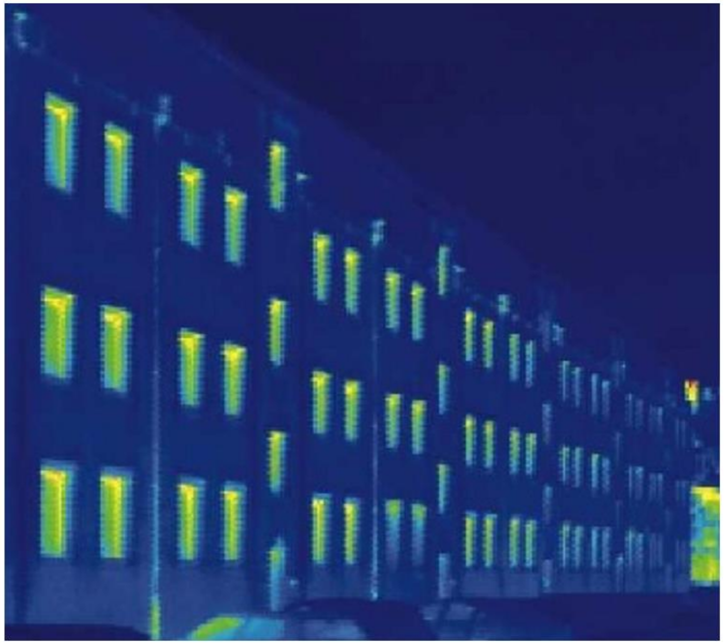
Robust Insulation at a Competitive Price



Performing Organization(s) : Lawrence Berkeley National Lab and Oak Ridge National Lab
PI Name and Title: Ravi Prasher, Associate Lab Director, LBNL
PI Tel and/or Email: 510-486-7291, rsprasher@lbl.gov

Project Summary

Timeline:

Start date: Oct 1st, 2016

Planned end date: Dec 31st, 2019

Key Milestones

1. **Milestone 1:** Demonstrate thermal conductivity < 0.016 W/m·K, R/inch of 9 in sample with surface area of >1 cm^2 . March 2018
2. **Milestone 2:** Assemble nanoparticles over relatively large area (> 1 $inch^2$). Demonstrate the assembly of a larger sample thermal conductivity < 0.016 W/m·K, R/inch of 9. June 2018

Budget:

Total Project $ to Date:

- DOE: $1000,000
- Cost Share: $0

Total Project $: 1,600,000

- DOE : $1,350,000 (LBNL) and $150,000 (ORNL)
- Cost Share: $100,000 (CEC)

Key Partners:

Oak Ridge National Lab
California Energy Commission (CEC)

Project Outcome:

- Cost-effective high R/inch insulation. By tweaking size, surface energy and acoustic mismatch, our **current R/inch value is 9.03** By end of this project we aim to achieve R/inch ≥ 12.
- High R/inch insulation in both rigid and flexible form factor.

Team

LBNL

Ravi Prasher,
Principal Investigator
LBNL

Area of expertise:
Phonon Transport

Suman Kaur,
Project Scientist
LBNL

Area of expertise:
Nanomaterial synthesis and surface chemistry, Advanced thermal metrology

Sean Lubner,
Postdoc, LBNL

Area of expertise:
Advanced thermal metrology

D. Charlie Curcijia, LBNL

Area of expertise:
Energy Analysis

Howdy Goudey, LBNL

Area of expertise:
Macro scale thermal measurement

ORNL

Andre Omer Desjarlais,
ORNL

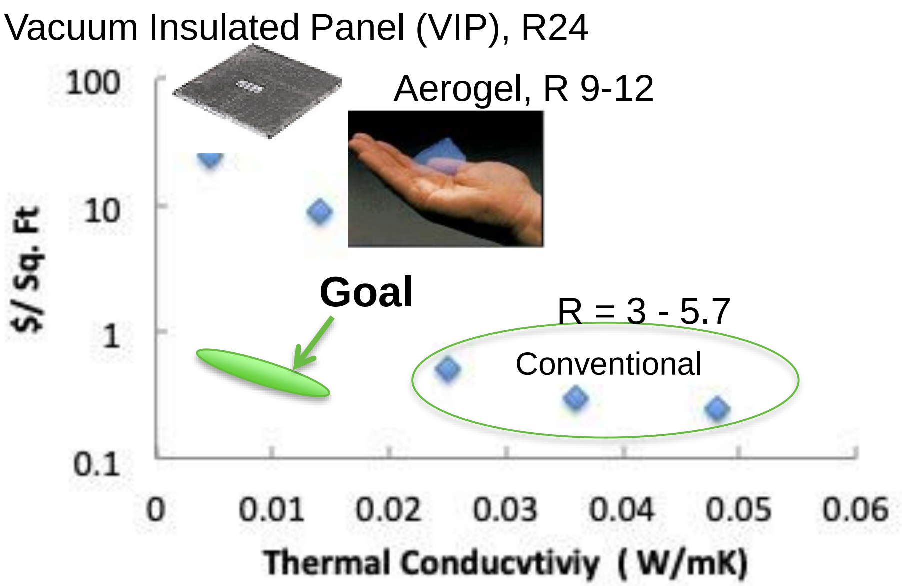
Area of expertise:
Energy Saving Analysis

CEC

Karen Perrin, California Energy Commission (CEC)

Energy Commission Specialist (Efficiency)

Challenge



- Space heating and cooling accounts for 37% of overall building energy consumption amounting to **15.1 quads**.
- US building sector is dominated with under-insulated existing buildings: Big retrofit market

