# Nanoporous Wood Chips Based Sizable, Robust, and Low-Cost Honeycomb Vacuum Insulation Panels

Performing Organization(s): InventWood, LLC (College Park, Maryland)
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Presenter Name and Title: Dr. Kishore Ramakrishnan, Thermal and Mechanical Materials Scientist

# Project Summary

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## Team and Partners

- Dr. Amy S. Gong, InventWood (Lead Org.)
- Dr. Liangbing Hu, UMD
- Dr. Jan Kosny, UML
- Dr. Junyong Zhu, USDA-FPL

## Objectives and Outcomes

- Develop a highly insulative nanoporous wood chip (Nanochip) foam core.
- Design a scalable fabrication process for the core assembly, vacuum-cell-array structure including envelope formation, and vacuum sealing and on-site resealing.
- Demonstrate a Nanochip-VIP prototype that is cuttable without significant performance loss.
- Conduct comprehensive cost analysis, market opportunity evaluations for Nanochip-VIP as a potential affordable yet high-performance building insulation material.

## Stats

Performance Period: 10/01/2021 – 12/31/2023

DOE budget: $1,601,017, Cost Share: $400,284

Milestone 1: Optimization and fabrication of nanochip foam core of size 6in x 6in with a thermal conductivity of <33mW/m·K in air.

Milestone 2: Design and fabrication of cellular array nanochip foam core-based VIP with a performance of R15 when fully sealed.

Milestone 3: Comprehensive cost analysis and technology-to-market strategy of the nanochip based cellular VIP product.

# Problem

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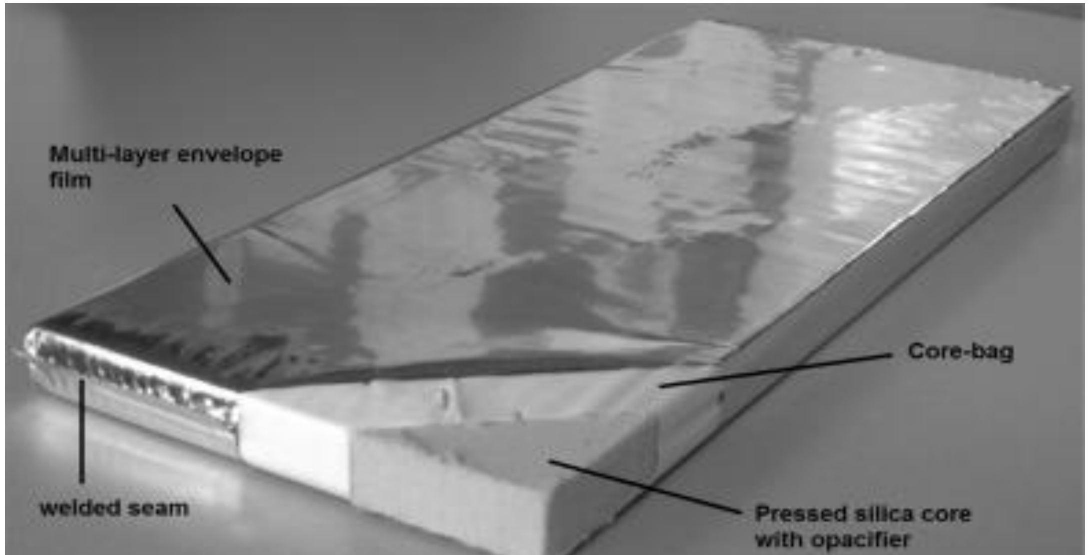
## Limitations of Conventional VIPs

- Energy-extensive and pollutive production of the traditional core materials (e.g., fumed silica, aerogels, etc.)
- High cost \$10~\$12/ft$^2$
- High vulnerability to perforation (non-trimmable)
- Significant performance degradation due to vacuum loss over time (15~20 years for typical VIPs)



Energy and Buildings 109 (2015): 183-194.

## Limitations of Current Cellulose-Based Insulations (e.g., Sawdust Foams)

- High thermal conductivity ~50 mW/*m*·K
- High content of binding agents (>40wt.%)
- Limited environmental benefit due to high polymer content in the composite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# Impact

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## Scientific

- Amalgamation of concepts from material science and thermodynamics.
- A multiple front effort from researchers involved to develop this novel sustainable solution.
- Success of this project will encourage further research in this area.

## Commercial

- A strong partnership between industry, academia and federal research facility.
- Technology transfer and discussions between the entities involved has given rise to several innovations.

## Environmental

- Proof-of-concept of sustainable core-based vacuum insulated panel.
- Improves insulation while being environment friendly.
- Making a sustainable product economically viable to enable wide adoption.

# Approach

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**Milestone 1. Fabrication of nanochip foam core**

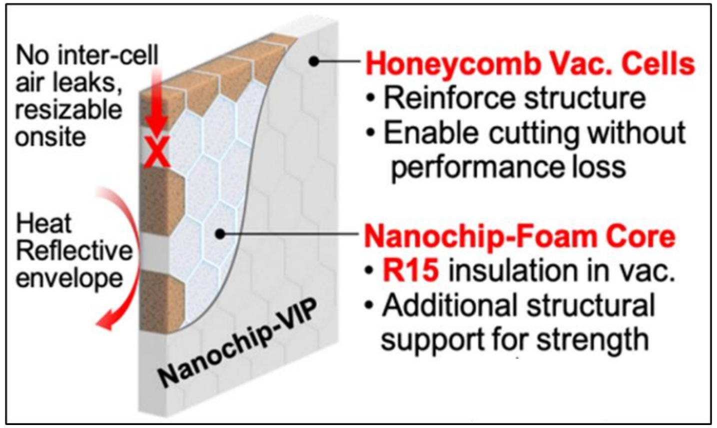
- Develop/optimize lignin modification process for wood chips;
- Fabricate nanoporus structure for nanochip foam core.
- Characterize nanochip foam core.
    - Thermal conductivity
    - Mechanical strength

