Aerogel for Thermal Insulation of Interior Wall Retrofits in Cold Climates

Nitin C. Shukla, Ali Fallahi and Jan Kosny
Fraunhofer Center for Sustainable Energy Systems, Cambridge, MA 02141

Steve Harasim and Chris Blair
Aspen Aerogels Inc., Northborough, MA 01532

Abstract

In this paper, we investigate the economic viability of applying aerogels to supplement (in specific situations) existing building thermal insulation materials for retrofit projects. In the first part of this study, we present a general overview on aerogel synthesis process. In the second part, we evaluate the potential cost-effectiveness of aerogels as thermal insulation for internal wall retrofit applications. We estimate cost for several scenarios where aerogel blankets with different target R-values were installed from the interior side on top of the gypsum board. We further compare these estimates with retrofit costs associated with the application of conventional building insulations on the interior surface of the wall to achieve similar thermal performances. For a target value of R-4, our cost analysis shows that significant savings of ~25% can be achieved employing aerogel method compared to interior conventional insulation method using fiber glass. For a target value of R-8, we determine that aerogel method is cost effective compared to the current price range of conventional insulation methods except the fiber glass method. In addition, we find that for a target value R-12, the aerogel method is ~18-23% less expensive compared to the cases where the conventional insulation is applied on the exterior surface of the wall.

1. Introduction

In retrofit building projects, aerogels are promising candidates for potential replacement of conventional building thermal insulations due to their very low thermal conductivity. Aerogels were invented by Samuel Stephens Kistler in 1931. They consist of a gel that has had its liquid component replaced by air—in fact, the material is 99% air by volume. Due to its micro/nano-porous structure, aerogels have considerably higher thermal resistivity values of ~R-10 per inch compared to the commonly used plastic foams such as XPS (apr. R-5 per inch), EPS (apr. R-4 per inch), PIC (apr. R-6.5 per inch), and PU (apr. R-6 per inch). They are fire resistant, light weight, non-toxic and water repellent; highly desirable properties for a building thermal insulating material.

General opinion is today, that due to relatively low production volumes and high capital production costs, aerogels are currently more expensive than traditional foam insulation materials. At present, three U.S. companies, Aspen Aerogel, Cabot, and American Aerogel have commercial products available in the market, and their production volumes are increasing. Meanwhile, ongoing research activities seek to achieve dramatic cost reductions in production of high-performance insulation. If these efforts are successful, aerogels may become cost-competitive with existing thermal insulation technologies within the next few years. One market research report indicates that aerogels will find a small but profitable niche in thermal envelope applications, with a market size of approximately $230 million by year 2020 [1].

In this study, we present results of the cost analysis for retrofit applications where aerogel blankets are installed from the interior side, then compare the price with conventional insulation cases.

2. Production of Aerogel Insulation

Aerogel production has remained a costly affair mainly due to high prices of raw materials and relatively lower production volumes. Traditionally, aerogel synthesis involves the following three steps [2]:

2.1. Sol-Gel Preparation

The gel is prepared using silicon precursors, such as tetramethylorthosilicate (TMOS), tetraethylorthosilicate (TEOS), polyethoxydisiloxane (PEDS), methyltriethoxysilane (MTES), silicon alkaoxide, etc.

2.2. 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 production phase, the batch processing step may increase product cost due to increased process line downtime and frequent stopping/starting of the production line. A continuous process is desirable because it helps to increase output. However, as with any multi-step process, the individual step only adds time to the overall process if it is the bottleneck. Since aging is not the capital intensive part of the process, larger aging vessels can be used to reduce the process time for this step.

2.3. Gel Drying

In this step, the liquid inside the gel network is removed using a liquid to gas phase change process. However, due to the surface tension of the liquid in contact with the solid, the liquid changing phase tends to pull the gel network along with it. This causes the gel network to shrink and collapse. To retain the integrity of the gel structure during the drying process, the aged gel is brought to supercritical conditions. Under the supercritical conditions, surface tension vanishes as there is no distinct liquid-vapor phase boundary. The supercritical conditions may be realized either at low or high temperatures depending on the liquid (CO_2, ethanol etc.), but high pressures are always required.

