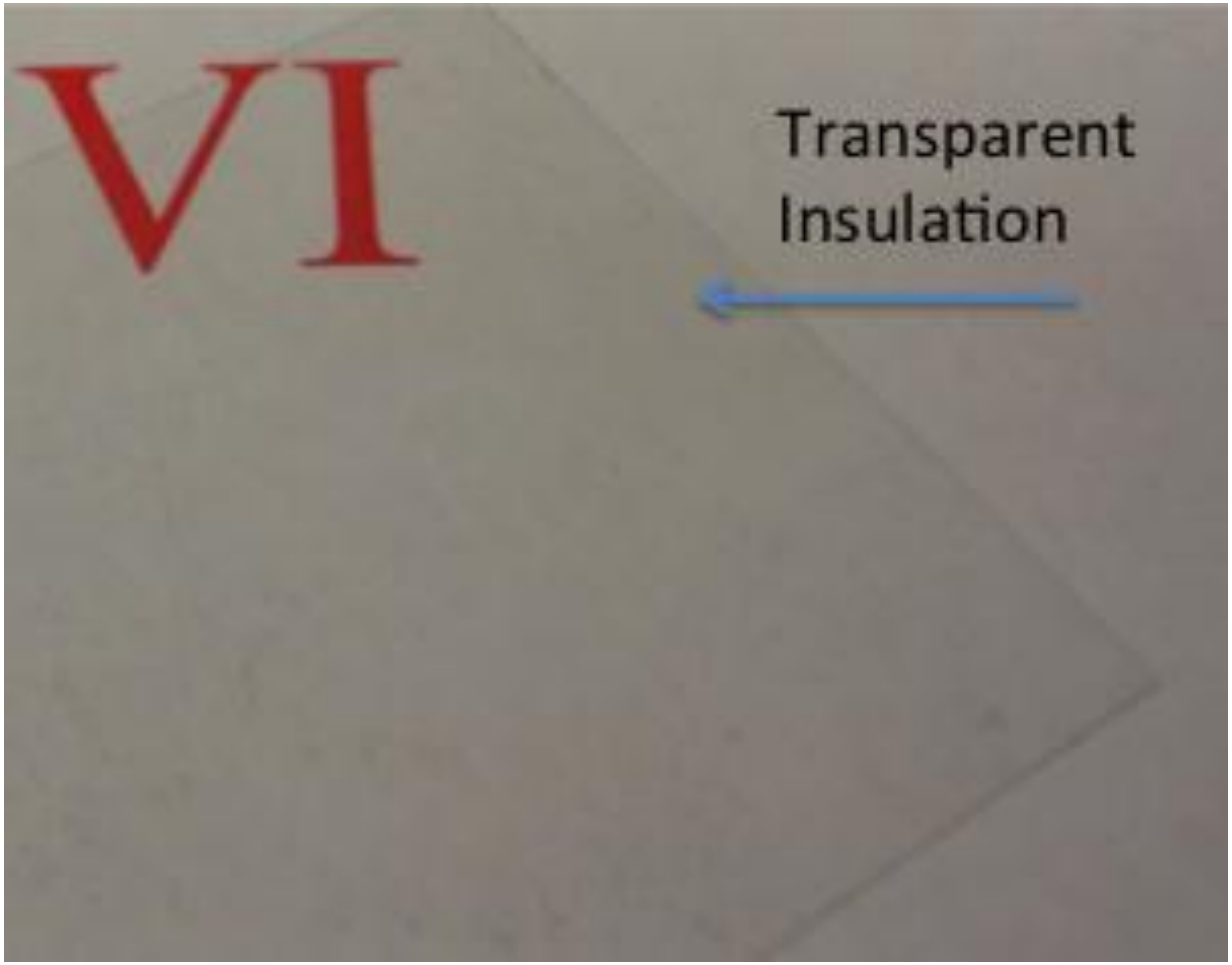
Vacuum Insulation for Windows

2014 Building Technologies Office Peer Review



Picture of NREL's transparent vacuum insulation for windows. The picture demonstrates that the evacuated components are transparent while providing superior insulation in a flexible structure that can be retrofitted to installed windows.

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Project Summary

New Competively Selected Award FOA 823

Initial TRL: laboratory validation and development

Timeline:

Start date: October 1, 2013

Planned end date: September 30, 2015

Key Milestones

1. Assess vacuum insulation materials with less than 0.007 W/m-K thermal conductivity; September 30, 2014
2. Deliver VI with low-e for external testing; September 30, 2015

Budget:

Total DOE $ to date: $375,000 FY14

Total future DOE $: $375,000 FY15

Target Market/Audience:

This effort addresses the large installed windows retrofit and inexpensive high performing new windows markets to substantially improve fenestration and building envelope energy efficiency.

Key Partners:

Have begun discussions with commercial companies that can provide key strategic alliances for manufacturing and specific market applications. Partners to include vacuum capsule, low-e film, and window manufacturers.

Key milestone at end of year one is to have a commercial partner(s)

Project Goal:

This effort is assessing the impact vacuum insulation (VI) will have for window applications using novel evacuated materials (that are so small as to be invisible) integrated with low-e coated plastic films. The ultimate goal is to develop materials that have R-10 to R-20 insulation values and have the correct form factor for easy integration with installed windows (i.e., flexible, thin, and applied like tinting products).

Purpose and Objectives

- **Problem Statement:** *Buildings use ~40% of the energy and produce ~40% of the CO_2 emissions in the United States (US) today*.
  - Windows can account for 30% to 50% of the energy losses in buildings.
    - It ***could take decades and trillions of dollars before replaced*** with highly insulating windows.
    - Thus substantial need for ***retrofitting*** installed windows to improve energy efficiency.
  - This effort is assessing vacuum insulation (VI) for window applications using novel evacuated materials (that are so small as to be invisible) integrated with low-e coated plastic films.
  - Goal: develop R-10 to R-20 insulation that has the correct form factor for easy integration with installed windows (i.e., flexible, thin, and applied like tinting products).
- **Target Market and Audience**: This effort addresses the large installed windows retrofit and inexpensive high performing new windows markets to substantially improve fenestration and building envelope energy efficiency.
  - Could save 1 to 3 quads of energy annually in US.
- **Impact of Project:** The project creates R-10 to R-20 transparent VI films that utilize nano- to micrometer sized vacuum capsules integrated with standard low-e coated flexible window plastics.
  - Near-term impact path: quantify insulation, transparency, cost, and other performance criteria to identify high-value market opportunities to support initial transition to commercial products.
  - Intermediate-term impact path: Work with commercialization partners to optimize performance for specific applications
  - Long-term impact path: Work with commercial and residential building communities to develop rapid market penetration strategies to help decrease energy use and CO_2 emissions as quickly as possible