Current and emerging insulation solutions

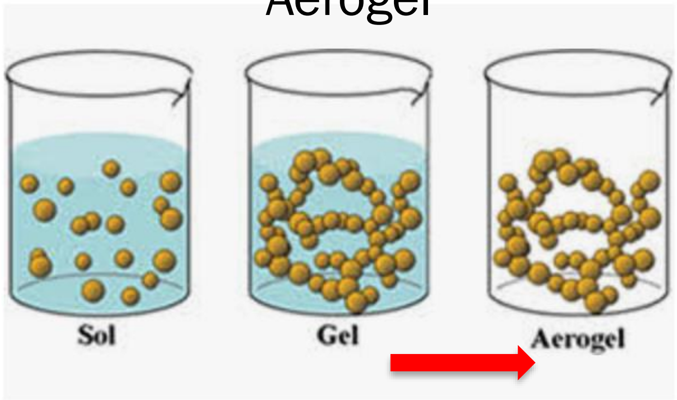
- **Conventional insulation materials such as fiberglass, although cheap have** relatively low R/inch value. Hence they reduce living space when placed on interior walls or require significant alteration of window/door openings and face zoning regulations. Very labor intensive and invasive for customers.
- Emerging insulations such as aerogel or VIPs have high R/inch value but are @10 times more expensive than conventional insulations. **Not cost-effective for customers.**
- **The Challenge is to make affordable insulation especially for retrofit market.**

Approach

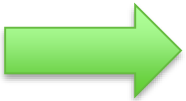
- The R&D efforts in insulation field so far have centered on achieving high R-values by *either reducing the solid volume fraction (as in aerogel)* or using vacuum as in VIP

- The scientific and technological question for high-R insulation is: ***Does achieving a high R-value require using either a low volume fraction of solids (as in aerogel) or vacuum-enclosed panels?***

Aerogel



Supercritical Drying makes it very expensive



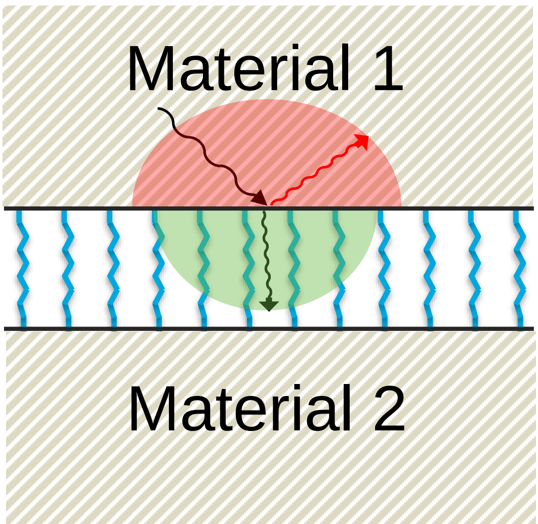
Our approach:

- Use high solid volume fraction
- Manipulate thermal transport in solids
- Avoid wet chemistries

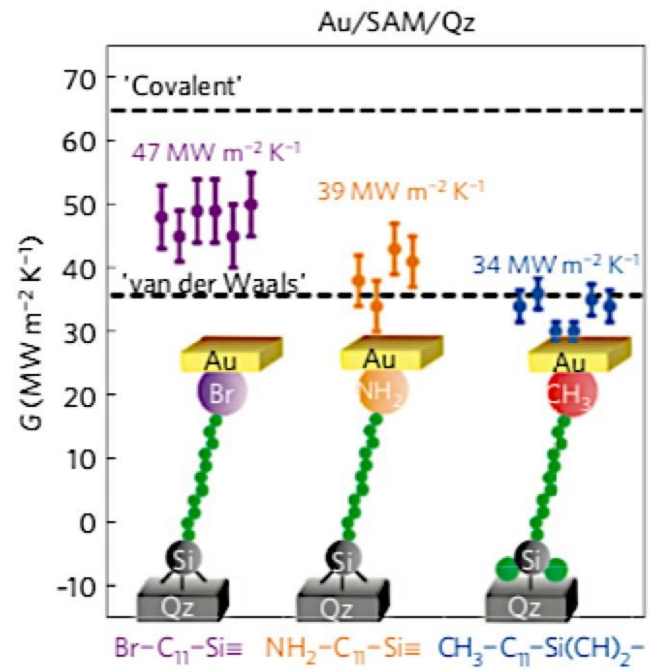
Approach: Two Solids in Contact

- Traditional acoustic mismatch model (AMM) assumes two contacting surfaces are in very good welded contact (no effect of interface on thermal transport)

- Modified AMM theory highlights effect of interfaces: Weak interfaces results in poor thermal transport



Prasher, APL, 2009



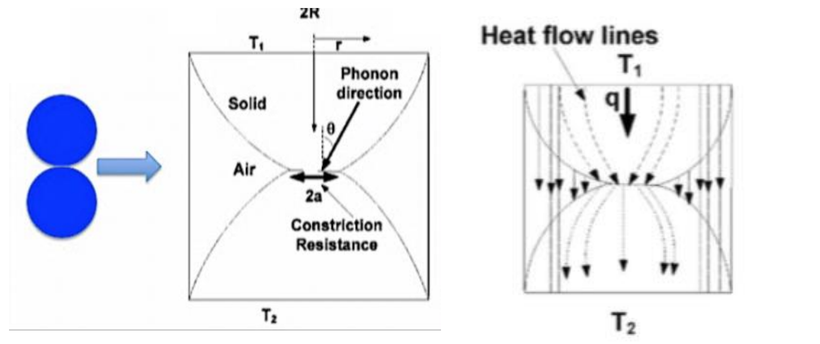
Losego et al. 2012 (Nature Materials)

