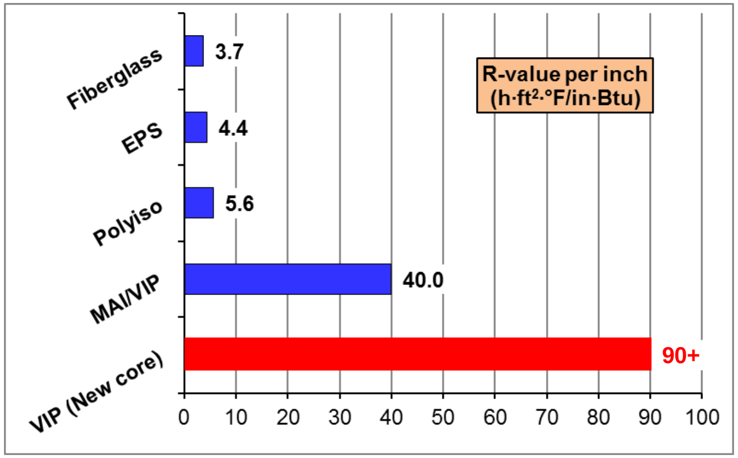
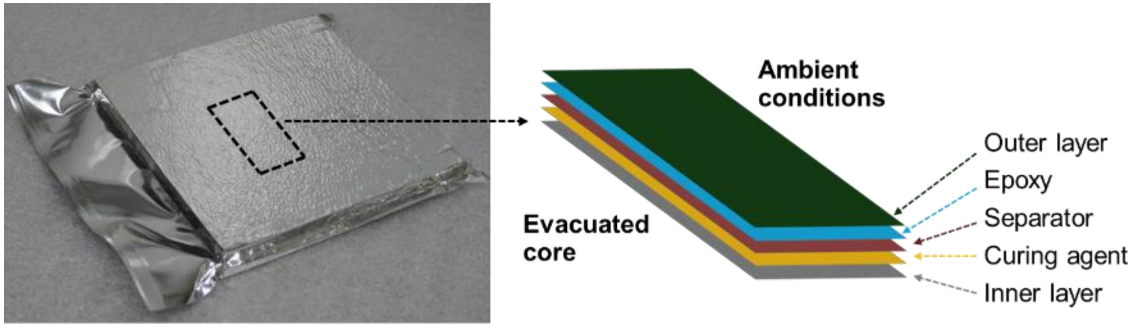
Ultra-high R/inch VIP with developmental core material and self-healing films to improve durability of VIPs





Oak Ridge National Laboratory
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Project summary (High R/inch VIP)

Timeline:
Start date: October 1, 2017
Planned end date: September 30, 2019

Key Milestones
1. Periodic measurements of ≤0.1 mbar VIPs with different barrier films showing no significant increase in conductivity (3/31/19)
2. VIPs created with developmental core material that can achieve R80+/inch (6/30/19)
3. Cost reduction of ≥50% compared to silica-based VIP in terms of $\$/ft^2/R$-value (9/30/19)

Budget:

Total Project $ to Date:
- DOE: $1,300,000
- Cost Share: $0

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- DOE: $1,300,000
- Cost Share: $0

Key Partners:

NanoPore Incorporated
Firestone Building Products Company

Project Outcome:

The overall goal is developing cost-effective insulation systems with at least twice the thermal performance of current building insulations. The new high R/inch insulations will enable easier retrofits of existing buildings.

Project summary (Self-healing films)

Timeline:

Start date: October 1, 2018
Planned end date: September 30, 2019

Key Milestones

1. Small-scale (~4"x4") test coatings created to identify the most appropriate deposition methods with respect to processability, uniformity, and adhesion (3/31/19).
2. Prototype films tested in a vacuum apparatus with demonstrated ability to heal a puncture or cut (9/30/19).

Budget:

Total Project $ to Date:

- DOE: $500,000
- Cost Share: $0

Total Project $:

- DOE: $500,000
- Cost Share: $0

Key Partners:

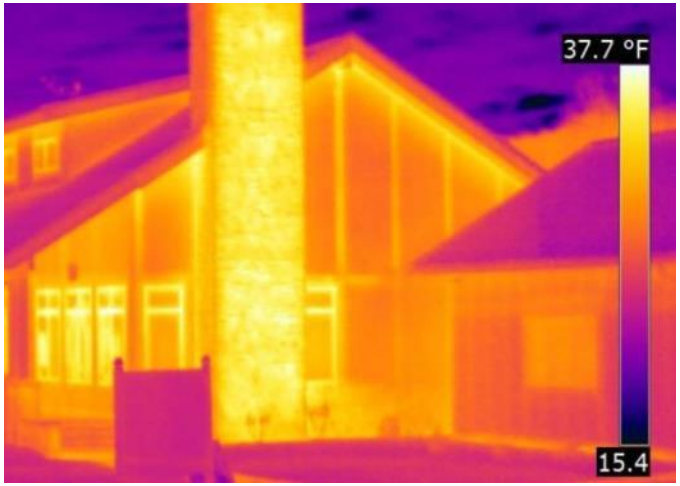
Key partners to be identified once we have demonstrated prototype film development using scalable roll-to-roll manufacturing methods

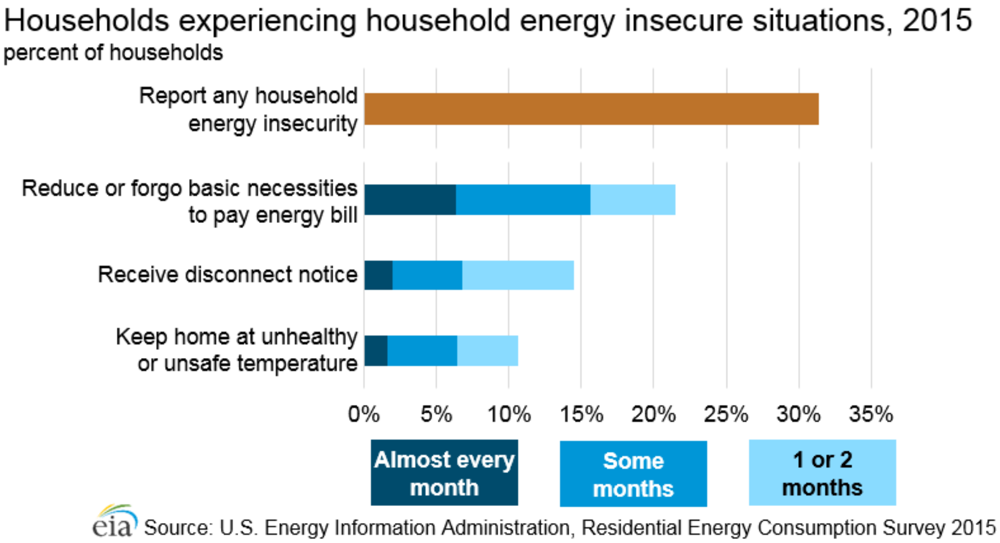
Project Outcome:

Development of prototype self-healing films using scalable roll-to-roll (R2R) manufacturing processes using slurries of the selected self-healing chemicals. The self-healing films are intended to improve durability of VIPs by *in situ* remediation of film defects.

