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Energy Research and Development Division

FINAL PROJECT REPORT

Robust Super Insulation at a Competitive Price

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Robust Super Insulation at a Competitive Price is the final report for the Contract Number EPC-15-067 conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at

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ABSTRACT

Existing buildings currently dominate the U.S. building sector, and the United States must continue to increase the energy efficiency of its buildings to enjoy a sustainable energy and environmental future. The existing buildings sector accounts for 41 percent of the United States' energy consumption, more than any other end-use sector including transportation and industry. Space heating and cooling represent about 36 percent (14.5 quads) of the energy used in buildings. High-performance and cost-effective thermal insulation can significantly reduce cooling and heating loads. By 2035, more than 50 percent of residential and commercial stock will be pre-2010 buildings. Retrofit offers a significant market for building insulation, however, retrofitting existing buildings is challenging using conventional insulations because of the buildings' size and design restraints. Retrofit projects require insulating materials that are cost-effective and easy to install.

This research aimed to produce an insulation material suitable for retrofit projects with 2- 4 times the R-value of current insulation, and at a lower total cost. The team successfully developed and tested a nanoparticle-based composite with a high R/inch of 9 with the potential to be a viable retrofit insulation material composed of nanoparticles with an extremely high thermal insulation and could fit within the space limitations of existing buildings. The technology readiness level increased from level 2 to level 4.

Keywords: insulation, nanoparticle, super insulation, fumed silica, acoustic mismatch

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EXECUTIVE SUMMARY

Introduction

The U.S. building sector is expected to account for more than 50 percent of residential and commercial stock by 2035 with most of these buildings constructed before 2010. In California, residential and commercial sectors account for 70 percent of electricity use and 54 percent of naturals gas use and most of this energy use is to heat and cool these buildings. Retrofitting the building stock is essential and many of the buildings are under-insulated.

The most commonly used building insulation materials are fiberglass, rock wool, expanded polystyrene insulation, extruded polystyrene insulation, polyisocyanurate and cellulose. Although conventional insulation materials are relatively inexpensive, they are not feasible for retrofits because of their low thermal resistance. The conventional thermal insulation materials typically take the form of mats or boards that are 2 to 4 inches thick. Such thick insulation is not practical because it reduces living space when placed on interior walls or requires significant alteration of window/door openings and at a much higher cost.

The development of cost-effective energy-efficient technologies and solutions using more effective thermal insulation could significantly lower energy consumption and energy-related carbon dioxide (CO_2) emissions. However, retrofitting projects can be challenging because insulation must meet durability and structural requirements, have a high R value and be easy to install. R-value measures the thermal or heat resistance and the higher the R value, the better the insulating properties of the material.

Currently, there is a lack of insulation on the market that can cost-effectively render building envelope energy efficient. The research and development efforts have centered on achieving high R-values by making a highly porous material or making vacuum-enclosed panels.

One important lesson learned from this agreement was the need for instrumentation to accuratley measure the thermal performance of small insulation samples. This has led to further research funded by the U. S. Department of Energy, to develop high throughput thermal meterology which can measure small, highly porous, and high-R value insulation samples accurately.

Project Purpose

Heating and cooling represent the greatest energy consumption in buildings. The project focused on developing a super insulation material to significantly reduce the cost of manufacturing and significantly increase energy savings for existing buildings. Available state-of-the art insulations are typically too thick and costly to be practical for retrofit projects. This research aimed to produce an insulation material with an increased the R-value, suitable for retrofit projects by 2- 4 times the R-value of current insulation, and at a lower total cost

The team focused on manipulating the heat transfer at nano-scale in nanoparticles (ultra-fine particles). The goal was to increase the resistance in the path of the heat flow. For nanoparticles, as the size reduces, result in poor heat transfer.

Project Approach

The team at Lawrence Berkeley National Laboratory explored and developed insulation material, from multilayers of nanoparticles (ultra-fine particles) of various size, shape, form, and composition that are chemically treated to significantly lower thermal transport.

Nanotechnology is not simply working in smaller dimensions. When particles are created in such reduced sizes (viewed only with specialized microscopes) their properties change significantly.

The materials selected for nanoparticle bed were silica and alumina, mainly due to its low cost. Silica is inexpensive and has poor thermal conductivity, which rationalizes its extensive use in the existing insulation industry.

Project Results

The Lawrence Berkely National Laboratory team successfully developed a nanoparticle-based composite with a high R/inch of 9. The research team engaged with industry to get feedback on the project. Manufacturers expressed interest in developing a flexible insulation material with an R/inch of 9. However, due to the on-going need for a more accurate means of thermal measurement for small sized samples, the research resulted in a low technology readiness level.

This research has the potential to be a game-changer and could set the ground work for other research projects that are looking into functionalization effects on interfacial thermal transport, and the effect of porosity and porous nanoparticles on thermal insulation material properties. The project identified additional resources are needed to scale up to a larger sample size that can achieve a high R-value at a competitive price point.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

Based on the feedback from industry representatives, the team focused efforts to increase the R/inch value in both rigid and flexible forms. Based on the feedback from the technical advisory committee, the team reached out to additional sectors that could benefit from high R/inch insulation. Non-disclosure agreements were signed with a few manufacturers in the US and abroad, however the industry required a larger sample size for commercialization.

In addition to the building sector, the team contacted cold storage, pharmaceuticals and transportation industries, but did not receive any traction. The results of this project were presented at Materials Research Society conference, International Heat and Transfer Conference and Department of Energy peer review conferences.

Benefits to California

The solution proposed in this research aimed to offer a significant breakthrough solution to reduce costs, increase efficiency and benefits to the environment.

Cost-effective thermal insulation for the retrofit of many under- or un-insulated buildings in California could reduce heating and cooling costs to benefit California investor-owned utility ratepayers, building owners, and tenants.

