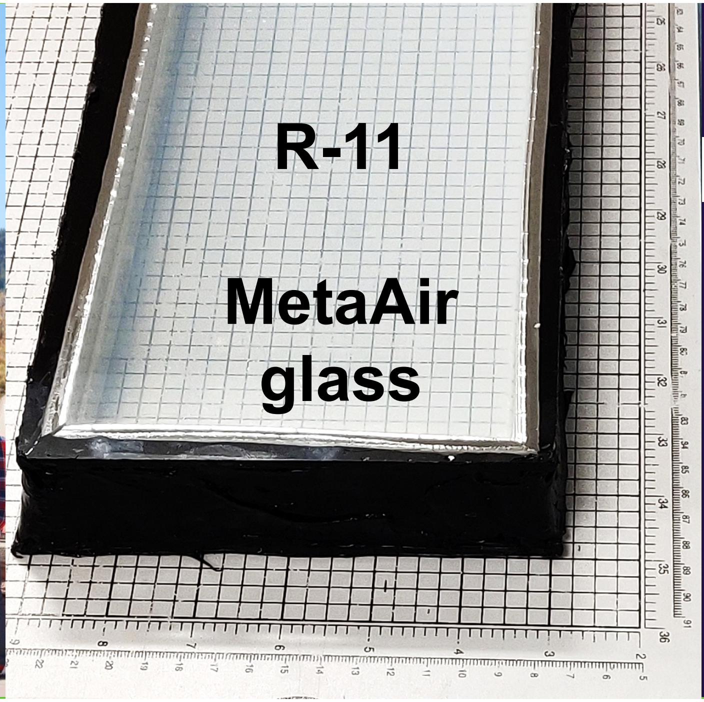
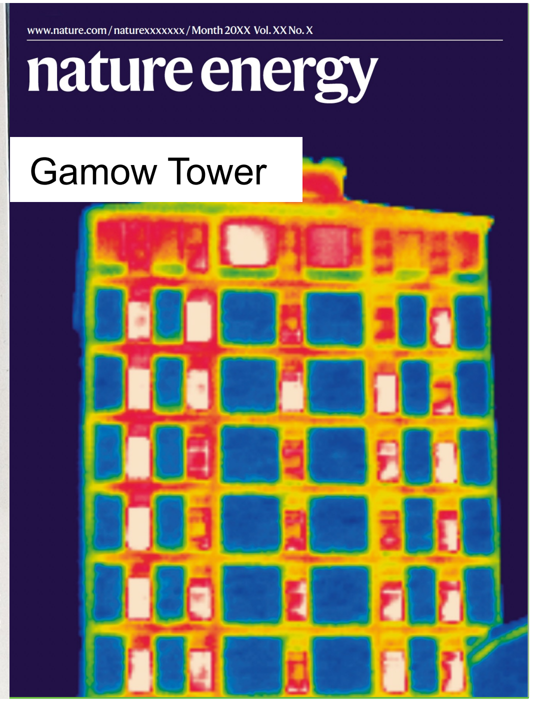
Monolithic Mesoporous Metamaterials for R-10 to R-15 Glazing



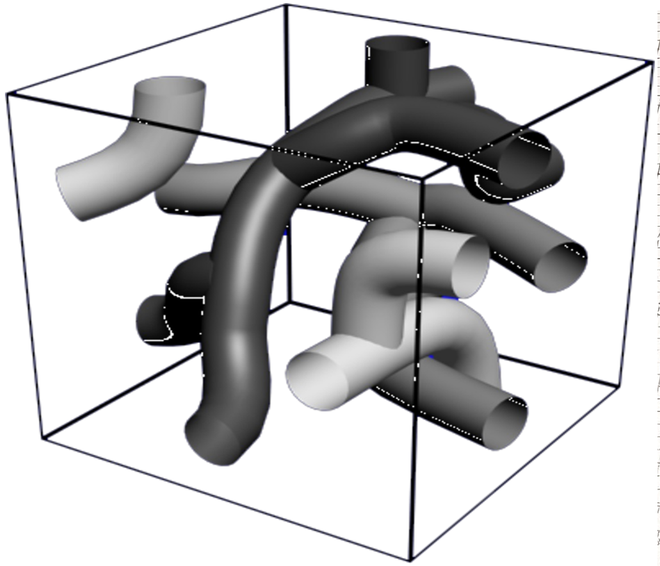


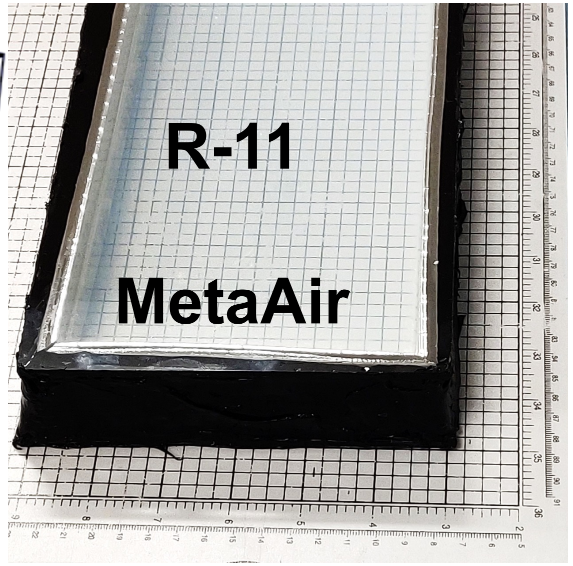
Performing Organization(s): University of Colorado Boulder
PI Name and Title: Professor Ivan I. Smalyukh
PI Tel and/or Email: ivan.smalyukh@Colorado.edu
WBS #, FOA Project # and/or any other Project #: DE-EE0009699

