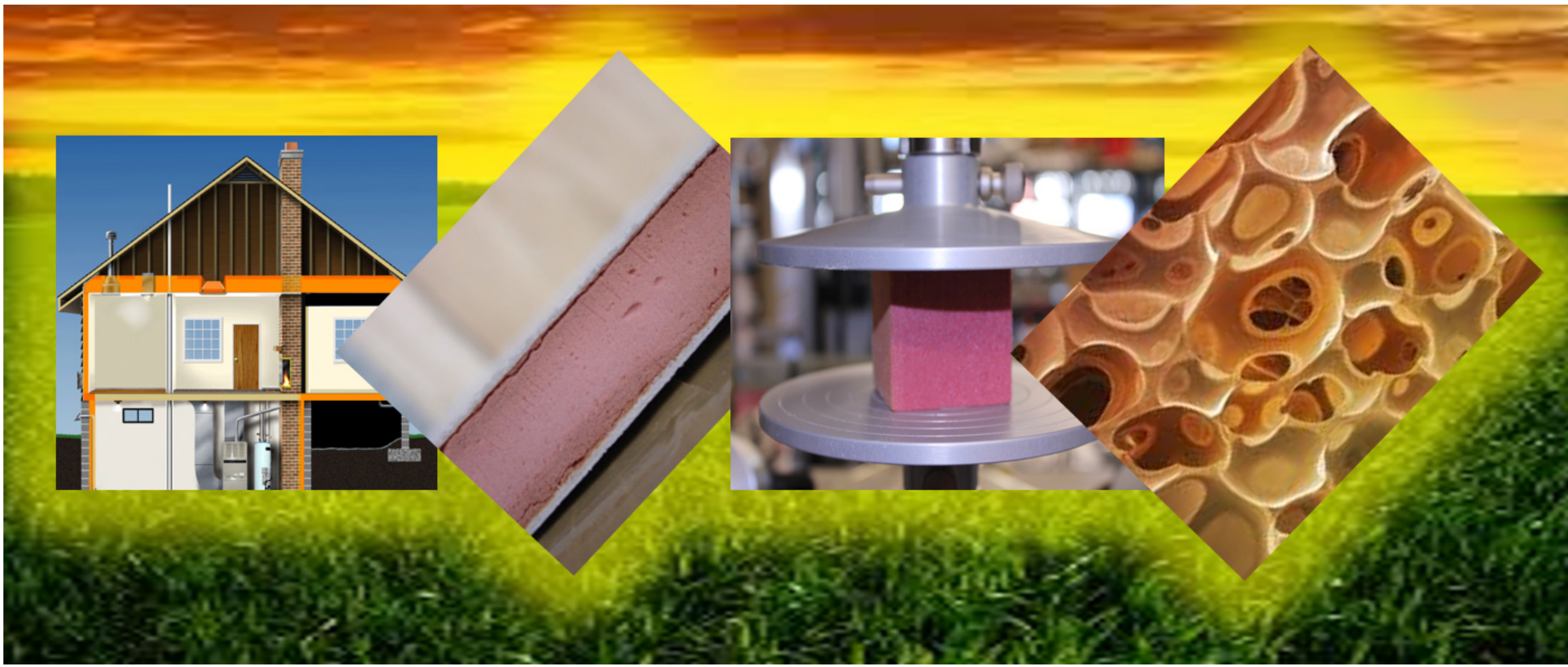
Development of a Bio-based, Inexpensive, Noncorrosive, and Nonflammable Phenolic Foam for Building Insulation

2016 Building Technologies Office Peer Review



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Project Summary

Timeline:

Start date: October 1st 2014.

Planned end date: September 30th 2016

Key Milestones:

1. Identify Acid Catalyst System(s) (M6)
2. Finalize bio-foam formulation (M9)
3. Produce phenolic foam samples of pH ≥4.5 (M12)
4. Achieve ~ 50% improvement in flexural strength and a minimum 20% increase in compressive strength compared to non-reinforced phenolic foam, tested in accordance with ASTMs D1621 and C203. (M15)

Budget:

Total Project $ to Date (Jan 31st 2016):

- DOE: $480,115
- Cost Share: $is a new bio-based, less acidic, non-corrosive, mechanically stronger, and less expensive phenolic foam insulation derived from low-cost components113,038

Total Project $:

- DOE: $610,116
- Cost Share: $139,058

Key Partners:

Atlas Roofing Corp.