As-produced aerogels are fragile and unsuitable for use in any practical application unless they are reinforced with glass fiber, mineral fiber, carbon fiber etc. or cross-linked with polymers [3]. Although the reinforcement process provides mechanical strength and flexibility to the aerogel, it may result in an undesirable increase in the thermal conductivity and density of the resulting aerogel composite [4,5]. If the mechanical requirements for the aerogel application permit, the thermal conductivity increase might be minimized by using lower volume fractions of inferior thermal conductivity fibers. IR opacifiers, such as carbon black, titanium oxide, and iron oxide, with suitable fiber diameters may also be added during the sol-gel process to reduce the radiative part of the thermal conductivity [6]. The radiative contribution can be further reduced by using IR opacified fibers, such as PET fibers coated with carbon black.

3. Retrofit and Insulating Techniques

High R-value building envelopes reduce energy consumption for space heating and cooling in addition to providing thermal comfort for occupants [7]. Advanced framing and exterior insulating sheathings can significantly improve thermal continuity of insulation, resulting in higher R-values for walls [8]. However, very often, buildings have numerous space constraints for wall cavity or exterior installations of insulations, particularly in retrofit projects. Also, very thick building envelopes are not desirable due to several issues, such as indoor floor space reductions for internal insulation applications, zoning regulations in case of the exterior foam sheathing, a common need for alteration of window and door openings, architectural restrictions, and material usage [9].

To achieve the highest possible thermal insulation resistance within existing space limitations of retrofit projects, new thermal insulation materials with low thermal conductivity, such as aerogels, are promising alternatives to conventional insulation materials. As mentioned before, the main barrier to application of aerogel insulation is its higher cost.

In this section of the paper, we compare the current cost of wall retrofit projects using aerogel and conventional insulation approaches. To estimate the cost, different aerogel configurations—both interior and exterior installations—are considered. In addition, we propose a new, quick and simple application of aerogel into the stud cavities for retrofit projects and provide an estimated price within which this new application of aerogel might be cost competitive with conventional insulations.

3.1. Retrofit Cost Estimation

The total cost[1] to retrofit the wall of a baseline house[2] with conventional insulations, and aerogels are estimated and compared using RS Means Cost Data [10].

To estimate the cost of a wall retrofit with aerogel, we assumed the cases where aerogel blankets are installed from the interior side, on top of the existing gypsum board. Aerogel becomes an attractive candidate for interior installation since it is non-toxic, air permeable, and provides high R-value in thinner layers. Three target R-values are assessed: R-4, R-8, and R-12. These were selected as practical and cost effective approaches for an interior retrofit. The three R-value targets reflect 1, 2, and 3 layers of aerogel blankets, respectively (10 mm thick with thermal resistance of R-4 per layer). The main tasks required in this retrofit approach are insulation installation, readjustment of electric outlets and installation of gypsum board. This is a quick retrofit method that requires limited alteration of the interior space (corners, electrical, heating unit re-location, and window and door openings) and minimizes occupant disruption. This method can be an excellent solution for internal retrofits of vaulted ceilings, cathedralized attics, knee walls, and exterior walls when exterior insulation is more costly or is not possible for technical reasons or code regulations. To evaluate the cost effectiveness of this strategy, we compare the cost with the addition of conventional insulation installed on the interior wall surface. The conventional insulations considered are fiber glass batts, spray applied foam and foam board insulations. The conventional retrofit method mainly requires tasks such as new internal wall frame build up, interior rearrangement of fenestration openings, and readjustment of radiators in addition to tasks mentioned for aerogel retrofit method.

Additionally, we compare the cost of adding conventional insulation to the exterior wall surface for the case of a target value of R-12. This approach involves mainly the following tasks: removal of exterior cladding, installing of house wrap, strapping screws, insulation installation, furring, alterations of fenestration openings, and installation of exterior vinyl cladding.