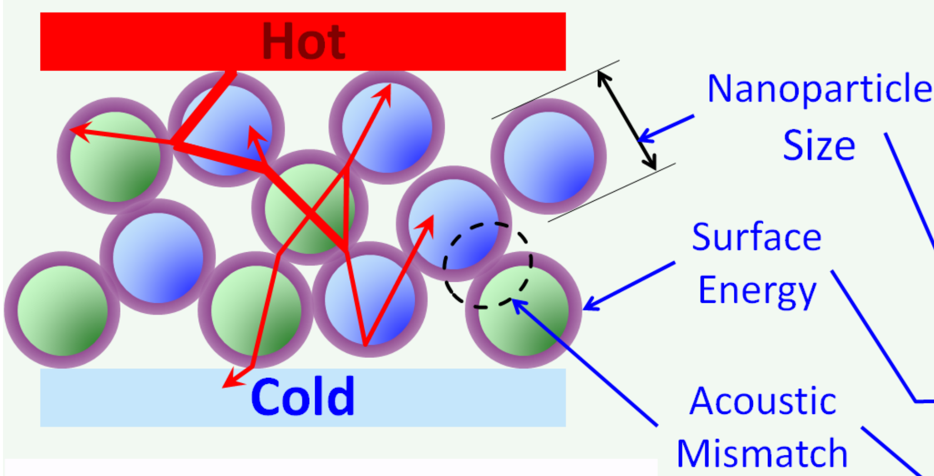
$$\tau_{\text{v-AMM}} = \frac{4z_1z_2\cos\theta_1\cos\theta_2}{(z_1\cos\theta_1 + z_2\cos\theta_2)^2 + \boxed{\frac{\omega^2}{K_A^2}(z_1z_2\cos\theta_1\cos\theta_2)^2}}. \quad K_A \propto \gamma$$

→ Surface Energy

Approach : Reduce l_{eff} ⟶ Reduce K_{eff}

In case of interfaces between nanoparticles, constrictions play significant role in reducing thermal transport: **a^2/R where a is constriction and R is nanoparticle radius respectively**





Reducing the effective mean free path (l_{eff}) of phonons reduces a material's thermal conductivity. For two contacting nanoparticles of radius R, l_{eff} is given by:

$$l_{eff} = 3\left(1.125\frac{\pi\gamma}{E}\right)^{\frac{2}{3}} R^{\frac{1}{3}} \int \tau \sin\theta \cos\theta \, d\theta$$

$$\tau = \frac{4 z_1 z_2 \cos\theta_1 \cos\theta_2}{\left(z_1\cos\theta_1 + z_2\cos\theta_2\right)^2 + \frac{\omega^2}{K_A^2}\left(z_1 z_2 \cos\theta_1 \cos\theta_2\right)^2}$$

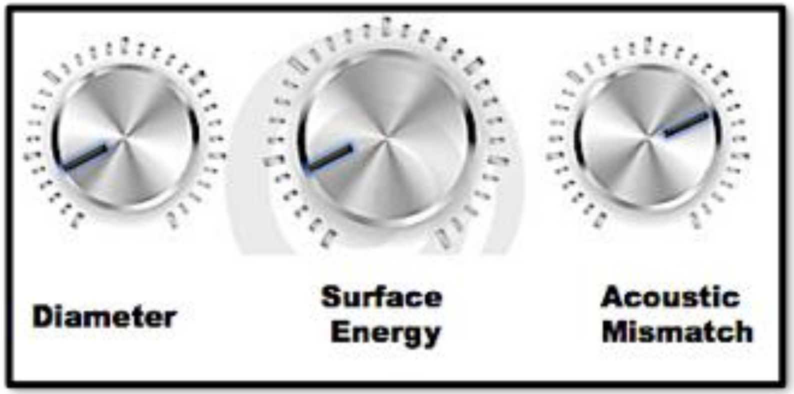
$$k_{eff} = (1/3) c v l_{eff}$$

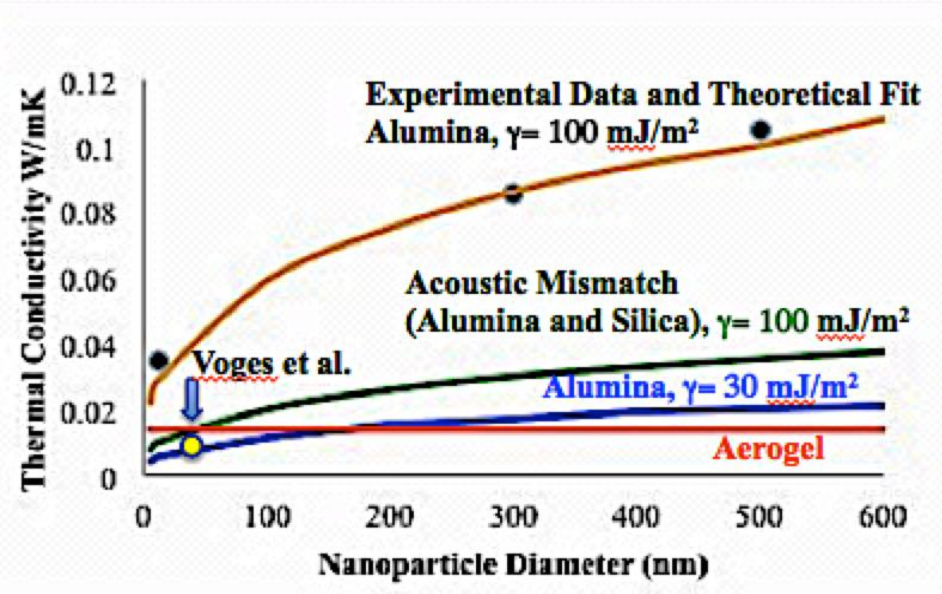
k_{eff} = effective thermal conductivity
c = specific heat per unit volume
v = speed of phonons (sound)
l_{eff} = effective mean free path

Prasher, Phys. Rev. B, 2006

Approach

The KEY Knobs





- Experimental data showing effect of size of alumina nanoparticles on thermal conductivity (*Hu et al. Applied Physics Letters 91, 203113, 2007*) with volume fraction ~ 0.6.

