partially filled cavities. Only thermal components are shown and drainage design is omitted.



(a)



(b)



(c)

Figure 2. 3D thermal modeling of modeled VIP encapsulated with XPS protection layers: (a) plan view of 1 ft × 1 ft ×1 in. VIP panel with XPS protection dividers, (b) VIP layer sandwiched between two 1-in. layers of XPS. The whole assembly has an effective thermal resistance of R-35. (c) Temperature mapping of VIP. The panel size is 1 ft × 1 ft ×1 in. and composed of three VIPs divided by XPS protection layers.

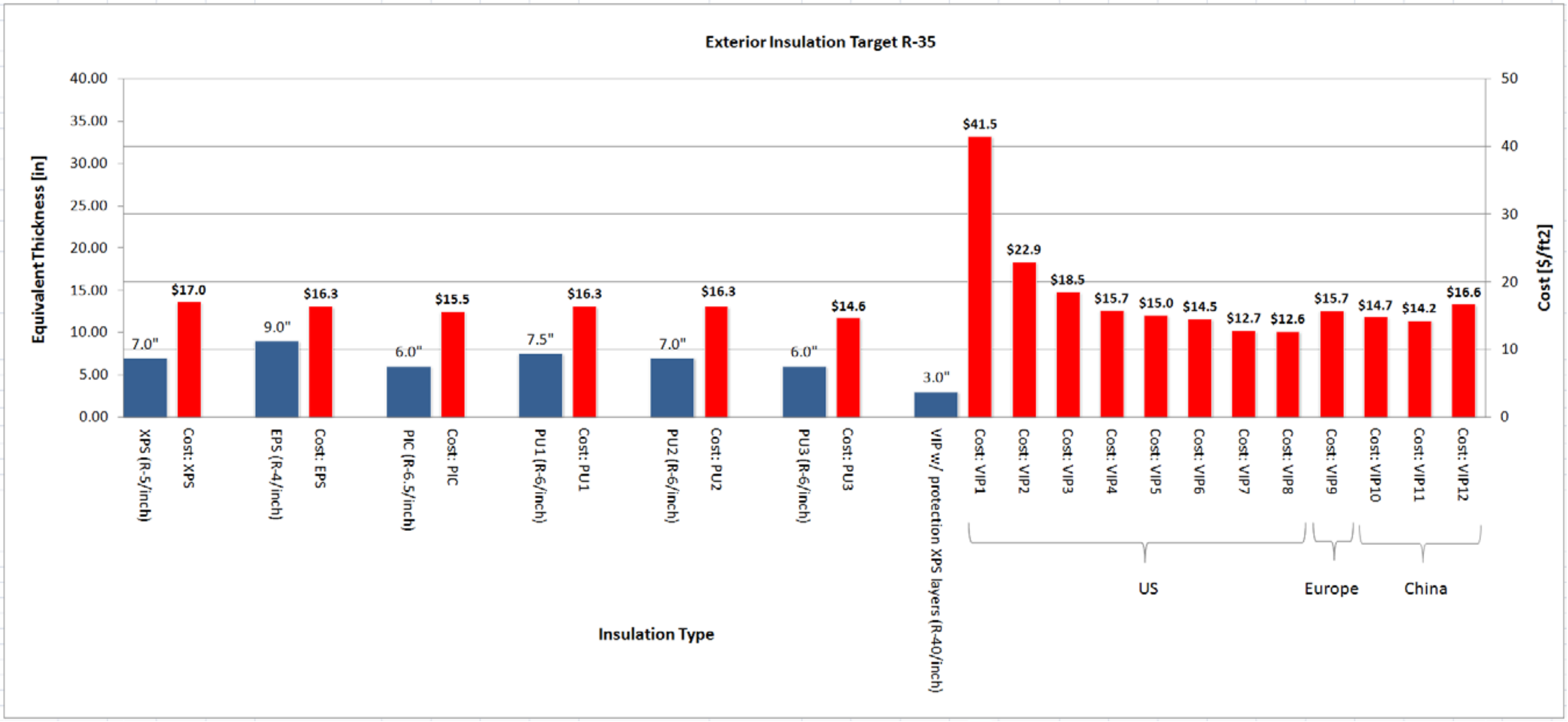


Figure 3. Equivalent thicknesses and installed cost of different exterior wall insulation systems to achieve R-35. The thicknesses in this figure are rounded from the manufactured thickness (rigid board with at least 1 in. thickness and spray foam with at least 0.5 in. thickness). The equivalent thickness for PU takes into account the thermal bridging effect of wood studs. VIP encapsulated in XPS insulation has effective thermal resistance of R-35 (Figures 4 and 5). The VIP cost was collected either directly from manufacturers or from published data on the internet for U.S., European, and Chinese markets.

PU1: Closed cell polyurethane foam was applied inside of 2 × 4 wood studs.

PU2: Closed cell polyurethane foam was applied inside of 2 × 6 wood studs.

For both cases, the added stud is installed from inside and standing off few inches from existing stud.

PU3: Closed cell polyurethane foam was applied in exterior furring.

VIP1 - Glacier Bay (according to http://passivehousetoronto.blogspot.com/2011/03/vacuum-insulated-panels-and-prices.html)

VIP2 - Dow Corning - Silica Core (according to Dow Corning's quoting)

VIP3 - Popular Mechanics (according to Popular Mechanics magazine, Oct 2009)

VIP4 - Richard T. Bynum (according to Richard T. Bynum, Technology and engineering)

VIP5 - Dow Corning - Mineral Wool Core (according to Dow Corning's quoting)

VIP6 - University of Chicago (according to Alan Feinerman)

VIP7 - Thermal Vision (according to Thermal Vision company's quoting)

VIP8- Dow Corning Future price (estimated by Dow Corning)

VIP9 - Alam et al. (published paper)

VIP10 - Qingdao Kerui New Environmental Materials Co. (according to company's quoting for R-30 VIP)

VIP11 - Sinoarch Shanghai Co. ; http://www.alibaba.com/showroom/vip-insulation.html

VIP12 - hangzhou Sanyou Dior Insulation Materials MFG Co., Ltd (according to company's quoting)

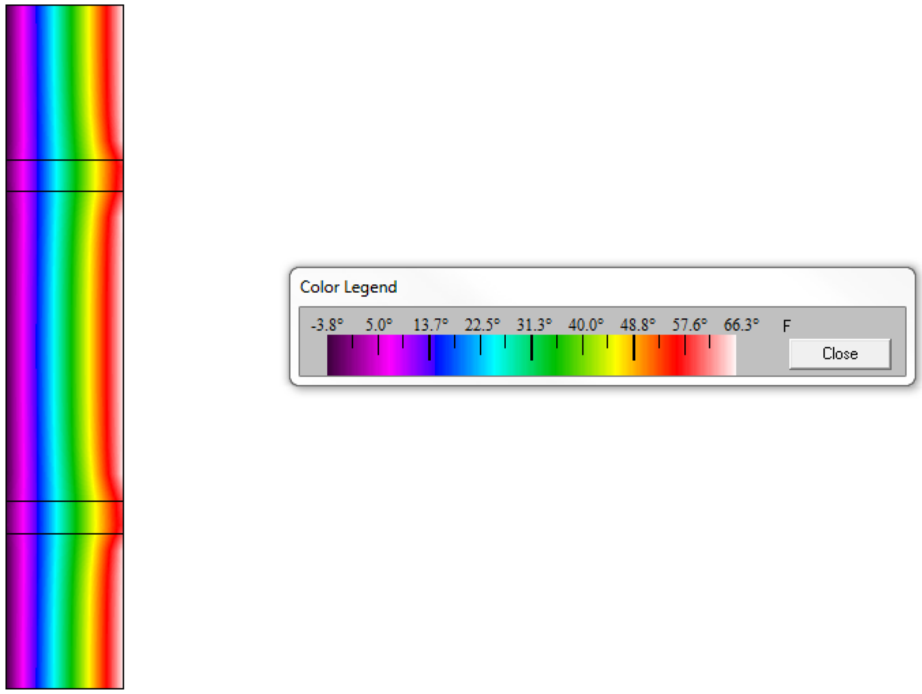


Figure 4. Modeled thermal resistance of PU foam sprayed into studs 2 × 6; 16 in. o.c. The effective thermal resistance of 5.5 in. PU foam is R-25 (excluding air film resistances). To reach target R-35, it was assumed that the studs are installed on the exterior and standing off 2 in. away from the exterior sheeting. The 2 in. gap is filled with PU spray foam and collectively with the 5.5 in. stud spaces provides the required target R-value. Therefore, approximately 7.5 in. PU foam is required to reach target R-35.