Challenge

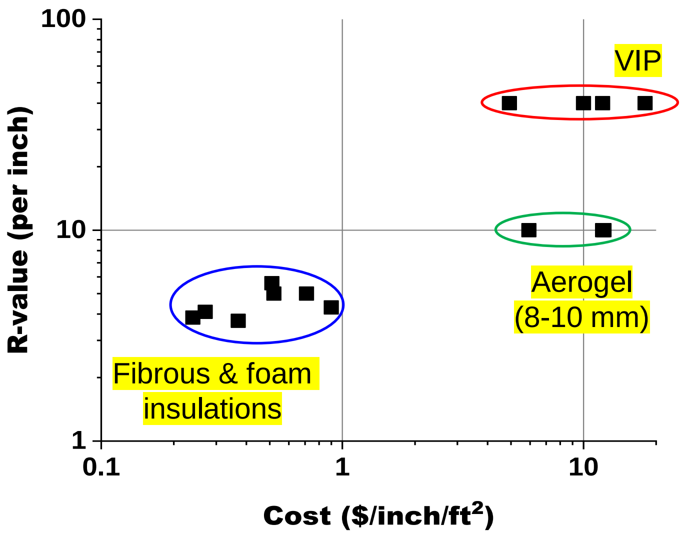
- In 2010, the primary energy consumption due to building walls and roofs was 5.8 quadrillion BTUs (*~6% of entire US consumption*).
- 2014 DOE Roadmap highlights the need for high-performance, cost-effective insulations.
- Economic implications: More than 20% of US house-holds face hardships due to high energy costs.
- Envelope retrofits with existing insulations (≤ R6/inch) are disruptive and have not proven to be cost-effective.
- Vacuum insulation-based systems (≥ R12/inch) are promising solutions.



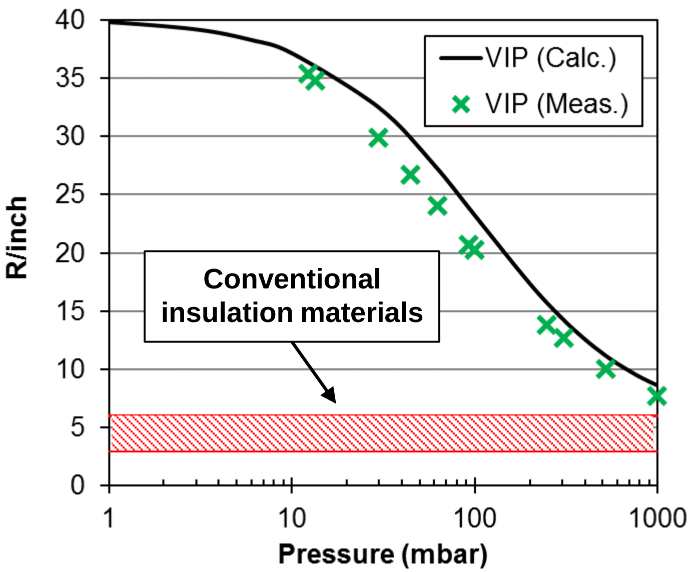


Challenge (contd.)

- Concerns with vacuum insulation panels (VIPs):
  - High cost
  - Durability and loss of R-value
  - Long-term performance
- ORNL and industry partners (and the VIP industry in general) are working to address above concerns
  - Improved barrier films and sealing methods (for longevity), lower-cost processing methods, etc.



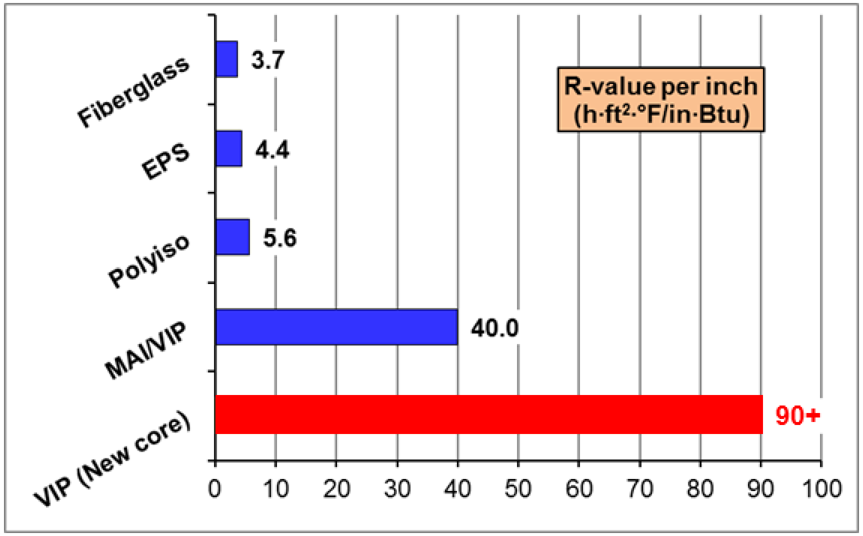
Typically-stated R-value and cost of VIPs vs. other insulations



Loss of VIP R/inch with pressure

Impact

- Developing cost-effective R12+/inch insulation is a stated goal of the 2014 DOE Envelopes Roadmap.
- 2030 energy savings potential of R25 insulation is >1.6 quads, based on the DOE Market Calculator
  - Includes existing commercial walls and roofs, and residential walls



- Building codes require ≤R10 of exterior continuous insulation (CI) in residential walls when combined with cavity insulation
  - R25 composite insulation will overcome lack of or poorly installed cavity insulation (often the case with old buildings)
  - At 1.25-1.5 inch, the developmental VIP-foam composite can make retrofits cost-effective [*Kosny et al., 2013*. *Cold climate building enclosure solutions*]

Impact (contd.)

- Cost, market and durability considerations
  - Current projects support BTO goals by seeking to increase thermal performance, reduce cost and increase the durability of VIPs .
  - A technoeconomic analysis from a previous project indicated a consistent market growth for VIP-based systems due to factors such as utility rate structures and peak demand, tax incentives and carbon policies, etc.
  - The global VIP market in construction is projected to grow to $5.5B in 2024 (www.grandviewresearch.com/industry-analysis/VIP-market).

- The current projects, if successful, promise a disruptive impact on building insulation technologies and will enable the DOE target of 45% reduction in building energy use intensity by 2030.

Team (High R/inch VIP)





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NanoPore

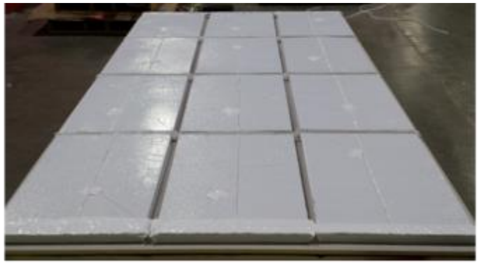
Firestone
BUILDING PRODUCTS

- ORNL: Kaushik Biswas, PhD & Andre Desjarlais - Project management, experimental and numerical evaluations, and reporting; Rohit Jogineedi – Research intern (PhD student).
- Douglas Smith, PhD (NanoPore): Micro-/Nanoporous insulation expert, VIP manufacturer.
- John Letts, PhD (Firestone): Foam manufacturing expert, foam-VIP composite manufacturing.