- The impact of surface energy (100 mJ/m^2 and 30 mJ/m^2) and acoustic mismatch by as estimated by theoretical model is also shown.

- Vogue et. al.(*Physica Status Solidi (a) 212, 2014*) showed less than air k in bed of nanoparticles with volume fraction~0.5 by just using acoustic mismatch and size.

Impact

Energy demand dropped by 90% after refurbishment
(Nature 452, 3 April 2008)

We anticipate that the new insulation technology being developed in this project would be a potential replacement for insulations used in walls of residential buildings and walls and roofs of commercial buildings esp. retrofit market.

Building Sector	Market Size 2030, (TBtu)	Technical Potential 2030, (TBtu)	Unstaged Max Adoption potential 2030, (TBtu)
Residential Sector	1592	836	267
Commercial Sector	1434	836	267
	3026	1672	534

R&D Roadmap For Emerging Window And Building Envelope Technologies

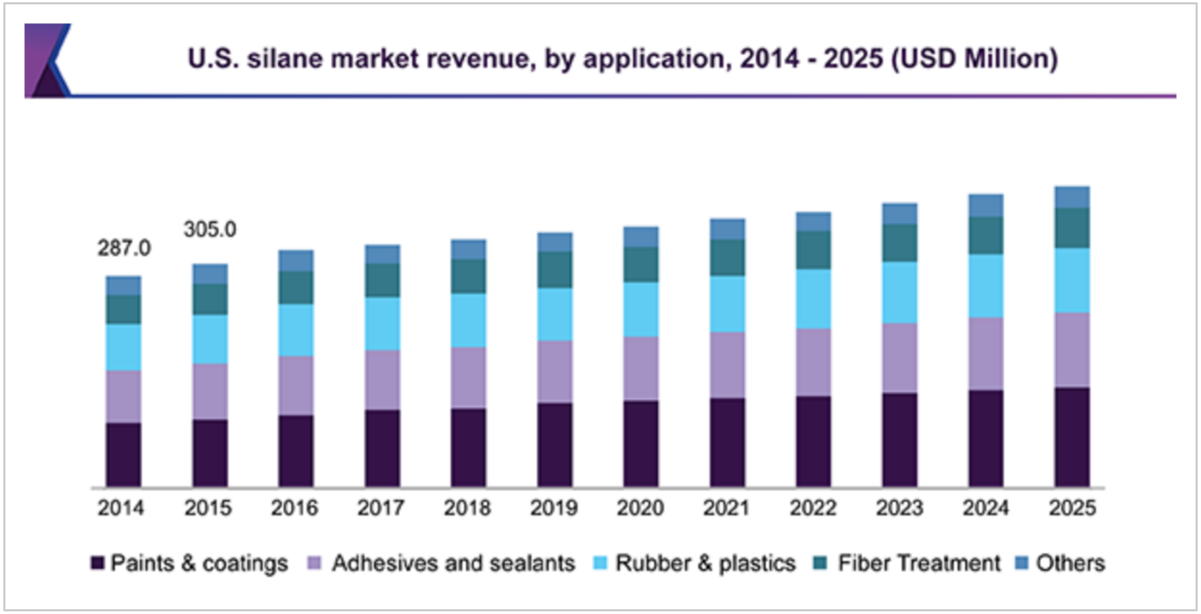
Due to the use of high volume compatible and low energy consumption manufacturing process we expect the cost to be significantly reduced.
Compared to existing polymeric based insulation, this new insulation with provide high flame resistant

Progress: Reduce Surface Energy

Goal:

- Reduce surface energy significantly
- Use gas phase technique to avoid nanoparticle agglomeration
- Use chemistry which is currently in use in industries for other applications.

The selected chemistries were all silane based



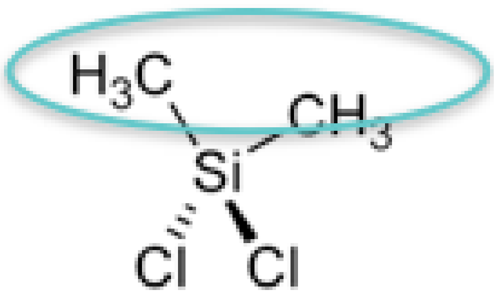
The global silane market size was valued at USD 1.48 billion in 2016 and is expected to ascend at a CAGR of 4.3% from 2017 to 2025. Silanes is a silicone - based compound with four organic or inorganic substituent groups attached to the central silicon atom. The product finds usage as a coupling agent, crosslinking agent, adhesion promoter, and resin additive in various applications.

Progress: Reduce Surface Energy

Surface Energy

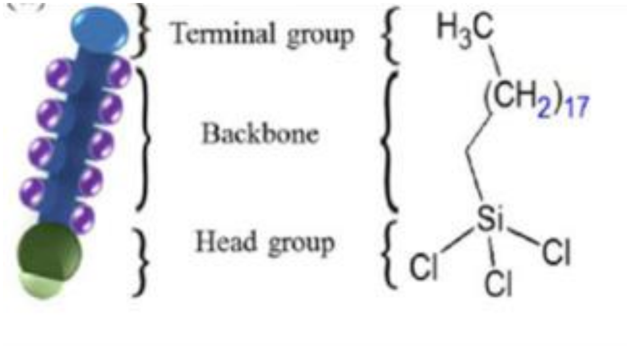
The following three chemistries were down-selected to study and isolate effect of terminal groups and effect of carbon chain on thermal transport.