University of Tennessee Knoxville

Project Outcome:

1. The major project outcomes are as follows:

- Development of a novel less acidic, non-corrosive, mechanically stronger, and cost competitive bio-based phenolic foam.

- Development of novel foaming and foam curing methods

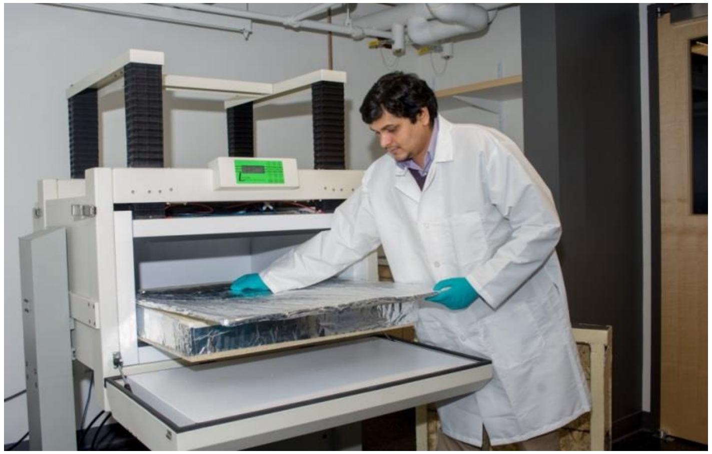
2. Based on the project technological developments, we will identify key challenges and the mechanism for successful introduction of a new bio-base foam product to the building material market.

Key Members of the Project Team

Dr. Jan Kosny
Fraunhofer CSE
Project PI

Jim Thornsberry
Atlas Roofing Corp.

Prof. Arthur Ragauskas
ORNL and
Univ. of Tennessee, Knoxville
Dept. of Chemical and Biomolecular Eng.



Dr. Nitin Shukla - Fraunhofer CSE

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Purpose and Objectives

Problem Statement: Among all plastic foams, only phenolic foam can obtain or **exceed R-8.0 per inch**. It is also inherently fire resistant. Despite these benefits, current phenolic foam technology is rarely used in the U.S., due to wide perception of **corrosion potential and poor mechanical characteristics,** which led to roof failures in 1980-90s.

Target Market and Audience: The major target markets for this technology are **Residential and Commercial Building sectors**, which account for **41% of total U.S. energy** consumption, or about **40 Quads**. Other areas for applications are **Industrial Insulation market**, **Military, Transportation, and Space Industry**.

Impact of Project: Novel formulation and production methods for less acidic and non-corrosive, mechanically stronger, and cost competitive phenolic foam will notably impact the North American foam industry, which will adopt this new technology. It will lead to the conversion of a part of the Polyiso (PIR) foam facilities into production of the new foam. This will supply U.S. market with a variety of high performance non-flammable thermal insulation products. Also, new types of foams will be developed utilizing technologies from this project

Technology short term outcomes and scale up details:

- *Industrial lab scale trials (during or up to 1 yr after completion of the project)*
- *Design of the industrial scale manufacturing line (1-3 yr after completion of the project)*
- *Technology to be licensed out, full-scale production trials (3+ yr after project completion)*

Project Approach

Approach *for development of a new bio-based phenolic foam formulation, using a typical phenolic foam formulation (leading to pH-2.8) as a baseline*:

- Selection of common low-cost, bio-based, waste products for use in foam resin
- Development of a new foaming process with use of bio-base precursors
- Selection of new catalysts and blends of catalysts for reduction of phenolic foam acidity
- Development of novel foaming and foam curing methods for reduction of phenolic foam acidity and corrosion potential
- Improvement of foam cellular structure to reduce heat transfer, hygrothermal performance, and to improve mechanical strength characteristics
- An application of micro- and nano-reinforcement/fillers for improvement of foam mechanical strength characteristics and reduce gas diffusion through the cell structure

Key Issues:

- Slow foam nucleation in a neutral environment, leading to use of acidic catalysts
- Combination of high corrosion potential caused by use of high acidity (low pH level) acidic catalyst, and poor mechanical strength of phenolic foam

Distinctive Characteristics: pH between 4.5 and 6.0; corrosion potential similar to tap water; foam density ~ 1.5 to 2.0 lb/ft^3; R-value per in. 8.0, compressive strength 20% better than PIR foams, cost ceiling: below PIR foams

Progress and Accomplishments (I)