Approach

- Use basic processes and materials to form smooth vacuum capsule layers with structure that minimizes thermal conductivity
- Maintain most of the properties typically associated with **thin flexible plastic sheets** used for applications like tinting.
  - **Inexpensive and scalable** to high throughput, such as the production lines at plastics and insulation manufacturing companies.
- Work with companies to identify and measure vacuum capsules that have the light transmission, strength, and evacuation/vacuum properties needed for VI.
  - When possible, use commercially available materials and low-e coated films from retail suppliers.
- Assess vacuum capsule materials insulation properties better.
  - With low-e coated films, create transparent R-10 to R-20 films

Key Issues: Thermal conductivity measurements below 20 mW/m-K

Distinctive Characteristics: Highly insulating transparent film will be a game changer for windows, resulting in substantial energy and CO_2 reductions

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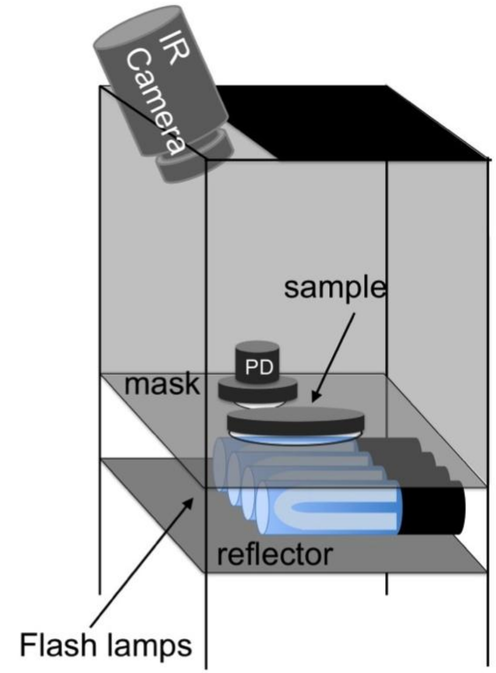
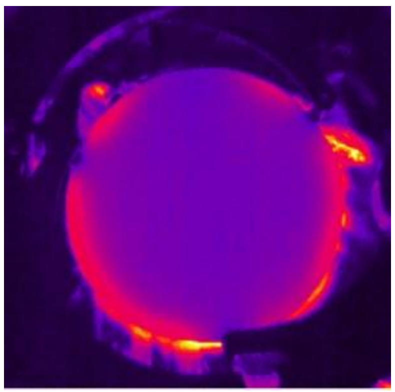
Progress and Accomplishments: Measurements

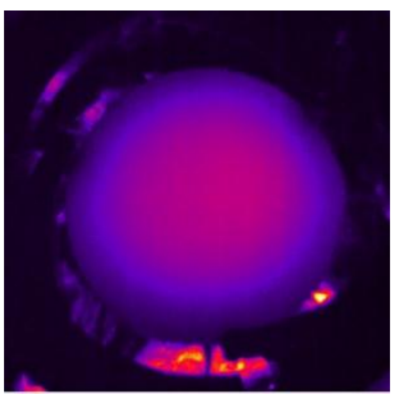
- Improved flash system sensitivity
  - Can measure small thin samples typical of initial R&D
    - IR camera and analyzing full time dependence of heat transport improves accuracy
    - Does not require heat capacity measurements
    - Demonstrated that IR camera easily monitors heating from edges, and that edge heating was not an issue
    - Independent of sample or measurement area and intensity
    - Accurate for cork and plexi-glass thermal conductivity

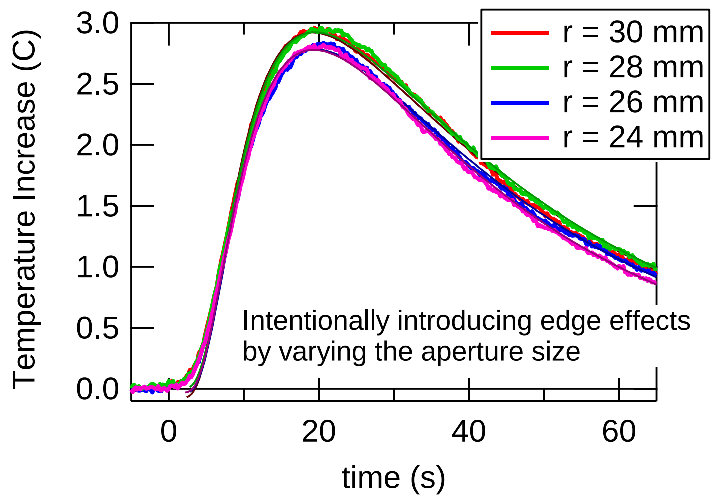


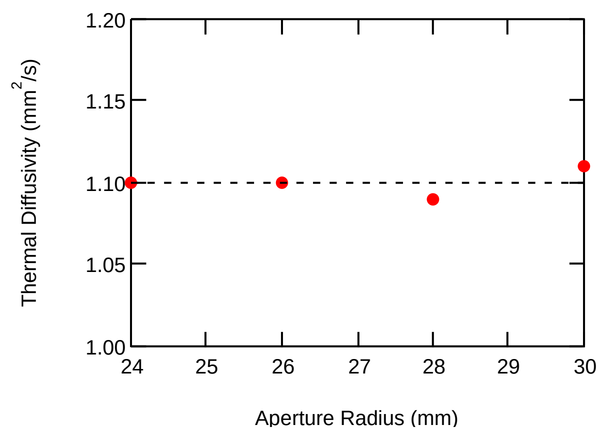
Hot edges (r = 30 mm)



Cold Edges (r = 24 mm)







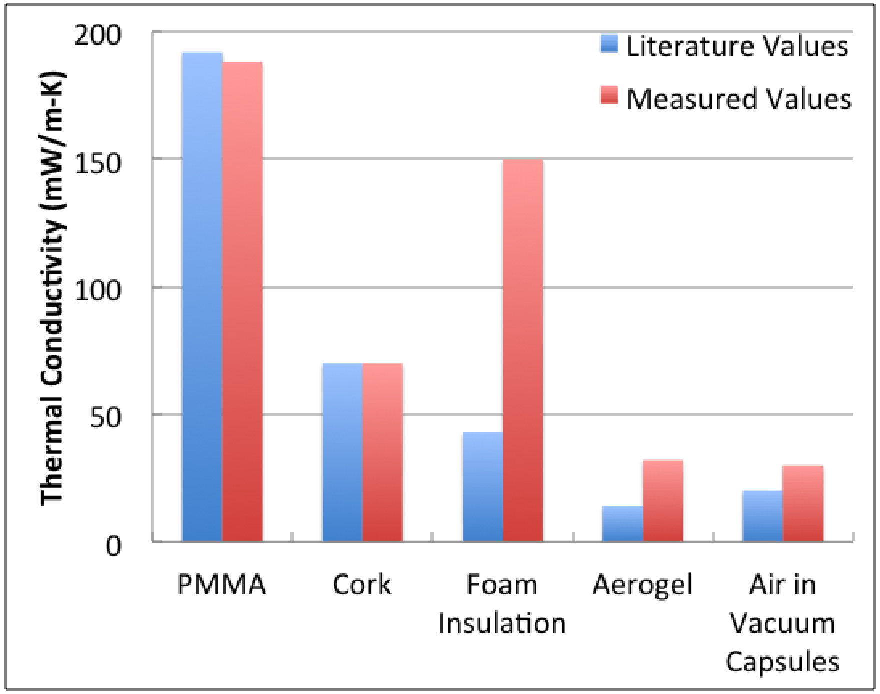
For these samples with t ≤ 12 mm, diffusivity is unaffected by edge effects