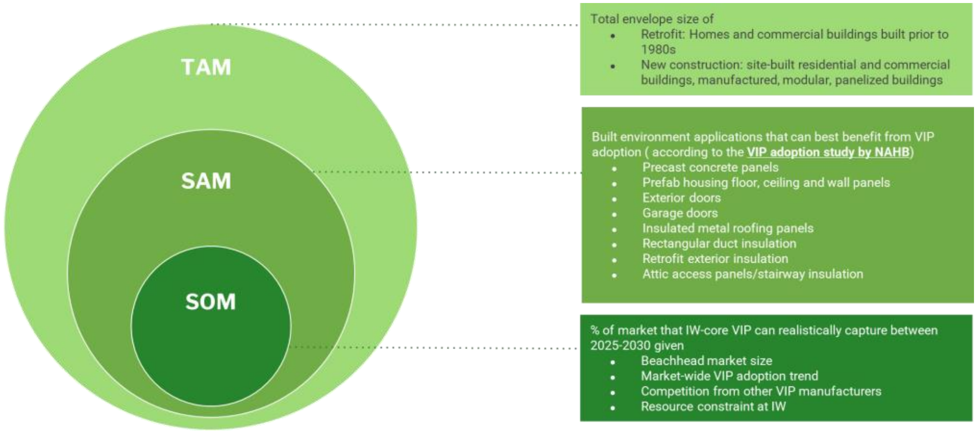
**Milestone 2. Fabrication of nanochip based VIP**

- Thermal conductivity of core under vacuum.
- Design of cellular array.
- Fabrication of cellular array VIP.
- Test cuttability of the nanochip-based cellular array VIP.

**Milestone 3. Cost analysis and technology-to-market**

- Comprehensive cost analysis with Nanochip-VIP cost target $1/ft2in.
- Market study and T2M strategy for entering the VIP market.

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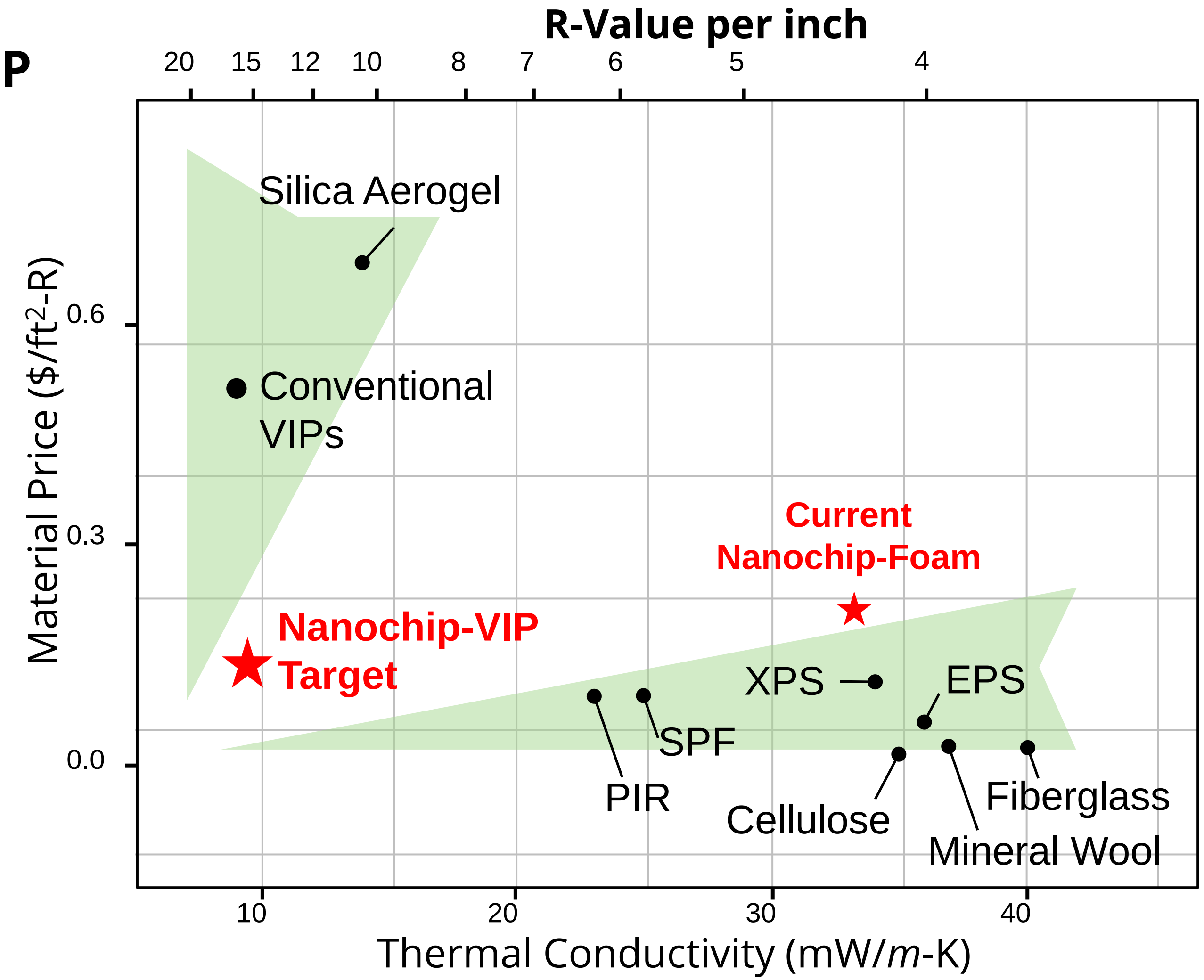
## Innovations & Advantages of Nanochip-VIP

1. The optimized lignin modification process creates additional nanopores into the mesoporous wood chips, leading to **high thermal resistance**

2. Wood-cellulose-based material enables cost target of $1/ft$^2$·in, a **significant cost reduction**

3. The vacuum-cell-array structure that **is forgiving of puncturing** without significantly sacrificing overall insulation performance

4. The cell arrays double as structural reinforcement, which **decouples the porosity and mechanical strength trade-offs** of the core material



# Approach




- We have developed a one-step lignin modification process to create micro/nanoscale pores at a cellular level by using a high temperature treatment process.
- The newly created pores (2-10 um) can reduce the thermal conductivity of bulk woods to < 40 mW/(m·K), due to the reduced solid conduction.