---

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

[2] 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 28.

To estimate the total cost of each retrofit strategy, the following steps are followed:

1) A target R-value is estimated.
2) Equivalent thickness is calculated (required thickness) to achieve the target R-value.
3) A list of required retrofit tasks is determined for each strategy. The retrofit work for different insulation types and equivalent thicknesses includes a series of tasks, from alteration of the existing wall openings and roof overhangs to installation of the insulation, and exterior cladding.
4) The cost associated with each retrofit task is estimated.

The calculated equivalent thicknesses for conventional insulations are shown in Figure 1; the costs were estimated and compared in Table I- IV.

3.2. Cost Comparisons

The comparisons presented in this paper are based on the current cost of commercially available aerogel in the U.S. market and short-term cost reduction predictions. We estimate that in the U.S. the cost of a 10 mm thick aerogel blanket of R-4 per 10 mm will be between \$2.50- \$3.00/ft^2 in the near future. For the purposes of this evaluation, a price of \$2.75/ft^2 was used which might be slightly different from the present U.S. market prices. We first estimated the cost of aerogel method to achieve target values of R-4, R-8 and R-12; then compared with conventional insulation methods where conventional insulations are installed on the interior side of a retrofitted wall.

Figure 1 (a) shows results for aerogel method to achieve a target value of R-4. For this case, we considered fiber glass batts application since it was the most popular low-cost internal insulation strategy acceptable from the long-term hygrotermal performance perspective. It was also most-likely the cheapest choice among all the conventional insulations mentioned previously (with overall R-value over 2 times higher than the target of R-4 of aerogel blankets). Interior application of conventional insulation requires installing 3.5" deep wood framing, then filling the frame with the insulation. As fiber glass batts are available with a minimum thickness of 3.5", a fiber glass batts with ~R-3.7 per inch will offer a total thermal resistance of R-13. Considering thermal bridging effects through the frame and other components, the effective resistance would be ~R-9 to R-10 [11]. Our cost estimates show that the aerogel method for a target value of R-4 is not only cost competitive with the cheapest conventional choice i.e. fiber glass batt insulation method, but has ~25% cost advantage. However, it is good to remember that due to differences in R-values, both technologies are not fully thermally equivalent.

Figure 1 (b) shows the results for the aerogel method to achieve a target value of R-8. The thickness of conventional insulations was selected such that the thermal resistance was closest to the target R-value. The cost calculations show that the aerogel method is only 2.7, 5, 6.4 and 7.2% more expensive compared to the XPS, EPS, PIC and PU insulation methods, respectively. However, the aerogel method costs as much as 27% more than the fiber glass method.

Figure 1 (c) shows the results for the aerogel method to achieve a target value of R-12. However, in this case we find that the aerogel method is ~23 and 73% more expensive than retrofits with foam and fiber insulations, respectively.

We also compared the aerogel method for a target R-12 with the conventional method where conventional insulation is applied on the exterior surface of the wall. The results are shown in Figure 1(d). We find that in this case the aerogel method becomes ~18 to 23% less expensive compared to the conventional insulation cases.

4. Conclusions

Although at present, aerogels are expensive materials due to the high costs associated with the raw materials and synthesis processes, there is a significant potential to cut down the cost by employing the following two strategies:

1) By reducing the cost associated with processing materials. This will involve using less expensive source materials and processing solvents, and utilizing lesser amount of reinforcement to achieve a fair reduction in the production cost.
2) By decreasing the production process related costs by implementing a continuous production methodology and employing APD.