Progress and Accomplishments: Measurements

- Two main issues have limited accurate measurements for low TC materials.
  - Highly porous materials appear to be IR transparent
  - Need to correctly account for multiple interfaces
- For rigid materials, TC measurements good to less than 70 mW/m-K
- TC measurements not good for porous materials
  - Foam insulation
  - Aerogels, vacuum capsules, or vacuum in general
  - Preliminary results agree with literature that vacuum capsules may be substantially better insulation than foams

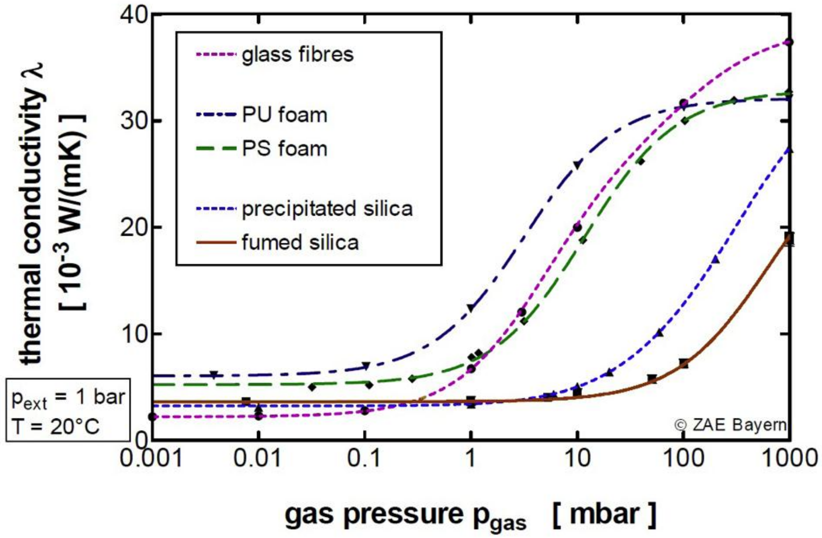
Table of Thermal Transport Values

Sample/illumination	Diffusivity (mm2/s)	Conductivity (mW/m/K)
PMMA: Literature Value	0.120	192
PMMA: Previous Measurements	0.128	203
PMMA: New system configurations	0.116	188
Cork: Literature Value		70
Cork: Measured		70
Foam Insulation: from R-Value		43
Foam Insulation: Measured	0.9	100 to 200
Aerogel: Literature Value (1 atm)		14
Aerogel: Measured (1 atm)	0.103	32
Vacuum: Literature Value (0.01 mtorr)		8 for vacuum insulated glass
Air in Vacuum Capsules: Literature (1 atm)		20
Air in Vacuum Capsules: Measured (1 atm)	0.047	30

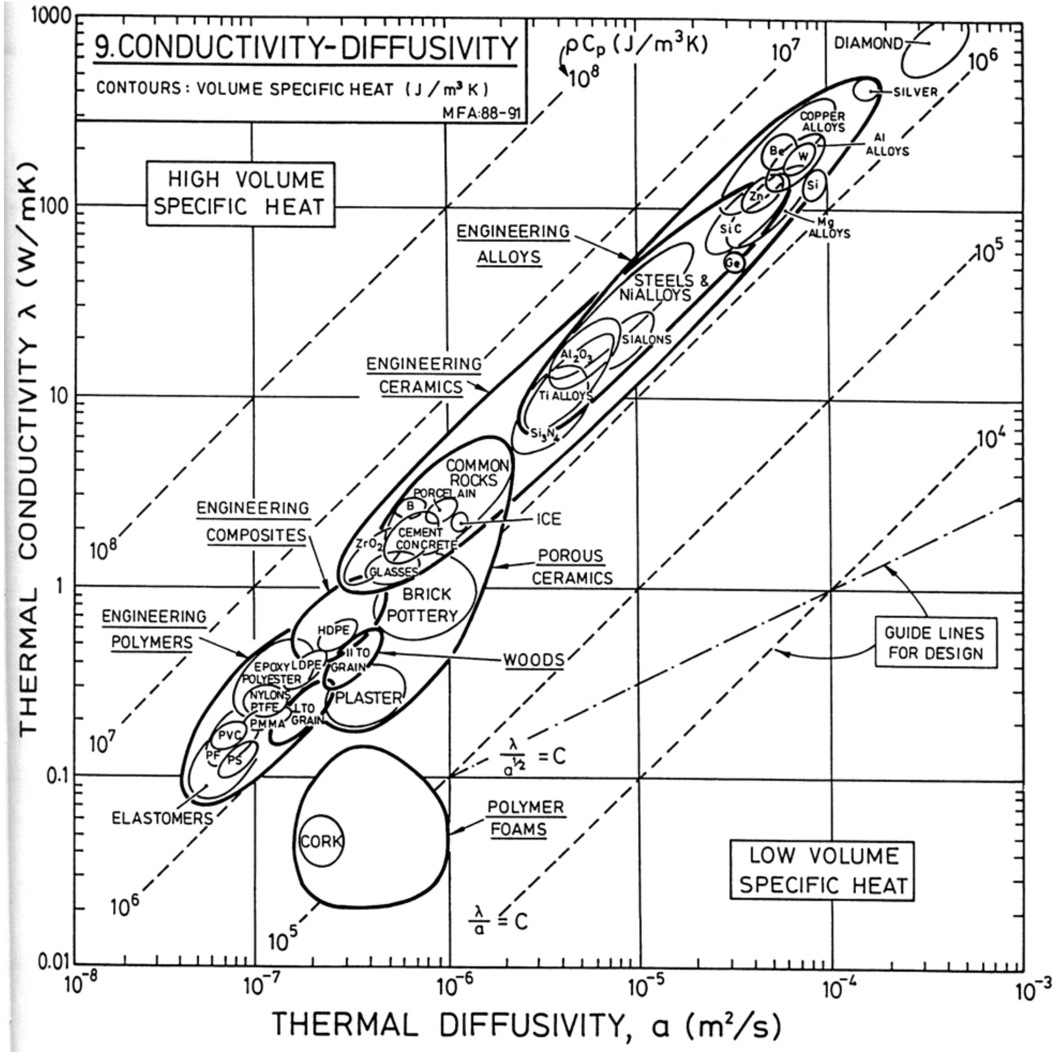


Progress and Accomplishments: Measurements

- For calibration, will need to go to aerogels and evacuated samples to get materials with low enough thermal conductivities



Bouquerel, et. al., Proceedings of Building Simulation, Sydney, 1973 (2011).