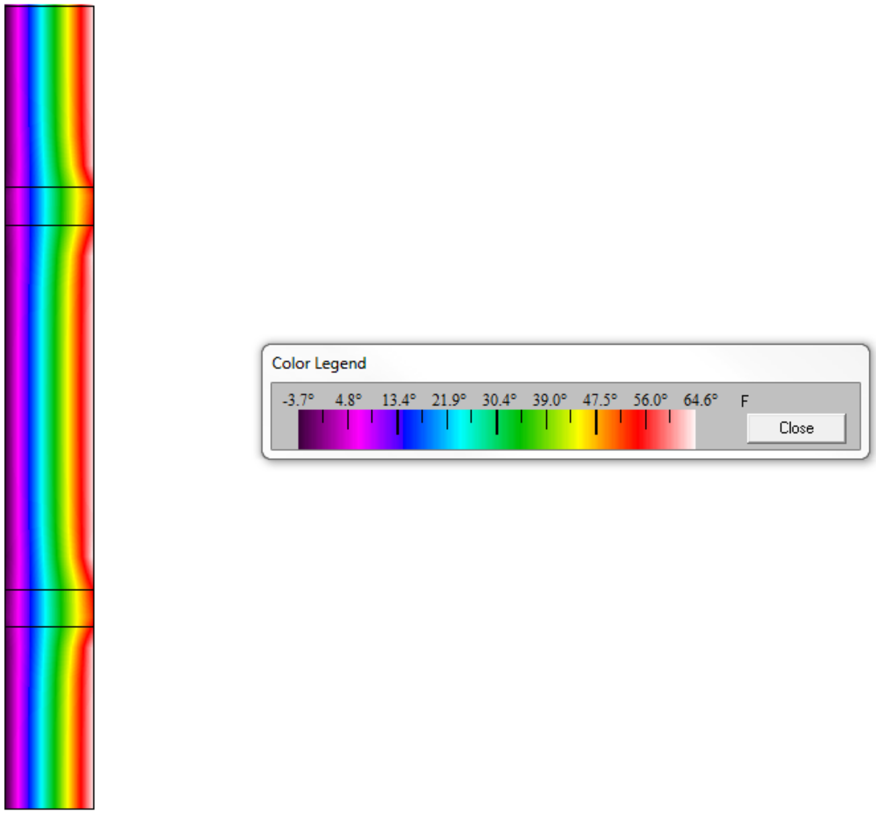
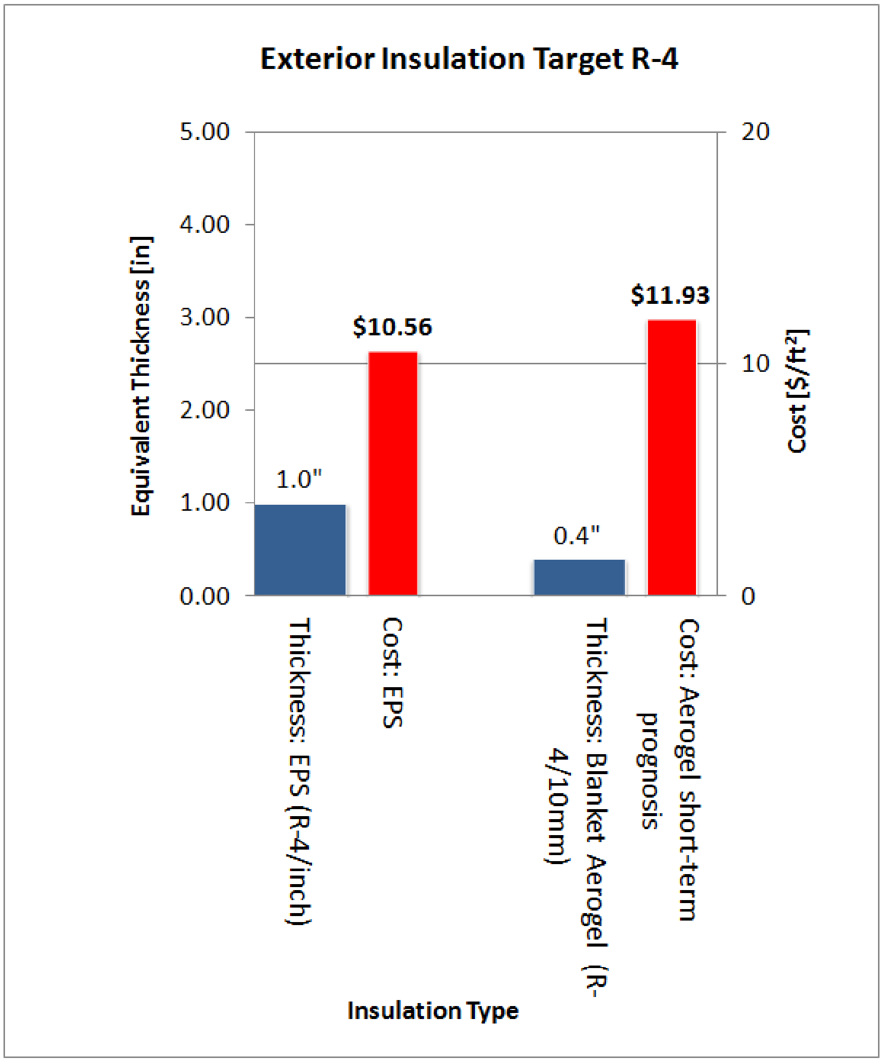
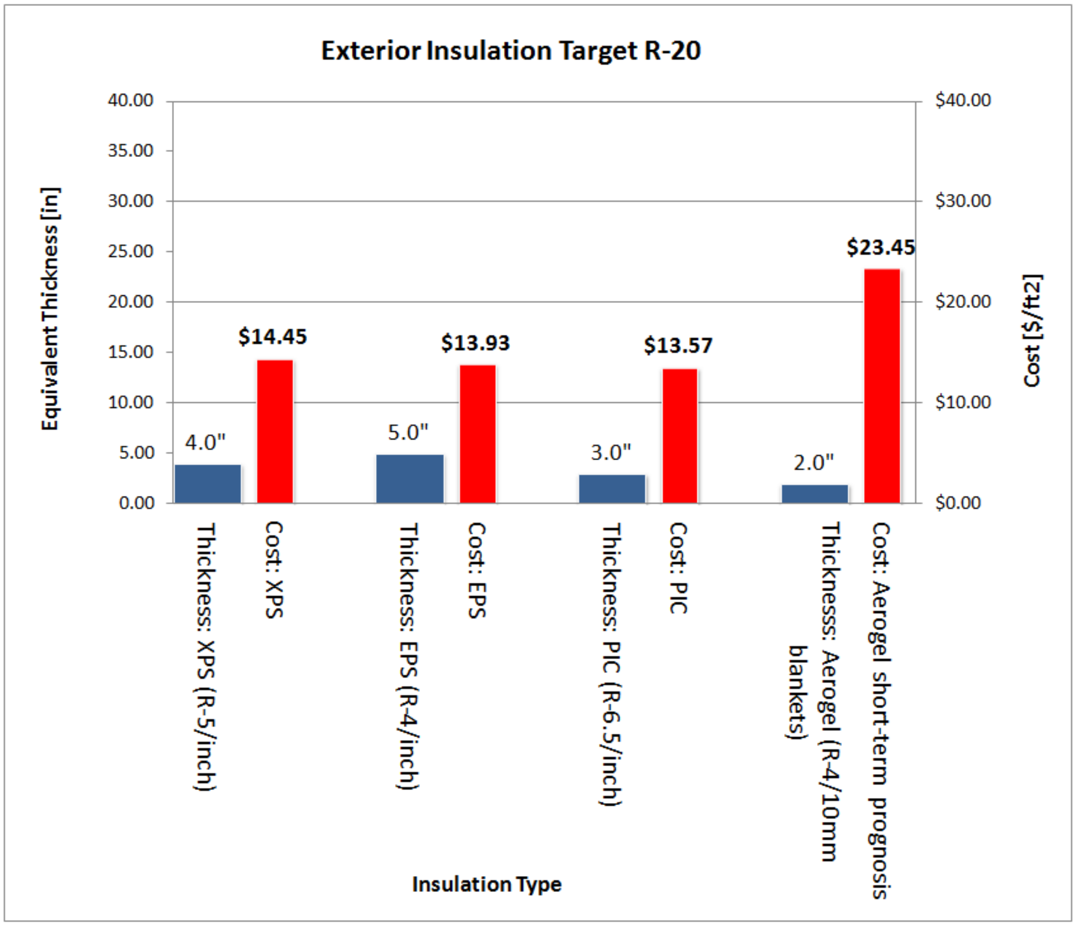


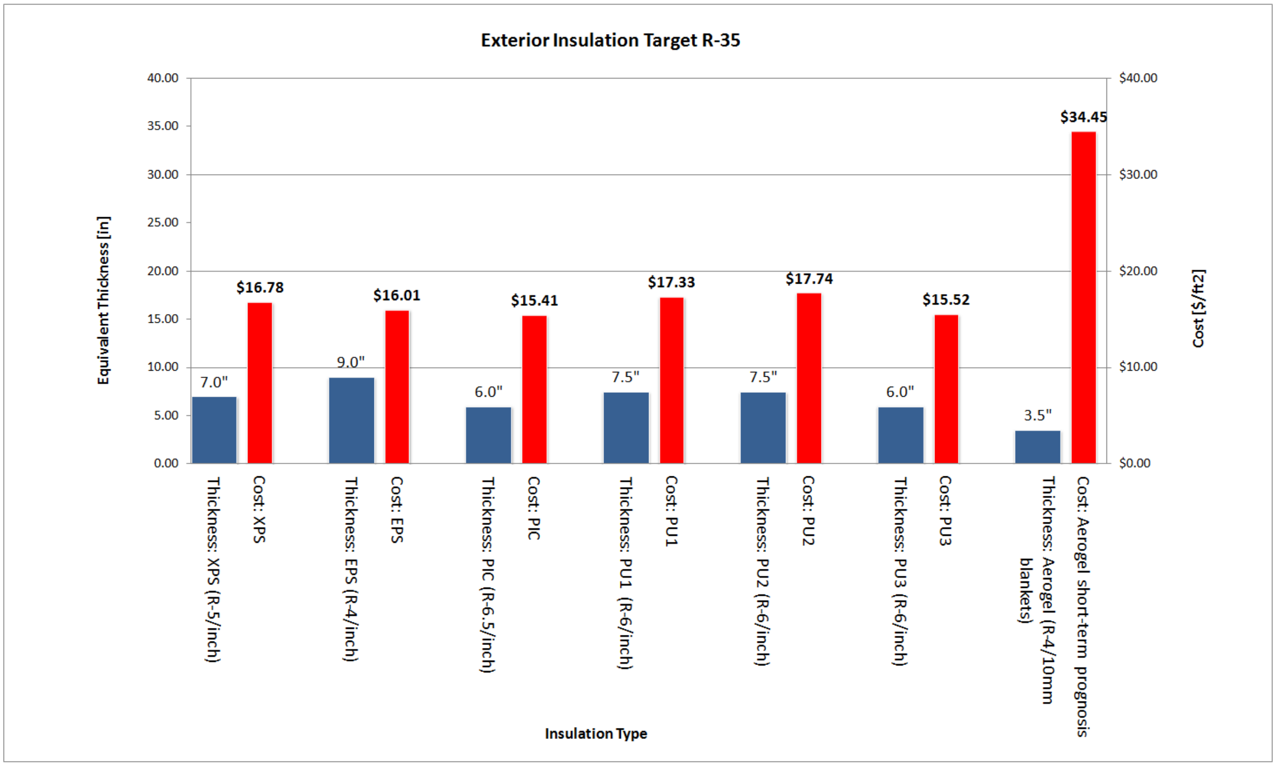
Figure 5. Modeled thermal resistance of PU foam sprayed into studs 2 × 4; 16 in. o.c. The effective thermal resistance of 3.5 in. PU foam is R-16.3 (excluding air film resistances). To reach target R-35, it was assumed that the studs are installed on the exterior and standing off 3.5 in. away from the exterior sheeting. The 3.5 in. gap is filled with PU spray foam and collectively with the 3.5 in. stud spaces provides the required target R-value. Therefore, approximately 7 in. PU foam is required to reach target R-35.


Exterior Insulation Target R-4
Equivalent Thickness [in]
5.00
4.00
3.00
2.00
1.00
0.00
20
10
0
Cost [$/ft²]
$10.56
$11.93
1.0"
0.4"
Thickness: EPS (R-4/inch)
Cost: EPS
Thickness: Blanket Aerogel (R-4/10mm)
Cost: Aerogel short-term prognosis
Insulation Type

(a)

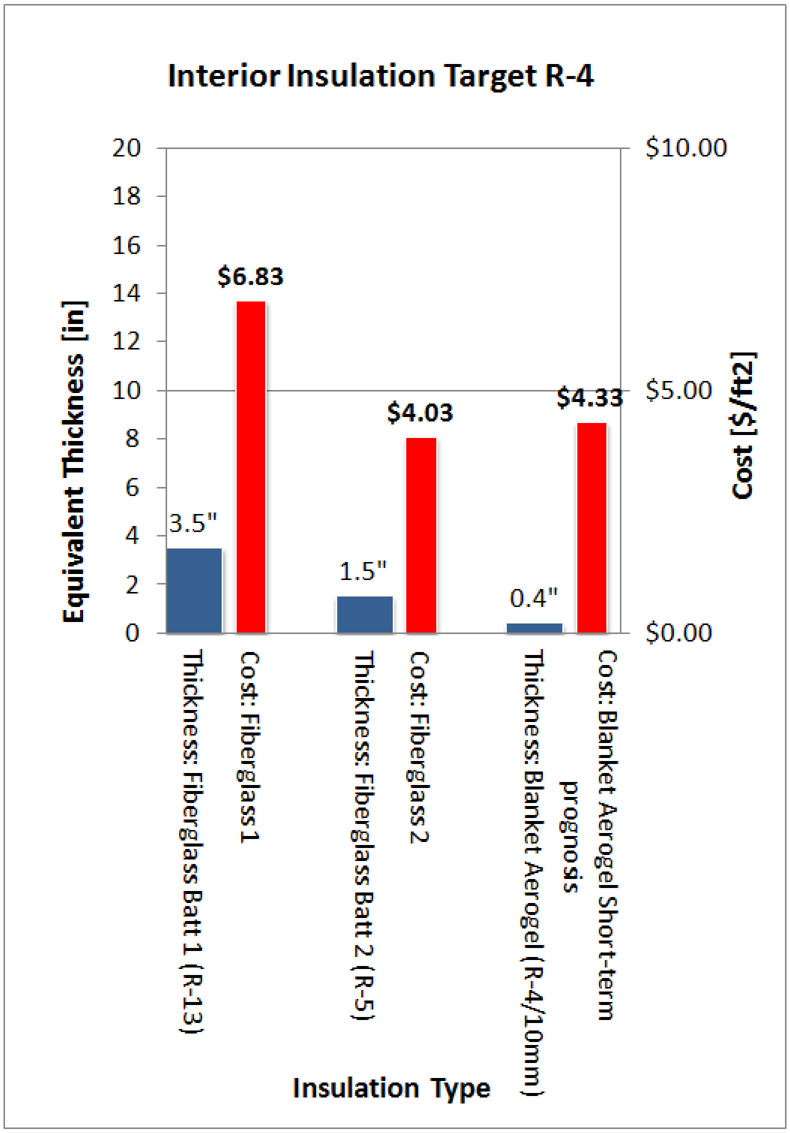

Exterior Insulation Target R-20
Equivalent Thickness [in]
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
$40.00
$30.00
$20.00
$10.00
$0.00
Cost [$/ft2]
4.0"
$14.45
5.0"
$13.93
3.0"
$13.57
2.0"
$23.45
Thickness: XPS (R-5/inch)
Cost: XPS
Thickness: EPS (R-4/inch)
Cost: EPS
Thickness: PIC (R-6.5/inch)
Cost: PIC
Thicknesss: Aerogel (R-4/10mm blankets)
Cost: Aerogel short-term prognosis
Insulation Type