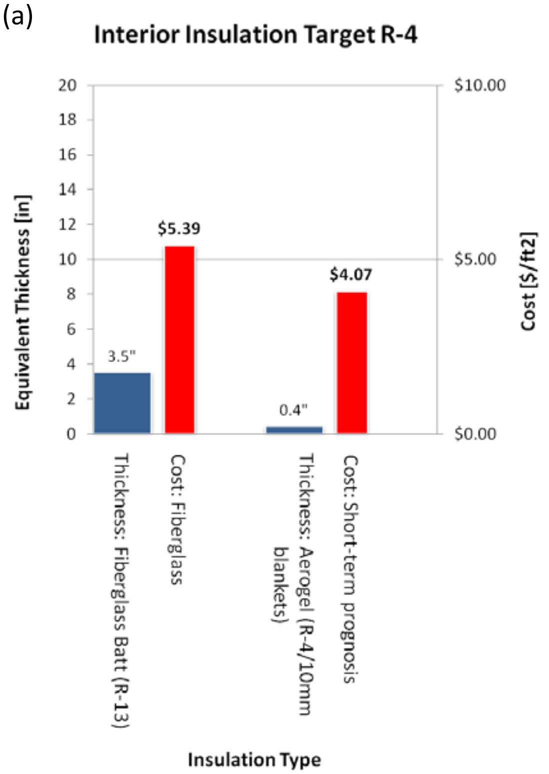
We believe that even today, aerogels may become a cost-effective option for providing local insulation and mitigating thermal bridging effects in building envelope such as in window and steel frames, and complex architectural details.

We estimated costs for both aerogel and conventional insulation applications in various building retrofit scenarios. Due to their high R-values, aerogels occupy significantly less space than conventional insulations; therefore, we considered applying aerogels on the interior side of the wall surface. Three target R-values were considered in the cost analysis: R-4, R-8 and R-12 that correspond to one, two and three layers of 10 mm thick aerogel blankets, respectively. Based on the current cost of the aerogel, we found that for a target value of R-4, the wall insulation retrofits utilizing aerogel is ~25% cheaper than the R-13 fiber glass batts and 2x4 interior wood framing option. For a target R-value of R-8, the aerogel method is cost competitive to most of conventional insulations, except the fiber glass which is ~27% less expensive. However, for a target value of R-12, the cost of the aerogel method is 23-73% higher than the current conventional fiber and foam insulation costs. An interesting finding is that the aerogel method saves ~18-23% of the total installed cost when compared to the conventional methods (where insulation is applied on the exterior surface of the wall). Since these insulations represent the most-common cases of the exterior residential wall retrofits, it might be good to start considering a thin layer of the interior aerogel insulation as a serious competition for these exterior applications.

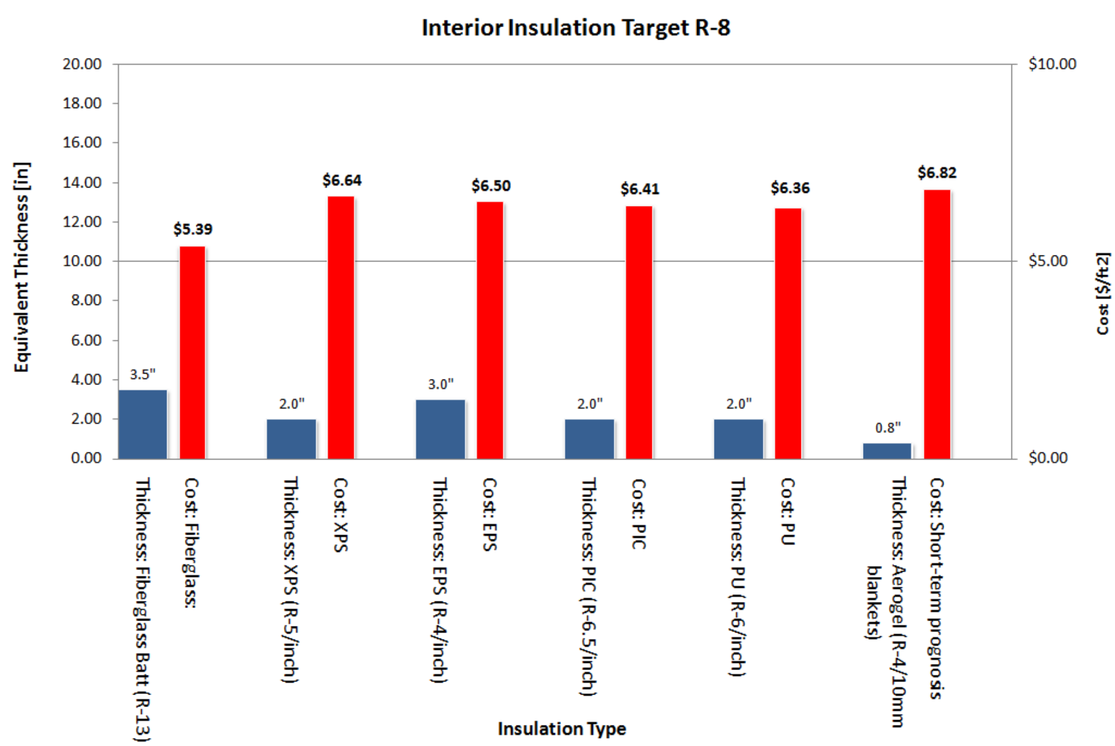
We are currently developing hygrothermal properties of different aerogel blanket products. In the future, we will examine the hygrothermal behavior of aerogel blankets to develop a better understanding of the short-term and long-term durability of aerogels in different building applications (including retrofits of basement and foundation walls). Interestingly, one of the main applications of aerogels is in the subsea pipeline industry to insulate oil pipelines; a testimony to the fact that they can perform ably in adverse aquatic and moist conditions.