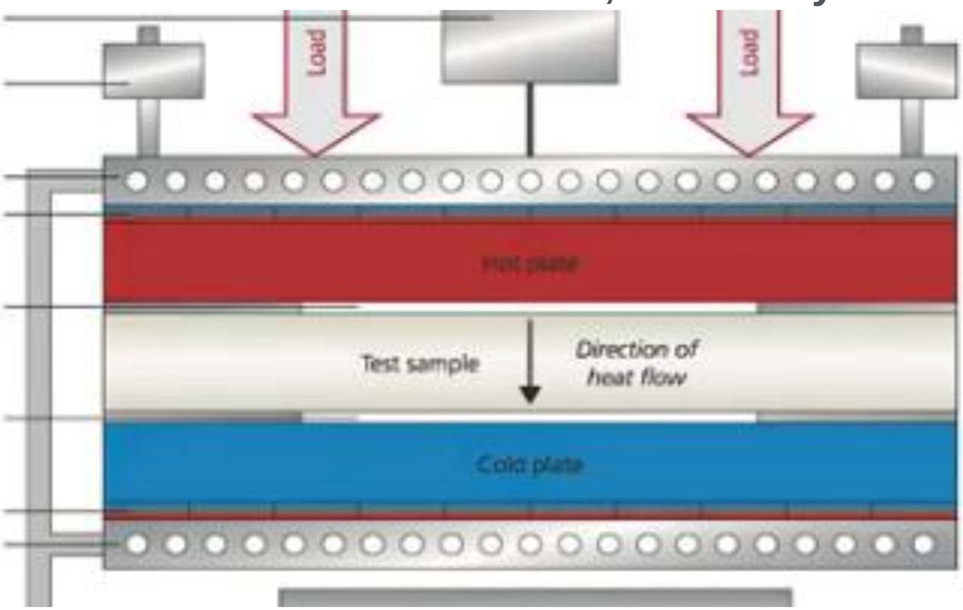


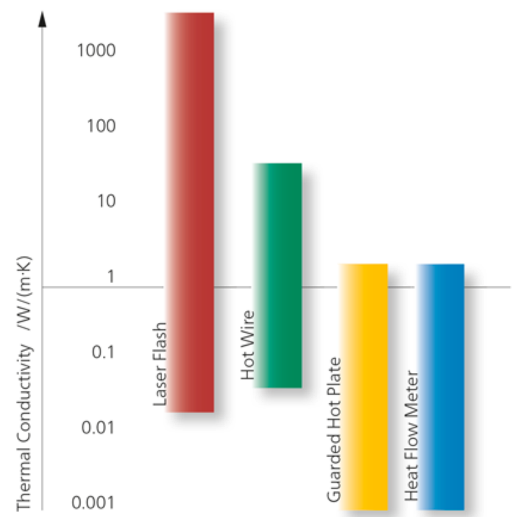
http://web.mae.ufl.edu/tribology/Courses/MessageBoard/Fluids/messages/chart9.jpg

Highly Insulating Transparent Fenestration Testing

- Ultimately need to perform ASTM standards to compare VI with other products
  - ASTM Standard C1199 − 12 “Standard Test Method for Measuring the Steady-State Thermal Transmittance of Fenestration Systems Using Hot Box Methods” on Transparent Vacuum Materials in system.
  - ASTM Standard ASTM C1363 – 11: “Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus”
  - May purchase commercial Hot Plate system to perform initial TC measurements
    - Main problem requires 30 cm X 30 cm x 1 cm sample sizes

Heat Flow Meter or Hot Plate, eventually NTS Differential Thermal Cycling Unit (DTCU)





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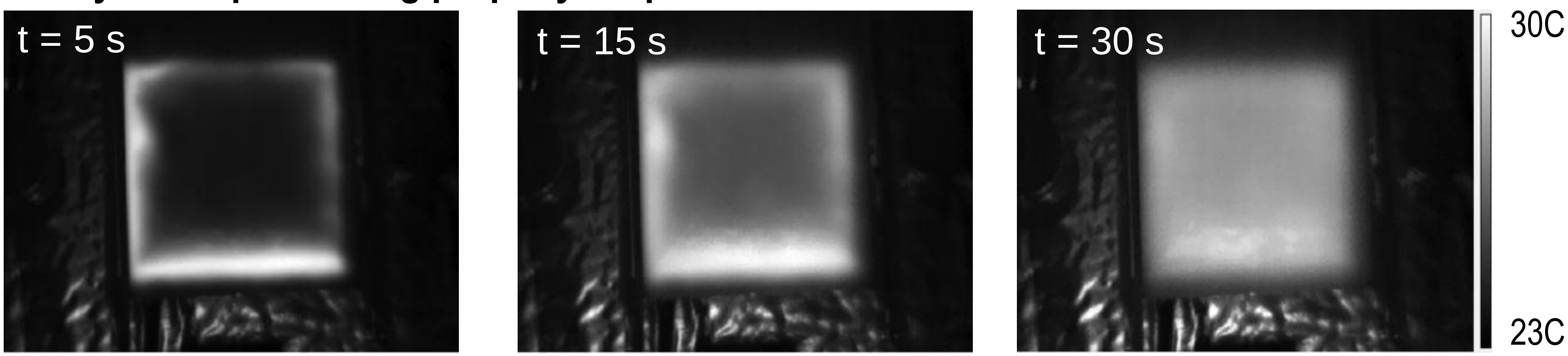
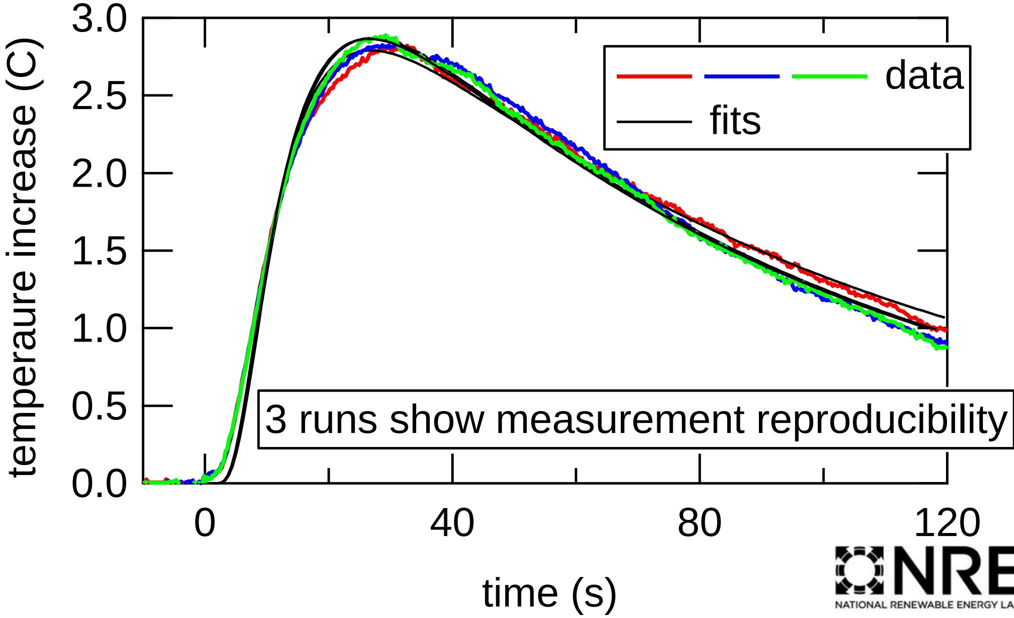
Progress and Accomplishments: Materials