Accomplishments: SIX PATENT APPLICATIONS ON THE WAY

- Identification of **new types of organic catalysts**
- Development of foam formulations leading to **pH level over 4.5 (after curing)**
- Development of the **NON-CATALYST FOAMING METHOD**, which allows production of the **chemically neutral foam**
- Successful production of phenolic foam samples with **pH between 4.5 and 9.0**
- **Reduction of post-process foam curing time from up-to 24 hours to ~ 2-min.** This leads to production energy savings and will reduce the size of production line.
- Development of phenolic **foam formulation using bio-based precursors**
- Development of **the SINGLE COMPONENT FOAMING TECHNOLOGY** for phenolic foam, which **doesn't require Blowing Agent**

First successful foaming sample of bio-based phenolic foam

Phenolic foam samples reinforced with nano-cellulose

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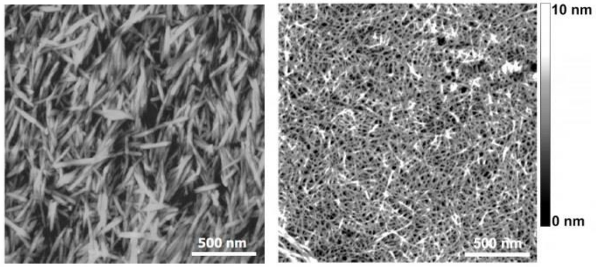
Progress and Accomplishments (II)

Recent Work Tasks:

- Mechanical testing of Nano- and Micro-Reinforced foam samples



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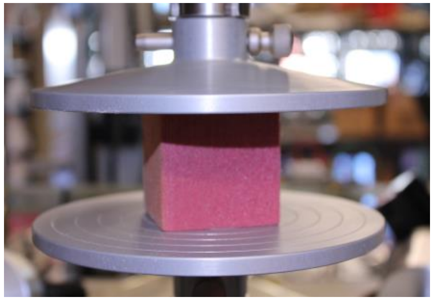
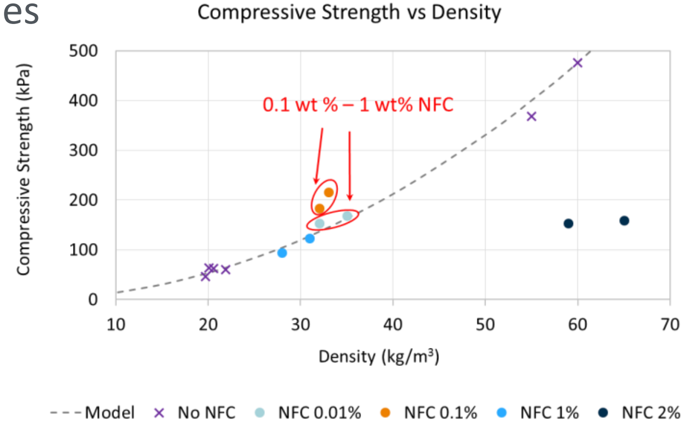
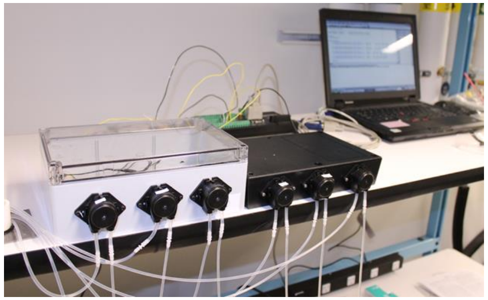
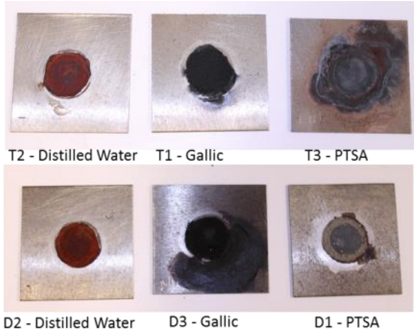
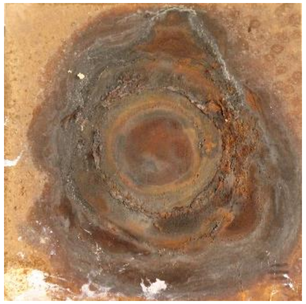




- Accelerated metal corrosion testing for different foam formulations







- Development of high R-value phenolic foam – foam cell structure enhancement

- Long-term hygrothermal performance testing

Progress and Accomplishments (III)

Market Impact:

Foaming and foam curing technologies developed during this project can modernize plastic foam production in the U.S. and worldwide

- Currently developed of bio-based formulation will lead to market introduction of a first ever bio-based and non-flammable plastic foam
- A new line of high performance building and industry-type insulations can follow this project
  - new non-flammable insulations, which will not require fire retardants
  - novel open cell, very low density and low-cost foams
  - a new type of sprayed-applied building air sealing material
- Current foam curing inventions will reduce a cost of foam manufacturing

What efforts are being done to ensure or accelerate impact?