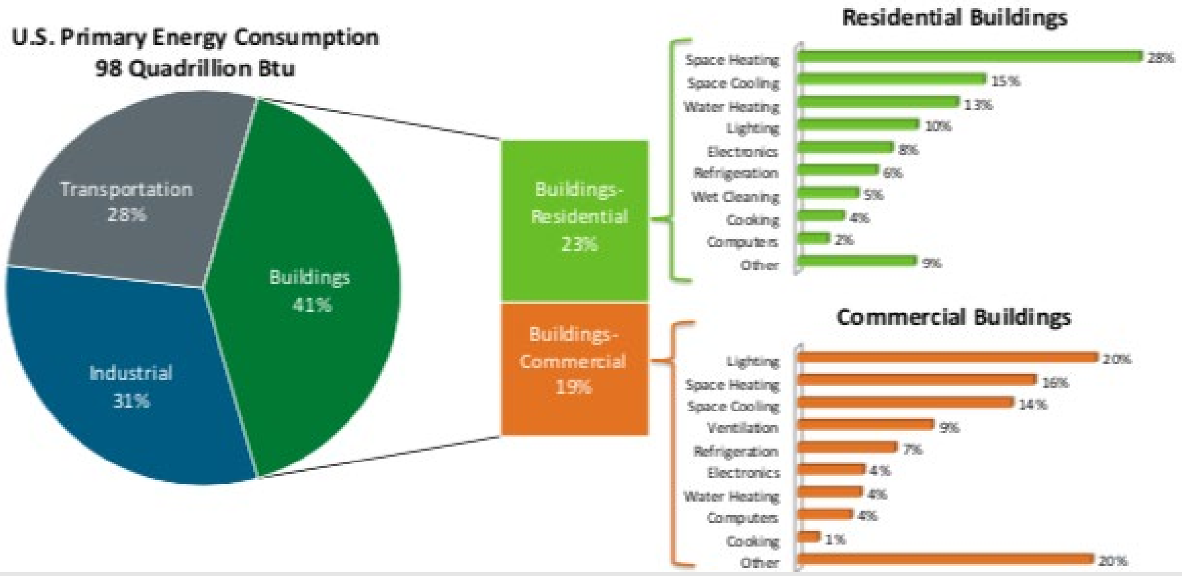
The initial discussions with insulation manufacturer and vendors indicated that cost for the proposed insulation with R/inch of 9 will be about $3 per board foot. This cost estimate is competitive to current rigid foam insulation materials which have lower R values. With a scale up, the cost would be expected to decrease dramatically because the proposed manufacturing process is highly scalable and requires very small amount of energy. The team expects the cost could be lower than $3 if a layered technique were used to sandwich the nanoparticle insulation between glass wool to attain flexibility.

The nanoparticle based super insulation could increase safety because it is made from silica and other oxide materials, which is more fire resistant when compared to the current foam insulation materials. In addition, the development of state of the art, rigid building insulation could be disruptive in the market due to the Environmental Protection Agency rule change to reduce blowing agents with harmful chemicals into the air.

CHAPTER 1: Introduction

The primary United States energy consumption for 2010 (Figure 1)[1], shows that the energy consumption from the building sector is higher than the transportation and industrial sectors. In 2010, buildings used 40 quadrillion Btu (quads) of energy, of which space heating and cooling represented 36 percent, or 14.5 quads. Retrofitting commercial and residential building with an effective thermal insulation could significantly lower energy consumption and energy-related CO2 emissions. However, retrofit projects have more size and space constraints.

Figure 1: United States Primary Energy Consumption 2010



Source: R&D Roadmap For Emerging Window And Building Envelope Technologies, DOE Report 2014[1].

The goal of the agreement was to develop a highly effective insulation with an (R/inch) with a total installed cost (material cost and retrofit cost) comparable to that of state-of-the-art (conventional) insulations. The most commonly used building insulation materials are fiberglass, rock wool, expanded polystyrene insulation (EPS), extruded polystyrene insulation (XPS), polyisocyanurate and cellulose. The materials with high-efficiency insulation, are challenging to use in retrofitting existing buildings. For example, the rigid mats or boards with a R 12 rating are 2 to 4 inches thick. This is not practical to add to existing buildings because it reduces living space when placed on interior walls or requires significant alteration of window/door openings and at a much higher cost. The need, therefore, is for super insulation, which could provide extremely high thermal insulation (R/inch of 9 or higher) cost-effectively and within the space limitations of existing buildings efforts have not yet achieved insulation

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[1] Sawyer, K. Windows and Building Envelope Research and Development: Roadmap for Emerging Technologies. 1–86 (2014)

materials that achieve high R-values and are cost effective. The emerging technologies currently available include the following:

Aerogel

Developed by NASA for insulation materials for space exploration, the advanced material is lightweight and typically contains 95 percent to 99 percent air by volume. It is commercially available as a good thermal insulator but is very expensive. The high price is an integral barrier to commercializing aerogel, due to the high temperatures or high pressures required for manufacturing which consume large amounts of energy. The high-energy requirements and the limited batch processing of aerogel limits production to small quantities. In addition, aerogel with an R-value of 9.6 per inch, is extremely fragile and difficult to handle unless it is integrated or reinforced with a fibrous matrix.

Vacuum-insulated panels (VIPs)

VIPS are an expanding market, providing very high R values. They consist of an open-pore core material that is vacuum-enveloped by foil that prevents the entry of air and water vapor. Since the R/inch values of VIPs are between R35 – R45, a very thin (9 mm) VIP can provide thermal insulation equivalent to thick mats (76 to 100 mm) of conventional insulation materials. VIPs, however, have several limitations [3] and can fail for many reasons. They are vacuum-enveloped, in precut forms and cannot be cut or modified at the building site, they are generally unsuitable for retrofits, which typically require a custom fit. VIPs also are vulnerable to failure if the barrier encounters anything sharp, such as being punctured by nails or screws, which could decrease their R/inch value to approximately 7. In addition, the performance of VIPs tends to decline over time because the foil is not completely impermeable to air and moisture.