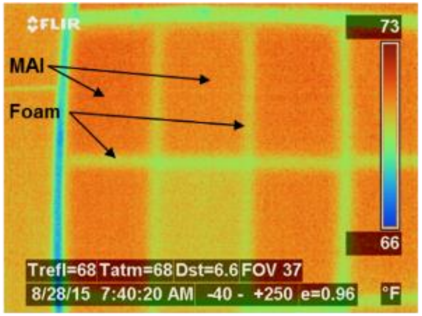
ORNL has decades-long building science expertise. ORNL researchers are well-versed in experimental and numerical evaluations of insulation materials and systems, including vacuum insulation. NanoPore has 100+ patents on porous insulation materials and has spun-off the largest VIP producers in the US and UK. Firestone is an industry leader for building materials and foam insulation, with over $1.4 billion in annual sales. The team of ORNL, NanoPore and Firestone successfully developed an R12/inch foam-VIP composite in 2017.

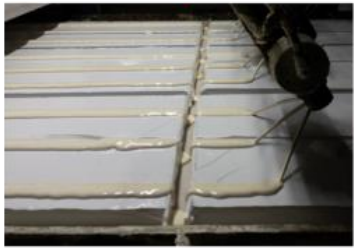
Approach (High R/inch VIP)

- The team previously developed 2 inch thick foam-VIP composites that achieved R25 (i.e. R12.5/inch)
  - Utilized low-cost fumed silica VIPs called Modified Atmosphere Insulation (MAI)
- Focus areas of the current high R/inch VIP project:
  - Developing higher R/inch VIPs at lower cost than MAI
  - Evaluating long-term performance of foam-MAI composites via field-testing and accelerated aging

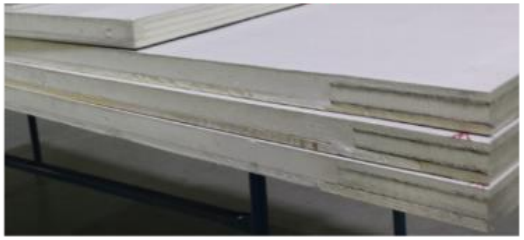


Modified Atmosphere Insulation (MAI) panels on high-density (HD) foam substrate

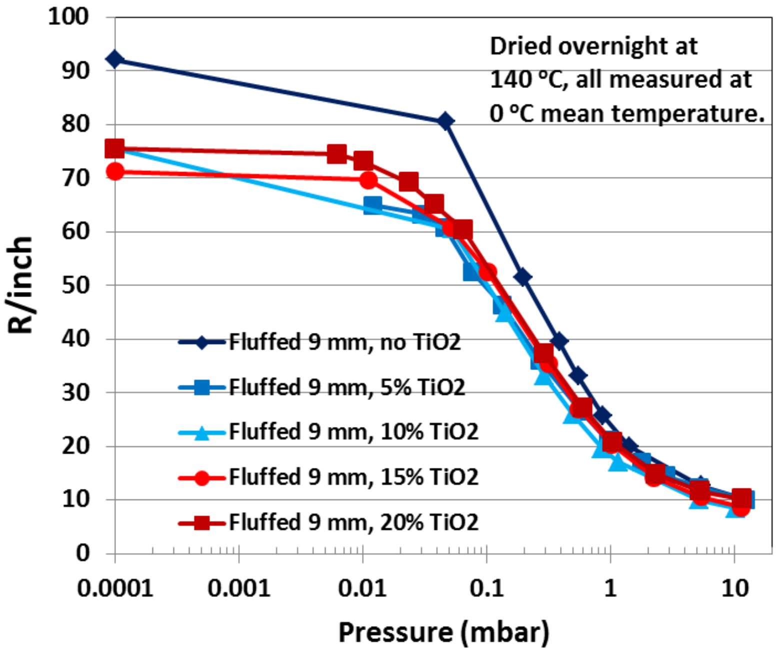




Foam application on manufacturing line



Finished composite insulation boards



Approach (High R/inch VIP)

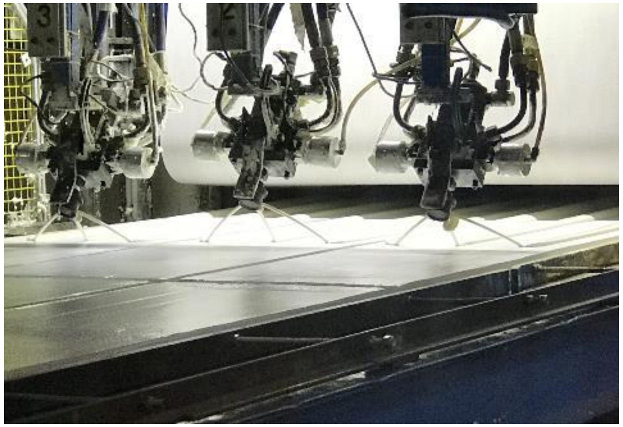
- Silica-based MAI: R40/inch and projected cost of $0.05/ft^2/R-value at 1 inch thickness.
- Developmental core-based VIPs: R80+/inch and projected cost of $0.025/ft^2/R-value at 0.5 inch thickness.
- Foam-VIP composite with new core can get R25 at lower thickness
  - Lower material and shipping costs compared to foam-MAI composite
  - Lower thickness (1.25-1.5" vs. 2") is highly beneficial for wall retrofits.
- Major FY19 goals:
  - Characterization of core material by R/inch measurements, imaging and modeling of conduction and radiation heat transfer within the core
  - Develop systems to create VIPs at <0.1 mbar internal pressure and verify the final internal pressure
  - Thermal performance testing and cost analysis of the new developmental core at large scale production to verify R80+/inch at 50% lower cost than MAI

Progress (High R/inch VIP)

- The high R/inch VIP work started on October 1, 2017
- Retrofit demonstration and long term performance of R25 boards
  - Manufactured 100+ R25 foam-MAI boards in a continuous process at Firestone
  - Retrofitted a 5500 ft^2 low-slope roof of an occupied building
  - Performing natural and accelerated aging of MAI and foam-MAI composites
- Development of new core to achieve R80+/inch
  - Developed vacuum pump system to rapidly make 0.1 mbar VIPs
  - Evaluating polymeric and metallized films to maintain <0.1 mbar internal pressure
  - Demonstrated feasibility of achieving R80+/inch
  - Performed preliminary cost analysis of the new VIP core

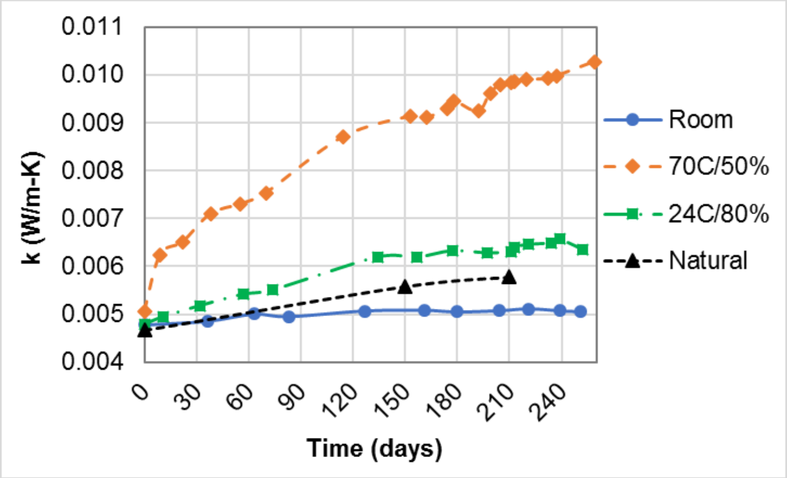
Continuous composite manufacturing and roof retrofit