1) Dichlorodimethylsilane (DDMS)



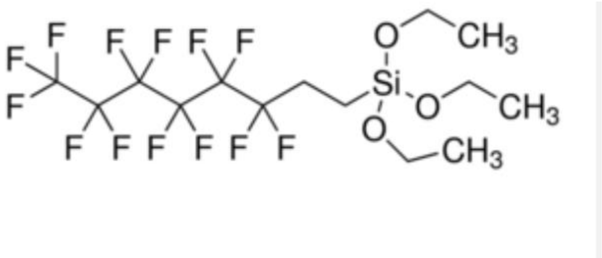
Shorter chain
(1 carbon),
Terminal group CH_3

2) Octadecyltrichlorosilane (OTS)



Longer chain
(17 carbon),
Terminal group CH_3

3) 1H, 1H, 2H,2H-Perfluorooctyltrichlorosilane (FDTS)

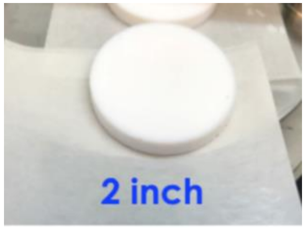


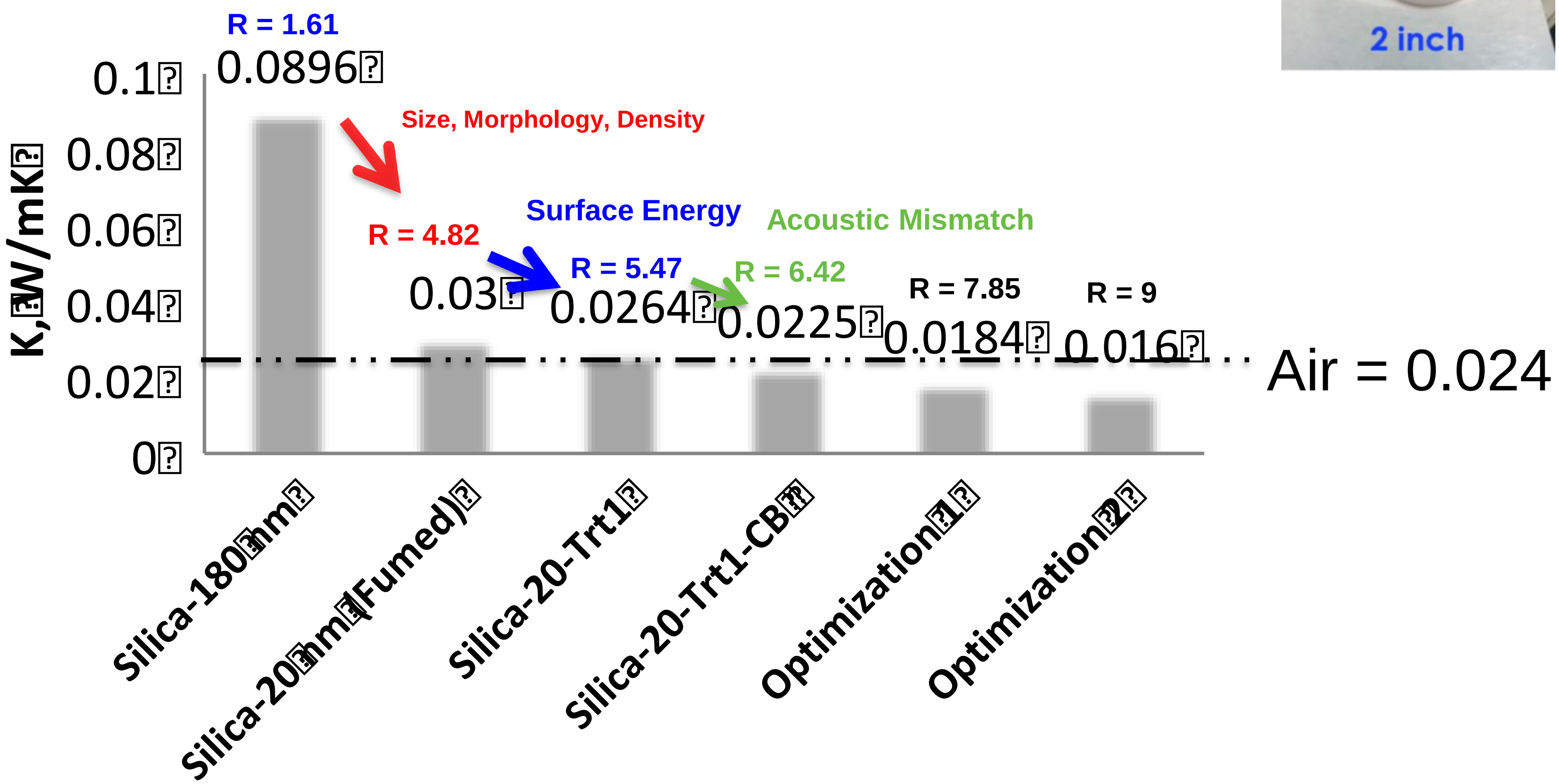
Long chain
(8 carbon),
Terminal group F

Progress: Thermal Performance

Current Status

R/inch = 9

