Low-Cost Haziness-Free Transparent Insulation Based on Hierarchical Porous Silica Particles

2015 Building Technologies Office Peer Review

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Project Summary

Timeline:
Start date: 10/01/2014
Planned end date: 09/30/2016

Key Milestones:
1. Particles with 0.5% light scattering and air volume ≥80%; 09/30/2015
2. Insulation material with ≥ 80% visible transmittance (09/30/2016)

Key Partners:
The main partner in the project is VELUX®
We have initiated communications with many other industry partners who can synthesize the material at large scale

Budget:

Total Project $ to Date:
• DOE: $473,631
• Cost Share: $75,000

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Project Outcome:
A thermal insulation material with a:
• Visible transmittance ≥80%
• Haze ≤ 0.5%
• R-value ≥ 5
• Premium cost ≤ $6/ft²
Why window insulation?

- Buildings consume 40% of energy in USA
- Energy loss through windows makes 10-15% of that 40% energy

Current Insulation approaches

- Air/Argon/Krypton/Xenon filling
- Vacuum insulation
- Aerogels (emerging technology)

Challenges to current approaches

- Cost
- Durability
- Retrofitting
- Leakage
- Visible transmittance/Haze
Heat loss through windows and skylights ≈ 5.2 quads of energy in USA
Assuming developed technology saves 10% of energy, 0.52 quads of energy will be saved.

The maximum number of sales units that could be achieved

<table>
<thead>
<tr>
<th>Glazing type</th>
<th>Number of units</th>
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<tbody>
<tr>
<td>Residential glazing</td>
<td>20,500,000</td>
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<td>Residential doors</td>
<td>6,486,000</td>
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<tr>
<td>Skylights</td>
<td>683,000</td>
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<tr>
<td>Commercial windows</td>
<td>43,355,000</td>
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<tr>
<td>Total</td>
<td>71,024,000</td>
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<tr>
<td>Triple glazed and similar high</td>
<td>2,151,500</td>
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<td>performance units</td>
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<td>make 1.4% of the total</td>
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Source: WDMA Window and Entry Door Industry, 2014 US Market Study
Purpose and objectives: Project impact

Final product
At the end of the project, a thermal insulation material that can provide a R-value 5, but with a visible transmittance $\geq 80\%$ and haze $\leq 0.5\%$ is expected at a premium cost of $6/\text{ft}^2$

Outcome
— Near term outcome: Material scale up
— Intermediate outcome: Inclusion of the technology in prototype units and their lab scale testing
— Long-term outcome: Market penetration – At a minimum, 2.1 million windows/skylights in commercial and residential buildings
**Approach: Scientific principles**

Effect of pore size on the air thermal conductivity (Knudsen effect)

\[ S \propto \frac{d^6}{\lambda^4} \]

Particle size and light scattering (Rayleigh scattering)

where ‘\( S \)’ is Rayleigh scattering; ‘\( d \)’ is the diameter of a particle or an interacting unit; and ‘\( \lambda \)’ is the wavelength of interacting light

Plot adapted from Sci. Eng. 21 075004–14 (2013)
Approach: methodology

- **Thermal insulation**
  - Pore size control by micelle size
  - Particle size control by manipulating reaction parameters

- **Visible transmittance and haze**
  - Keeping the particle and pore size very small compared to the visible light wavelength

- **Cost and scalability**
  - Room/low temperature synthesis and processing
  - Methods other than supercritical drying

From: https://en.wikipedia.org/wiki/Micelle#/media

Micelle size ≈ Pore size ≈ (2-7 nm)
Key Issues and Distinctive Characteristics

Key issues
• Solvent removal from the pores
• Pore collapsing

Distinctive Characteristics (compared to aerogels)
• Low cost—no costly drying step (supercritical drying) that is used for aerogel synthesis
• Minimal haze
• High visible transmittance
• Better mechanical properties
**Progress and Accomplishments: Porous silica particles**

- **SEM image of particles** with an average diameter ≈60 nm
- **TEM image of particles**
- **Scaled up particles**
- **Particles in insulated sample box**

**BJH analysis for pore size**

**Volume (cm³/g)**

- 0.0
- 0.2
- 0.6
- 1.0

**Diameter (nm)**

- 2.0
- 4.0
- 6.0
- 10

**Pore size ≈2.5 nm**

**Density = 0.3g/cm³**

- Amorphous silica density = 2.2 g/cm³

- % of solid silica = 0.3/2.2 x 100 = 13.63

- % of air volume = 100 – 13.63 = 86.37

**Thermal conductivity= 0.038 W/m.K**
Progress and Accomplishments: Pore size tuning

Pore size tuning

- Average particle size 60 nm
- Pore size ≈ 4 nm
- Thermal conductivity = 0.032 W/m.K
- By tuning the pore size thermal conductivity of the particles can be tuned

TEM image of porous silica particles with a pore size ≈ 4 nm
Progress and Accomplishments: Particles with ≤0.5% light scattering