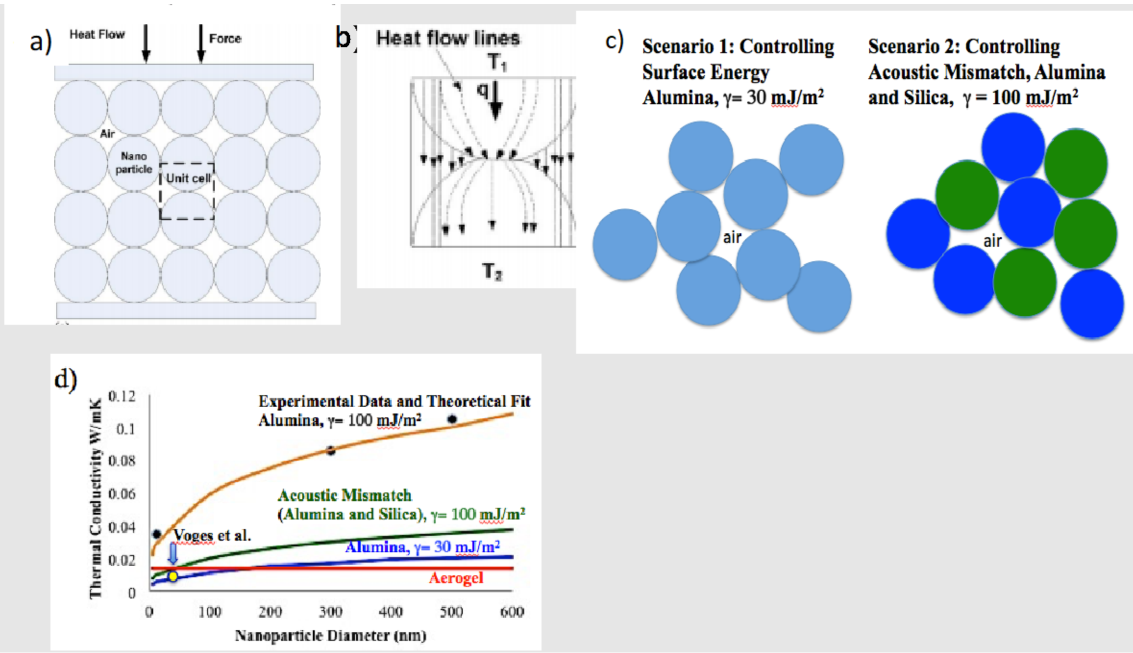
In this research, the team developed material for insulation with very low thermal conductivity cost-effectively (high R/inch) by manipulating the heat transfer at nano-scale in nanoparticles. This was achieved by manipulating the heat transfer at boundaries between nanoparticles. Nanoscale materials were used because they have far larger surface areas, which helps create a lower thermal conductivity and the heat transfer exchanges thermal energy (heat) between physical systems.

CHAPTER 2:
Project Approach

The technical approach to producing a high R value insulation was to provide more resistance to heat flow. This was achieved by manipulating heat flow at interfaces at nano-scale (nano means 10^{-9} meters). The size of particles can be changed to allow researchers to fine-tune the properties of a material.

Interfaces (boundaries) between materials create discontinuity in the heat flow because phonons (medium of heat flow) are scattered at the interfaces. For nano materials, the density of interfaces increases which makes it possible to attain super low thermal conductivity. Theoretically, the team [4-6] showed that to achieve very low thermal conductivity the following key parameters must be used: 1) low surface energy 2) small nanoparticle size and 3) mixing different type of nano particles to increase acoustic mismatch. Figure 2 shows the heat flow in a bed of nanoparticles and its effect of these parameters on heat flow. Based on the theoretical models developed, it is plausible to have two scenarios as shown in Figure 2c that will enable the nanoparticle bed to have lower thermal conductivity than aerogel. The figure also shows various effects of interfaces (boundaries) on the thermal transport using the key parameters. In one scenario surface energy is reduced and in the other acoustic mismatch is generated by using two different materials (silica and alumina for example).

Figure 2: Effect of Interfaces on Thermal Transport



Source: Lawrence Berkeley National Lab

Based on theoretical model both these scenarios show that it is possible to achieve very low thermal conductivity (lower than aerogel) with nanoparticle diameter in the range of 50 to

100 nm as shown in Figure 2d. In fact, based on the model, it should be possible to achieve as low as 0.005 W/m-K (about 50 percent of aerogel) by combining lower surface energy and acoustic mismatch leads K as shown in Figure 2d.

The Key parameters which were manipulated to achieve high R value insulation were: 1) diameter, 2) surface energy and 3) acoustic mismatch.

Material Selection: The materials selected for nanoparticle bed were silica and alumina, mainly due to the cost. Silica is inexpensive and has poor thermal conductivity, which rationalizes its extensive use in the existing insulation industry. Alumina was chosen as second material based on the developed thermal model which shows that the acoustic mismatch between silica and alumina nanoparticles (of diameters ~50 nm) is effective to achieve R/inch of 12.

Size: Silica, titania and alumina are commercially available materials and come in the desired size regime (50-200nm). Table 1 summarizes the vendors, materials, size and form of various materials that were considered during this project.