# Fabrication Methods

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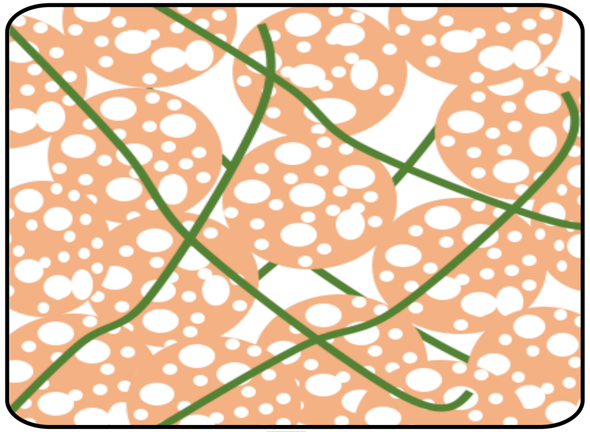
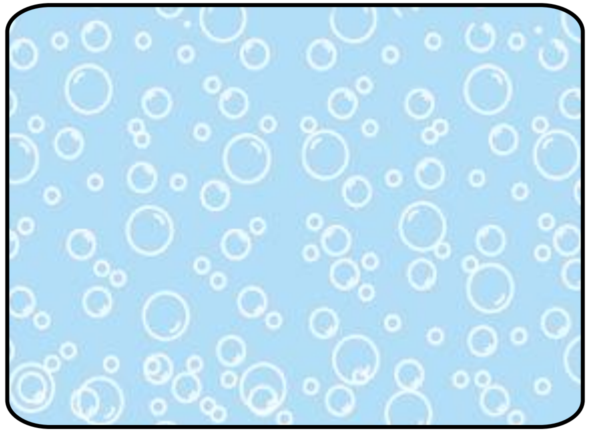
| Porous wood chip foam | Air bubble-enabled aqueous pulp foam | Pulp-polyester hybrid-foam |
| --- | --- | --- |
|  |  |  |
| Freeze drying 39.1 mW/(m·K) | Oven drying 35.8 mW/(m·K) | Thermal bonding 37.1 mW/(m·K) |
|  |  |  |

The UMD/IW team have developed and validated three scalable technical routes for utilizing the lignin modified wood fibers (chips or pulp) for core materials of Vacuum Insulation Panels (VIPs).