- Produced 100+ composite insulation boards in a continuous operation at Firestone
- Boards were used to retrofit a 5500 ft^2 low-slope roof by professional contractors

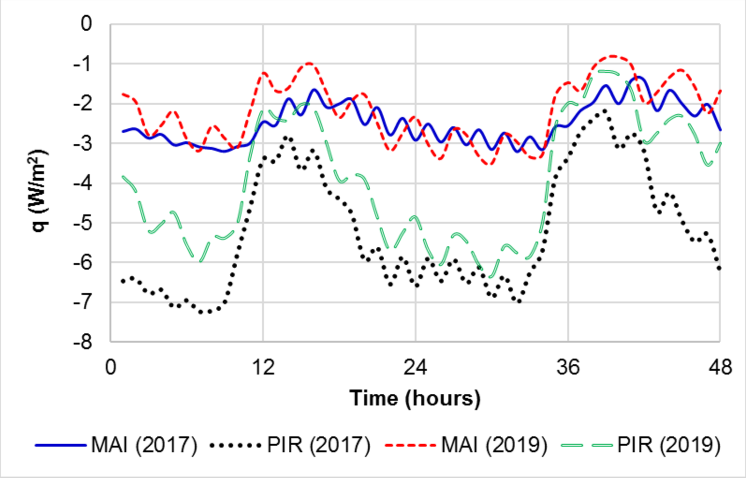


Long-term performance of R25 composite

- Natural aging tests at Charleston, SC, Oak Ridge, TN and Caribou, ME as well as aging in the laboratory.
  - Room aging and accelerated aging at 24ºC/80% RH and 70ºC/50% RH
- Side-by-side tests with polyiso (PIR)
- 2+ years at Charleston: $q_{MAI} << q_{PIR}$



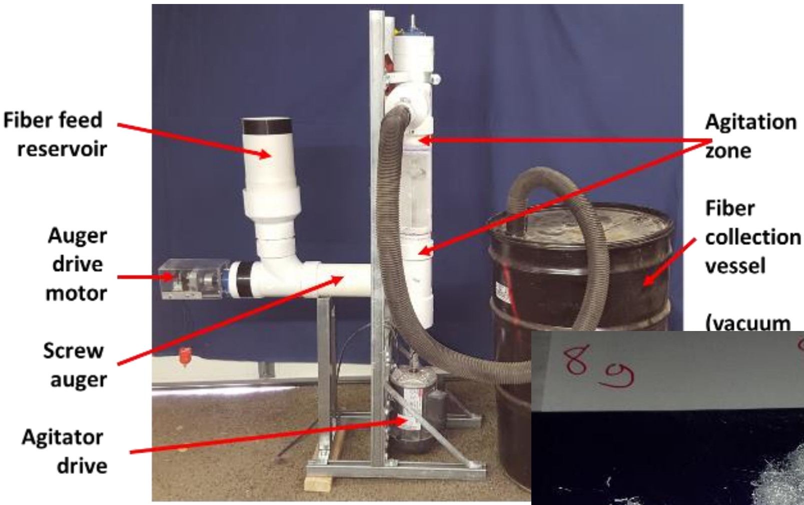
Natural (low-slope roof application) vs. laboratory aging in Oak Ridge, TN



Comparison of heat fluxes through R25 and PIR over two days during winter 2017 and winter 2019

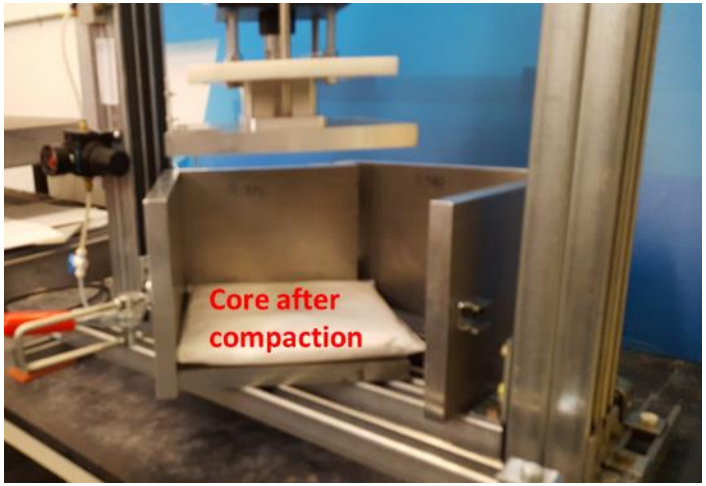
Development of high R/inch VIPs

- Novel low-cost polymer fiber-based core
- Developed a dry compaction process to make the cores directly to size
  - Traditional wet process: higher number of steps and energy use (needs drying), core need to be cut to size generating scrap, waste water cleanup
- Major steps: Fiber fluffing > Core compaction > Evacuation and sealing in barrier bags