Table 1: Nanoparticle Vendors

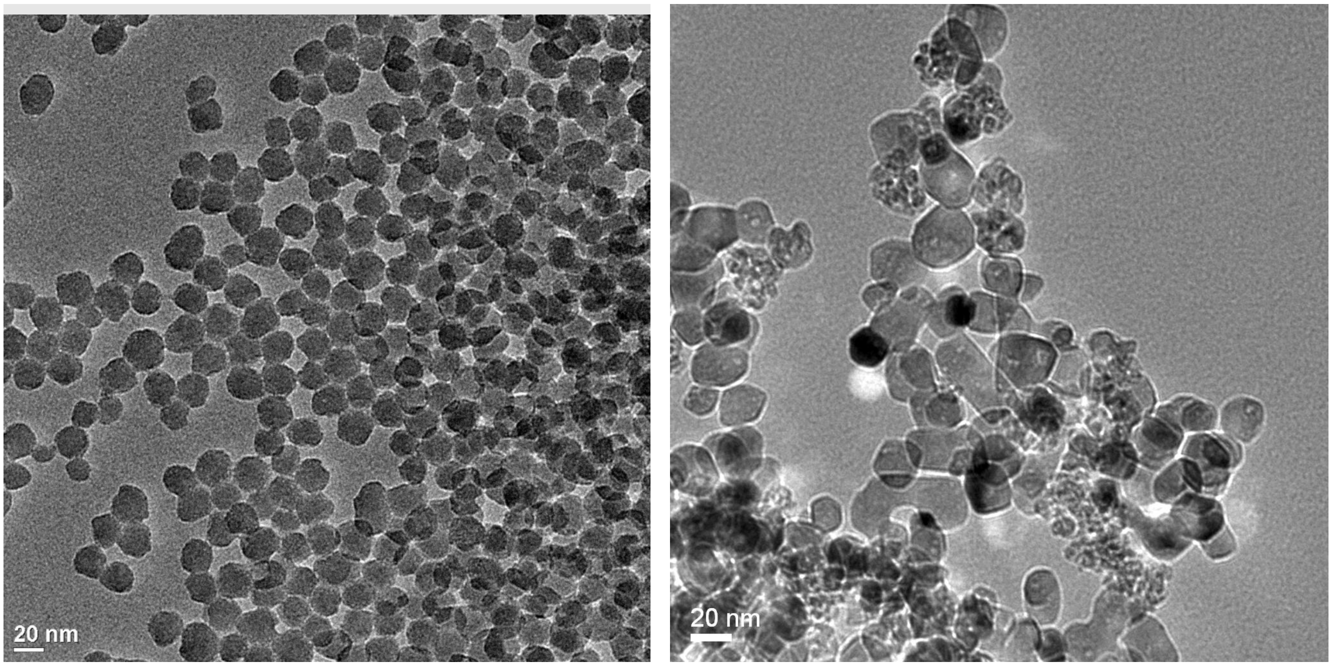
Vendors	Materials	Size (nm)	Form	Comments
American Elements	SiO_2	100	Dry Powder	Only size available
	Al_2O_3	100	Dry Powder	
MTI Corporation	SiO_2	100	Dry Powder	Only size available
	Al_2O_3			Not available
	TiO_2	30	Dry Powder	Only size available
nanoComposix	SiO_2	20	In Solution	All sizes available
		120	In Solution	
		160	In Solution	
	Al_2O_3			Not available
Stanford Materials	SiO_2	30	Dry powder	Only size available
Evonik	SiO2, Al2O3, TiO2	20-200nm	Dry Powder	All sizes available

Source: Lawrence Berkeley National Lab

The characterization of nanoparticles for size, size distribution and shape used various techniques such as scanning electron microscope (SEM) and Transmission Electron Microscope

(TEM). Figure 3 shows the use of TEM to see the shape and size of silica and titania nanoparticles, the silica nanoparticles are can be seen on the left photo and titania on the right.

Figure 3: Transmission Electron Microscope Characterization of Nanoparticles of Silica and Titania



Source: Lawrence Berkeley National Lab

Surface Modification: Textiles, optics, food packaging, and optoelectronic devices have routinely used surface modifications of nanoparticles to achieve distinctive end goals. The team primary investigator had significant experience using surface modifications to alter thermal transport. In previous research the team used surface functionalization to increase adhesion (the opposite of what is needed for insulation) to increase thermal transport at interfaces for applications ranging from carbon nanotube based thermal interface materials for microelectronics cooling[7] to cell level thermal management in Lithium ion battery[8].

However, surface modifications are almost always necessary for nanoparticles to determine their interaction with the surroundings and help keep them stable in a solution. The project carried out surface modification to lower the surface energy of nanoparticles that served two vital purposes: reduced the thermal conductivity and made the nanoparticles hydrophobic. Hydrophobicity of the nanoparticles would improve the insulation moisture resistance because condensed water cannot stick to the surface, which is a much-desired property. The chemical functionalization of the nanoparticle's surfaces used a vapor phase process with the end goal of attaining very low-energy surfaces (hydrophobic surface).

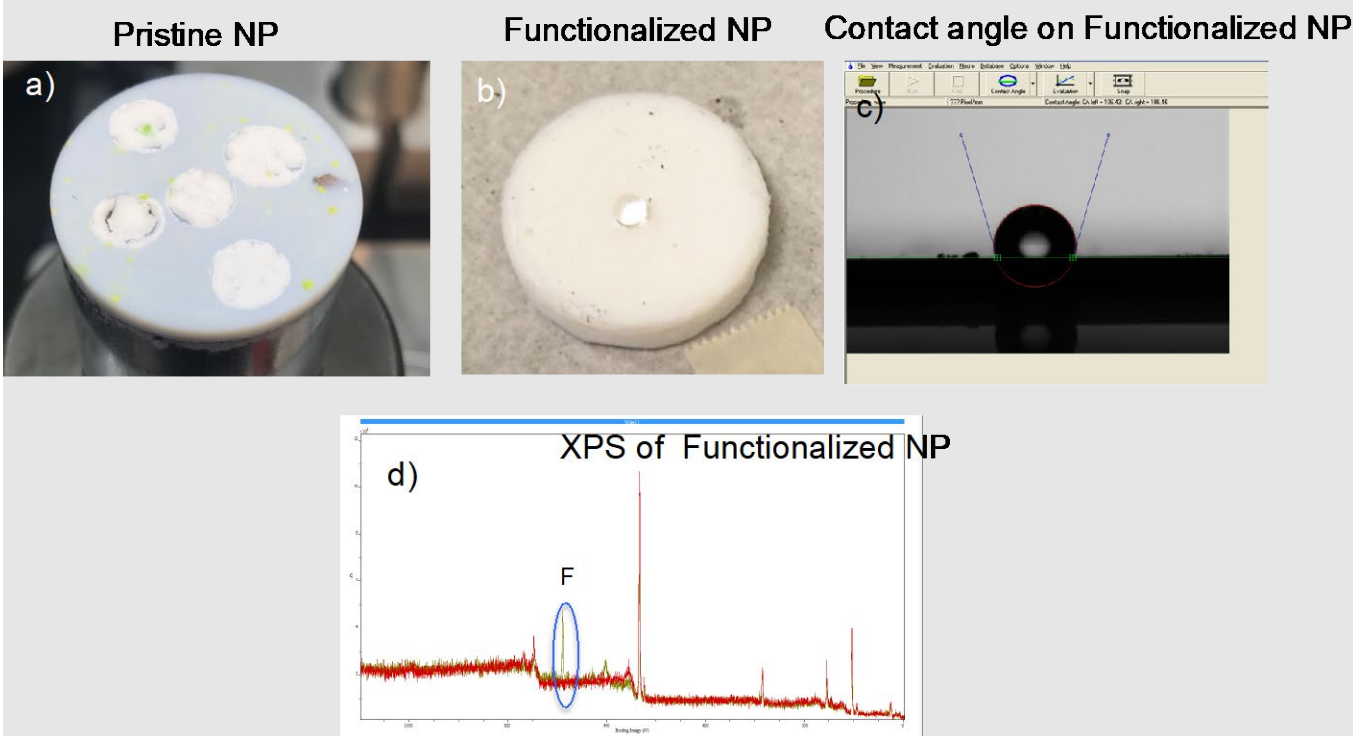
Silane based chemistry was used for surface modifications since it is well established in the academic and industrial fields. Wet and gas phase functionalization routes were explored with silane chemistry. The gas phase functionalization was used to avoid nanoparticle agglomeration, which could happen if wet chemistry was used.