(b)

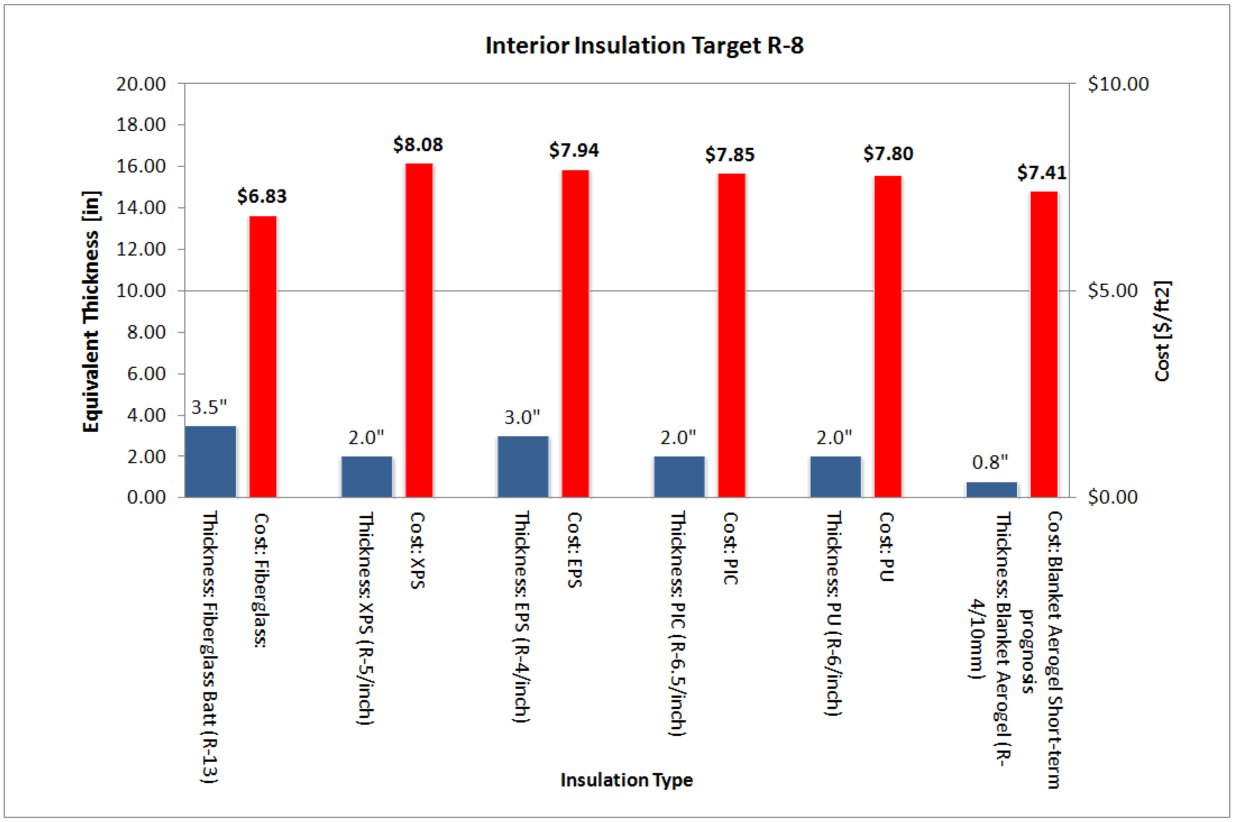


(c)

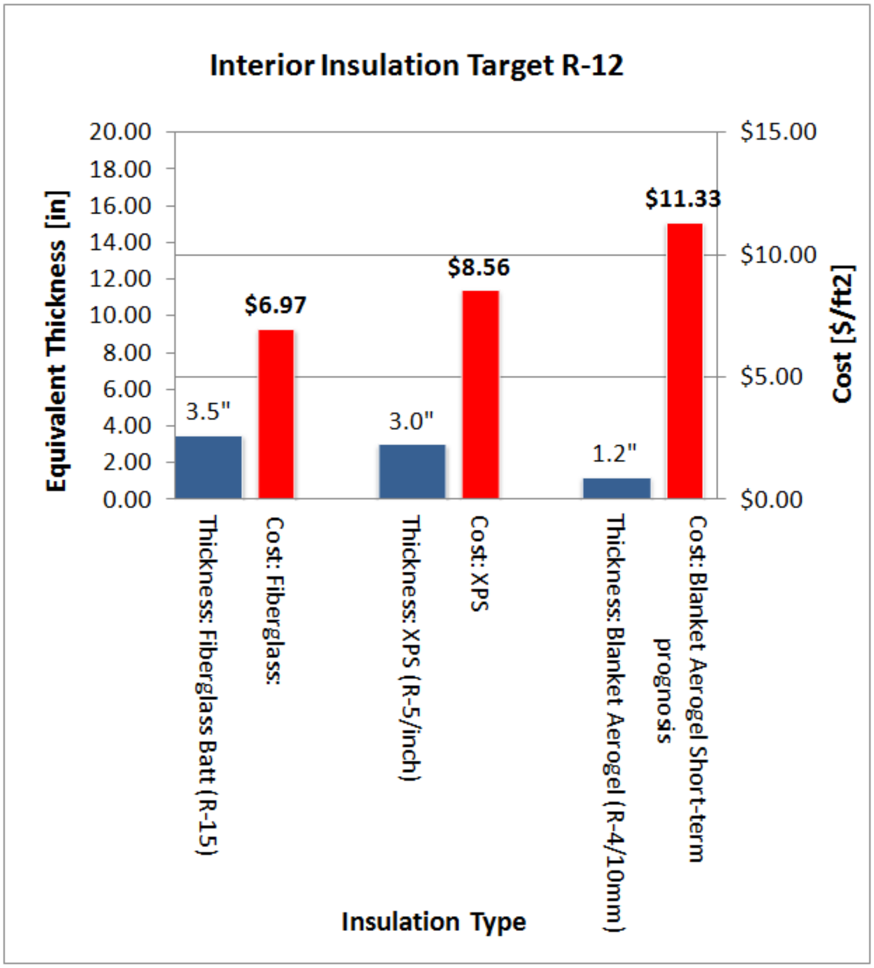
Figure 6. Equivalent thicknesses and total cost of aerogel and foam insulation techniques to retrofit the wall of a baseline house to achieve target R-values of (a) R-4, (b) R-20, and (c) R-35. The thicknesses in this figure are rounded from the manufactured thickness (rigid board with at least 1 in. thickness, spray foam with at least 0.5 in. thickness, and blanket aerogel with minimum of 10 mm thickness). The material cost was collected either from manufacturers or published data on the internet. Costs of the exterior wall finishes are not included in analysis for all considered cases of wall retrofits; only the insulation part of the retrofit strategy is analyzed.


Interior Insulation Target R-4
Equivalent Thickness [in]
Cost [$/ft2]
20
18
16
14
12
10
8
6
4
2
0
$10.00
$5.00
$0.00
3.5"
$6.83
1.5"
$4.03
0.4"
$4.33
Thickness: Fiberglass Batt 1 (R-13)
Cost: Fiberglass 1
Thickness: Fiberglass Batt 2 (R-5)
Cost: Fiberglass 2
Thickness: Blanket Aerogel (R-4/10mm)
Cost: Blanket Aerogel Short-term prognosis
Insulation Type

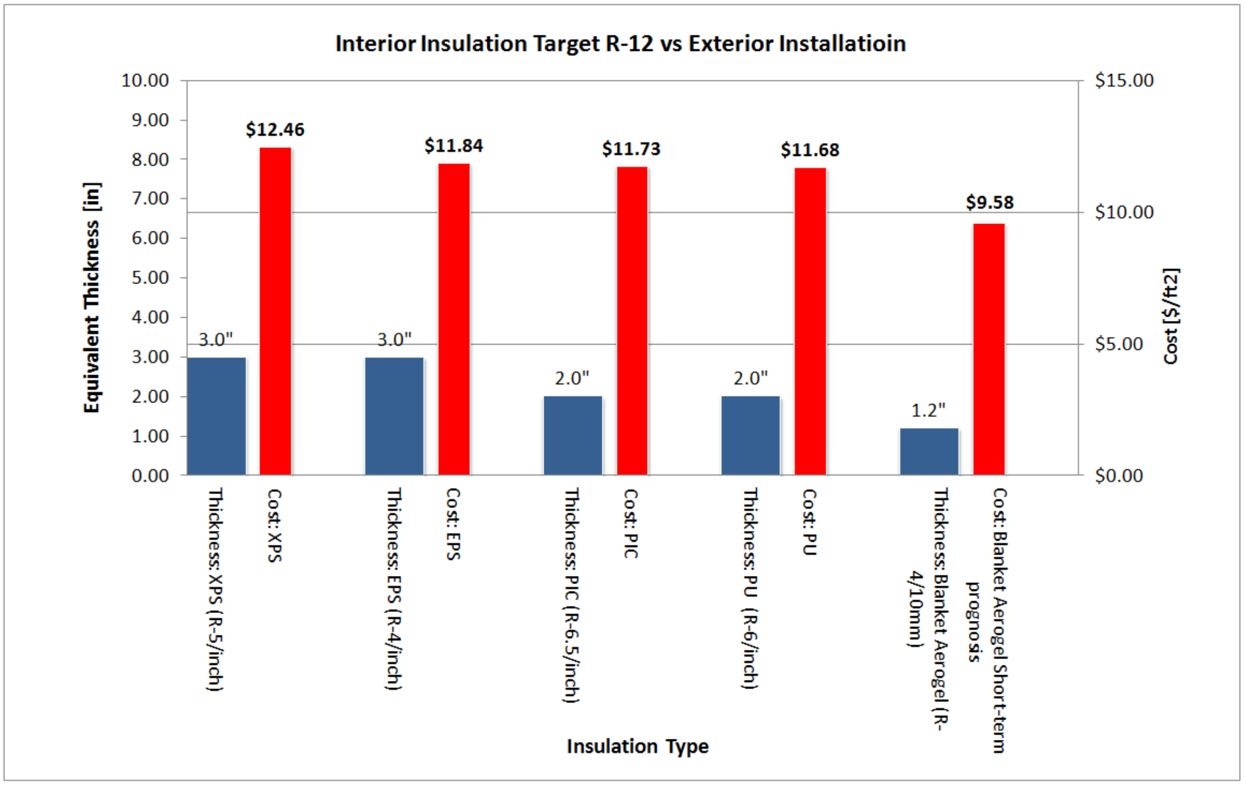
(a)