Fiber fluffing

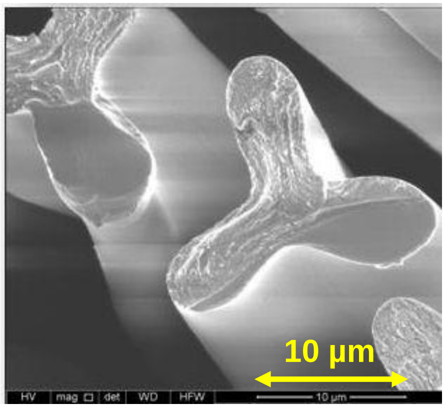
As-received vs. fluffed fibers

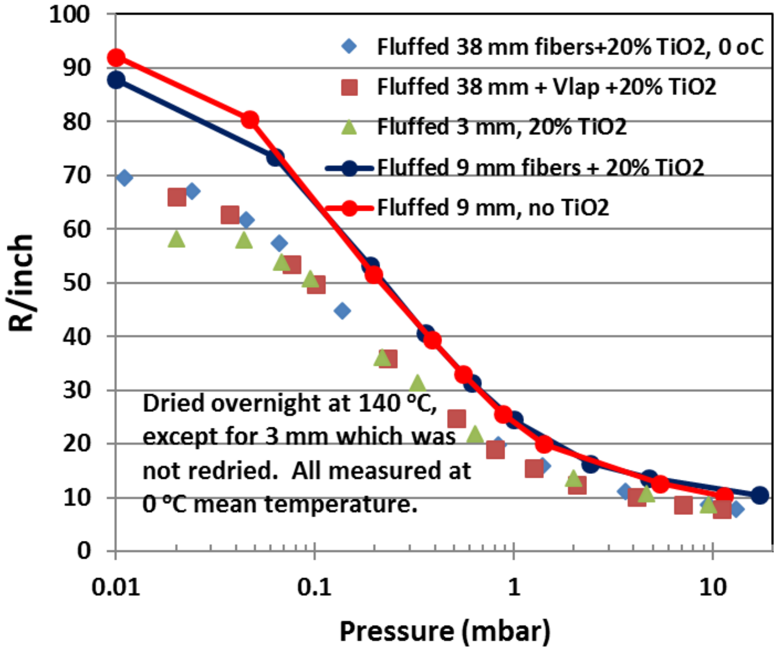


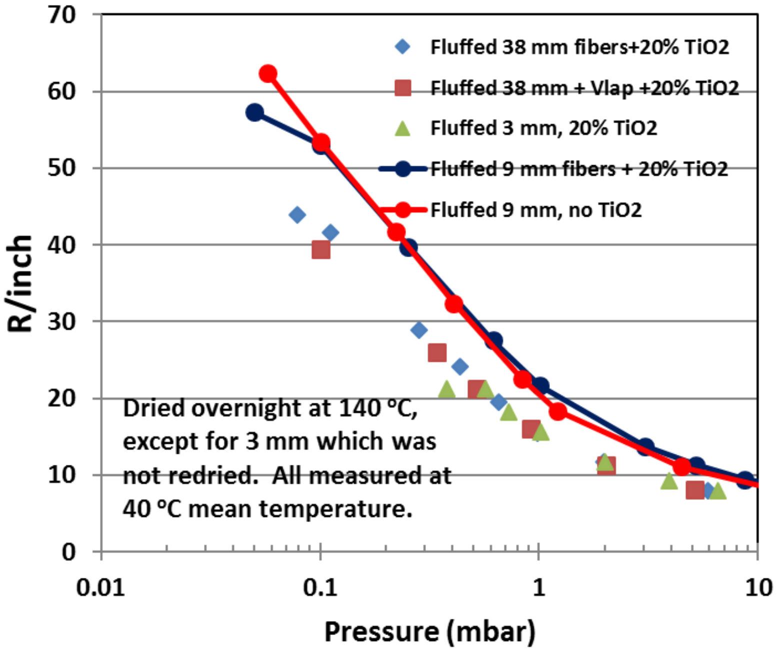
Fiber fluffing followed by compaction yields high degree of anisotropy in the fibers providing higher R/inch

Development of high R/inch VIPs

- Novel trilobal fibers yield higher number of fiber-fiber contact points (*greater contact resistance → higher R/inch*)
- Lobe diameters similar to near IR wavelengths, so they are effective at scattering radiation (*i.e. no opacifiers needed*)
- Larger overall fiber diameter reduces cost (*cost α 1/diameter*)
- Still room for improvement in fiber drying (impacts the low core pressure), IR optimization and core compaction







Preliminary cost analysis

- Preliminary cost comparison of developmental core VIPs and silica MAI
  - Table shows cost of goods sold (COGS), i.e. without profits
- New core VIP costs include an opacifier (silicon carbide)
  - Opacifiers are added to silica VIPs/MAI to reduce the radiation heat transfer
  - Developmental core can eliminate/reduce radiation without any opacifier

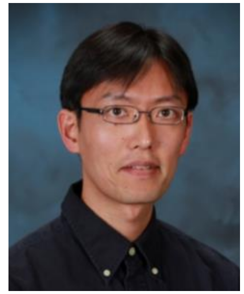
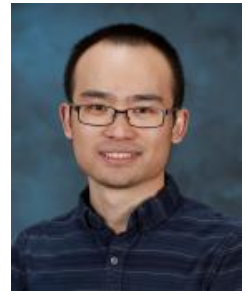
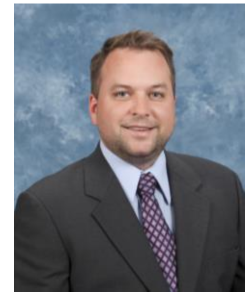
	Silica MAI	Developmental core VIP		
Thickness (inch)	1	0.5	0.75	1
R-value	40	40	60	80
	300,000 ft^2/year			
COGS ($/ft²)	4.76	3.06	3.3	3.54
COGS/R ($/ft²/R)	0.119	0.077	0.055	0.044
	18,000,000 ft^2/year			
COGS ($/ft²)	1.98	1.01	1.24	1.48
COGS/R ($/ft²/R)	0.050	0.025	0.021	0.019

- Projected cost of R25 board vs. foam insulation of same R-value
  - Cost offsets due to lower thicknesses are not included

	Silica MAI	New core VIP	Polyiso
VIP/MAI thickness (inch)	1	0.5	N/A
Board thickness (inch)	2	1.5	4
COGS ($/ft²)	2.54	1.87	1.25

Team (Self-healing films)

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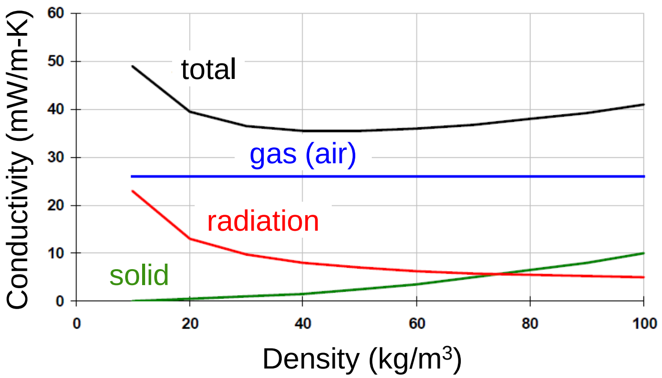
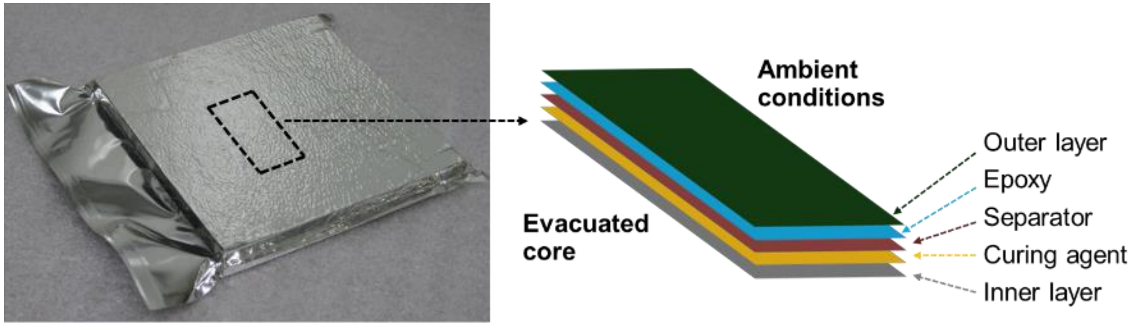
- Natasha Ghezawi, Kenisha Gardner and Kelsey Grady: Research interns/Technical staff
- Tomonori Saito, PhD and Pengfei Cao, PhD: Synthetic polymer chemists, with expertise in self-healing chemistry and reaction kinetics
- David Wood, PhD: Materials electrochemist and chemical engineer with expertise in composite coatings and roll-to-roll manufacturing processes
- Kaushik Biswas, PhD: Principal investigator; Building scientist with expertise in advance insulation systems (including VIPs)

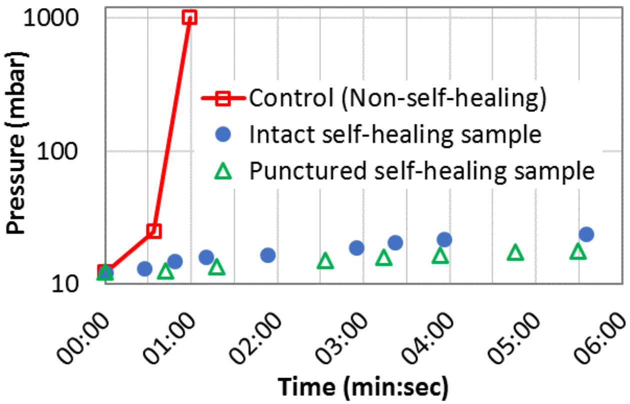
ORNL's Chemical Sciences Division has the necessary expertise in fabricating and evaluating chemical slurries for creating thin film coatings. ORNL's Manufacturing Demonstration Facility (MDF) has access to all necessary equipment for slurry processing and thin film, multi-layer coatings. R2R coating capabilities include two slot-die coaters, a tape caster, and a calender mill. Film quality can be monitored and controlled in-line using non-destructive techniques. The R2R facility has the flexibility to accommodate new materials and processes.