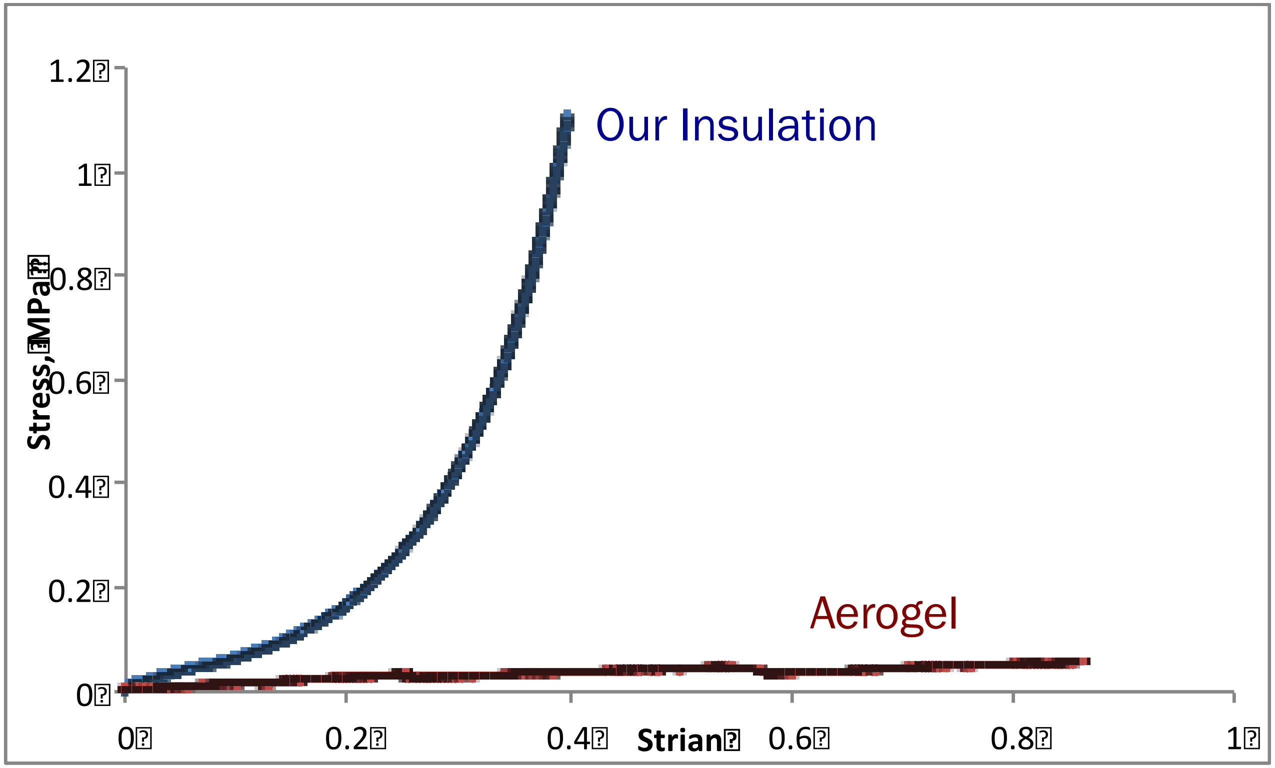




Progress: Mechanical Data

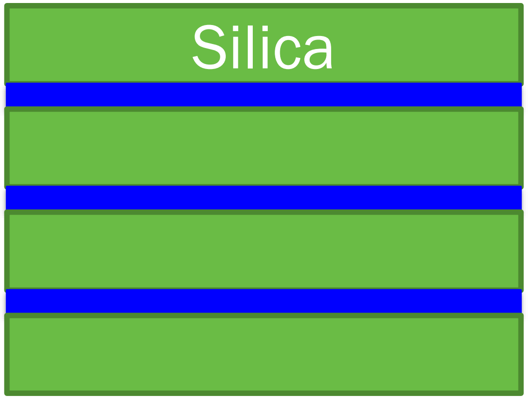
Currently : Using Instron tester, testing samples of 1cm in diameter under compression

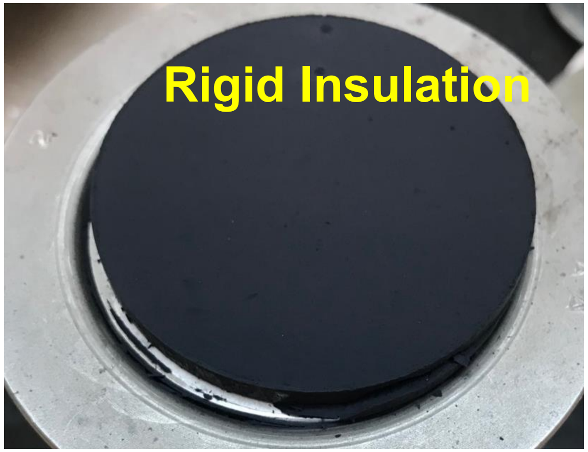
- Very preliminary mechanical data using Instron tester
- Mechanical properties depends on insulation composition and processing steps
- Currently characterizing mechanical properties of various optimized recipes