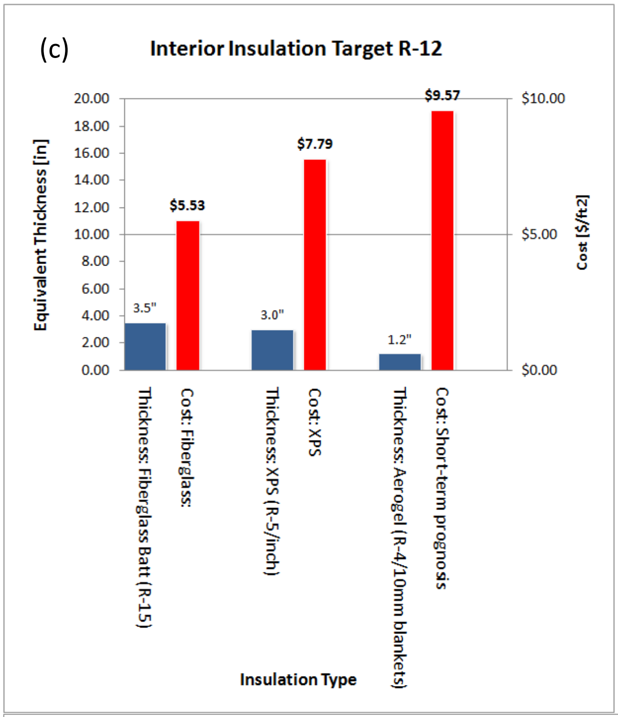
There is a worldwide focus on improving building energy efficiency that this focus will soon translate into a huge demand for building thermal insulation. We expect that in the future, the rising demand for insulation material along with space limitations will be favorable factors for aerogel market growth and in bringing down the production cost.

(a)


Interior Insulation Target R-4
20
18
16
14
12
10
8
6
4
2
0
$10.00
$5.00
$0.00
Equivalent Thickness [in]
Cost [$/ft2]
$5.39
$4.07
3.5"
0.4"
Thickness: Fiberglass Batt (R-13)
Cost: Fiberglass
Thickness: Aerogel (R-4/10mm blankets)
Cost: Short-term prognosis
Insulation Type

(b)


Interior Insulation Target R-8
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
$0.00
Equivalent Thickness [in]
Cost [$/ft2]
$5.39
$6.64
$6.50
$6.41
$6.36
$6.82
3.5"
2.0"
3.0"
2.0"
2.0"
0.8"
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: Aerogel (R-4/10mm blankets)
Cost: Short-term prognosis
Insulation Type