# Performance Comparison

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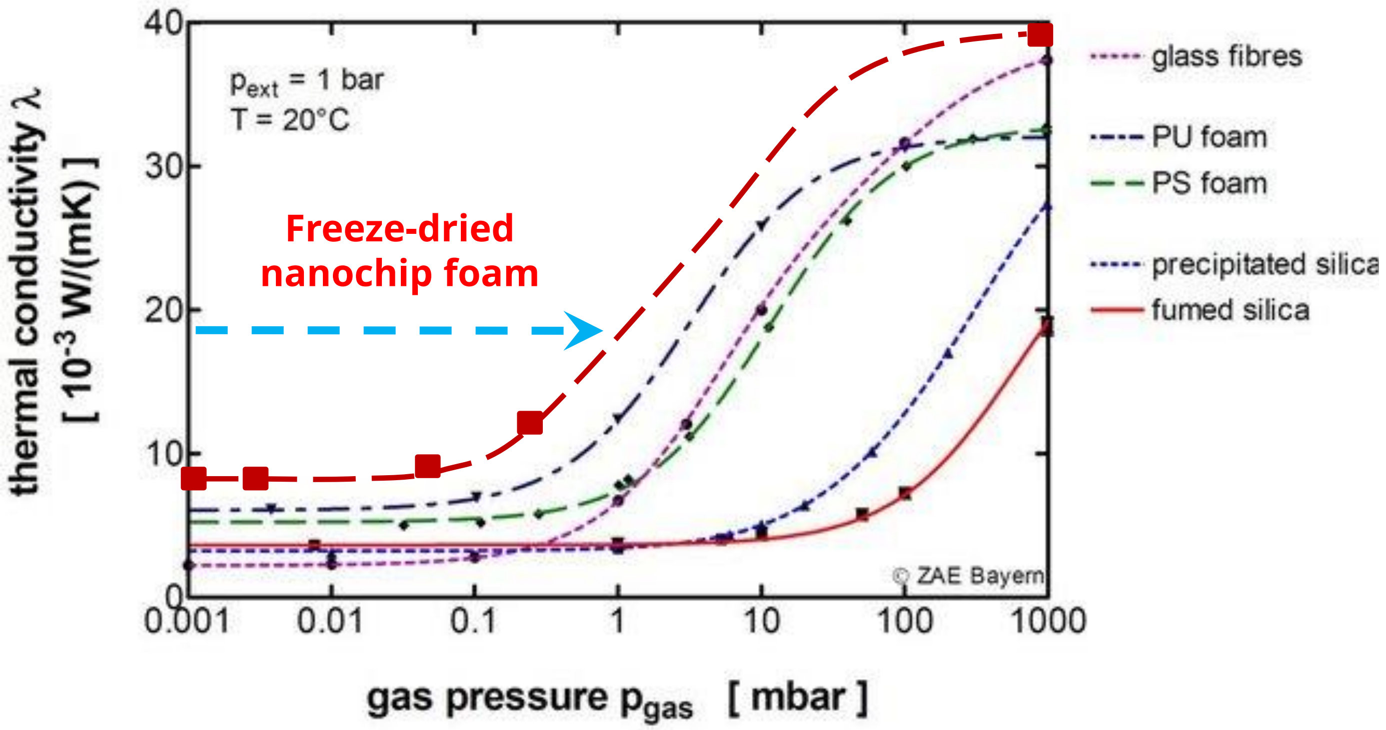
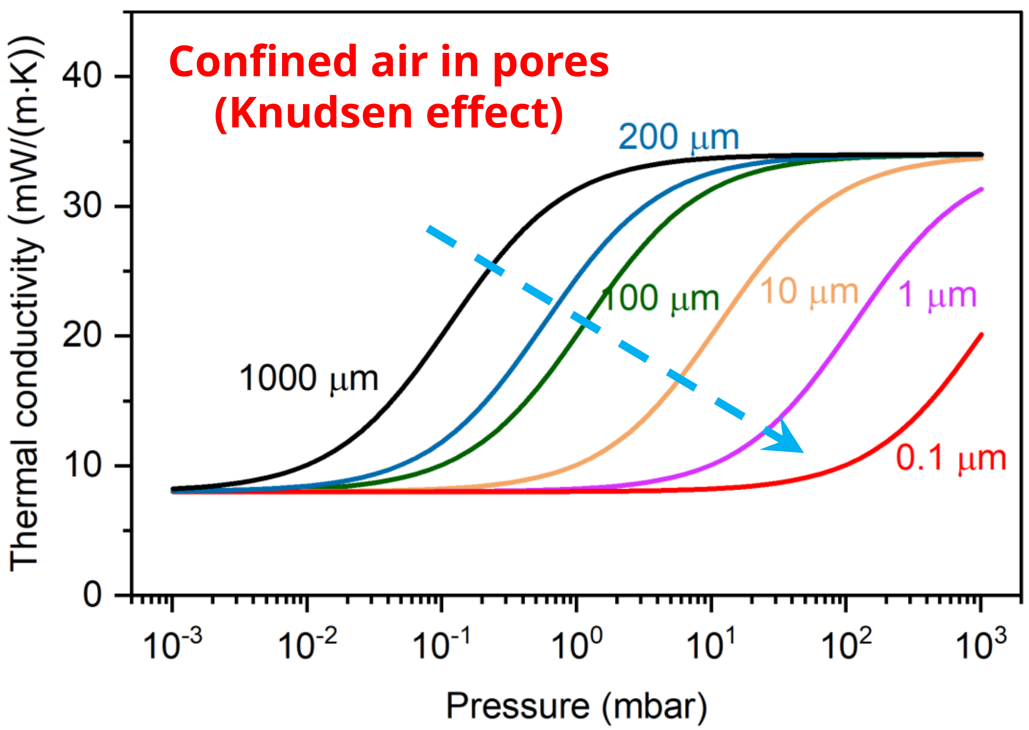



Hans-Peter Ebert – ZAE Bayer, DOI: 10.1051/epjconf/20159808001




- Due to the application of vacuum, the gaseous conduction is minimized in the VIP's core.
- Small meso- and nano-sized pores (< 1 μm) are preferred to improve vacuum requirements and improve the lifetime of VIPs.