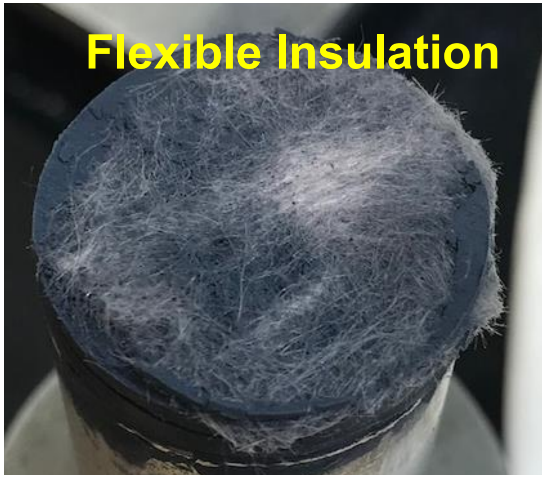


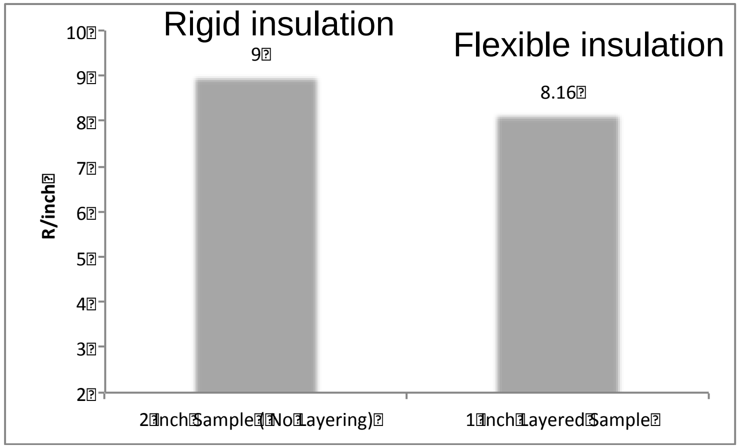
Progress : Rigid to Flexible

- Explored various ways of making the insulation flexible: spraying, dip coating, dry mixing and layering
- Promising results from dry mixing and layering
- Shown here one example in rigid and flexible form









Progress- Major roadblocks during last 2 years

Key Challenge for Progress: Selection of Thermal Metrology

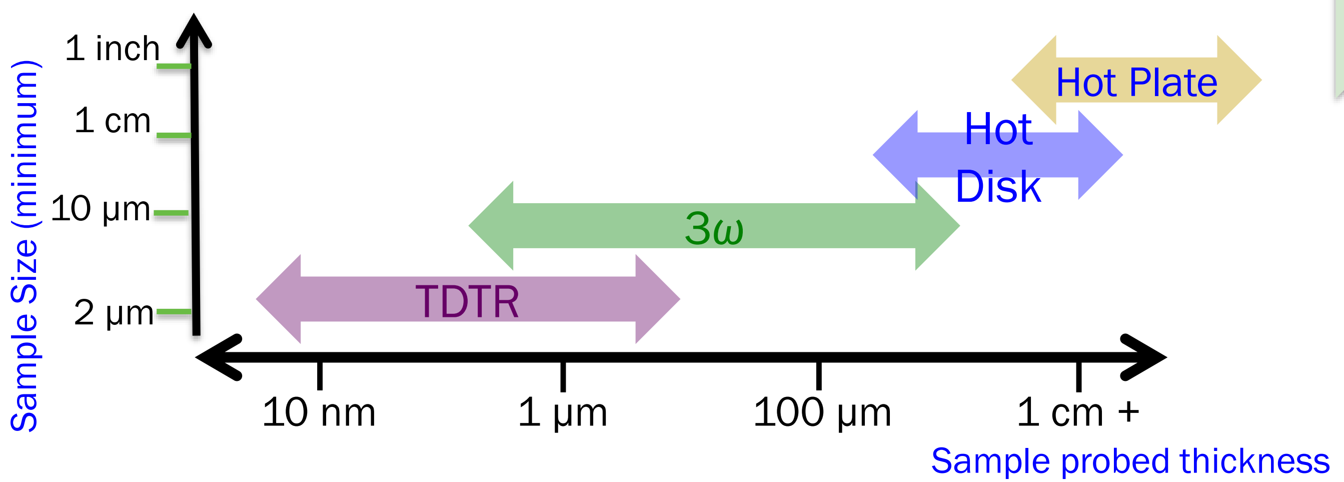
Q1
Initial Evaluation – Preference to available thermal metrology at LBNL: Guarded Hot Plate and TDTR

Q1-Q2
Selected and Built in house thermal capabilities of 3-omega

Q3
Bought commercially available Hot Disk for high throughput

Q4-Present
Realized accuracy issues with transient techniques.

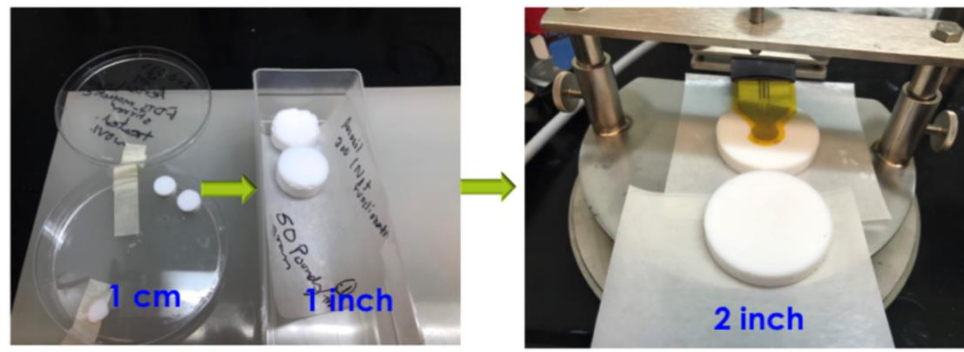
Using Guarded Hot Plate and Hot Disk in parallel



Progress- Effort and resources shifted to scale-up very early on

- In proposal goal was to optimize recipes on 1 cm diameter in first year and only scale up selected recipes in second year.
- We had no choice but to scale to one inch 5 months into the project for all the recipe.
- Made guarded hot plate work for one inch samples: required lot of calibration using standard reference samples and also commercially available aerogel samples before we can measure our one inch samples.