- Advanced IP protection work (6 patent applications)
- Atlas Corporation leadership. Contacts with other foam manufactures regarding potential licensing
- Contacts with resin manufactures about joint work on new types of bio-based resins

Awards/Recognition: Not Yet! – Great interest from other foam companies

Lessons Learned: **(i) Good foams and cakes are equally difficult to make.** In both cases experienced technologist, or a baker are mandatory. **(ii)** It takes long time and hundreds of foam samples to develop a new type of foam. **(iii)** This project should take at least 4 years to explore full benefits associated with current technology developments

Project Integration and Collaboration

Project Integration: This team is comprised of a leading academic researcher, a nonprofit organization committed to applied R&D focused on commercialization of clean energy technologies, and a leading North American company with extensive market knowledge and manufacturing expertise in commercial foam insulation products (17 plants in the U.S. and Canada). Team collaboration includes facility site visits (UTK labs, Fraunhofer labs, and Atlas manufacturing plant) as well as bi-weekly calls to review progress, identify obstacles and strategize path forward.

Partners, Subcontractors, and Collaborators:

- University of Tennessee Knoxville, Prof. **Arthur Ragauskas** and Dr. **Thomas Moore**
- Atlas Roofing Corp. has provided valuable foam manufacturing guidance:
  - **James Thornsberry**, Technology Manager, Commercial Products Group
  - **Andy McLaughlin**, Marketing & Sales Technical Director
  - **Greg Sagorski**, Director of Technology Commercial Products Division and
  - **Darrel Thompson**, Product Technology Manager
- Plenco has provided variety of phenolic resols and valuable industrially relevant guidance: **Dr. Andreas Henke**, Industrial Resin Application and Development Manager

Communications: <u>Minor announcements</u> at : BEST 4 Conference Apr. 2014, World Innovation Conference and Expo June *2015*. <u>First major presentation</u> will be at Buildings XIII Conference in Dec. 2016. <u>More detailed outside presentations</u> are planned after the submission of provisional patent applications

Next Steps and Future Plans

Next Steps and Future Plans:

1. Scaling up the foam formulation and production attempts to the industrial pilot line level
2. Scaling up the non-catalyst foaming technology and design of necessary industrial-size equipment.
3. Series of accelerated and field foam corrosion tests to assure that new foam formulations using acidic catalysts will not cause corrosion
4. Series of foam flammability tests
5. Development of a conversion plans for the PIR foam manufacturing line into the phenolic foam production
6. Line conversion and pilot production runs
7. Work with resin manufactures on development of bio-based precursors for the new foam
8. Secure IP rights (patents)
9. Development of technology license agreements

REFERENCE SLIDES

Project Budget

Project Budget: The federal funds have not changed during the period of performance and remain contracted at $610,116. Cost share obligation was reduced from $284,057 to $139,058 (32% to 19%, although the minimum required is 10%). The contracted BP2 cost share reduction does not reflect any reduction in effort. CSE's cost share comes from unreimbursed indirect costs and the indirect rate was lower than estimated.
Variances: Actual BP1 Cost Share ($75,138) is higher than the contracted BP1 cost share ($70,842). Actual BP1 Cost Share was 21%.
Cost to Date: We have spent 79% of the funds and are 70% of the way through the period of performance (17 months/24 months).
Additional Funding: Our partners, UTK and Atlas, have also both contributed towards the cost share.