Interior Insulation Target R-8
Equivalent Thickness [in]
Cost [$/ft2]
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
$10.00
$5.00
$0.00
3.5"
$6.83
2.0"
$8.08
3.0"
$7.94
2.0"
$7.85
2.0"
$7.80
0.8"
$7.41
Thickness: Fiberglass Batt (R-13)
Cost: Fiberglass:
Thickness: XPS (R-5/inch)
Cost: XPS
Thickness: EPS (R-4/inch)
Cost: EPS
Thickness: PIC (R-6.5/inch)
Cost: PIC
Thickness: PU (R-6/inch)
Cost: PU
Thickness: Blanket Aerogel (R-4/10mm)
Cost: Blanket Aerogel Short-term prognosis
Insulation Type

(b)

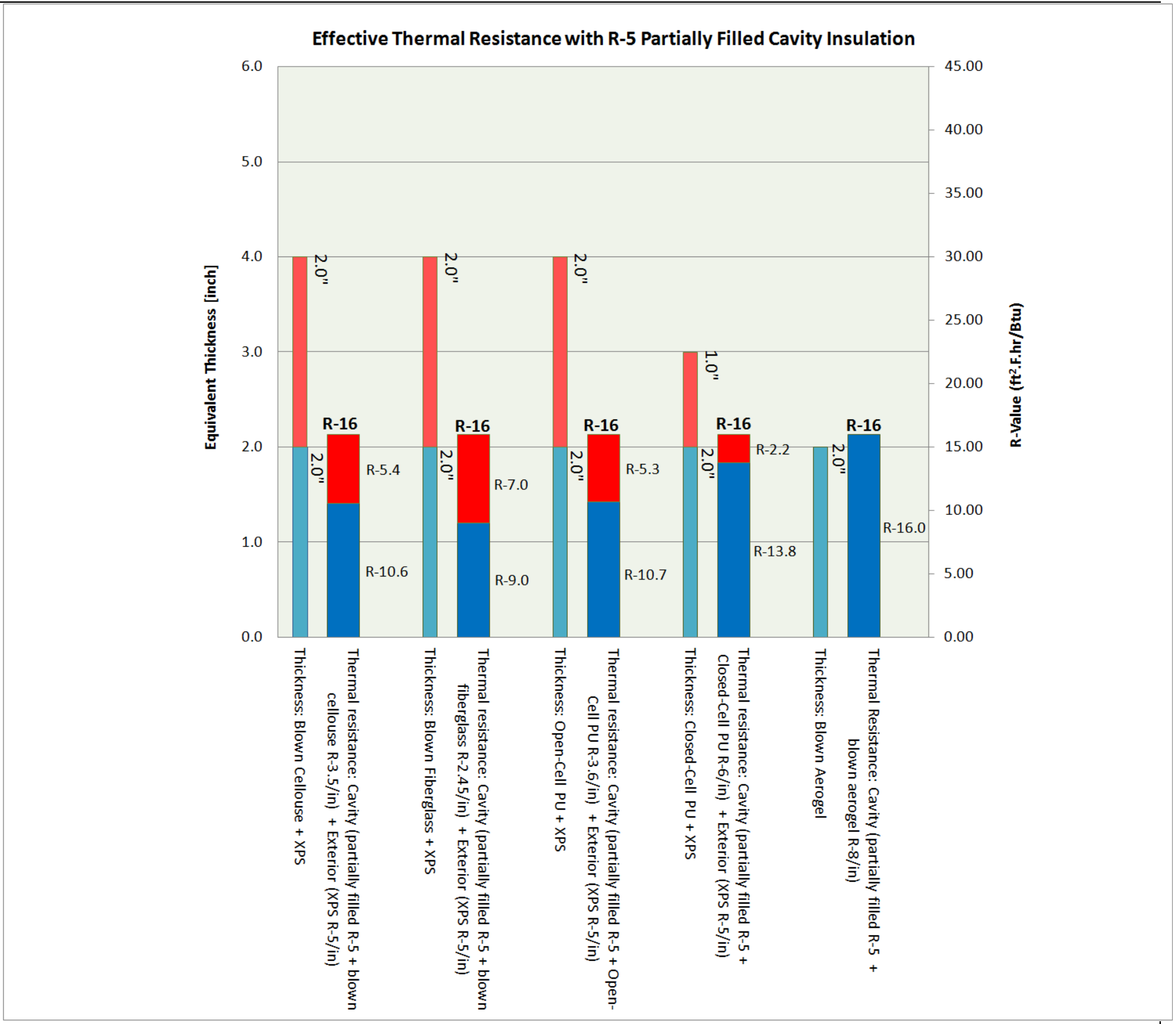

Interior Insulation Target R-12
Equivalent Thickness [in]
Cost [$/ft2]
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
$15.00
$10.00
$5.00
$0.00
3.5"
$6.97
3.0"
$8.56
1.2"
$11.33
Thickness: Fiberglass Batt (R-15)
Cost: Fiberglass:
Thickness: XPS (R-5/inch)
Cost: XPS
Thickness: Blanket Aerogel (R-4/10mm)
Cost: Blanket Aerogel Short-term prognosis
Insulation Type

(c)



(d)

Figure 7. Equivalent thicknesses and total cost of aerogel and conventional insulation techniques to retrofit the wall of a baseline house from interior to achieve target R-values of (a) R-4, (b) R-8, (c) R-12 (compared with interior installation case), and (d) R-12 (compared with exterior installation case). Blanket aerogel installed from the interior side on top of the existing gypsum board. Conventional insulations installed from interior. For the case of R-12, both interior and exterior installations analyzed and shown. The thicknesses in this figure are rounded values of the manufactured thickness (rigid board with at least 1 in. thickness, spray foam with at least 0.5 in. thickness and blanket aerogel with minimum of 3/8 in. thickness). The material cost was collected either from manufacturers or published data on the internet.



To achieve target R-values, we assumed XPS exterior installation. Aerogel, open cell PU, closed cell PU and XPS have R-values of R-8/in., R-3.6/in., R-6/in. and R-5/in., respectively. Blown cellulose has R-value between R-3.2 to R-3.8 per inch and blown fiberglass between R-2.2 and R-2.7/in. (http://www.energysavers.gov/your_home/insulation_airsealing/index.cfm/mytopic=11650). For this study, blown cellulose and blown fiberglass have R-values of R-3.5/in. and R-2.45/in., respectively. Note that the thermal resistance bar in the chart is composed of two parts. The blue part is an effective R-value of initial R-5 plus 2” conventional insulation (either blown cellulose, blown fiberglass, open-cell PU, closed-cell PU, or blown aerogel); the red part is the minimum required R-value to reach target R-16. Therefore, the total effective R-value of the cavity and XPS might exceed the minimum required R-16.

Figure 8. Equivalent thickness and thermal resistance of aerogel and conventional insulations installed in a 2 × 4 stud cavity with R-5 existing insulation to retrofit the wall of a baseline house. The team assumed the existing R-5 took approximately 1.5 in. thickness of the cavity and the remaining 2 in. is filled with blown cellulose, blown fiberglass, injected PU foam, or aerogel.

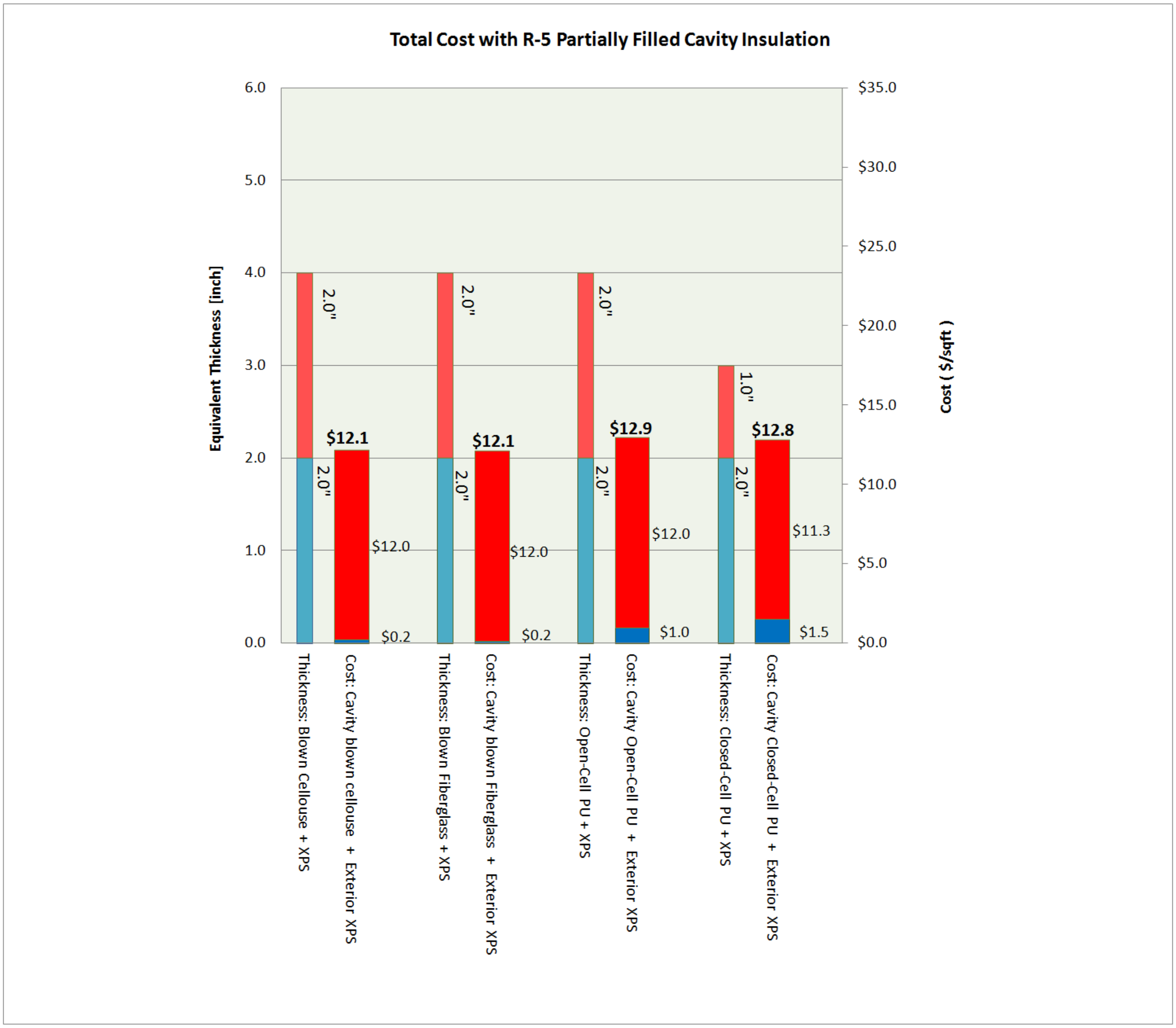


Figure 9. Equivalent thicknesses and total cost of XPS foam insulations installed into a 2 × 4 stud cavity that already has R-5 existing insulation to retrofit the wall of a baseline house. For comparison purposes, the team assumed the R-5 insulation already existing in the wall cavity took approximately 1.5 in. of the cavity and the remaining 2 in. is filled with aerogel. Based on this estimation, proposed installation of the blown aerogel into a 2 × 4 stud cavity would be cost competitive if its price would be lower than $12.1–$12.8/ft^2.