Chemistries selected for surface functionalization:

1. Dichlorodimethylsilane (DDMS)
2. Octadecyltrichlorosilane (OTS)
3. 1H, 1H, 2H,2H-Perfluorooctyltrichlorosilane (FDTS)

The contact angle on the samples before and after surface treatment was measured using a goniometer. X-Ray photoelectron spectroscopy was carried out to analyze effect of surface functionalization on the nanoparticles. This is a surface sensitive technique, which measures elemental composition and chemical states of the elements on the surface. Figure 4 shows the results of the characterizations, 4a shows that the water droplets spread and wet the nanoparticles whereas when the nanoparticles are surface treated, the water droplet beads up as shown in Figure 4b and 4c.

Figure 4: Surface Functionalization of Nanoparticles



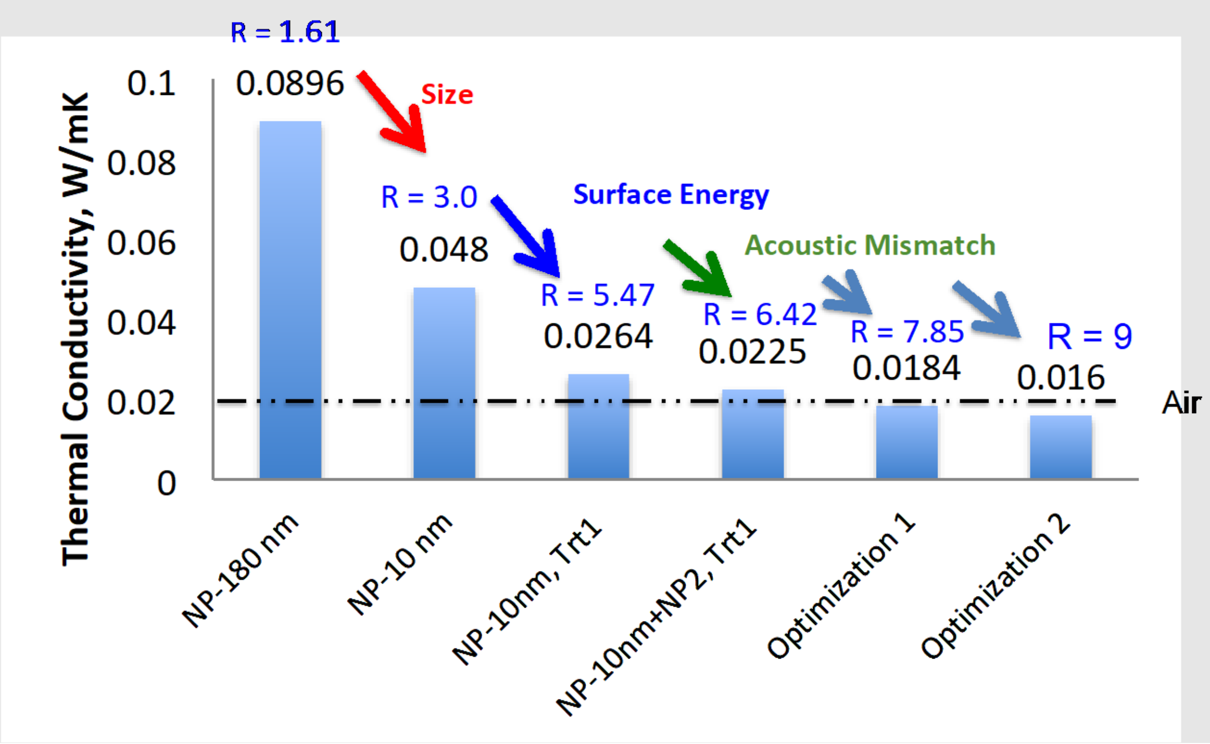
Source: Lawrence Berkeley National Laboratory

CHAPTER 3:
Project Results

Developed Insulation with High R/inch (R/inch of 9)

The team developed nanoparticle-based insulation with an R/inch of 9. This was achieved by manipulating the thermal transport at nano-scale by optimizing the three key parameters: size, surface energy and acoustic mismatch. The outcome of this approach is summarized in Figure 5, which shows the effect of each of these parameters on the R-value.

Figure 5: Effect of Key Parameters on R-value of the Insulation



Source: Lawrence Berkeley National Lab

Successful Scale-Up From 1 cm to 2-inch Diameter Samples

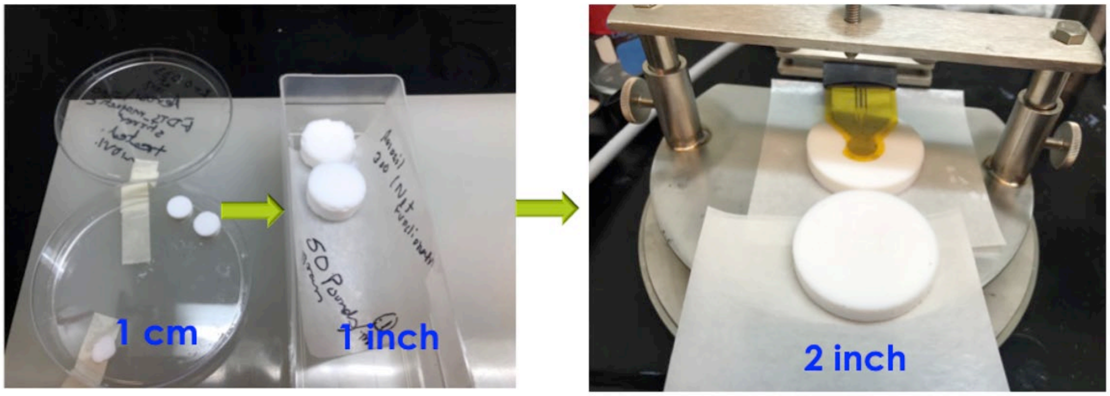
Typically, smaller dimensional properties do not translate well when scaled up. During this project the team also focused on the scaling up to various dimensions without compromising the thermal performance. Initially 1 cm (diameter) samples were optimized for thermal performance of R/inch of 9. To achieve this thermal performance in 1 cm sample, nanoparticles were surface treated (functionalized) to reduce the surface energy and then mixed with other nanoparticles to reduce the acoustic mismatch. Uniform surface treatment and mixing of the nanoparticles were the two key steps for the scale up.