# Future Work

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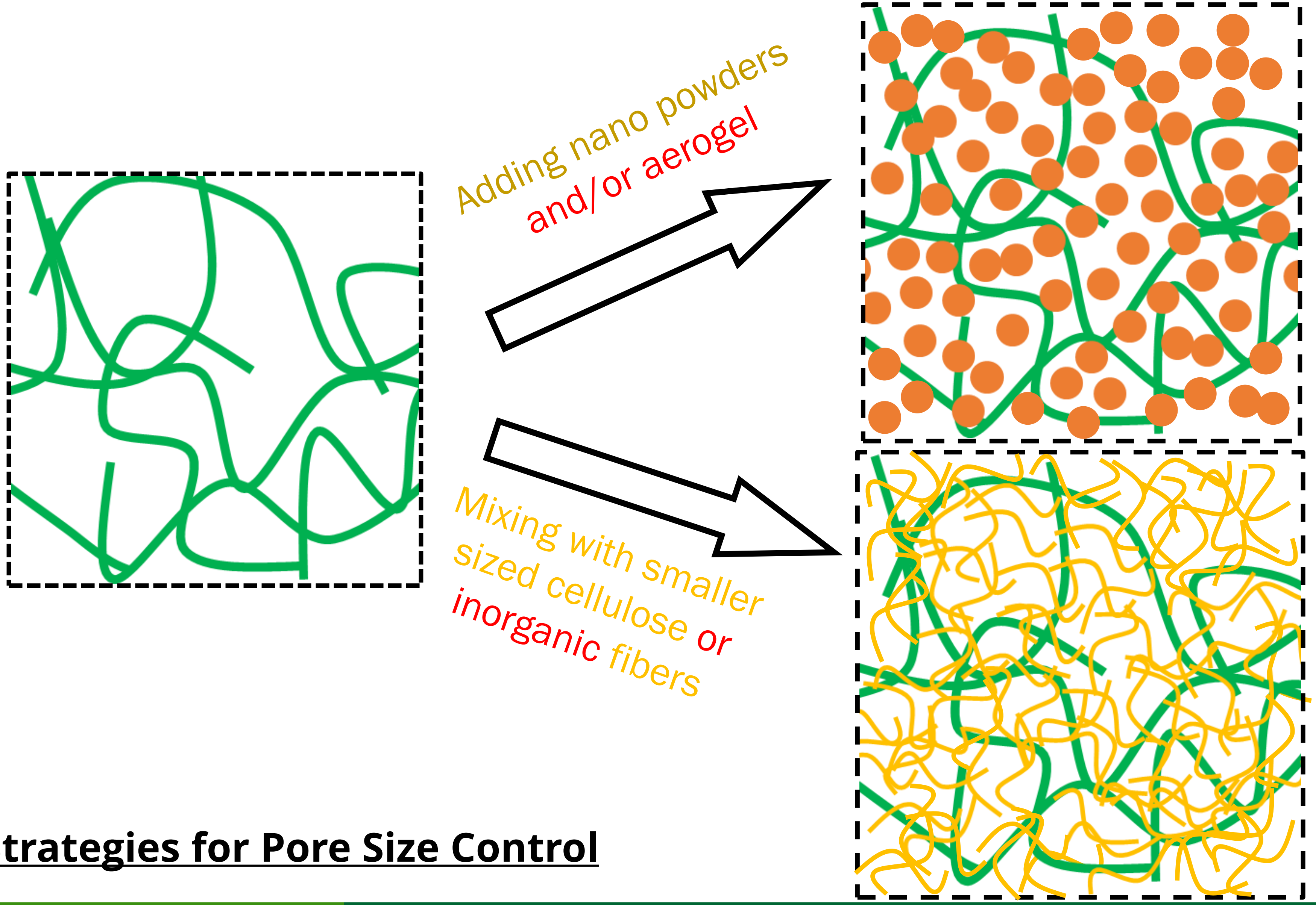
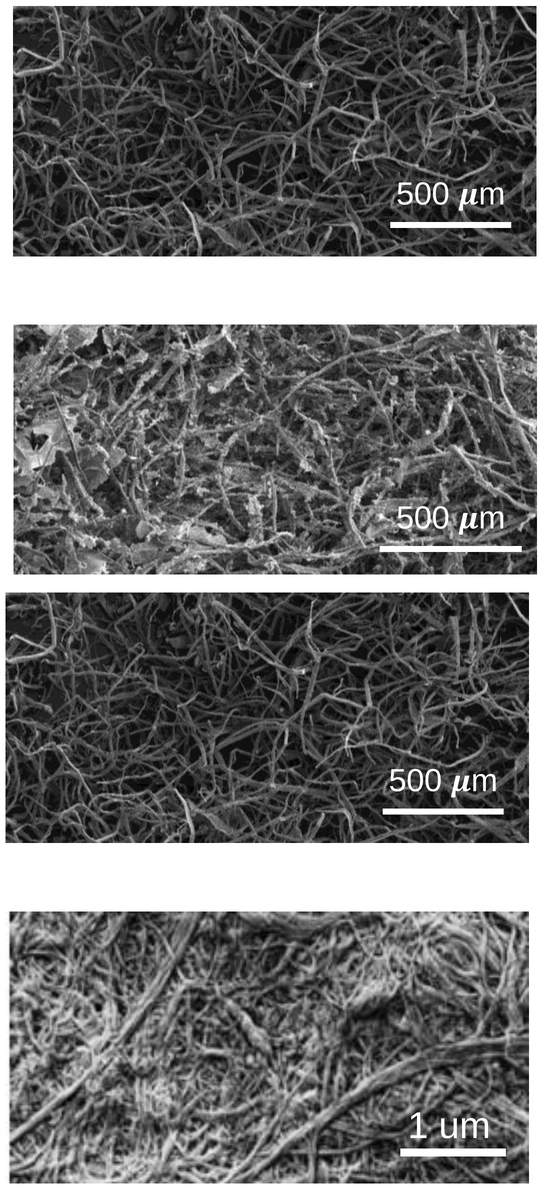
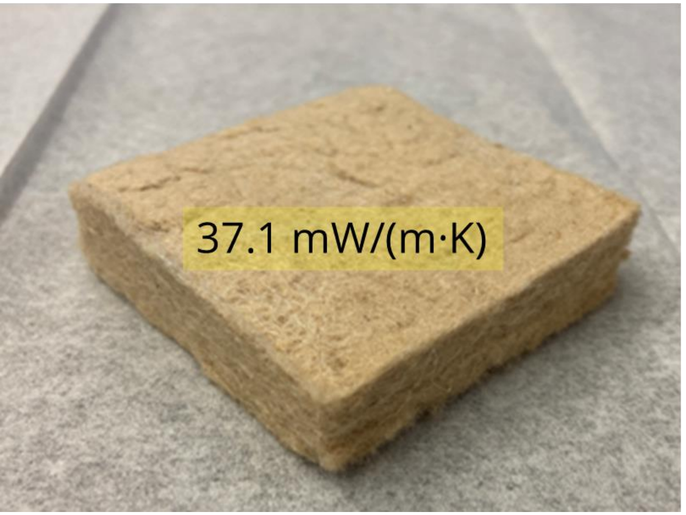


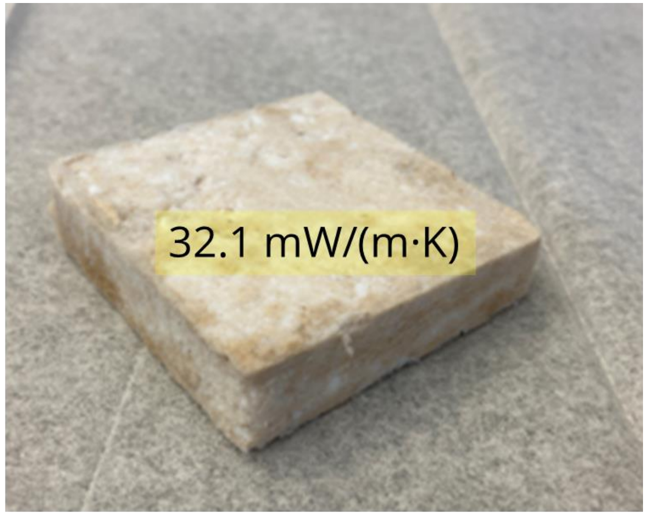

## Strategies for Pore Size Control

# Future Work






Mixing with proprietary nanoparticle mix




By mixing with proprietary nanoparticle mix, we have successfully reduced the thermal conductivity of the thermal bonding foam from 37.1 mW/(m·K) to 32.1 mW/(m·K).