- **Identified and obtained initial vacuum capsules; formed insulation and evacuated capsules**
  - **Capsules easily evacuated and maintain high vacuum. Will perform accelerated durability testing**
- **Measured thermal transport properties of vacuum capsules even though measurement system clearly is not performing properly for porous materials**





- Heat transport through vacuum capsules structured so that sample edges are not an issue
- Measurement system provides uniform illumination that is repeatable and fit to model.
- Measurements show difference between air and vacuum inside capsules

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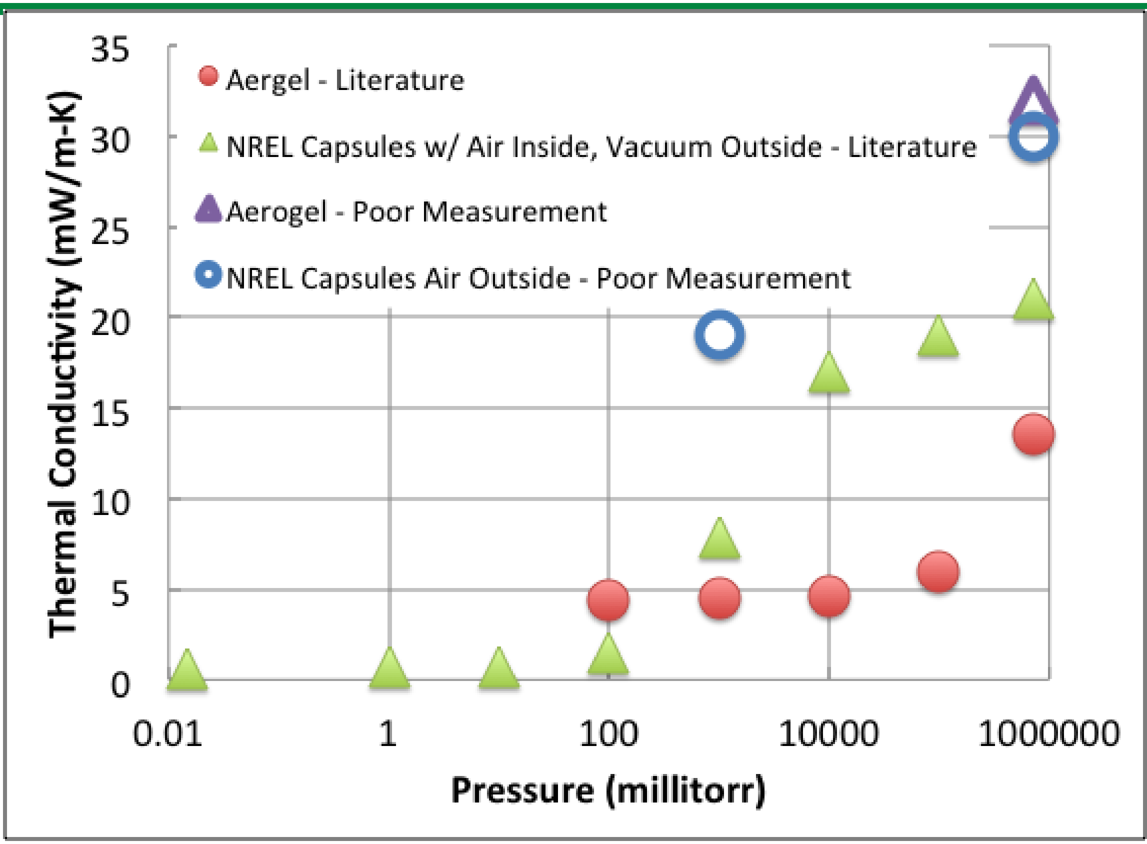
Materials: Pressure Dependence

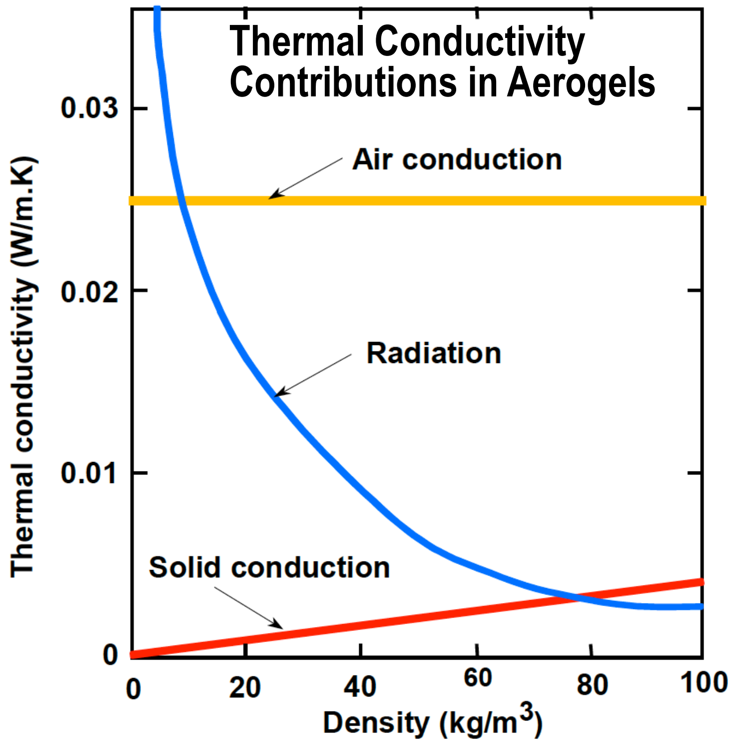
- From literature, with air inside capsules, the thermal conductivity decreases from ~20 mW/m-K at atmospheric pressure to ~0.6 mW/m-K at ~1 mtorr for pressures outside capsule
- Because most of the volume is inside the capsule; when evacuated, should see a similar type of thermal conductivity decrease, even with air on the outside of the capsule
  - Preliminary results: evacuated capsules shows some decrease in thermal conductivity
    - Measurements are not accurate.
  - The measured aerogel results are more than a factor of 2 higher than expected.