Budget History

	Oct 1st – Sept 30th GFY 2015 (BP1)		Oct 1st – Sept 30th GFY 2016 (BP2)		Total	
	DOE	Cost-share	DOE	Cost-share	DOE	Cost-Share
Original Budget (start of BP1)	$312,733	$144,568	$297,383	$139,489	$610,116	$284,057 (32%)
Mod 04 Budget (start of BP2)	$277,992	$70,842	$332,123	$68,216	$610,116	$139,058 (19%)

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Budget: as Contracted, and Estimated through 1/31/16

	BP1	BP2	SubTotals
Federal Share			
Fraunhofer	$159,491	$151,667	$311,159
UTK	$111,001	$120,477	$231,478
Atlas Roofing	$7,500	$59,979	$67,479
	$277,992	$332,123	$610,116
Cost Share			
Fraunhofer	$53,815	$52,025	$105,840
UTK	$15,360	$10,360	$25,720
Atlas Roofing	$1,667	$5,831	$7,498
	$70,842	$68,216	$139,058
Totals			SubTotals
Fraunhofer	$213,306	$203,692	$416,998
UTK	$126,361	$130,837	$257,198
Atlas Roofing	$9,167	$65,810	$74,977
SubTotal	$348,835	$400,339	$749,174

	Fraunhofer	Atlas	UTK
BP1 Federal	$159,491	$7,500	$111,001
BP2 Federal (through 1/31/16)	$74,300	$42,485	$85,338

Federal Expenses, through 1/31/2016:

$480,115

Cost Share: Estimated through 1/31/16	
BP1 CS	75,138
BP2 CS	$37,900
Cumulative, estimated to date through 1/31/2016	$113,038

Cost Share, through 1/31/2016:

$113,038; 19%

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Milestone Summary Table

Fraunhofer Center for Sustainable Energy Systems							
Development of a BioBased, Inexpensive, Noncorrosive, NonFlammable Phenolic Foam Building Insulation							
Task #	Task Name	Milestone Type	Number	Milestone Description (Go/No-Go Decision	Milestone Verification Process (What, How,	Anticipated Month	Anticipated Quarter
2.0 Laboratory-Scale Batch Trials to Increase pH Levels							
2.1	Assess acid catalyst systems	Milestone	M2.1.1	Identify acid catalyst system	Document increased pH of catalyst systems studied	15	**5**
2.2	Comprehensive Foam Characterization	Milestone	M2.2.1	Finalize foam formulation	Engineering validation of formula	18	**6**
2.3	Corrosion Testing	Milestone	M2.3.1	Attainment of pH between 4.5 and 6.0	Laboratory testing	15	**5**
3.0 Batch Trials on Cell Reinforcement							
3.1	ID reinforcement nanofibers	Milestone	M3.1.1	Identify composition	Identify composition and loading level of reinforcing material	6 already completed	**2**
3.2	Mechanical characterization and cell structure analysis	Milestone	M3.2.1	Test mechanical properties	Demonstrate 50% increase in flexural following ASTM C203and 20% increase in compressive strength following ASTM	18	**6**
		Go/No-Go		Attain foam samples with pH≥4.5	Perform ASTM C871 Test to verify pH≥4.5	12 already completed	**4**
4.0 Development of High R-Value Phenolic Foam with Minimum R-7 per inch, leading to R-8 after opacification							
4.1	Optimization of foam cell size	Milestone	M4.2.1	Finalize cell size to maximize thermal props	Perform ASTM C518 Test to demonstrate R≥7 per inch	20	**7**
4.2	Improve long-term thermal aging	Milestone	M4.3.1	Foam formulation to improve LTTR	Demonstrate LTTR to be at least 10% higher than as described in PIMA	23	**8**
5.0 Characterization of hygrothermal and corrosion properties							
5.1	Characterization of water absorption and long-term mechanical and corrosion properties	Milestone	M5.1.1	Achieve water absorption in new foams equal to or lower than PIC boards	As quantified through ASTM C272.	23	**8**
6.0 Commercialization Plan							
6.1	Development of the novel foam's commercialization plan					24	**8**

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Project Plan and Schedule

Project Schedule		
Project Start: October 1st 2014		Completed Work
Projected End: September 30th 2016		Active Task (in progress work)
		Milestone/Deliverable (Missed)
		Milestone/Deliverable (Actual)
		GO-NO-GO

	FY2015				FY2016				FY2017			
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)
Task 2. Laboratory Scale Batch Trials to Increase pH												
M2.1.1. Identify acid catalyst system												
M2.2.1. Finalize foam formulation												
M2.3.1. Attainment of pH 4.5 and 6.0												
Task 3. Batch Trials on Cell Reinforcement												
M3.1.1. Identify composition and loading level of reinforcement												
M3.2.1. Test mechanical properties												
Task 4. Development of High R-value Phenolic Foam												
M4.2.1. Finalize cell size to max. thermal properties												
M4.3.1. Foam formulation to improve LTTR												
Task 5. Characterization of Hygrothermal and Corrosion Properties												
M5.1.1. Charaterization of Water Absorption and long term characteristics												