## Next steps

- Cell size optimization for honeycomb-like cell design.
- Preparation of the core materials for the vacuum-cell array.
- Fabrication and demonstration of VIP panel.

# Tech-to-Market – Customer & Market Insights

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## Potential Manufacturers and Distributors

BASF The Chemical Company
Mayaterials, Inc. Tailored Silicas and Silicon Based Chemicals
Owens Corning
Kingspan
JM Johns Manville
Dow
C-Safe Global
VAKU ISOTHERM THE SUPERINSULATION COMPANY
Evonik Leading Beyond Chemistry
Kevothermal
Panelwrights
Thermal Visions The Ultimate Insulator
Porextherm
Camvac
Sealed Air Re-imagine
Panasonic
va-Q-tec

## Domain Experts / Researchers

Oak Ridge National Laboratory
Cold Climate Housing Research Center
Brunel University London
SIP School
SIPschool

## End Users

DVELE
FischerSIPS
plant PREFAB
Mighty Buildings
icon
sto
Module

+ Cellulose Insulations Manufacturers Association (CIMA)

# Key Takeaways from Manufacturers

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- Market: Most common VIP use is for transportation and logistics of pharmaceuticals or in refrigerant appliances
  - The largest U.S. VIP manufacturer – Sealed Air – is in transportation and logistics
  - However, there is optimism about growth in the building applications in the U.S.
  - Segments: 70% retrofit, 30% new construction
- Best use cases:
  - Commercial roofing retrofits
    - Occur on a timeline that aligns with the VIP lifespan
    - Clear value proposition: the avoided cost of expensive building alterations needed when traditional insulation is used to meet energy codes
    - Flat commercial roofs are ideal for VIP applications without the use of fasteners
  - Cold climate regions – benefits of increase in R-value
  - Space-constrained areas / areas with high-cost real estate – benefits of the thin profiles
  - Regions with stringent energy codes – benefits of requirements to meet codes
  - Areas with high labor costs – benefits of shorter retrofit schedule and/or less labor needed
  - Combination of the above: Commercial retrofits in cold climates with expensive labor and stringent energy codes
  - Modular/off-site/prefabricated construction – benefits of controlled installation and reduced transport cost

**Key Barriers:**
Cost, fragility, availability, and reluctance to change

**Key Opportunities:**
Space-constrained areas, retrofits, and prefabrication

# Key Takeaways from Domain Experts/Researchers

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- Optimism for built environment VIP end-uses for retrofits if R&D can alleviate the barriers to market adoption
  - Cost
  - Durability
  - Lifespan and aging testing – need validated lifespan and aging testing to encourage consumer purchases. Accelerated aging testing and pilot sites can be of use.
- Regional differences highlighted
  - U.S.: 99% packaging and logistics; 1% building applications
  - Europe: 50% packaging and logistics; 50% building applications
  - Retrofit vs. new construction opportunity depends on the region
- Best use cases:
  - Commercial roofing – roofs often require higher R-value insulation (vs. walls or floors)
  - Modular/prefab – benefits of controlled conditions to minimize damage
  - Panelized sidings
- Market adoption can be primed by
  - Incentives / Rebates
  - Retrofit programs
  - Energy codes

**Key Barriers:**
Cost, fragility, lifespan, and availability

**Key Opportunities:**
Space-constrained areas, energy codes / incentives, retrofits, and prefabrication

# Key Takeaways from End-Users

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- Many new construction prefabricators are not using VIPs due to:
  - Unfamiliarity
  - Lack of market pull
  - Technical barriers
  - Cost
  - However, new construction (in the U.S.) is often not space-constrained or meets performance-based energy code requirements with alternative methods
- Best use cases:
  - Prefabricated wall panels to mitigate on-site damage risk
  - Panelized overclad retrofit systems - benefit from the space-savings offered by VIPs while increasing building envelope performance
  - Structural insulated panels (SIPs) to allow for better performance and ease on-site installation

**Key Barriers:**
Awareness, cost, availability, and hesitation to change

**Key Opportunities:**
Controlled installation, transport savings (lower size & cost), integration with structural

# Project Risk Assessment

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| Potential Risk | Mitigation Plan |
|---|---|
| *Technical & Manufacturing* | |
| The lignin modified nanochip-foam may shrink during the drying process. | Develop speed-controllable drying processes (e.g., solvent exchange, freeze-drying) and adding stabilizers. |
| Cell walls of the sealed cells may cause thermal bridging. | Select proper inner film with low thermal conductivity, and design proper cell size and shape to reduce thermal bridging. Increase core R value to compensate thermal bridging. |
| Insulation performance may degrade through edge loss after cutting due to insufficient sealing of the vacuum cells. | Investigate methods to seal the VIP panels with enough durability. Simplify cell structure to reduce total seam length to reduce leakage. |
| Particle size of the lignin modified nanoporous wood chips may be too big to form a robust mesoporous structure through foaming. | Add a blending step using blender for wood pulp to break down chip size. Wood pulp are soft and easy to decompose, therefore blending can be achieved at a low processing cost and energy consumption. |
| Binder usage may increase materials cost and decrease thermal insulation. | Investigate "dry-packing" methods to form nanochip-foam cores. This method utilizes high pressure to press small sized wood chips directly without adding binders. The wood particles bind together by contact friction, which can drastically reduce the amount of binder needed. |
| *Business & Regulatory* | |
| IP risks, resource challenges (e.g., labor shortage, etc.) and unforeseen circumstances/force majeure | Develop and execute data management plan and contingency plans, revisit often to adjust strategy and action plans. |
| Low customer acceptance and high barriers to market entry | Provide samples for customer evaluation and initiate joint product development collaborations. |