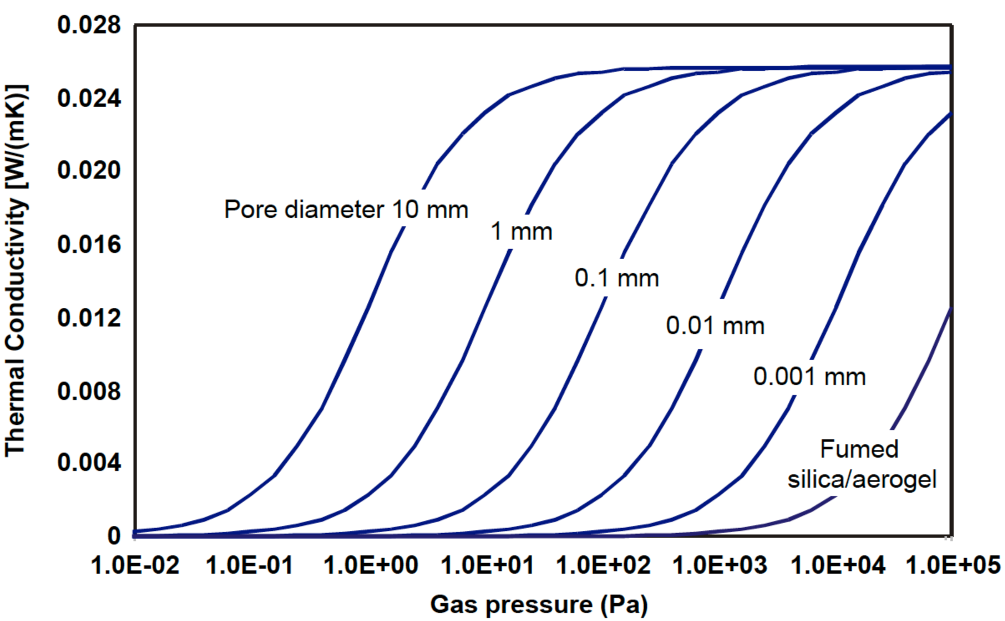
Preliminary data suggest that with accurate measurements, evacuated capsules may have lower thermal conductivity values than evacuated aerogels.

Materials: Lower Thermal Conductivity

- 3 main strategies to improve NREL's transparent insulation
  - Evacuate vacuum capsules which accounts for majority of volume
  - Minimize amount and size of spaces outside capsules
  - Minimize radiation heat transport with low-e coatings
- Achieve thermal conductivities between 0.2 and 5 mW/m-K



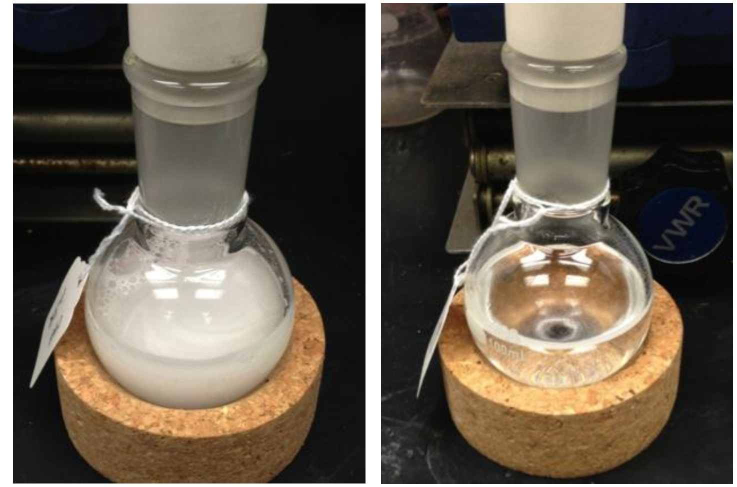
Aerogel: Air conductivity (nanopore) < Air conductivity (macropore)



www.oboa.on.ca/events/2010/sessions/files/710.pdf

Progress and Accomplishments: Processing

- Capsule Functionalization and Assembly
  - Identified and tested initial vacuum capsule layer integration methods from literature to create suspensions that work
    - Note: after 24 hr some capsules settle to bottom
    - Suspension sufficient for different deposition techniques, including dip and lamination
  - These same techniques provide excellent stacking of vacuum capsules to form high quality optical coatings with limited voids
    - Limited stacking voids important
    - Use different suspension materials to tailor processes from transparency and insulation



Images of vacuum capsule suspensions right after mixing and 24 hours later

Image of Vacuum Capsules Deposited using Dip Coating, demonstrating virtually no visual degradation.

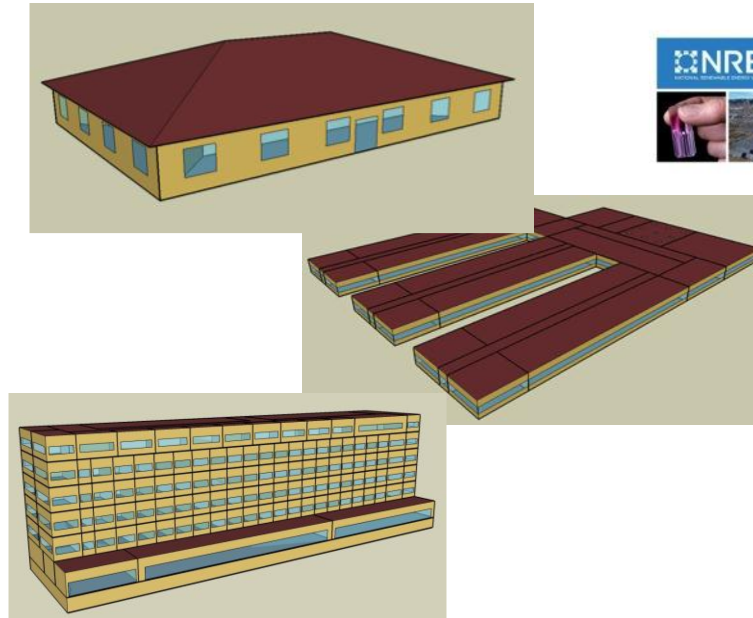
Single dip had ~75% coverage of ~100 nm thick layer