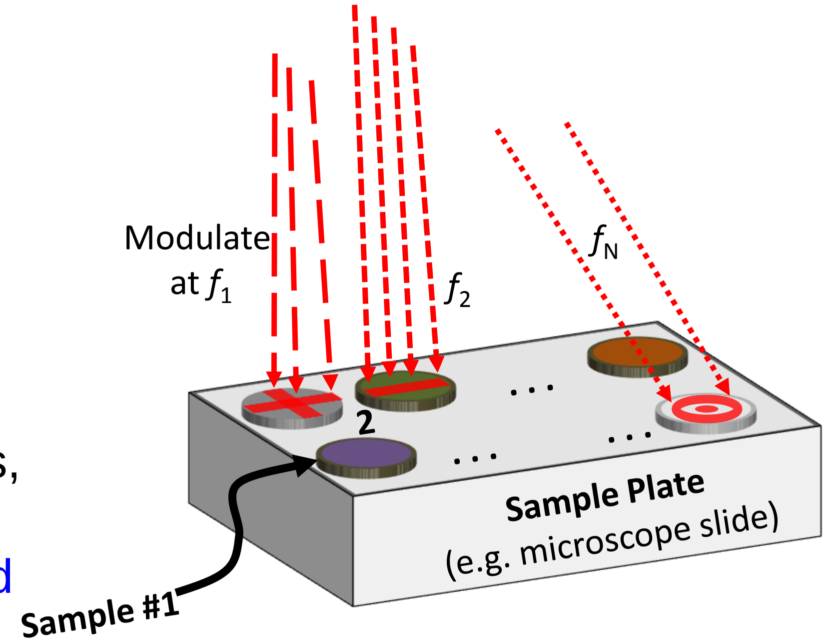
To avoid edge effects in one inch sample, we scaled up the samples to 2 inch.



Currently scaling up to 5” by 5”

Progress- Reliable High throughput Thermal Metrology

- In general lots of resources and efforts have been focused into high throughput material synthesis.
- Typically characterization becomes a bottleneck



The team (UC, LBNL) led by Prof. Chris Dames, UC Berkeley, is now working on solving this problem for thermal characterization: Goal rapid thermal characterization of small samples (<1 cm in dia) by using minimal sample prep.

Stakeholder Engagement

- We constituted an industry advisory board of people from insulation and energy efficiency industries and academia. The board advised us on potential funding opportunities, guiding us on early stage applications and market.
- Industry advisory board consists of
  - 3M: Raghu Padiyath, Division Scientist
  - **Stone Energy Associates:** Nehemiah Stone, Principal

    Energy efficiency and renewable energy expert with extensive experience in the design, implementation, management and evaluation of utility programs,
  - **Arizona State University**: Patrick Phelan, Professor
  - **Inficold Inc**: Himanshu Pokharna, CEO

    Thermal storage integrated refrigeration technology
  - **McHugh Energy Consultants Inc :** Jon McHugh, **PE**

    Energy efficiency company serving public agencies, utilities and other entities. They do market assessments and life cycle costing to provide decision-makers with strategic energy information for policy or investment decisions
- We are in talks with companies to test our samples.

Remaining Project Work

Near Future

- Goal to achieve R/inch =12

  Process optimization for the right combination of nanoparticle size, surface chemistry and acoustic mismatch to achieve final goal of R/inch = 12

  We are pursuing various strategies:

  - a) Other forms and surface areas of silica materials
  - b) Optimization of mixing step
  - c) Combination of 3 to 4 nanoparticles
  - d) Density optimization

- Scaling up to 5" by 5" samples

  This will allow us to provide insulation/other interested industries with samples for evaluation in thermal, mechanical and flammability performance.

- **Mechanical properties of the samples: both in rigid and flexible form factor**

  Preliminary mechanical data on the rigid samples looks very promising. More systematic studies of the mechanical properties is both form factors, rigid and flexible, will be carried out.

Thank You

Performing Organization(s): LBNL, ORNL

PI Name and Title: **Ravi Prasher, Associate Lab Director, LBNL**

PI Tel and/or Email: 510-486-7291 & rsprasher@lbl.gov

REFERENCE SLIDES

Project Budget

Project Budget: DOE budget was $1,500,000 over 3 years (last year –no cost extension) and then CEC was part of a cost share agreement for $100,000

Variances: There was a delay in funding the CEC award due to significant administrative hurdles which have since been cleared, and cost share will soon be spent.

Cost to Date: $774,638

Additional Funding: The cost share is being provided by California Energy Commission for $100,000.

Budget History					
Oct1st, 2016– FY 2017 (past)		FY 2018 (past)		FY 2019 – 12/20/2019 (Current +Present)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
489,786	0	571,703	0	289,510	50,000

Project Plan and Schedule

Project Schedule		
Project Start: Oct 1st, 2016		Completed Work
Projected End: Dec 31st, 2019		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned) use for missed milestones
		Milestone/Deliverable (Actual) use when met on time

	FY2017				FY2018				FY2019			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Q1 Milestone: Procurement of nanoparticles and characterization of procured nanoparticles												
Q2 Milestone: Achieve thermal conductivity < 0.14 W/m·K, R/inch > 1 and compressive strength > 1 MPa (>10x better than aerogel)												
Q3 Milestone: : Identify surface functionalization chemistries with surface energy less than < 100 mJ/m2 and contact angle > 90 deg using substrates made of same material as the nanoparticles												
Q4 Go/No Go Decision: Achieve thermal conductivity < 0.024 W/m·K, R/inch of 6, using the right surface chemistry, particle size and acoustic mismatch												
Q5: Milestone: Identify target market applications and develop a product requirements, Energy saving Report*												
Q5: Constitute Industrial advisory Board												
Current/Future Work												
Q6: Milestone: Introduce technology to DOE deployment												