Approach (Self-healing films)

- VIPs achieve high R/inch by evacuating the core and eliminating gas conduction
- Damage to the barrier film results in loss of vacuum and R-value
- ORNL is developing self-healing films that can instantly heal from punctures and cuts
  – Proof-of-concept was shown via an internal seed project
- This is a new FY19 project, with the following major goals:
  – Develop chemical slurries that can rapidly react and heal any damage
  – Optimize the rheology of the chemical slurries to create thin film coatings and multi-layered films using R2R manufacturing methods
  – Create prototype films using scalable methods and verify self-healing ability by puncture tests

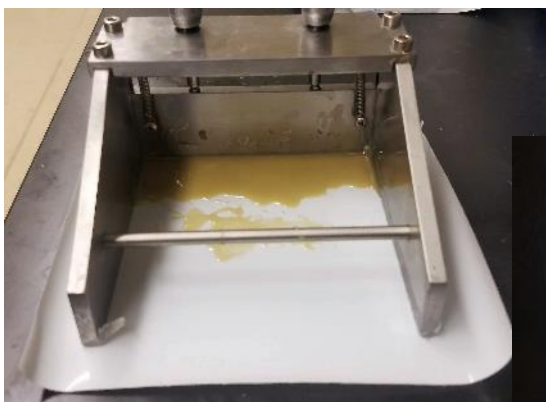






Progress - Selection of chemical slurries

- Critical parameters are quick reaction time and processability for thin coatings
- Candidates are commercial epoxies and curing agents (CA)
  - Nanoclay (NC) added for better viscosity control and lower gas permeability
  - Multiple tests indicated rapid reaction (~20 s) between selected chemicals
- Candidate substrates are regular and metallized polyethylene terephthalate (PET/mPET) and other polymeric films
  - Successfully created 50-100 μm coatings on mPET and coextruded polymer films

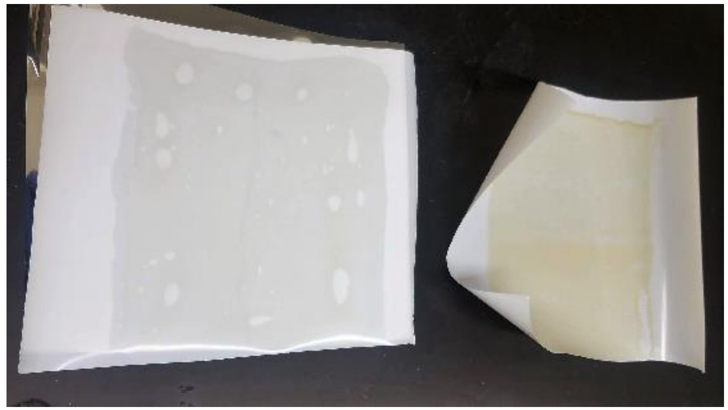


Small-scale tape casting

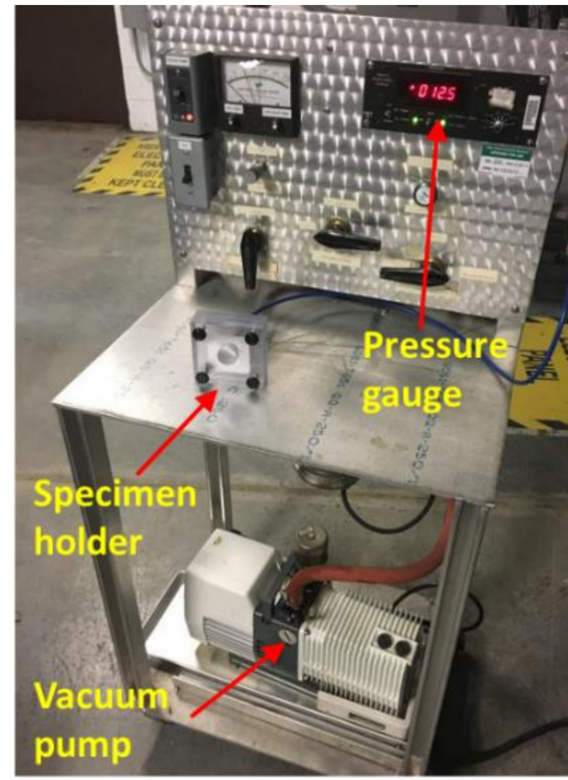
Coatings retain their shape when held vertically