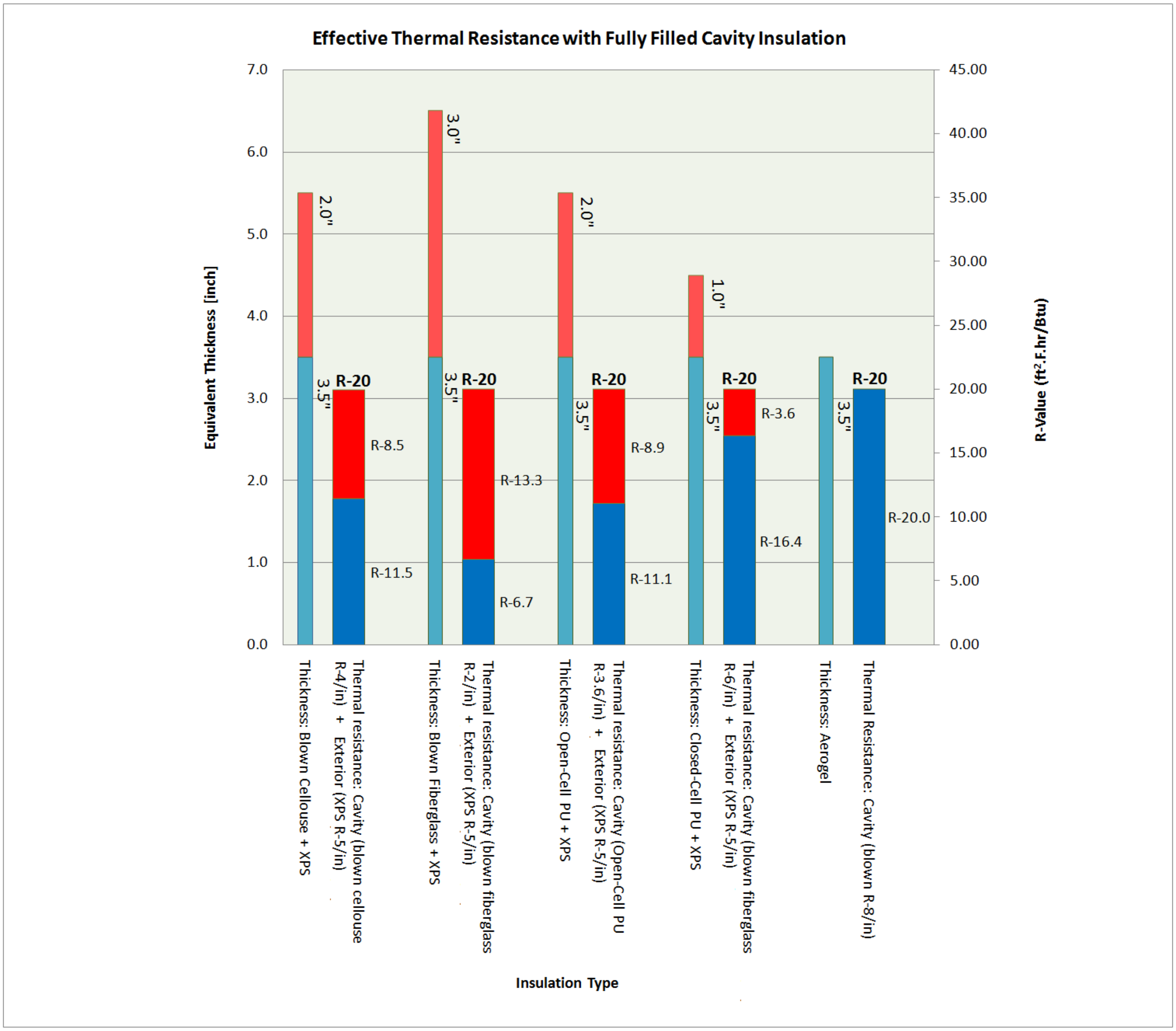


Figure 10 . Equivalent thickness and thermal resistance of aerogel and conventional insulations installed into an empty 2 × 4 stud cavity to retrofit the wall of a baseline house. The 3.5 in. stud cavity is filled with blown cellulose, blown fiberglass, injected PU foam, or aerogel. To reach the target R-values, the team assumed that exterior XPS foam was installed in addition to PU foam cavity injection. Aerogel, open cell PU, closed cell PU, and XPS have R-values of R-8/in., R-3.6/in., R-6/in., and R-5/in., respectively. Blown cellulose has an R-value between R-3.2 and R-3.8/in. and blown fiberglass between R-2.2 and R-2.7/in. (See http://www.energysavers.gov/your_home/insulation_airsealing/index.cfm/mytopic=11650 for more information). For this study, blown cellulose and blown fiberglass have R-values of R-3.5/in. and R-2.45/in., respectively.

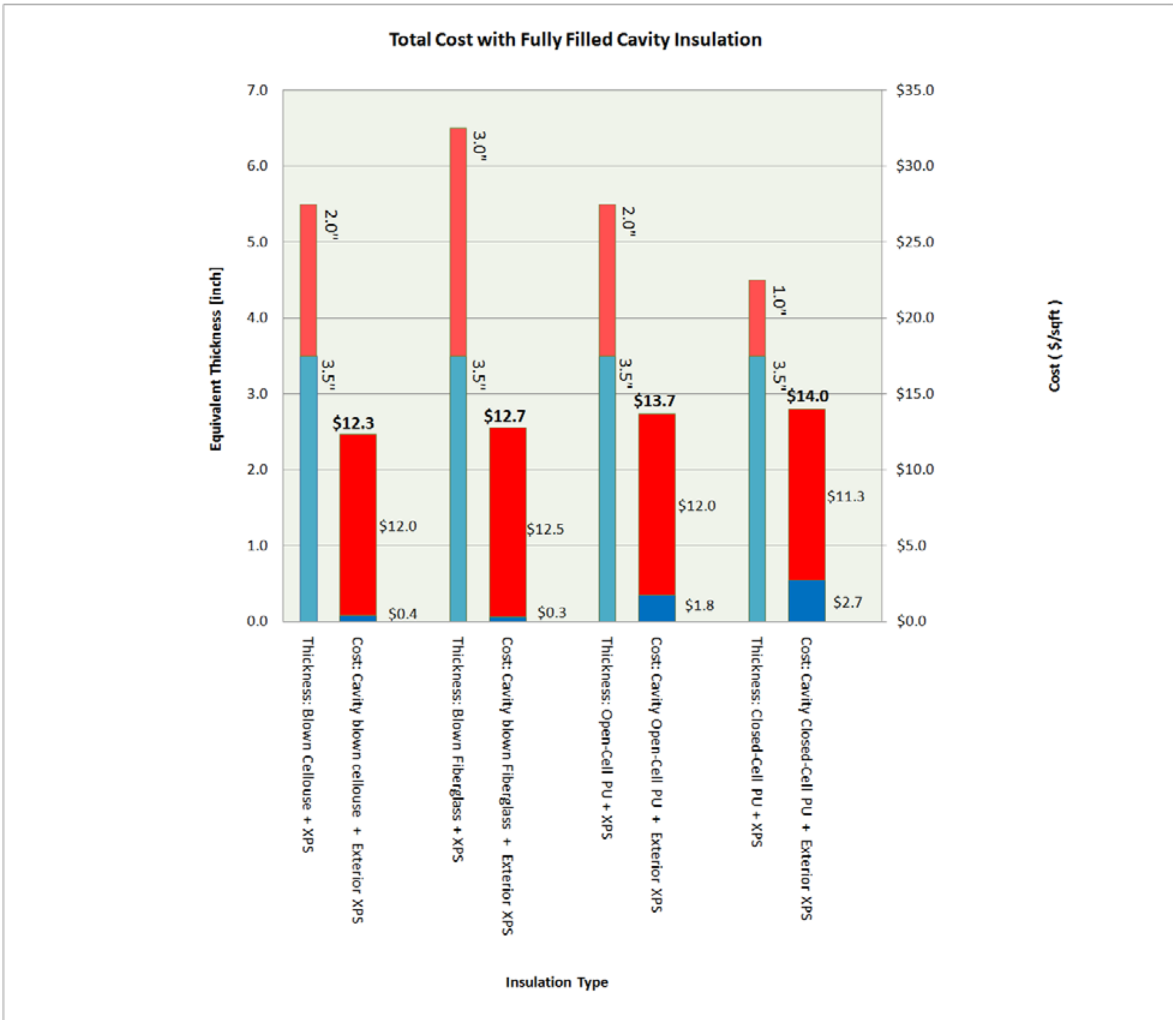
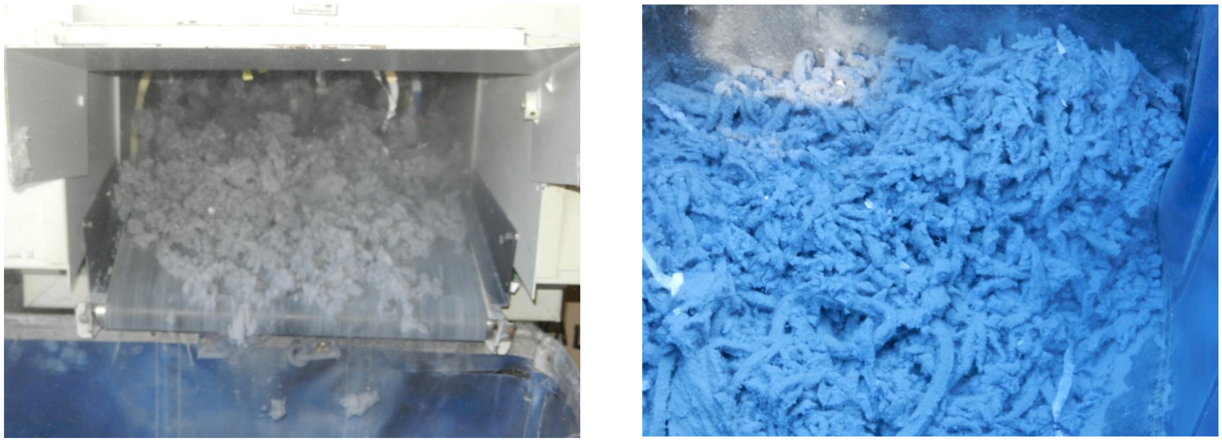


Figure 11. Equivalent thicknesses and total cost of aerogel and conventional insulations installed in empty 2 × 4 stud cavity to retrofit the wall of a baseline house. The 3.5 in. stud cavity is filled with blown cellulose, blown fiberglass, injected PU foam, or aerogel. To reach the target R-values, the team assumed XPS exterior installation in addition to PU cavity injection. Based on this estimation, proposed blown aerogel into a 2 × 4 stud cavity would be cost competitive if the price is within or lower than $12–$14/ft^2.



(a) (b)

Figure 12. Shredding of Spaceloft aerogel blankets: (a) finely chopped pieces of aerogel blanket as they exit the shredder, and (b) final product.