# Project Schedule – Year 1

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| Tasks | | Oct-21 | Nov-21 | Dec-21 | Jan-22 | Feb-22 | Mar-22 | Apr-22 | May-22 | Jun-22 | Jul-22 | Aug-22 | Sep-22 | Oct-22 | Nov-22 | Dec-22 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Project Schedule - Year 1** | | | | | | | | | | | | | | |
| | | **Q1** | | | **Q2** | | | **Q3** | | | **Q4** | | | **Q4-2** | | |
| **TASK 1.0 (10/21-06/22)** | **Overall project management and planning.** | | | | | | | | | | | | | | | |
| Milestone 1.0 & 1.1 | Create project management plan (PMP). | IW | IW | IW | | | | | | | IW | IW | IW | | | |
| **TASK 1.1 (01/22-06/22)** | **Optimize lignin modificaiton process for wood chips.** | | | | | | | | | | | | | | | |
| Milestone 1.2 | Make nanochip-foam core thermal conductivity ≤ 33 mW/*m*·K in air. | | | | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD | | | |
| **TASK 1.2 (10/21-06/22)** | **Fabricate nanoporous structure for nanochip-foam core.** | | | | | | | | | | | | | | | |
| Milestone 1.3 | Demonstrate 6 in x 6 in nanochip-foam core. | UMD | UMD | UMD | IW | IW | IW | | | | | | | | | |
| Milestone 1.4 | Make 5 pieces of 6 in x 6 in nanochip-foam core 12 mW/m·K in vacuum. | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD | IW | IW | | | |
| **TASK 2.2 (01/22-12/22)** | **Characterizations of nanochip-foam core.** | | | | | | | | | | | | | | | |
| Milestone 1.6 | Test thermal conductivity mechanical strength, and durability. | | | | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD |
| **TASK 1.3 (10/21-09/22)** | **Design Nanochip-VIP.** | | | | | | | | | | | | | | | |
| Milestone 1.5 | Identify 3 and select 1 vacuum cell size through modeling. | | | | | | | | | | | | | UML | IW | IW |
| Milestone 1.7 | Source, purchase, and test packaging materials. | UML | UML | UML | UML | UML | IW | | | | | | | | | |
| **TASK 1.4 (10/21-09/22)** | **Fabrication of the honeycomb vacuum-cell-array and the full panel.** | | | | | | | | | | | | | | | |
| Milestone 1.9 | Fabricate honeycomb vacuum-cell-array and the full panel. | | | | | | | | | | UMD | UMD | UMD | UMD | UMD | UMD |
| **TASK 1.5 (01/22-09/22)** | **Cost analysis for the nanochip-foam core.** | | | | | | | | | | | | | | | |
| Milestone 3.1 | Complete initial cost analysis for lab-scale process. | | | | IW | IW | IW | IW | IW | IW | IW | IW | IW | | | |
| **TASK 2.8 (10/21-09/22)** | **Technology-to-market strategy.** | | | | | | | | | | | | | | | |
| Milestone 3.3 | Complete initial market study of the VIP industry. | IW | IW | IW | IW | IW | IW | IW | IW | IW | | | | | | |

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# Accomplishments

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| Objective | Metric/Goal | Accomplishments |
|---|---|---|
| Optimize lignin modification process | Process parameters determined | • Examined influence of wood species, wood chip size, temperature & time, and NaOH concentration on the lignin modification process. |
| Create 6.0 in x 6.0 in foam core pieces and achieved 35.8 mW/m·K in air and 8.1 mW/m·K under vacuum | Created 50+ samples | • Examined binder species and concertation on the foaming process.<br>• Created multiple 6.0 in x 6.0 in foam core pieces, using different foaming recipes. |
| Formulate tech-to-market strategy | Year 1 initial round completed | • Conducted initial round of stakeholder interviews and identified suitable beachhead applications<br>• Evaluated regional demand, market size and regional variances to inform the next steps in market entry strategies |
| Model the production cost, analyze cost drivers, and identify path to target cost | VIP Cost Target: $\$1/ft^2 \cdot in$ | • Evaluated initial production alternatives, calculated IW core and core-based VIP cost estimates using different starting raw materials and identified path to cost reductions. The cost estimates signal techno-economic viability of the core and VIP products. |