Figure 6 shows the scaling up from 1 cm to 2 inch (diameter). The process parameters were optimized to ensure uniform coating of the chemicals. To achieve uniform mixing, ball milling as shown in Figure 7, (top left photo) was used to obtain uniform mixing of nanoparticles The photo on the top right shows an inhomogeneous sample result due to improper mixing of nanoparticles.

The bottom right photo shows a homogenous sample obtained after optimizing the process parameters.

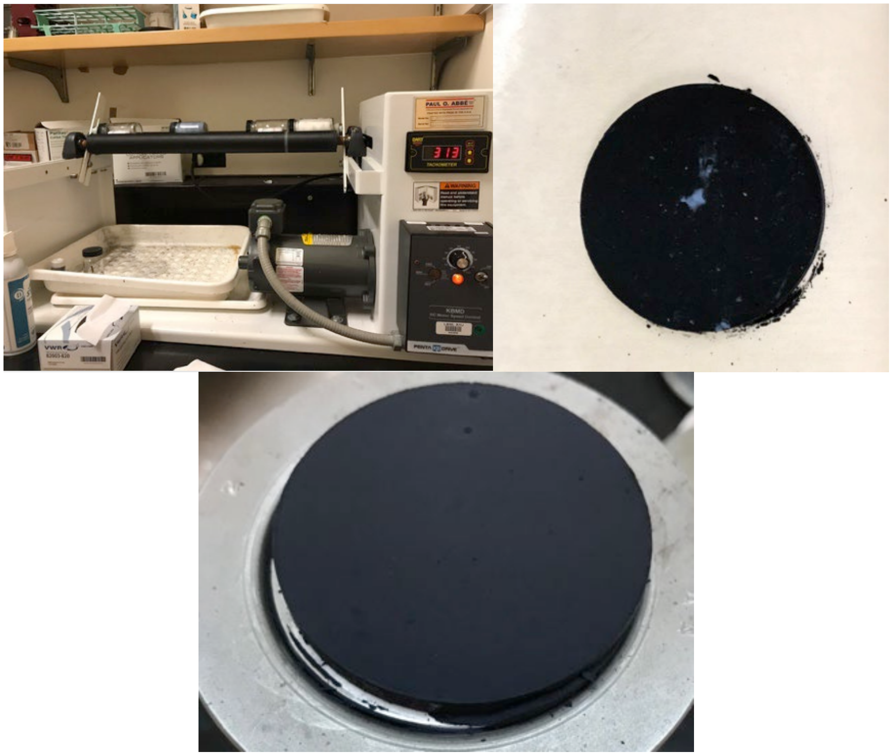
The ball milling process is shown in Figure 7, (photo on the left side). The (photo on the right side) shows that an un-optimized mixing parameter could lead to inhomogeneous sample. The last photo shows that a homogenous sample was obtained after optimizing the process parameters for the ball milling.

Figure 6: Scale-Up From 1-cm Diameter to 2-inch Diameter Insulation Samples in Rigid Form Factor



Source: Lawrence Berkeley National Lab

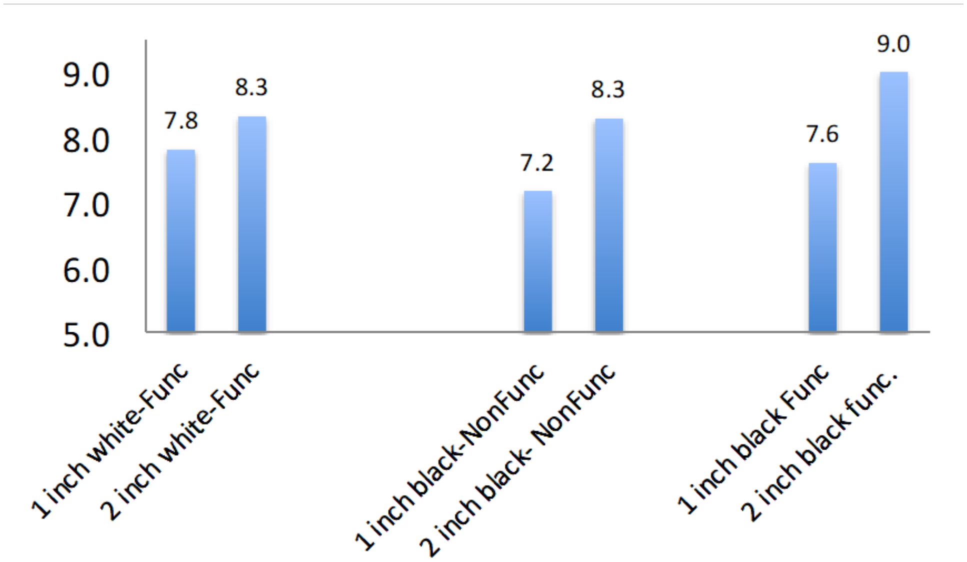
Figure 7: Ball Milling Used to Obtain Uniform Mixing of Nanoparticles



Source: Lawrence Berkeley National Lab

Figure 8 shows the thermal measurements achieved of one inch and two-inch samples using one-inch sensor using guarded the hot plate measurement for thermal properties. The low values of R in all the one-inch diameter samples are due to inaccuracy in thermal measurement. However, the same recipe when scaled up to 2-inch showed a higher R/inch value.