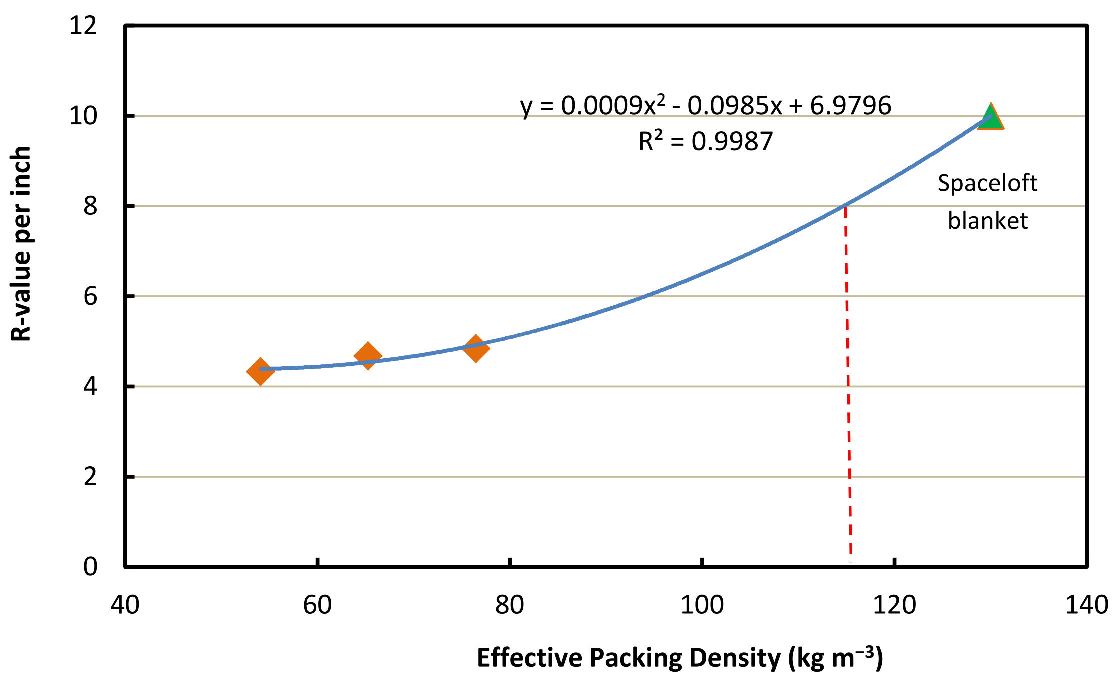


Figure 13. R-value per inch as a function of effective packing density for shredded aerogel samples (three leftmost data points). Data for Spaceloft aerogel blanket are included as well [Error! ookmark not defined.**] (rightmost data point). Literature data on the thermal performance of shredded aerogels are lacking. To develop an approximate relation between conductivity and packing density, the team measured thermal conductivity for three effective packing densities. Then a very approximate extrapolation was made between measured data and Spaceloft aerogel data to predict R-values in the intermediate density range. The red line marks the density value required to obtain R-value of 8/in.**

Table 1. Installed cost estimates for conventional and emerging insulation techniques to retrofit the wall of a baseline house. Aerogel or 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 ($/SqFt)																			Total Cost ($/SqFt)
Rigid Insulation	Removal of Exterior Cladding (vinyl siding) [1]	Furring [1]	Framing (2 × 4; OC 16)	Framing (2 × 6; OC 16)	Window Relocation for deep window wells[2]	Insulation Installation (material & labor) [3]	Insulation protection layers (2 XPS layers)	EIFS with 1/2" cement board sheathing and 2.5#/S.Y metal lath subtrate	Removal of shingles (two layers) [8]	Removal of OSB Deck [9]	Rafter extension (4 feet) [10]	Fascia Boards Installation [9]	Soffit Nailer [4]	Replace-ment of OSB Deck [9]	Replace ment of shingles [9]	Rake Overhang [5]	Building Kraft Paper [1]	Strapping Screws [11]	Installation of exterior cladding (vinyl siding) [1]	
XPS(7")	$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")	$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")	$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	Removal of Exterior Cladding (vinyl siding) [1]	Furring [1]	Framing (2 × 4; OC 16) [4]	Framing (2 × 6; OC 16) [4]	Window Relocation for deep window wells[2]	Insulation Installation (material & labor)[3]	Insulation protection layers (2 XPS layers)	EIFS with 1/2" cement board sheathing and 2.5#/S.Y metal lath subtrate	Removal of shingles (two layers) [8]	Removal of OSB Deck [9]	Rafter extension (4 feet) [10]	Fascia Boards Installation [4]	Soffit Nailer [4]	Replace-ment of OSB Deck [9]	Replace ment of shingles [9]	Rake Overhang [5]	Building Kraft Paper [1]	Strapping Screws [11]	Installation of exterior cladding (vinyl siding) [1]	
PU[1] (7.5")	$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")	$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")	$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
Comboined Cavity & Exterior Insulations	Removal of Exterior Cladding (vinyl siding) [1]	Furring [1]	Framing (2 × 4; OC 16) [4]	Framing (2 × 6; OC 16) [4]	Window Relocation for deep window wells	Cavity Insulation (material & labor) [12]	Insulation protection layers (2 XPS layers)	EIFS with 1/2" cement board sheathing and 2.5#/S.Y metal lath subtrate	Removal of shingles (two layers) [8]	Removal of OSB Deck [9]	Rafter extension (4 feet) [10]	Fascia Boards Installation [4]	Soffit Nailer [4]	Replace-ment of OSB Deck [9]	Replace ment of shingles [9]	Rake Overhang [5]	Building Kraft Paper [1]	Strapping Screws [11]	Installation of exterior cladding (vinyl siding) [1]	
Blown Cellulose (5 3/16") [1]	$0.59		-	-	-	$1.88	-	-	-	-	-	-	-	-	-	-	-	-	-	
XPS (3")	-	$0.92			-	$2.30	-	-	-	-	-	-	-	-	-	-	-	-	$7.79	$13.48

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

PU2: Closed cell polyurtheane 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.

PU3: Closed cell polyurtheane foam was applied in exterior furring.

VIP1 - Glacier Bay (according to http://passivehousetoronto.blogspot.com/2011/03/vacuum-insulated-panels-and-prices.html).

VIP2 - Dow Corning - Silica Core (based on price quotations from Dow Corning's).

VIP3 - Popular Mechanics (according to Popular Mechanics magazine, Oct 2009).
(See http://www.popularmechanics.com/home/improvement/3455301 for more information)

VIP4 – Richard T. Bynum (according to Richard T. Bynum, Technology and Engineering).

VIP5 - Dow Corning - Mineral Wool Core (according to Dow Corning's quoting).

VIP6 - University of Chicago (personal communication with Dr. Alan Feinerman, Associate Professor, University of Illinois at Chicago).

VIP7 - Thermal Vision (according to Thermal Vision company's quoting).

VIP8- Dow Corning Future price (estimated by Dow Corning).

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).
VIP11 - Sinoarch Shanghai Co. (according to company's quoting); http://www.alibaba.com/showroom/vip-insulation.html.
VIP12 - hangzhou Sanyou Dior Insulation Materials MFG Co.,Ltd (according to company's price quotation).
Aerogel1: According to Aspen Aerogel. 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).

Table 2. Total cost of aerogel and conventional insulation techniques to retrofit the wall of baseline house to exterior R-4 target value. Aerogel retrofit technique does not require all retrofit tasks because of low thickness. The retrofit tasks are not in order.

Target R-value	Insulation Type	Retrofit Tasks and Cost ($/SqFt)							Total Cost ($/SqFt)
Exterior R-4	Conventional Insulation	Furring [1]	Insulation Installation (material & labor) [2]	Adhesive to attach aerogel to subtrate	Removal of Exterior Cladding (vinyl siding) [1]	Building Kraft Paper [1]	Strapping Screws [4]	Installation of exterior cladding (vinyl siding) [1]	
	EPS (1.0")	$0.92	$0.98	-	$0.59	$0.22	$0.06	$7.79	$10.56
	Aerogel Blanket [5]	Furring [1]	Insulation Installation (material & labor) [3]	Adhesive to attach aerogel to subtrate [6]	Removal of Exterior Cladding (vinyl siding) [1]	Building Kraft Paper [1]	Strapping Screws [4]	Installation of exterior cladding (vinyl siding) [1]	
	Aerogel (0.4")	-	$3.26	$0.01	$0.59	$0.22	$0.06	$7.79	$11.93

[1] According to RSMeans Building Construction Cost Data 2011.

[2] According to RSMeans Building Construction Cost Data 2011; 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 in. + 1 in.). For PU, thermal bridging effect was taken into account while calculating required thickness to achieve the target R-value. This cost includes material and labor costs. The labor cost varies from $0.43/ft^2 to $0.47/ft^2, depending on insulation type.

[3] This cost is composed of $2.75/ ft^2 material cost and $0.51/ ft^2 labor cost; labor cost assumed the same as 1 in. rigid foam board installation cost from RSMeans Building Construction Cost Data 2011.

[4] According to http://www.bestmaterials.com/SearchResult.aspx?CategoryID=750.

[5] After conversation with aerogel manufacturers and reviewing cost data, the team assumed that in short-term prognosis, a cost of an R-4/10 mm blanket can be chosen at $2.75/ft^2.

[6] According to RSMeans Building Residential Cost Data 2011. Estimated based on $10.40/ 5 gal. and 18 (S.Y/gal.) coverage

Table 3. Total cost of aerogel and conventional insulation techniques to retrofit the wall of baseline house to exterior R-20 target value. Aerogel retrofit technique does not require all retrofit tasks because of low thickness. The retrofit tasks are not in order.

Target R-value	Insulation Type	Retrofit Tasks and Cost ($/SqFt)																Total Cost ($/SqFt)
Exterior R-20	Conventional Insulation	Furring [1]	Window Relocation for deep window wells[2]	Insulation Installation [3]	Adhesive to attach aerogel to substrate	Removal of shingles (two layers) [1]	Removal of OSB Deck [1]	Rafter extension (4 feet) [1]	Fascia Boards Installation [4]	Soffit Nailer [4]	Replacement of OSB Deck [1]	Replacement of shingles [1]	Rake Over hang [5]	Removal of Exterior Cladding (vinyl siding) [1]	Building Kraft Paper [1]	Strapping Screws [7]	Installation of exterior cladding (vinyl siding) [1]	
	XPS (4.0")	$0.92	$0.52	$3.51	-	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.59	$0.22	$0.16	$7.79	$14.45
	EPS (5.0")	$0.92	$0.52	$3.04	-	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.59	$0.22	$0.11	$7.79	$13.92
	PIC (3.0")	$0.92	$0.52	$2.68	-	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.59	$0.22	$0.12	$7.79	$13.57
	Aerogel Blanket [8]	Furring [1]	Window Relocation for deep window wells	Insulation Installation (material & labor) [6]	Adhesive to attach aerogel to substrate [9]	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 Over hang	Removal of Exterior Cladding (vinyl siding) [1]	Building Kraft Paper [1]	Strapping Screws [7]	Installation of exterior cladding (vinyl siding) [1]	
	Aerogel (2.0")	-	$0.52	$14.26	$0.01	-	-	-	-	-	-	-	-	$0.59	$0.22	$0.06	$7.79	$23.45

[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 ft^2 (total façade area of the base case house).
[3] According to RSMeans Building Construction Cost Data 2011; 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 in. + 1 in.). For PU, thermal bridging effect was taken into account while calculating required thickness to achieve the target R-value. This cost includes material and labor costs. The labor cost varies from $0.43/ft^2 to $0.47/ft^2, depending on insulation type.
[4] According to RSMeans Building Residential Cost Data 2011.
[5] According to William A. Zoeller from Steven Winter Associates, Inc., Norwalk, CT.
[6] This cost is composed of $13.75/ ft^2 material cost and $0.51/ ft^2 labor cost; labor cost assumed the same as 1 in. rigid foam board installation cost from RSMeans Building Construction Cost Data 2011.
[7] According to http://www.bestmaterials.com/SearchResult.aspx?CategoryID=750.
[8] After conversation with aerogel manufacturers and reviewing cost data, the team assumed that in short-term prognosis a cost of R-4/10mm blanket can be chosen at $2.75/ft^2.
[9] According to RSMeans Building Residential Cost Data 2011. Estimated based on $10.40/ 5 gal. adhesive for 18 (S.Y/gal.) coverage.