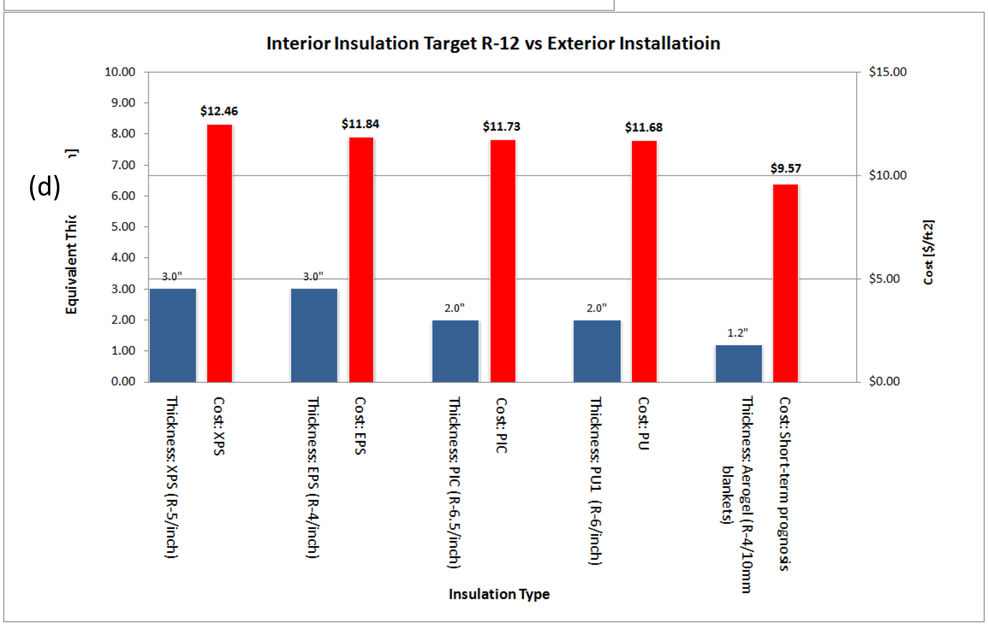


Figure 1: **Equivalent thicknesses and total cost of aerogel and conventional insulation techniques to retrofit the wall of a baseline house. An aerogel blanket is applied on the interior surface of the wall. Cases (a), (b) and (c) represent target values of R-4, R-8 and R-12 with interior application of conventional insulation, respectively, while case (d) corresponds to a target value of R-12 with exterior wall application of conventional insulation. Blanket aerogel is installed from the interior side on top of the existing gypsum board. Conventional insulations are installed from the interior. For the case of R-12, both interior and exterior installations are analyzed and shown. The thicknesses in this figure are rounded values of the manufactured thickness (rigid board with at least 1" thickness, spray foam with at least 1" thickness for practicality and blanket aerogel with a minimum of 3/8" thickness). The material cost was collected either by quoting directly from manufacturers or published data on the internet. Costs of the exterior wall finishes are included in the analysis for all considered cases of wall retrofits. In cases of retrofits of vaulted ceilings or catherdralized roofs, the proposed aerogel insulation does not face any competitive insulation technologies of similar thermal performance, which is why no cost comparisons are shown.**

Table I: **Total cost of aerogel and conventional insulation techniques to retrofit the wall of a baseline house. The aerogel retrofit technique does not require all retrofit tasks due to its lower thickness.**

Target R-value	Insulation Type	Retrofit Tasks and Cost ($/SqFt)							Total Cost ($/SqFt)
Interior R-4 (vs. Interior Installation)	Rigid Insulation	Framing (2x4; OC 16) [1]	Wall Openings' Interior Rearrengmen[2]	Insulation Installation [3]	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Readjustment of Radiators [5]	Living area loss by application of 2x4 interior framing [6]	
	Fiberglass Batt[8]	$0.73	$0.24	$0.57	$0.15	$0.66	$1.04	$2.00	$5.39
	Aerogel Blanket [9]	Framing (2x4; OC 16)	Wall Openings' Interior Rearrengmen	Insulation Installation (labor & equipment) [7]	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Readjustment of Radiators	Living area loss by application of 2x4 interior framing	
	Aerogel	-	-	$3.26	$0.15	$0.66	-	-	$4.07

[1] According to RS MEANS Building Construction Cost Data 2011.