Figure 8: Thermal Measurements of Samples



Source: Lawrence Berkeley National Lab

Two Form Factor: Rigid and Flexible Insulation With R/inch of 9

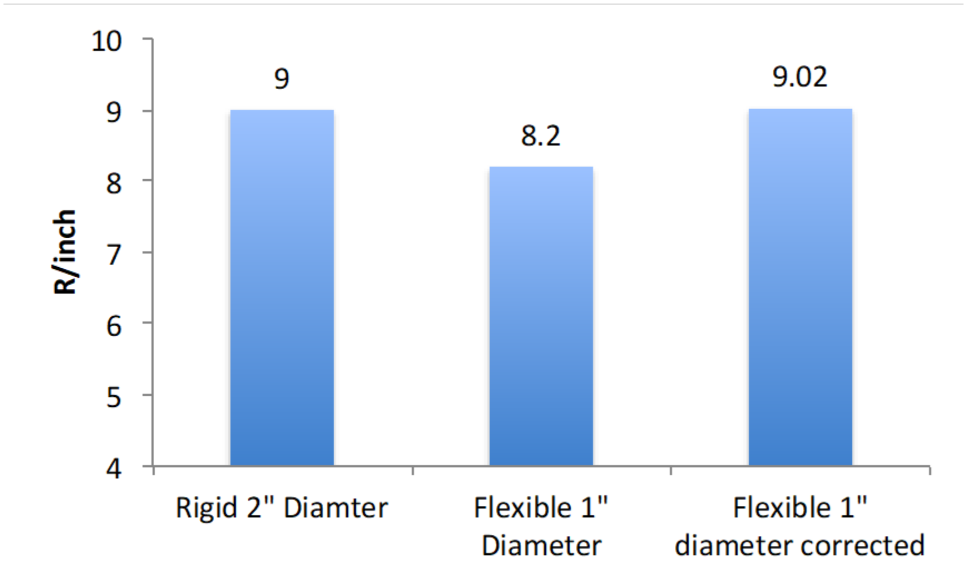
The team engaged with industry on a continuous basis to get their feedback. One of the main outcomes of these discussions was to focus on the development of a flexible insulation without reducing R/inch value. Various techniques were investigated, and a layering technique showed the most promising results. Figure 9 shows, that with this technique, alternating layers of glass wool and compressed (dry) nanoparticle disc were used to determine if the flexibility of the overall assembled structure could be improved. Dry fumed silica was compressed to make thin disc of nanoparticles and by alternating the glass wool and compressed nanoparticle disc. Figure 10, shows the material laying and the final achieved flexible insulation sample. To achieve the final layered sample, the assembly was compressed again. This optimized the thickness of each layer is to achieve desired mechanical and thermal properties.

Figure 9: Schematic Showing Layering Technique Used to Prepare Flexible Insulation Samples

Source: Lawrence Berkeley National Lab

The thermal performance of the flexible and rigid samples (Figure 10), shows similar R values (R/inch of 9) for both the rigid and flexible form factors.

Figure 10: Thermal Performances of Insulation in Both Form Factors (Rigid and Flexible)

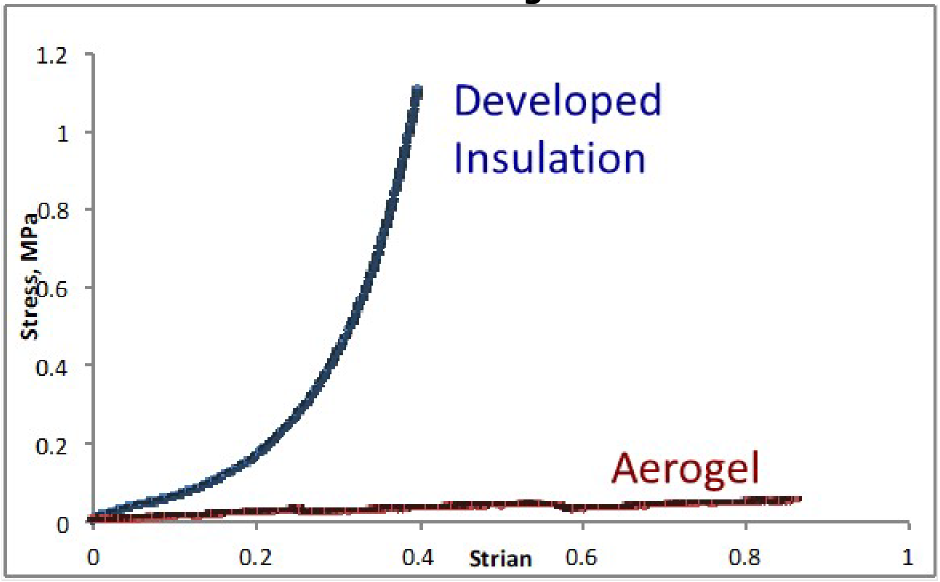


Source: Lawrence Berkeley National Lab

Demonstrated Better Mechanical Properties

The mechanical properties of the nanoparticle-based insulation samples were investigated. As expected, the mechanical properties varied with insulation composition and processing steps. Figure 11 shows the nanoparticle-based insulation had better mechanical properties compared to aerogel.

Figure 11: Comparison of Mechanical Properties of Nanoparticle-Based Insulation with Aerogel