Table 4. Total cost of aerogel and conventional insulation techniques to retrofit the wall of baseline house to exterior R-35 target value. Aerogel retrofit technique does not require all retrofit tasks because of low thickness. The retrofit tasks are not in order.

Target R-value	Insulation Type	Retrofit Tasks and Cost ($/SqFt)																		Total Cost ($/SqFt)
	Conventional Insulation	Furring [1]	Framing (2 × 4; OC 16) [12]	Framing (2 × 6; OC 16) [12]	Window Reloca-tion for deep window wells [2]	Insula-tion Installa-tion (material & labor) [3]	Adhe-sive to attach aerogel to substrate	Removal of shingles (two layers) [4]	Removal of OSB Deck [5]	Rafter exten-sion (4 feet) [6]	Fascia Boards Installa-tion [4]	Soffit Nailer [1]	Replace-ment of OSB Deck [5]	Replace-ment of shingles [5]	Rake Over hang [7]	Removal of Exterior Cladding (vinyl siding) [1]	Building Kraft Paper [1]	Strapping Screws [8]	Installation of exterior cladding (vinyl siding) [1]	
	XPS (7.0")	$0.92	-	-	$0.52	$5.81	-	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.59	$0.22	$0.20	$7.79	$16.78
	EPS (9.0")	$0.92	-	-	$0.52	$5.04	-	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.59	$0.22	$0.20	$7.79	$16.01
	PIC (6.0")	$0.92	-	-	$0.52	$4.51	-	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.59	$0.22	$0.12	$7.79	$15.41
Exterior R-35	PU[1] (7.5")	-	$1.50	-	$0.52	$5.78	-	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.59	$0.22	$0.20	$7.79	$17.33
	PU[2] (7.5")	-	-	$1.91	$0.52	$5.78	-	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.59	$0.22	$0.20	$7.79	$17.74
	PU[3] (6.0")	$0.92	-	-	$0.52	$4.62	-	$0.04	$0.03	$0.129	$0.01	$0.01	$0.03	$0.09	$0.39	$0.59	$0.22	$0.12	$7.79	$15.52
	Aerogel Blanket [9]	Furring [1]	Framing (2 × 4; OC 16)	Framing (2 × 6; OC 16)	Window Relocation for deep window wells	Insula-tion Installa-tion (material & labor) [10]	Adh-esive to attach aerogel to substrate [11]	Removal of shingles (two layers)	Removal of OSB Deck	Rafter exten-sion (4 feet)	Fascia Boards Installation	Soffit Nailer	Replace-ment of OSB Deck	Replace-ment of shingles	Rake Over hang	Removal of Exterior Cladding (vinyl siding) [1]	Building Kraft Paper [1]	Strapping Screws	Installation of exterior cladding (vinyl siding) [1]	
	Aerogel (3.4")	-	-	-	$0.52	$25.26	$0.01	-	-	-	-	-	-	-	-	$0.59	$0.22	$0.06	$7.79	$34.45

PU1: Closed cell polyurethane foam was applied inside of 2 × 4 wood studs.

PU2: Closed cell polyurethane foam was applied inside of 2 × 6 wood studs.

Both cases the added studs are standing off a few inches from existing stud.

PU3: Closed cell polyurethane foam was applied in exterior furring.

[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 ft^2 (total façade area of the base case house).

[3] According to RSMeans Building Construction Cost Data 2011; 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 in. + 1 in.). For PU, thermal bridging effect was taken into account while calculating required thickness to achieve the target R-value. This cost includes material and labor costs. The labor cost varies from $0.43/ft^2 to $0.47/ft^2, depending on insulation type.

[4] 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).
[5] According to RSMeans Building Construction Cost Data 2011. Estimated the same way as [4].
[6] 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.
[7] According to William A. Zoeller from Steven Winter Associates, Inc., Norwalk, CT.
[8] According to http://www.bestmaterials.com/SearchResult.aspx?CategoryID=750.
[9] After conversation with aerogel manufacturers and reviewing cost data, the team assumed that in short-term prognosis, a cost of an R-4/10 mm blanket can be chosen at \$2.75/ft^2. Aerogel is adhered to the substrate.
[10] This cost is composed of \$24.75/ ft^2 material cost (nine layers of blanket aerogel \$2.75/ft^2 per layer) and \$0.51/ ft^2 labor cost; labor cost assumed the same as 1 in. rigid foam board installation cost from RSMeans Building Construction Cost Data 2011.
[11] According to RSMeans Building Residential Cost Data 2011. Estimated based on \$10.40/ 5 gal. adhesive for 18 (S.Y/gal.) coverage.
[12] According to RSMeans Building Residential Cost Data 2011.

Table 5. Total cost of aerogel and conventional insulation techniques to retrofit the wall of baseline house to interior R-4 target value. The aerogel retrofit technique does not require all retrofit tasks because of its lower thickness. The retrofit tasks are not in order.

Target R-value	Insulation Type	Retrofit Tasks and Cost ($/SqFt)									Total Cost ($/SqFt)
	Rigid Insulation	Framing (2 × 4; OC 16) [1]	Furring [1]	Window Interior Rearrangement [2]	Insulation Installation (material & labor) [3]	Adhesive to attach aerogel to substrate	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Readjustment of Radiators and pipes [5]	Living area loss by application of furring or 2 × 4 interior framing [6]	
Interior R-4 (vs. Interior Installation)	Fiberglass Batt 1[8]	$1.50	-	$0.24	$0.57	-	$0.15	$0.66	$1.04	$2.68	$6.83
	Fiberglass Batt 2[9]	-	$0.92	$0.24	$0.72	-	$0.15	$0.66	-	$1.34	$4.03
	Aerogel Blanket [10]	Framing (2 × 4; OC 16)	Furring [1]	Window Interior Rearrangement	Insulation Installation (material & labor) [7]	Adhesive to attach aerogel to substrate [11]	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Readjustment of Radiators and pipes	Living area loss by application of blanket aerogel [6]	
	Aerogel (0.4")	-	-	-	$3.26	$0.01	$0.15	$0.66	-	$0.25	$4.33

Fiberglass batt 2: 1 ½ in. thick and R-5.

[1] According to RSMeans Building Construction Cost Data 2011.

[2] Includes interior trim and casing and estimated based on RSMeans Building Residential Cost Data 2011.

[3] According to RSMeans Building Construction Cost Data 2011; 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 in. + 1 in.). For PU, thermal bridging effect was taken into account while caclulating required thickness to achieve the target R-value. This cost is composed of material and labor costs. The labor cost varies from $0.43/ft^2 to $0.47/ ft^2 depending on insulation type.

[4] According to RSMeans Building Residential Cost Data 2011.

[5] Assumed seven radiatiors for the base case house (one radiator for each two windows) and average cost of $180/radiator. According to http://answers.yahoo.com/question/index?qid=20080306132958AApZtBL and http://ths.gardenweb.com/forums/load/hvac/msg0219104426118.html.

[6] According to RSMeans Building Residential Cost Data 2011; the cost per square foot of living area of baseline house is $80.25. The leaving area loss = (furring/ framing/blanket aerogel thickness + 0.5 in. dry wall thickness) × 135 ft (base case house perimeter) × 2 floors × unit price (based on RS Means Building Residential Cost Data 2011 page 29) / total wall area (2,700 ft^2).

[7] This cost is composed of $2.75/ ft^2 material cost and $0.51/ ft^2 labor cost; labor cost assumed the same as 1 in. rigid foam board installation cost from RSMeans Building Construction Cost Data 2011.

[8] 3 ½ in. thick and R-13, according to RSMeans Building Construction Cost Data 2011. This is the minimum thickness of fiberglass batt available in the

market.
[9] The minimum fiberglass thickness available in the market is 3 ½ in. Less than this thickness is not common and is used just for odd jobs. For the sake of comparison, the cost of 1 ½ in. thick and R-5 was considered according to http://www.acehardwareoutlet.com/productdetails.aspx?sku=45791.
[10] After conversation with aerogel manufacturers and reviewing cost data, the team assumed that in short-term prognosis, a cost of an R-4/10 mm blanket can be chosen at $2.75/ft^2$.
[11] According to RSMeans Building Residential Cost Data 2011. Estimated based on $10.40/ 5 gal. and 18 (S.Y/gal.) coverage.

Table 6. Total cost of aerogel and conventional insulation techniques to retrofit the wall of baseline house to interior R-8 target value. The aerogel retrofit technique does not require all retrofit tasks because of its lower thickness. The retrofit tasks are not in order.

Target R-value	Insulation Type	Retrofit Tasks and Cost ($/SqFt)								Total Cost ($/SqFt)
Interior R-8 (vs. Interior Installation)	Rigid Insulation	Framing (2 × 4; OC 16) [1]	Window Interior Rearrangement [2]	Insulation Installation (material & labor) [3]	Adhesive to attach aerogel to substrate	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Readjustment of Radiators and pipes [5]	Living area loss by application of 2 × 4 interior framing [6]	
	Fiberglass Batt[8] (3.5")	$1.50	$0.24	$0.57	-	$0.15	$0.66	$1.04	$2.67	$6.83
	XPS (2.0")	$1.50	$0.24	$1.82	-	$0.15	$0.66	$1.04	$2.67	$8.08
	EPS (3.0")	$1.50	$0.24	$1.68	-	$0.15	$0.66	$1.04	$2.67	$7.94
	PIC (2.0")	$1.50	$0.24	$1.59	-	$0.15	$0.66	$1.04	$2.67	$7.85
	PU [11] (2.0")	$1.50	$0.24	$1.54	-	$0.15	$0.66	$1.04	$2.67	$7.80
	Aerogel Blanket [9]	Framing (2 × 4; OC 16)	Window Interior Rearrangement	Insulation Installation (material & labor) [7]	Adhesive to attach aerogel to substrate [10]	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Readjustment of Radiators and pipes	Living area loss by application of blanket aerogel [6]	
	Aerogel (0.8")	-	-	$6.01	$0.01	$0.15	$0.66	-	$0.58	$7.41

[1] According to RSMeans Building Construction Cost Data 2011.

[2] Includes interior trim and casing and estimated based on RSMeans Building Residential Cost Data 2011.

[3] According to RSMeans Building Construction Cost Data 2011; 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 in. + 1 in.). For PU, thermal bridging effect was taken into account while caclulating required thickness to achieve the target R-value. This cost is composed of material and labor costs. The labor cost varies from $0.43/ft^2 to $0.47/ ft^2 depending on insulation type.

[4] According to RSMeans Building Residential Cost Data 2011.

[5] Assumed seven radiators for the base case house (one radiator for each two windows and average cost of $180/radiator). According to http://answers.yahoo.com/question/index?qid=20080306132958AApZtBL and http://ths.gardenweb.com/forums/load/hvac/msg0219104426118.html.