Puncture tests of self-healing films

- Small-scale films prepared and tested in a custom vacuum apparatus

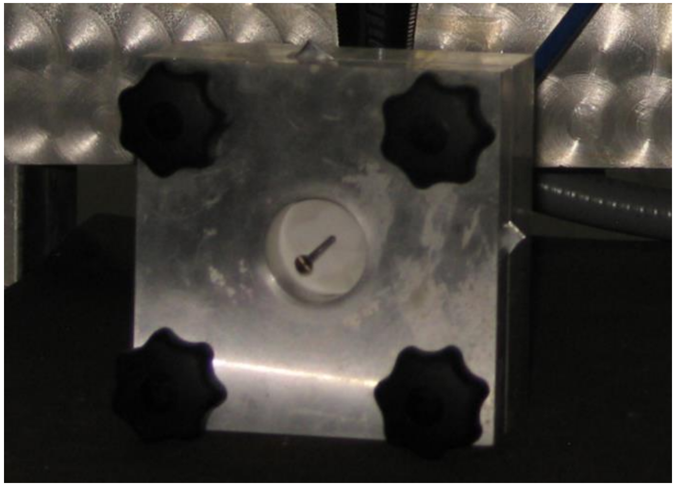


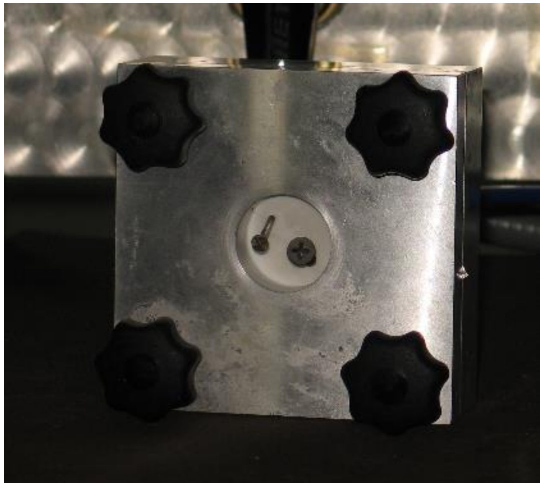
Small-scale multi-layered film

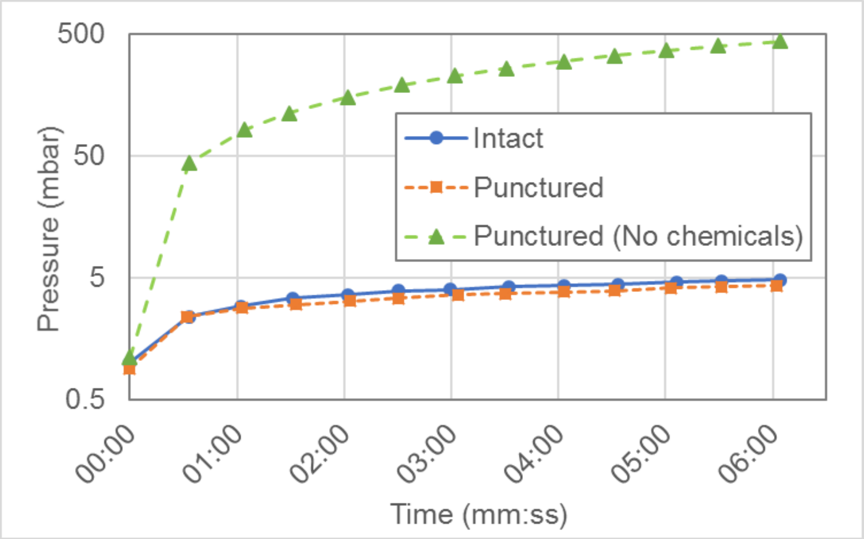


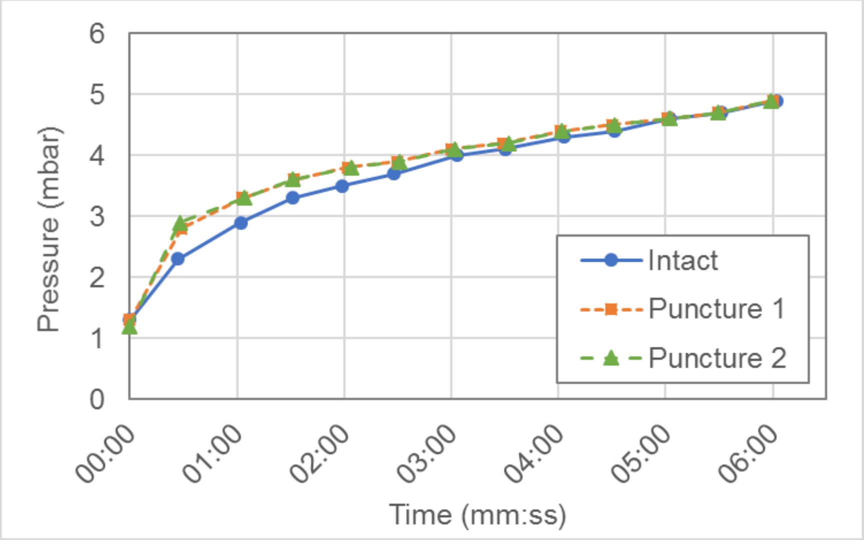
Puncture tests of self-healing films

- Successful single and multi-puncture tests

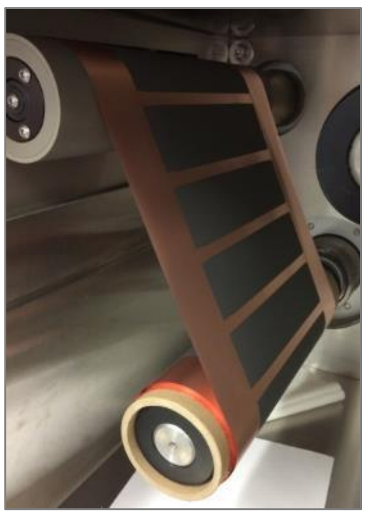


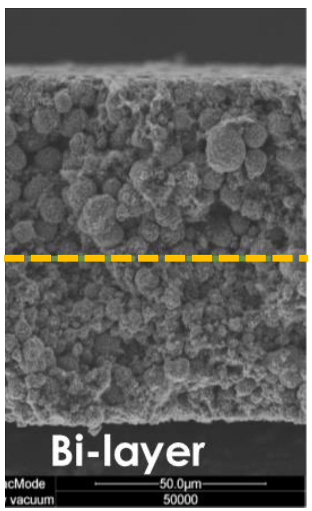




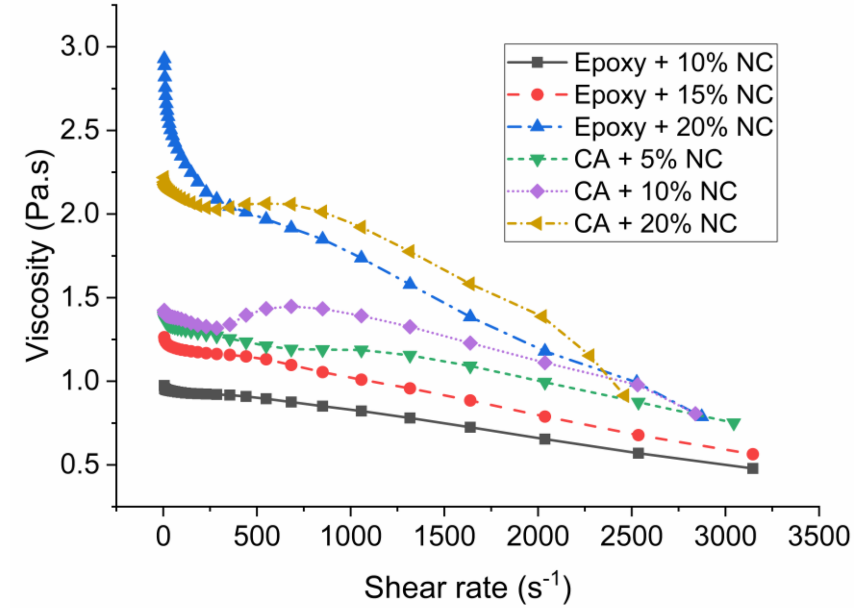


Slurry characterization for R2R trial





Slot die coating



- R2R facility specializes in thin film architectures (≥20 µm) like the proposed multi-layered films.
- Developed slurries in the appropriate viscosity range for slot die coating (< 5 Pa-s).
- Development of shear thinning slurries at typical slot-die coating shear rates (100-1000 s^{-1}) is critical for good coating deposition and thickness control.