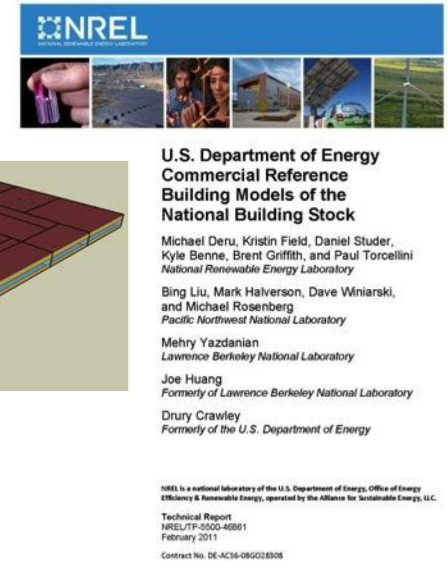
Image of vacuum capsules in water (4 mg/ml) used for dip coating

Progress and Accomplishments: Energy Savings Analysis

<u>Completed initial energy savings and cost per energy saved analyses</u>

- Apply technology to DOE commercial reference building energy models
  - Standard reference models provide a common set of inputs
- 16 building types and 16 locations
- Three sets of buildings
  - New construction – 90.1-2004
  - Post-1980 construction (~90.1-1989)
  - Pre-1980 construction (pre energy standards)
- Simulate models with and without technology in each location to provide savings potential values
- Apply factors that characterize the number of buildings that are similar to each reference building in each location to quantify impact potential




NREL
U.S. Department of Energy Commercial Reference Building Models of the National Building Stock

Michael Deru, Kristin Field, Daniel Studer, Kyle Benne, Brent Griffith, and Paul Torcellini
National Renewable Energy Laboratory

Bing Liu, Mark Halverson, Dave Winiarski, and Michael Rosenberg
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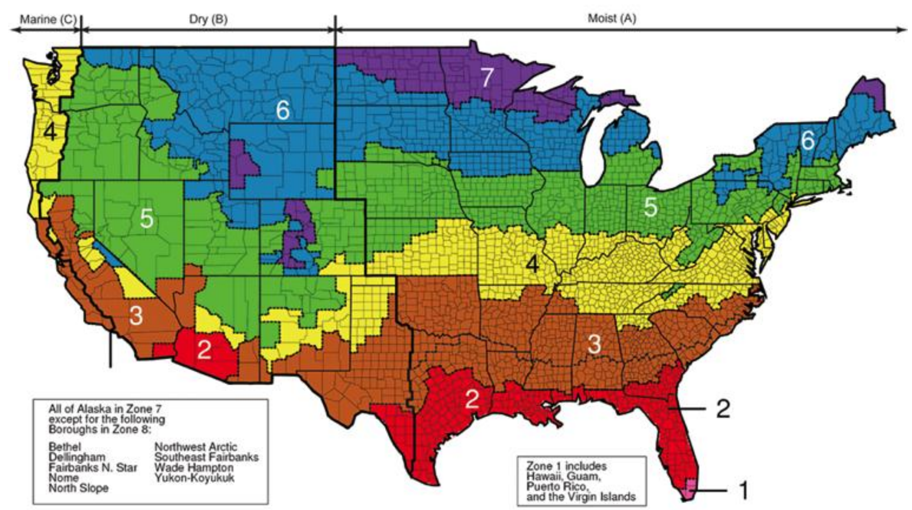

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Energy Model Details

Window Specifications: Assumed starting U-values of windows between 0.35 and 1.22, and added vacuum insulation with U-values between 0.2 and 0.025

Reference Buildings

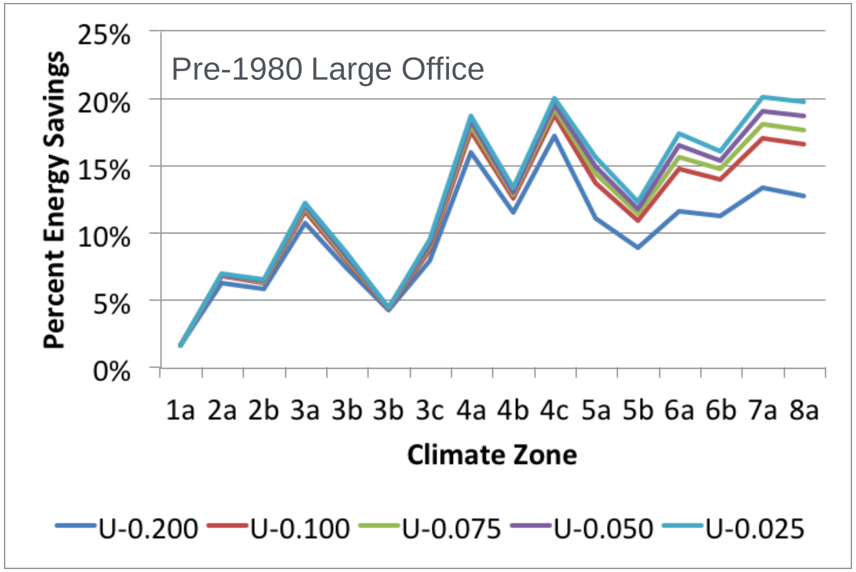
No.	Reference Building	Square Footage	Glazing Fraction
1	Full service restaurant	5,500 ft^2	0.17
2	Hospital	241,351 ft^2	0.15
3	Large hotel	122,120 ft^2	0.27
4	Large office	498,588 ft^2	0.38
5	Medium office	53,628 ft^2	0.33
6	Mid-rise apartment	33,740 ft^2	0.15
7	Outpatient healthcare	40,946 ft^2	0.19
8	Quick service restaurant	2,500 ft^2	0.14
9	Stand-alone retail	24,962 ft^2	0.07
10	Primary school	73,960 ft^2	0.35
11	Secondary school	210,887 ft^2	0.33
12	Supermarket	45,000 ft^2	0.11
13	Small hotel	43,200 ft^2	0.11
14	Small office	5,500 ft^2	0.21
15	Strip mall	22,500 ft^2	0.11
16	Warehouse	52,045 ft^2	0.006