# Project Schedule – Year 2

| Tasks | | Jan-23 | Feb-23 | Mar-23 | Apr-23 | May-23 | Jun-23 | Jul-23 | Aug-23 | Sep-23 | Oct-23 | Nov-23 | Dec-23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Year 2 Q1** | | | **Year 2 Q2** | | | **Year 2 Q3** | | | **Year 2 Q4** | | |
| **TASK 2.5 (01/23-06/23)** | **Larger batch lignin modification.** | | | | | | | | | | | | |
| Milestone 2.1 | Demonstrate lignin modification using digester with 10 kg/batch. | | | | FPL | FPL | FPL | FPL | FPL | FPL ◆ | | | |
| **TASK 2.6 (10/22-03/23)** | **Investigate shrink-free drying methods.** | | | | | | | | | | | | |
| Milestone 2.2 | Demonstrate drying methods with shrinkage ≤ 5%vol. | FPL | FPL | FPL | FPL | FPL | FPL | FPL | FPL | FPL ◆ | | | |
| **TASK 2.1 (10/22-06/23)** | **Fabricating nanoporous structure for nanochip-foam core.** | | | | | | | | | | | | |
| Milestone 2.3 | Demonstrate nanochip-foam core with size of 1 ft x 1 ft. | UMD | UMD | UMD | IW | IW | IW ◆ | | | | | | |
| Milestone 2.4 | Create 5 pieces of 1 ft x 1 ft Nanochip-VIP, thermal conductivity 12 mW/*m*·K. | IW | IW | IW | IW | IW | IW | UMD | UMD | UMD | UMD | UMD | UMD ◆ |
| **TASK 2.2 (01/22-12/22)** | **Characterizations of nanochip-foam core.** | | | | | | | | | | | | |
| Milestone 1.6 | Test thermal conductivity mechanical strength, and durability. | UMD | UMD | UMD ◆ | | | | | | | | | |
| **TASK 2.4 (01/23-09/23)** | **Comprehensive performance evaluation for Nanochip-VIP.** | | | | | | | | | | | | |
| Milestone 2.6 | Test structure, thermal, mechanical, and aging performance of VIP panels. | | | | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD ◆ |
| Milestone 3.5 | Energy consumption analysis for the scalable process. | | | | | | | IW | IW | IW | IW | IW | IW ◆ |
| **TASK 2.3 (10/22-09/23)** | **Fabricate a honeycomb vacuum-cell-array and a full panel.** | | | | | | | | | | | | |
| Milestone 2.5 | Make full VIP panel target R15 fully sealed, and R13 cut-open. | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD | UMD | IW | IW | IW ◆ |
| **TASK 2.7 (10/22-09/23)** | **Cost analysis for the Nanochip-VIP.** | | | | | | | | | | | | |
| Milestone 3.2 | Comprehensive cost analysis with Nanochip-VIP cost target $1/ft2in. | IW | IW | IW | IW | IW | IW | IW | IW | IW | IW | IW | IW ◆ |
| **TASK 2.8 (10/22-09/23)** | **Technology-to-market strategy.** | | | | | | | | | | | | |
| Milestone 3.4 | Market study and T2M strategy for entering the VIP market. | IW | IW | IW | IW | IW | IW | IW | IW | IW | IW | IW | IW ◆ |

Project Schedule - Year 2

- InventWood
- UMD-Hu
- UML-Kosny
- FPL-Zhu

# Thank You

Performing Organization(s): InventWood, LLC.
PI Name and Title: Amy S. Gong Chief Science Officer
PI Tel and/or Email: 240-249-8050 amy.gong@inventwood.com

# REFERENCE SLIDES

# Team

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## InventWood Team

**Dr. Amy S. Gong (CSO, Lead PI)**

*-Track Record*

*More than 10 years of research experience in chemical and materials engineering.*

*-Contributions*

- Primary Liaison between InventWood and DOE for Technical Topics
- Responsible for Subcontract, Invoice, and Reports

**Dr. Jiaqi Dai (CTO)**

*-Track Record*

*More than10 years of research experience on advanced energy technology and cellulose-based sustainable materials with over 24,000 citations.*

*-Contributions*

- Technical Development Lead;
- Product Development Lead;

**Dr. Kishore Ramakrishnan (Material Scientist)**

*-Track Record*

*More than 5 years of experience with experimental thermal and fluid sciences background.*

*-Contributions*

- Equipment and process design.
- Process scaling.

## UMD Team

**Prof. Liangbing Hu (Co-PI)**

*-Track Record*

*Tenured professor. Over 16 years of research experience in micro/nanoscale thermal transport and energy conversion. Outstanding scientist with over 50 publications on leading refereed journals.*

**-Contributions**

- Technical guidance;
- Structure Design for VIP;

**Dr. Xinpeng Zhao (Postdoc)**

**-Contributions**

Materials Characterization and Optimization;

**Amanda Siciliano (PhD student)**

**-Contributions**

Fabrication of Small-Scale Specimens; Carry out research and development.

## UML Team

**Dr. Jan Kosny (Co-PI)**

*-Track Record*

*Research Professor*
*Director - Building Energy Efficiency and Temperature Control Materials Laboratory. Through several government and industry funded projects, the UML's team has already gained significant experience in development and market introduction of advance bio-based insulations, including wood-based nanoporous materials.*

**-Contributions**

- Integration of novel cellulose-based sustainable insulation materials and their fabrication technology;
- Scale-up manufacturing processes;
- Commercialization;

## USDA FPL

**Dr. Junyong Zhu (USDA)**

*-Track Record*

*Over 26 years of research experience in production, characterization and utilization of cellulose nanomaterials. Fellow of International Academy of Wood Science and American Chemical Society (ACS). Research findings published on leading scientific journals.*

**-Contributions**

- Scale-up manufacturing;
- Raw material sourcing;
- Technical know-how;

**ADL Ventures**

**-Contributions**

- Market analysis;
- Cost modelling;

# Project Budget

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| Recipient / Sub-Recipient | Budget Period 1 | | Budget Period 1 Expenditure | | Budget Period 2 | | Total | | |
|---|---|---|---|---|---|---|---|---|---|
| | Federal | Cost Share | Federal | Cost Share | Federal | Cost Share | Federal | Cost Share | Total Project |
| **InventWood** | $418,791 | $116,770 | $291,355 | $187,070 | $424,922 | $116,659 | $843,713 | $233,429 | $1,077,142 |
| **UMD** | $240,000 | $60,000 | $193,444 | $80,900 | $240,000 | $60,000 | $480,000 | $120,000 | $600,000 |
| **UMass Lowell** | $94,004 | $23,514 | $61,834 | $11,877 | $93,300 | $23,341 | $187,304 | $46,855 | $234,159 |
| **USDA-FPL** | $28,474 | $0 | $6,785 | $0 | $21,526 | $0 | $50,000 | $0 | $50,000 |
| **ADL Ventures** | $20,000 | $0 | $20,000 | $0 | $20,000 | $0 | $40,000 | $0 | $40,000 |
| **Total** | $801,269 | $200,284 | $573,418 | $279,847 | $799,748 | $200,000 | $1,601,017 | $400,284 | $2,001,301 |
| **Cost Share %** | | 20% | Left 28% | 33% | | 20% | | 20% | |