Transmittance spectra of silica particle solution in ethanol

Transmittance spectra of particle solution (1) and pure ethanol (2)

Transmittance spectra of particle and ethanol coated slides

- Unaggregated silica particles with size ≈ 60 nm don’t scatter visible light significantly
- Thin layers show anti-reflection effect
Progress and Accomplishments: Scale up

- Process is scalable
- Less costly
- Reproducible

### Challenges faced
- Particle filling
- Possible health hazards
- Particle aggregation (transparency)

Porous silica particles

Unsealed prototype without particles

Sealed prototype with particles
Expected advantages compared to aerogels:

- Better mechanical strength
- Less pore collapsing
- Better pore size control
- Potential for scale up
- Less expensive
- High visible transmittance
- Less haze
Market impact

Market Impact
– The technology could result in an energy savings of 0.52 quad/yr ($1.51 billion/yr) and 26.78 billion kg of CO₂ emission reductions

– Other possible impacts of the technology are: incorporation of the developed material in insulation materials for refrigerators, cryogenic hydrogen storage, and coatings for windows

Efforts done to accelerate the impact
– Efforts are in progress to collaborate with new industry partners who can help in manufacturing the material at industry scale

- New collaborations with industry partners and universities are initiated to utilize the knowledge and materials obtained from this project for developing insulating, transparent, and retrofittable coatings and films for windows

Actual impact could be more than expected as the initial assessment did not include the use of developed material in single pane windows
**Project Integration and Collaboration**

**Project Integration:**
• Project team has already contacted potential industry partners that can help in industrial scale manufacturing and in bringing the technology to market quickly.
• Based on results obtained from the current project, the team has already started collaboration with new industry partners.

**Partners, Subcontractors, and Collaborators:**
The project includes a formal partner VELUX®.
• Other partners that can help in the industrial scale manufacturing of the material (have been contacted).
• New collaborations with universities and many industry partners have been initiated to employ the developed technology for insulation products.

**Communications:**
1. Colloidosome like structures: Self-assembly of silica microrods, RSC Adv., 6, 26734 – 26737, 2016 (impact factor 3.84)
2. One manuscript is ready for submission in a high impact (≈18) journal.
Next Steps and Future Plans

• Select and optimize methods to remove the solvent from inside the pores of the newly developed material

• Measure the optical and thermal properties of the developed material

Funding

• Efforts to achieve funding from potential sponsors such as BTO (BENEFIT), ARPA-E (SHIELD), VTO (hydrogen storage), have been initiated

• One industry partner is interested in funding the next stage of work
REFERENCE SLIDES
Project Budget: $289,000 in FY 2015 and $184,631 in FY 2016
Variances: NA
Cost to Date: $90 K (50% of FY16)
Additional Funding: NA
## Project Plan and Schedule

### Project Schedule

<table>
<thead>
<tr>
<th>Task</th>
<th>Q1 (Oct-Dec)</th>
<th>Q2 (Jan-Mar)</th>
<th>Q3 (Apr-Jun)</th>
<th>Q4 (Jul-Sep)</th>
<th>Q1 (Oct-Dec)</th>
<th>Q2 (Jan-Mar)</th>
<th>Q3 (Apr-Jun)</th>
<th>Q4 (Jul-Sep)</th>
<th>FY2015</th>
<th>FY2016</th>
<th>FY2017</th>
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<td>Past Work</td>
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<td>M1.1: Identify optimal particle size and air volume</td>
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<td>M1.2: Identify the pore size and porosity of particles</td>
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<td>D1.3.1: Present Initial transition strategy for project</td>
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<td>M1.3.1: Create Input for BTO prioritization tool</td>
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<td>M1.2.1: Porous particles with air volume ≥70%</td>
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<td>M1.2.2: Porous particles with air volume ≥80%</td>
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<td>D1.3.1: Market strategy and commercialization plan</td>
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<td>M1.2.3: Particles with ≤0.5% visible light scattering and 80% air volume</td>
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<td>Go/No-Go decision</td>
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<td>1. Particles with ≤0.5% light scattering</td>
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<td>2. Particles with ≥ 80% air volume</td>
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<td>3. Particles with thermal conductivity ≤ 0.015 W/m.K</td>
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<td>4. Particles with a cost $3 for filling a 6x6x0.75 inch cavity</td>
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<td>5. Obtain a letter of interest from industry partner capable of manufacturing silica particles at scale</td>
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<td>M2.1: A 6x6 inch cavity filled with porous material</td>
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<td>D2.5.1: Updated strategy for securing next round of funding and coordination activities with industrial partner(s)</td>
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<td>Final Deliverable</td>
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<td>DQ8: A 2 x 2 inch hybrid gel made by incorporating porous silica particles, with ≥ 80% visible transmittance and 0.032 W/m.K thermal conductivity</td>
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**Project focus changed from achieving lower thermal conductivity of porous particles alone to achieving a high visible transmittance, low haze, and lower thermal conductivity of final product**