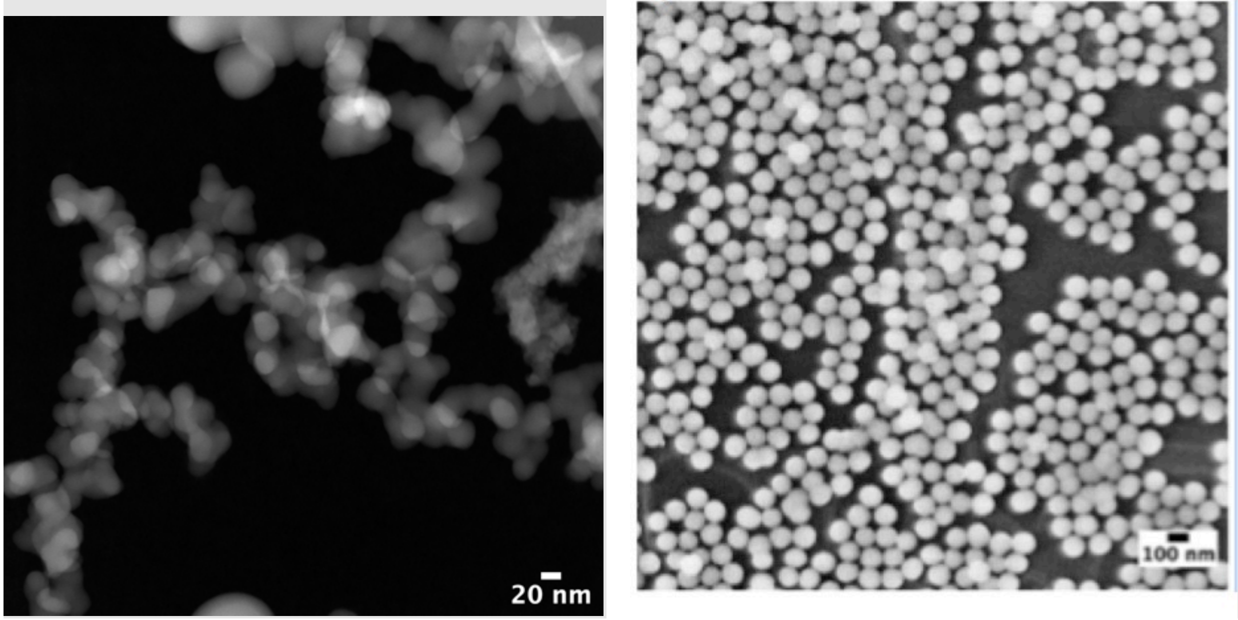
Source: Lawrence Berkeley National Lab

Major Lessons

Morphology of the Nanoparticles Plays a Crucial Role in the Thermal Transport

During the project the research team realized that the morphology or shape of the nanoparticles plays a crucial role in the thermal transport. Morphology of the nanoparticles has a strong effect on the porosity, pore size distribution and the density of compacted bed of nanoparticles. It also defines the surface area of the nanoparticles and contact area between the nanoparticle. This indicated that apart from the three key parameters (size, surface energy and acoustic mismatch), morphology is another key parameter which can be manipulated to achieve high R/inch value. To understand this effect, spherical and branched shaped nanoparticles were explored for thermal transport (Figure 12). In comparision to spherical nanoparticles, the samples made from branched morphology showed high R/inch value and resulted in samples with very high porosity with pores sizes in 10 to 100 nm. The density of these compacted bed was about 10 lbs/cc.

Figure 12: Transmission Electron Microscope Image Showing Branched Morphologies of Silica



TEM image showing branched morphologies of silica (left) and SEM image of the colloidal silica showing spherical morphology (right).

Source: Lawrence Berkeley National Lab

Lack of Thermal Metrology (Instrument) to Measure Thermal Properties for Small Insulation Samples Accurately

Achieving an accurate measure of thermal properties of the material was very challenging. Originally the “Hot Disk TPS 500 S” model from ThermTest Inc was used to therrmally measure the samples. However, it was discovered that the Hot Disk was not accurate to measure the thermal properties of the small samples when the thermal condutivity of the sample was below 0.024 W/mK (R/inch of 6). The guarded hot plate is typicaly the standard thermal metrology used for measurement of thermal properties but it requires bigger samples (at least 4 X 4 square inch area) and longer times, 4 to 24 hours depending upon machine and sample specifications.

A significant amount of time was spent calibrating the Hot disk results against Guarded Hot Plate. However, the Hot disk overpredicted thermal conductivity of samples by 20-25 percent when compared with that obtained from guarded hot plate.

Future Research

The future research in this work requires an industrial partner, to scale-up the product. This will allow for industrial testing of the product for thermal performance and other properties such as flammability

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

The team shared information with industry at conferences and conducted meetings with a large construction materials insulation manufacturer for who showed significant interest in flexible insulation material. They signed a nondisclosure agreement (NDA) in 2019 and their team visited the labs to explore potential future collaboration efforts. The manufacturer was part of the technical advisory committee (TAC) and also **s**igned an NDA. The team also engaged the interest of a European panel manufacturer who expressed an interest in understanding the flammability properties of the material samples.

Based on the feedback from the TAC committee, the team contacted various industrial sectors that could benefit from high R/inch insulation. The sectors included the building sector and cold storage including food and pharmaceuticals and transportation, but did not receive any traction.

The team has filed a provisional patent on the insulation material.

CHAPTER 5:
Benefits to California

The team developed a building insulation with the following characteristics: an R/inch value of 9, lower cost compared to other emerging technologies (aerogel) and a higher ability to resist change without adapting its initial stable configuration. This work can lead to technological advancement and breakthroughs to overcome barriers to the achievement of the State of California’s statutory energy goals.

The results from this project can benefit California investor-owned utility (IOU) ratepayers by providing cost-effective thermal insulation for the retrofit of many under or un-insulated buildings in California. According to *Comprehensive Energy Efficiency Program for Existing Buildings Scoping Report* (CEC, 2012).

Currently available, state-of-the art insulation solutions for building envelopes are too thick to be practical for retrofit projects. However, with further development, this new insulation material could become a potential and effective insulations solution for use in walls of residential buildings and walls and roofs of commercial buildings. Based on initial discussions with insulation companies and various vendors, the dollar per board foot cost for R/inch of 9 will be about $3 and depending on the insulation form factor. The team expects the cost per board foot to be lower than $3 if the layered technique were used to sandwich the nanoparticle insulation between glass wool to attain flexibility. Also, it is expected that with scale up, the cost should drop dramatically because the proposed manufacturing process is highly scalable and requires very small amount of energy.

This research could be a game-changer and has set the ground work for other research projects that are looking into effects functionalization on interfacial thermal transport, and the effect of porosity and porous nanoparticles on thermal insulation properties of material. Also, this research work has emphasized the need for an accurate means of thermal measurement for small sized samples. The resulting research funding from DOE to develop such thermal metrology for insulation materials, could significantly speed up research and development of high R-value insulation material (or composition). The research development of this new high throughput thermal metrology continues to be ongoing.

LIST OF ACRONYMS

Term	Definition
DDMS	Dichlorodimethylsilane
EPS	Expanded Polystyrene
FDTS	1H, 1H, 2H,2H-Perfluorooctyltrichlorosilane
OTS	Octadecyltrichlorosilane
R&D	Research and Development
SEM	Scanning Electron Microscope
TEM	Transmission Electron Microscope
VIP	Vacuum-Insulated Panel
XPS	Extruded Polystyrene

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