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

[3] According to RS MEANS Building Construction Cost Data 2011; the cheapest combination of rigid board insulation thickness was assumed for the cost analysis (e.g. 9” was assumed as 3 x 3” layer instead of 4 x 2” + 1”). For PU, the thermal bridging effect was taken into account while calculating the required thickness to achieve 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 RS MEANS Building Residential Cost Data 2011.

[5] According to http://ths.gardenweb.com/forums/load/hvac/msg0219104426118.html.

[6] According to RS MEANS Building Residential Cost Data 2011, the cost per sq foot of living area of baseline house is $80.25.

[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" rigid foam board installation cost from RS MEANS Building Construction Cost Data 2011.

[8] 3 1/2" thick and R-13, according to RS MEANS Building Construction Cost Data 2011.

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

Table II: **Total cost of aerogel and conventional insulation techniques to retrofit the wall of baseline house. The aerogel retrofit technique does not require all retrofit tasks due to its lower thickness. (For references, see Table I footnotes).**

Target R-value	Insulation Type	Retrofit Tasks and Cost ($/SqFt)							Total Cost ($/SqFt)
Interior R-8 (vs. Interior Installation)	Rigid Insulation	Framing (2x4; OC 16) [1]	Wall Openings' Interior Rearrengmen[2]	Insulation Installation [3]	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Readjustment of Radiators [5]	Living area loss by application of 2x4 interior framing [6]	
	Fiberglass Batt[8]	$0.73	$0.24	$0.57	$0.15	$0.66	$1.04	$2.00	$5.39
	XPS	$0.73	$0.24	$1.82	$0.15	$0.66	$1.04	$2.00	$6.64
	EPS	$0.73	$0.24	$1.68	$0.15	$0.66	$1.04	$2.00	$6.50
	PIC	$0.73	$0.24	$1.59	$0.15	$0.66	$1.04	$2.00	$6.41
	PU	$0.73	$0.24	$1.54	$0.15	$0.66	$1.04	$2.00	$6.36
	Aerogel Blanket [9]	Framing (2x4; OC 16)	Wall Openings' Interior Rearrengmen	Insulation Installation (labor & equipment) [7]	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Readjustment of Radiators	Living area loss by application of 2x4 interior framing	
	Aerogel	-	-	$6.01	$0.15	$0.66	-	-	$6.82

Table III: **Total cost of aerogel and conventional insulation techniques to retrofit the wall of baseline house. The aerogel retrofit technique does not require all retrofit tasks due to its lower thickness. (For references, see Table I footnotes).**

Target R-value	Insulation Type	Retrofit Tasks and Cost ($/SqFt)							Total Cost ($/SqFt)
Interior R-12 (vs. Interior Installation)	Rigid Insulation	Framing (2x4; OC 16) [1]	Wall Openings' Interior Rearrengmen [2]	Insulation Installation [3]	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Readjustment of Radiators [5]	Living area loss by application of 2x4 interior framing [6]	
	Fiberglass Batt[8]	$0.73	$0.24	$0.71	$0.15	$0.66	$1.04	$2.00	$5.53
	XPS	$0.73	$0.24	$2.30	$0.15	$0.66	$1.04	$2.67	$7.79
	Aerogel Blanket [9]	Framing (2x4; OC 16)	Wall Openings' Interior Rearrengmen	Insulation Installation (labor & equipment) [7]	Readjustment of electric outlets [4]	Installation of gypsum board [1]	Readjustment of Radiators	Living area loss by application of 2x4 interior framing	
	Aerogel	-	-	$8.76	$0.15	$0.66	-	-	$9.57