Stakeholder engagement

- High R/inch VIP project is a collaboration between ORNL and industry (NanoPore and Firestone)
  - Firestone and NanoPore have discussed the commercialization of MAI/VIP for large-scale R25 composite production
- Potential industry partners for self-healing films
  - FLEXcon develops many different barrier films and carrier sheets that could be implemented in multilayer coating designs
  - NanoPore works with three different barrier film suppliers in supplier-customer and co-development relationships
- ORNL has access to test beds for evaluations of prototypes of VIP-based insulation systems, particle surface charge stabilization, rheology development, multilayer polymer-composite coatings, R2R processing science and control

Stakeholder engagement

- Publications and presentations at technical conferences to disseminate information to relevant stakeholders.
  - Biswas et al. (2018). *Development and thermal performance verification of composite insulation boards containing foam-encapsulated vacuum insulation panels*. Applied energy, 228, 1159-1172.
  - Biswas, K. (2018). *Development and Validation of Numerical Models for Evaluation of Foam-Vacuum Insulation Panel Composite Boards, Including Edge Effects*. Energies, 11(9), 2228.
  - Biswas et al. (2019). *Demonstration of self-healing barrier films for vacuum insulation panels.* Vacuum, 164, 132-139.
  - 14th International Vacuum Insulation Symposium and VIPA International General Body Meeting, September 2019, Kyoto, Japan
  - 7th International Conference on Self-Healing Materials (ICSHM2019), June 2019, Japan
- Patent: Self-healing barrier films for VIPs, US Provisional 62/618,715
  - Non-provisional patent application is under consideration

Remaining FY19 work

- High R/inch VIP
  - Perform imaging analysis of fiber-based VIP cores with different degrees of anisotropy and try to correlate with thermal performance
  - Update numerical models of VIP core to estimate the radiation and conduction heat transfer to account for the trilobal fibers
  - Optimize the drying and IR opacification processes to improve R/inch
  - Develop a plan for scaled-up manufacturing and update cost analysis
- Self-healing films for VIPs
  - Develop slurry compositions suitable for R2R methods, which utilize slurries within certain viscosity ranges (for example, <5 Pa-s for the slot die coater)
  - Create prototype films using scalable R2R methods
  - Develop defect-free coatings of epoxy and curing agent with uniform thickness verified via microscopic techniques

Potential future work (High R/inch VIP)

- Evaluate long-term performance of the polymeric fiber core VIPs via natural and accelerated aging tests
- Develop and evaluate full-scale (4’ x 8’) foam-VIP insulation boards with the new R80/inch VIPs
  - Investigate the minimum composite board thickness that can still achieve R20 or R25 (*R20 maybe high enough for wall applications*)
  - Examine foaming methods to minimize the foam thicknesses encapsulating the VIPs while maintaining the structural integrity of the boards
- Updated cost analysis for the optimized core material and barrier films
  - In silica MAI, 90% of material cost is due to the core; with metallized barrier films, cost/performance curve will be different
- Determine pathways to scaled-up production of the R80/inch VIP and strategies for introduction to the building insulation market

Potential future work (Self-healing films)

- Develop VIPs using prototype self-healing films and address any process limitations
  - For example, impact of heat-sealing the edges of the film around the VIP core on the self-healing chemicals
- Investigate the minimum coating thicknesses that can still provide the self-healing capability
  - Current barrier films for VIPs are about 100-150 μm thick
- Optimize the film structure and the manufacturing methods
  - Residence time between consecutive coatings of the multi-layered films
  - Gas impermeability of the self-healing films to be the same as current VIP barrier films (nanoclay is very effective in improving impermeability)
  - Long-term stability of the self-healing chemicals
- Perform cost analysis and collaborate with an industry partner for commercialization and addressing barriers to large-scale manufacturing

Thank You

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REFERENCE SLIDES

Project Budget (High R/inch VIP)

Project Budget: $1,300,000
Variances: None
Cost to Date: $1,300,000 (includes full cost of FY19 commitments)
Additional Funding: None

Budget History					
FY 2018 (past)		FY 2019 (current)		FY 2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$1.3M	$0	$0	$0	$0	$0

Project Budget (Self-healing films)

Project Budget: $500,000
Variances: None
Cost to Date: $500,000 (includes full cost of FY19 commitments)
Additional Funding: None

Budget History					
FY 2018 (past)		FY 2019 (current)		FY 2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$500k	$0	$0	$0	$0	$0

Project Plan and Schedule (High R/inch VIP)

- Go/No-Go milestone (on schedule): R80/inch polymeric fiber VIPs at 50% lower cost at silica based MAI/VIP in terms of $/ft²/R-value
- A few milestones have been delayed due to unforeseen technical challenges

Project Schedule				
Project Start: Oct 1, 2017		Completed Work		
Projected End: Sep 30, 2019		Active Task (in progress work)		
		Milestone/Deliverable (Originally Planned)		
		Milestone/Deliverable (Actual)		
	FY2019			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work				
Interim report comparing performance degradation of MAI and foam-MAI composites under natural and accelerated aging conditions				
Demonstrated laboratory scale (>1 pound per batch) fluffing of fibers with at least a 5x decrease in bulk density as compared to unfluffed fibers				
Fiber-based VIPs created with at least 3 different barrier films and internal pressure of ≤0.1 mbar for long-term pressure retention tests				
Analysis report on evaluation of field data from Charleston and Caribou comparing performance of foam-MAI composites with regular foam insulation				
Current/Future Work				
Report on periodic conductivity measurements of ≤0.1 mbar VIPs with different barrier films showing no significant increase in conductivity				
Model describing the solid conduction and radiation heat transfer within fibrous cores based on the core structure				
VIPs created with optimized fiber core (diameter, length, morphology and opacifiers) that can achieve R80/inch				
Final report on periodic conductivity measurements of ≤0.1 mbar VIPs with different barrier films				
Updated cost analysis report and plan for scaled-up manufacturing of fiber-based VIPs.				
Final report on natural and accelerated aging study of silica-based MAI panels and foam-MAI composites				

Project Plan and Schedule (Self-healing films)

- Go/No-Go milestone (on schedule): Prototype films tested in a vacuum apparatus with demonstrated ability to heal a puncture or cut

Project Schedule				
Project Start: Oct 1, 2018		Completed Work		
Projected End: Sep 30, 2019		Active Task (in progress work)		
	◆	Milestone/Deliverable (Originally Planned)		
	◆	Milestone/Deliverable (Actual)		
	FY2019			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work				
Selection of films for the outer, inner and separator layer for the proposed multi-layered self-healing films based on known gas permeability and processability for R2R methods.	◆			
Candidate slurries characterized for viscosity and reaction kinetics with different wt. % of nano-clay to achieve a healing time of ≤1 minute.	◆			
Small-scale (~4"x4") test coatings created to identify the most appropriate deposition methods with respect to processability, uniformity, and adhesion.		◆		
Puncture tests of small-scale (pouch) self-healing samples in the vacuum pump apparatus following their exposure to high temperature and humidity.		◆		
Slurry compositions identified for coatings via R2R manufacturing based on coating method. Different R2R coating methods utilize slurries with viscosities in different ranges.		◆	◆ (planned)	
Current/Future Work				
First prototype film created using an R2R manufacturing process.				
Report describing results of literature survey and preliminary evaluations of alternative methods to increase durability of VIPs and enable recovery of VIPs from damage.				
Selection of advisory board and initial report summarizing the board's feedback on research plan and proposed outcomes.				
Developed defect-free coatings of epoxy and curing agent with uniform thickness verified via microscopic techniques.				
Prototype films tested in a vacuum apparatus with demonstrated ability to heal a puncture or cut and limit the rate of system pressure rise same as an intact film				