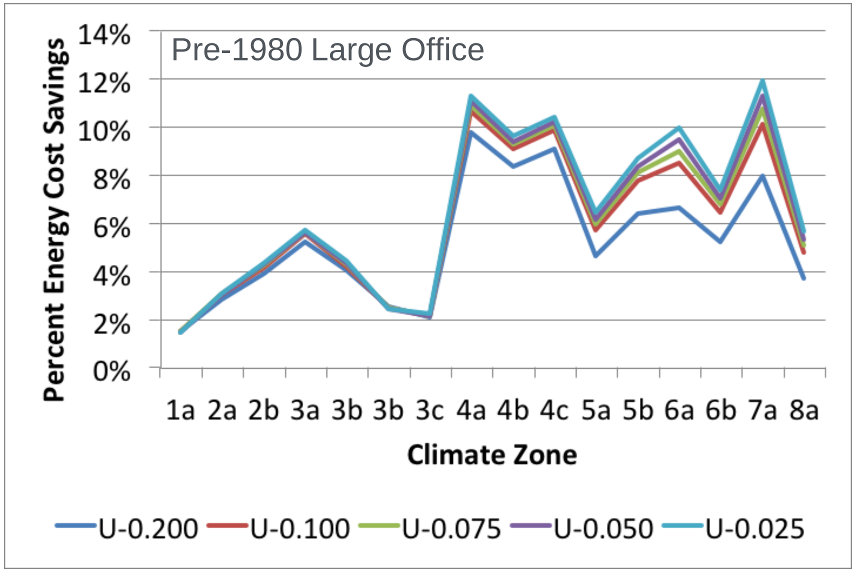
Climate Zones

No.	Climate Zone	Representative City	TMY2 Weather File Location
1	1A	Miami, FL	Miami, FL
2	2A	Houston, TX	Houston, TX
3	2B	Phoenix, AZ	Phoenix, AZ
4	3A	Atlanta, GA	Atlanta, GA
5	3B	Las Vegas, NV	Las Vegas, NV
6	3B:CA	Los Angeles, CA	Los Angeles, CA
7	3C	San Francisco, CA	San Francisco, CA
8	4A	Baltimore, MD	Baltimore, MD
9	4B	Albuquerque, NM	Albuquerque, NM
10	4C	Seattle, WA	Seattle, WA
11	5A	Chicago, IL	Chicago-O’Hare, IL
12	5B	Denver, CO	Boulder, CO
13	6A	Minneapolis, MN	Minneapolis, MN
14	6B	Helena, MT	Helena, MT
15	7	Duluth, MN	Duluth, MN
16	8	Fairbanks, AK	Fairbanks, AK

Energy Modeling: Example of Results

- Average energy savings from baseline for all commercial building types in all environments is between 2.5% and 5% for U values between 0.2 and 0.025
  - These values even include “warehouse” structures with very few windows.
- However, even U-0.2 can save ~19% for some buildings in some climates.
  - This increases to ~23% for U-0.025
- These energy savings translate to as much as 12% reductions in costs.





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Progress and Accomplishments: Summary

- Vacuum capsule selection and characterization
  - Identified/obtained initial vacuum capsules, formed insulation with evacuated capsules
  - Performed initial thermal conductivity measurements and determined that the thermal conductivity was substantially lower than ~R-13 insulation board.
- Began investigating optical properties of vacuum capsules.
- Identified and tested initial vacuum capsule layer integration
  - This initial process is compatible with dip-coating, spray, casting, and/or lamination type techniques to form initial insulation samples.
- Characterized thermal properties of vacuum insulation samples.
  - Characterized initial VI samples and measured insulation values.
  - Improved NREL's in-house thermal conductivity measurements and determined lower accuracy limit; presently at ~70 mW/m-K.
  - Procuring commercial thermal conductivity measurement system with 2 mW/m-K accuracy
- Performed initial Energy Modeling
  - Completed initial energy savings & cost per energy saved analyses assuming VI ultimate performance
  - Performed initial building energy modeling to show performance metrics
- Intellectual Property
  - Reviewed literature, completed IP portfolio evaluation and submitted initial provisional patent
  - ***Due to the early stage development nature of work, some details constrained due to IP concerns***
- Tech Transfer/Commercialization
  - Had initial discussions with material and end user companies

Project Integration and Collaboration

Project Integration:

- Work with NREL's commercial, residential, emerging technology, and technology transfer buildings groups that have substantial experience and contacts within the buildings community including potential commercialization partners.
- As project progresses and performance is quantified, more industrial collaborators and partners will be engaged to help guide development and identify specific market applications.

Partners, Subcontractors, and Collaborators:

- Continue discussions and work with commercial companies to form key strategic manufacturing and market alliances.
    - Partners to include vacuum capsule, low-e film, and window manufacturers.
    - Specific partners will be identified once more formal arrangements and permissions have been obtained.

Communications:

- New competitively awarded project and this review meeting is the first public presentation of some of the technology.
- Future presentations at conferences, workshops, and review meeting is anticipated.

Next Steps and Future Plans

- Continue developing new inexpensive transparent vacuum insulation to substantially improve the R-values of windows.
  - Finalize present thermal conductivity measurement system capabilities and determine if other instrument is needed
    - Determined upper insulation value limit of vacuum capsules
  - Continue investigating optical properties of vacuum capsules
    - Identify potential performance to help guide market analysis
  - Improve integration processes to form well-ordered vacuum capsule layers
    - Enhance performance while reducing costs
  - Perform additional Energy Modeling
    - Determine best configurations and high value applications
  - Hold more discussions with potential commercialization partners
    - Work with selected partners to identify commercialization paths for first adopter markets and value propositions

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Acknowledgements (Many People Providing Expertise)

- **Michele Olsen** and Phil Parilla: Thermal Conductivity Measurements
- **Chaiwat Engtrakul** and **Robert Tenent**: Coatings
- **Tim Snow** and Chaiwat Engtrakul: Durability and Reliability
- **Eric Bonnema:** Energy Performance Modeling and Cost Analysis
- **Ty Ferretti and LaNelle Owens**: Intellectual Property
- **Yoriko Morita**: Tech Transfer/Commercialization:
- **Pat Phelan and Karma Sawyer**: DOE Emerging Technology
- **Leon Fabick and Craig Livorsi**: DOE Golden Field Office

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REFERENCE SLIDES

Project Budget (New Project Started in FY2014)

Project Budget: $375,000 in FY14 and $375,000 in FY15
Variances: NA
Cost to Date: ~$180,000 or ~50%
Additional Funding: NA

Budget History					
FY2013 (past)		10/1/2014 - FY2014 (current)		FY2015 – Insert End Date (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
		$375,000	$0	$375,000	$0

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Project Plan and Schedule

Project Schedule												
Project Start: October 1, 2013		Completed Work										
Projected End: September 30, 2015		Active Task (in progress work)										
		Milestone/Deliverable (Originally Planned)										
		Milestone/Deliverable (Actual)										
	FY2014				FY2015				FY2016			
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)
Current Work												
MQ1.1: Initial energy savings and cost analysis.												
MQ1.2: Thermal conductivity pressure dependence												
MQ2.1: Initial material selections work with sunlight.												
MQ2.2: Show thermal conductivity measurement ability												
MQ2.3: Modeling analysis for VI placement on windows												
MQ2.4: Identify potential commercialization partners												
MQ3.1: Down-select initial processing, for 4"X4" samples												
DQ4.1: PHASE I GO/NO-GO DECISION: Evacuated vacuum capsule has < 0.007 W/m-K thermal conductivity.												
MQ4.1: Initial manufacturing cost estimates												
Final Milestone												
DQ8.1: Deliver VI with low-e for external testing												

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