Table IV: **Total cost of aerogel and conventional insulation techniques to retrofit the wall of baseline house. The retrofit tasks and cost break down are reported in this table. The aerogel retrofit technique does not require all retrofit tasks due to its low thickness.**

Target R-value	Insulation Type	Retrofit Tasks and Cost ($/SqFt)									Total Cost ($/SqFt
Interior R-12 (vs. Exterior Installation)	Conventional Insulation	Furring [1]	Fenestration Alteration[2]	Insulation Installation [3]	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	$0.92	$0.52	$2.30	-	-	$0.59	$0.22	$0.12	$7.79	$12.46
	EPS	$0.92	$0.52	$1.68	-	-	$0.59	$0.22	$0.12	$7.79	$11.84
	PIC	$0.92	$0.52	$1.59	-	-	$0.59	$0.22	$0.10	$7.79	$11.73
	PU [6]	$0.92	$0.52	$1.54	-	-	$0.59	$0.22	$0.10	$7.79	$11.68
	Aerogel Blanket[7]	Furring	Fenestration Alteration	Insulation Installation (labor & equipment) [8]	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	-	-	$8.76	$0.15	$0.66	-	-	-	-	$9.57

[1] According to RS MEANS Building Construction Cost Data 2011.

[2] Alterations of window openings according to Building Science Corporation (BSC).

[3] According to RS MEANS Building Construction Cost Data 2011; the cheapest combination of rigid board insulation thickness was assumed for the cost analysis (e.g., 9" was assumed as 3 x 3" layer instead of 4 x 2" + 1"). 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 RS MEANS Building Residential Cost Data 2011.

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

[6] Closed cell polyurethane foam was applied in exterior furring.

[7] After conversation with aerogel manufacturers and reviewing cost data, we assumed that in short term prognosis a cost of R-4/10mm 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" rigid foam board installation cost from RS MEANS Building Construction Cost Data 2011.

References

(1) LEX Research. 2011. "Opening the Thermal Envelope: Emerging Innovation in Dynamic Windows and Advanced Insulation". LEX Research Report. Available at: http://www.eco-business.com/press-releases/advanced-materials-tear-into-the-building-thermal-envelope/ .

(2) Soleimani Dorcheh, A., Abbas, M.H, 2008. Journal of Materials Processing Technology 199, 10-26.

(3) http://www.aerogel.org/?p=1058.

(4) Deng, Z., Wang, J., Wu, A., Shen, J., Zhou, B., 2009. Journal of Non-Crystalline Solids 225, 101–104.

(5) http://www.aerogel.com/products/pdf/Pyrogel_XT_DS.pdf.

(6) United States Patent Numer 5789075. http://www.google.com/patents?hl=en&lr=&vid=USPAT5789075&id=ckEnAAAAEBAJ&oi=fnd&dq=thermal+conductivity+of+reinforced+aerogel&printsec=abstract#v=onepage&q=thermal%20conductivity%20of%20reinforced%20aerogel&f=false.

(7) Straube J. 2007. "Thermal Metrics for High Performance Enclosure Walls: The Limitations of R-Value". Building Science Corporation.

(8) Straube, J. 2009. "High-R Walls Case Study Analysis". Building America Special Research Project. Building Science Corporation.

(9) McKinsey. 2009. "Pathways to a Low-carbon Economy, Version 2 of the Global Green HouseGas Abetment Cost Curve". McKinsey & Company.

(10) Waier Phillip R., Babbitt Christopher, Baker Ted, Balboni Barbara, Bastoni Robert A., RS Means Residential Cost Data 2011, 30th Annual Addition.

(11) Kosny, J., Yarbrough, D., Childs, P., and Syed, A., 2007. "How the Same Wall Can Have Several Different R-Values: Relations Between Amount of Framing and Overall Thermal Performance in Wood and Steel-Framed Walls" in *Thermal Performance of the Exterior Envelopes of Buildings X,* proceedings of ASHRAE THERM X, Clearwater, FL.