[6] According to RSMeans Building Residential Cost Data 2011; the cost per square foot of living area of baseline house is $80.25. The leaving area loss = (framing/blanket aerogel thickness + 0.5 in. dry wall thickness) × 135 ft (base case house perimeter) × 2 floors × unit price (based on RS Means Building Residential Cost Data 2011, page 29) / total wall area (2,700 ft^2).
[7] This cost is composed of $5.50/ ft^2 material cost and $0.51/ ft^2 labor cost; labor cost assumed the same as 1 in. rigid foam board installation cost from RSMeans Building Construction Cost Data 2011.
[8] 3 ½ in. thick and R-13, according to RSMeans Building Construction Cost Data 2011. This is the minimum thickness of fiberglass batt available in the market.
[9] After conversation with aerogel manufacturers and reviewing cost data, the team assumed that in short-term prognosis, a cost of an R-4/10 mm blanket can be chosen at $2.75/$ft^2$.

[10] According to RSMeans Building Residential Cost Data 2011. Estimated based on $10.40/ 5 gal. adhesive for 18 (S.Y/gal.) coverage.

[11] Required tackiness to reach effective R-8.

Table 7. Total cost of aerogel and conventional insulation techniques to retrofit the wall of baseline house from the interior side to a target insulation of R-12. The aerogel retrofit technique does not require all retrofit tasks because of its lower thickness. The retrofit tasks are not in order.

Target R-value	Insulation Type	Retrofit Tasks and Cost ($/SqFt)								Total Cost ($/SqFt)
Interior R-12 (vs. Interior Installation)	Rigid Insulation	Framing (2 × 4; OC 16) [1]	Window Interior Rearrangement [2]	Insulation Installation (material & labor) [3]	Adhesive to attach aerogel to substrate	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Readjustment of Radiators and pipes [5]	Living area loss by application of 2 × 4 interior framing [6]	
	Fiberglass Batt[8] (3.5")	$1.50	$0.24	$0.71	-	$0.15	$0.66	$1.04	$2.67	$6.97
	XPS [11] (3.0")	$1.50	$0.24	$2.30	-	$0.15	$0.66	$1.04	$2.67	$8.56
	Aerogel Blanket [9]	Framing (2 × 4; OC 16)	Window Interior Rearrangement	Insulation Installation (material & labor) [7]	Adhesive to attach aerogel to substrate [10]	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Readjustment of Radiators and pipes	Living area loss by application of blanket aerogel [6]	
	Aerogel (1.2")	-	-	$8.76	$0.01	$0.15	$0.66	-	$1.75	$11.33

[1] According to RSMeans Building Construction Cost Data 2011.
[2] Includes interior trim and casing and estimated based on RSMeans Building Residential Cost Data 2011.
[3] According to RSMeans Building Construction Cost Data 2011; 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 in. + 1 in.). For PU, thermal bridging effect was taken into account while calculating required thickness to achieve the target R-value. This cost is composed of material and labor costs. The labor cost varies from $0.43/ft^2 to $0.47/ ft^2 depending on insulation type.
[4] According to RSMeans Building Residential Cost Data 2011.
[5] Assumed seven radiators for the base case house (one radiator for each two windows) and average cost of $180/radiator. According to http://answers.yahoo.com/question/index?qid=20080306132958AApZtBL and http://ths.gardenweb.com/forums/load/hvac/msg0219104426118.html.
[6] According to RSMeans Building Residential Cost Data 2011, the cost per square foot of living area of baseline house is $80.25. The leaving area loss = (framing/blanket aerogel thickness + 0.5 in. dry wall thickness) × 135 ft (base case house perimeter) × 2 floors × unit price (based on RS Means Building

Residential Cost Data 2011, page 29) / total wall area (2,700 ft^2).
[7] This cost is composed of $8.25/ ft^2 material cost and $0.51/ ft^2 labor cost; labor cost assumed the same as 1 in. rigid foam board installation cost from RSMeans Building Construction Cost Data 2011.
[8] 3 ½ in. thick and R-15, to account for thermal bridging effect of the studs. The cost is according to RSMeans Building Construction Cost Data 2011.
[9] After conversation with aerogel manufacturers and reviewing cost data, the team assumed that in short-term prognosis, a cost of an R-4/10 mm blanket can be chosen at $2.75/$ft^2$.
[10] According to RSMeans Building Residential Cost Data 2011. Estimated based on $10.40/ 5 gal. adhesive for 18 (S.Y/gal.) coverage.
[11] 3 in. thick and R-15, to account for thermal bridging effect of the studs. The cost is according to RSMeans Building Construction Cost Data 2011.

Table 8. Total cost of aerogel and conventional insulation techniques to retrofit the wall of baseline house to interior R-12 target value. Aerogel retrofit technique does not require all retrofit tasks because of its low thickness. The retrofit tasks are not in order.

Target R-value	**Insulation Type**	**Retrofit Tasks and Cost ($/SqFt)**										**Total Cost ($/SqFt)**
Interior R-12 (vs. Exterior Installation)	Conventional Insulation	Furring [1]	Window Relocation for deep window wells [2]	Insulation Installation (material & labor) [3]	Adhesive to attach aerogel to substrate	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Removal of Exterior Cladding (vinyl siding) [1]	Building Kraft Paper [1]	Strapping Screws [5]	Installation of exterior cladding (vinyl siding) [1]	
	XPS (3.0")	$0.92	$0.52	$2.30	-	-	-	$0.59	$0.22	$0.12	$7.79	$12.46
	EPS (3.0")	$0.92	$0.52	$1.68	-	-	-	$0.59	$0.22	$0.12	$7.79	$11.84
	PIC (2.0")	$0.92	$0.52	$1.59	-	-	-	$0.59	$0.22	$0.10	$7.79	$11.73
	PU [6] (2.0")	$0.92	$0.52	$1.54	-	-	-	$0.59	$0.22	$0.10	$7.79	$11.68
	Aerogel Blanket [7]	Furring	Window Relocation for deep window wells	Insulation Installation (material & labor) [8]	Adhesive to attach aerogel to substrate [9]	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Removal of Exterior Cladding (vinyl siding)	Building Kraft Paper	Strapping Screws	Installation of exterior cladding (vinyl siding)	
	Aerogel (1.2")	-	-	$8.76	$0.01	$0.15	$0.66	-	-	-	-	$9.58

[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 ft^2 (total façade area of the base case house).
[3] According to RSMeans Building Construction Cost Data 2011, 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 in. + 1 in.). For PU, thermal bridging effect was taken into account while caclulating required thickness to achieve the target R-value. This cost includes material and labor costs. The labor cost varies from $0.43/$ft^2$ to $0.47/$ft^2$, depending on insulation type.

[4] According to RSMeans Building Residential Cost Data 2011.
[5] According to http://www.bestmaterials.com/SearchResult.aspx?CategoryID=750.
[6] Closed cell polyurethane foam was applied in extrior furring.
[7] After conversation with aerogel manufacturers and reviewing cost data, we assumed that in short-term prognosis, a cost of an R-4/10 mm blanket can be chosen at $2.75/ft^2.
[8] This cost is composed of $8.25/ ft^2 material cost and $0.51/ ft^2 labor cost; labor cost assumed the same as 1 in. rigid foam board installation cost from RSMeans Building Construction Cost Data 2011.
[9] According to RSMeans Building Residential Cost Data 2011. Estimated based on $10.40/ 5 gal. adhesive for 18 (S.Y/gal.) coverage.

Table 9. Total cost of aerogel and foam insulation techniques to retrofit the wall of baseline house to blown R-16 target value. The aerogel retrofit technique does not require all retrofit tasks because of its lower thickness. Required thicknesses were calculated based on effective R-value of cavity insulations. The retrofit tasks are not in order.

Target R-value	Insulation Type	Retrofit Tasks and Cost ($/SqFt)							Total Cost ($/SqFt)
	Application of conventional insulation into 2 × 4 Studs, 16 o.c. in conjunction with exterior XPS	Exterior Furring [1]	Insulation Installation (material & labor) [1]	Window Relocation for deep window wells [2]	Removal of exterior cladding (Vinyl siding)[1]	Building Kraft Paper [1]	Installation of exterior cladding (Vinyl siding)[1]	Strapping Screws [3]	
Blown R-16 (into Partially Insulated R-5 Cavity)	Blown Cellulose (2")[4]	-	$0.23	-	-	-	-	-	$12.19
	Exterior XPS (2")	$0.92	$1.82	$0.52	$0.59	$0.22	$7.79	$0.10	
	Blown Fiberglass(2")[4]	-	$0.16	-	-	-	-	-	$12.12
	Exterior XPS (2")	$0.92	$1.82	$0.52	$0.59	$0.22	$7.79	$0.10	
	Open-cell PU (2")[4]	-	$1.00	-	-	-	-	-	$12.96
	Exterior XPS (2")	$0.92	$1.82	$0.52	$0.59	$0.22	$7.790	$0.10	
	Closed-cell PU (2")[4]	-	$1.54	-	-	-	-	-	$12.85
	Exterior XPS(1")	$0.92	$1.21	$0.52	$0.59	$0.22	$7.79	$0.06	

[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 ft^2 (total façade area of the base

case house).
[3] According to http://www.bestmaterials.com/SearchResult.aspx?CategoryID=750.
[4] Effective R-value after taking into account thermal bridging effect.

Table 10. Total cost of aerogel and foam insulation techniques to retrofit the wall of baseline house to blown R-20 target value. The aerogel retrofit technique does not require all retrofit tasks because of its lower thickness. The retrofit tasks are not in order.

Target R-value	Insulation Type	Retrofit Tasks and Cost ($/SqFt)							Total Cost ($/SqFt)
	Application of conventional insulation into 2 × 4 Studs, 16 o.c. in conjunction with exterior XPS	Exterior Furring [1]	Insulation Installation (material & labor) [1]	Window relocation for deep window wells [2]	Removal of exterior cladding (Vinyl siding) [1]	Building Kraft Paper [1]	Installation of exterior cladding (Vinyl siding) [1]	Strapping Screws [3]	
Blown R-20 (into Empty Cavity)	Blown Cellulose [4] (2.0")	-	$0.40	-	-	-	-	-	$12.36
	Exterior XPS (2.0")	$0.92	$1.82	$0.52	$0.59	$0.22	$7.79	$0.10	
	Blown Fiberglass[4] (2.0")	-	$0.28	-	-	-	-	-	$12.74
	Exterior XPS (2.0")	$0.92	$2.30	$0.52	$0.59	$0.22	$7.79	$0.12	
	Open-cell PU [4] (2.0")	-	$1.75	-	-	-	-	-	$13.71
	Exterior XPS (2.0")	$0.92	$1.82	$0.52	$0.59	$0.22	$7.790	$0.10	
	Closed-cell PU (2.0")[4]	-	$2.70	-	-	-	-	-	$14.00
	Exterior XPS (1.0")	$0.92	$1.21	$0.52	$0.59	$0.22	$7.79	$0.06	

[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 ft^2 (total façade area of the base case house).
[3] According to http://www.bestmaterials.com/SearchResult.aspx?CategoryID=750.
[4] Effective R-value after taking into account thermal bridging effect.

Table 11. Thermal performance test data for aerogel samples. Data for Spaceloft aerogel blanket are taken from reference listed in footnote Error! Bookmark not defined.**.**

Density ($kg\ m^{-3}$)	Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)	R-Value/in.
130	0.014	10.00
76	0.030	4.84
65	0.031	4.68
54	0.033	4.33

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