Project Summary

Objective and outcome

Develop manufacturing of thermally-insulating, transparent monolithic mesoporous metamaterials (MMM or MetaAir) for glazing. Demonstrate R-10 IGUs with MetaAir-filled gap between glass panes formfactor of a standard double pane IGU. Demonstrate multi-pane IGUs with MetaAir-based panes of glazing meet R-15/inch insulation targets, under $1 per square foot manufacturing of MMMs with >99% transparency, <1% haze





Team and Partners

University of Colorado Boulder

University of Colorado **Boulder**

Partners: iFeather Technologies

Stats

Performance Period: 10/1/2021-9/302024

DOE budget: $792k, Cost Share: $198k

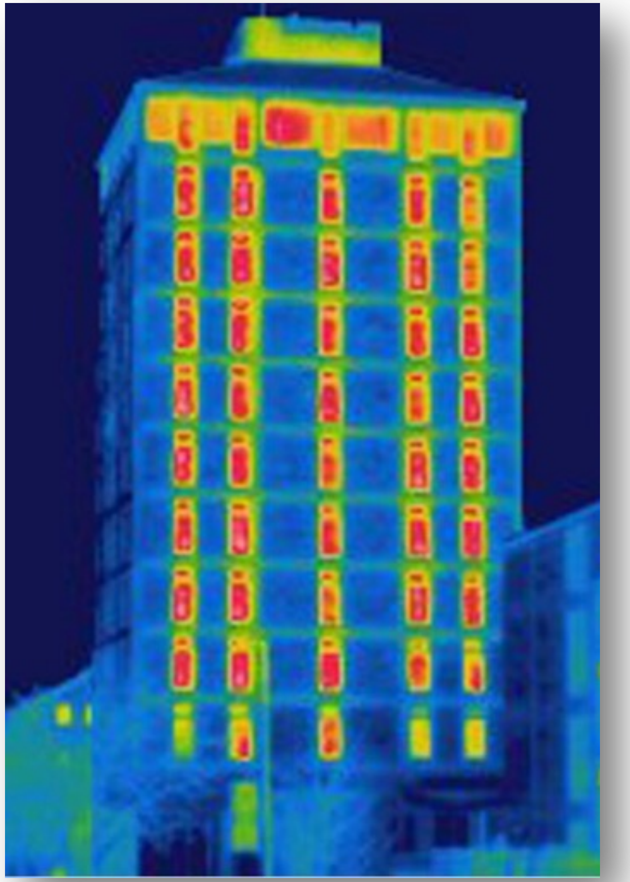
Milestone 1: R10—R11 MMM-based glazing

Milestone 2: R-15/inch insulation, <1% haze

Milestone 3: under $1 per square foot manufacturing

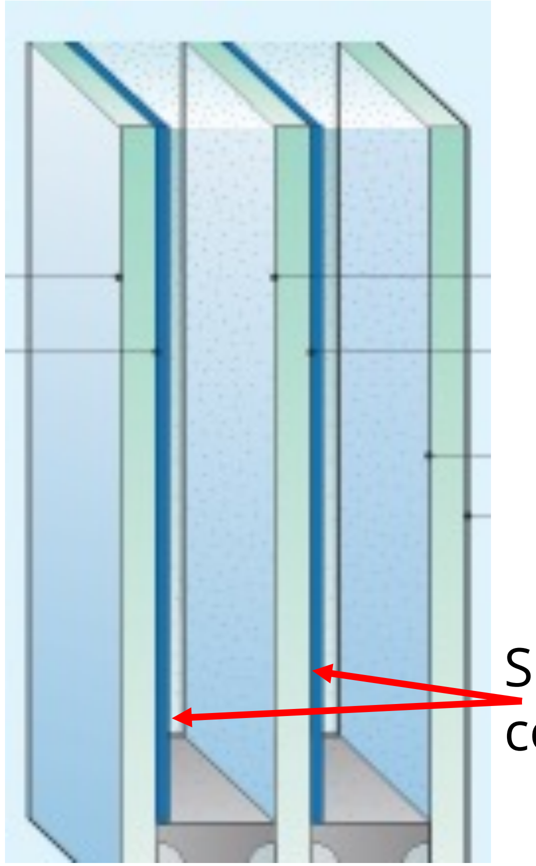
Problem: Windows waste energy & money…

Office & home windows



$2 million wasted every 15 min globally

Deployment <3%



Bulky, expensive

→20% of building energy lost through windows due to poor thermal insulation

→Low-income homeowners spend 5-15% of that income on heating and cooling

→Existing products cannot solve the problem as transparent super-insulators do not exist…

Alignment and Impact

→Maintain environment of buildings without energy consumption, or reduce this consumption
→Reduce/mitigate the growth of the energy demand
→Eliminate green house emissions that would be associated with generating energy consumed by buildings
→Help save ~20% of building energy wasted via windows

Greenhouse gas

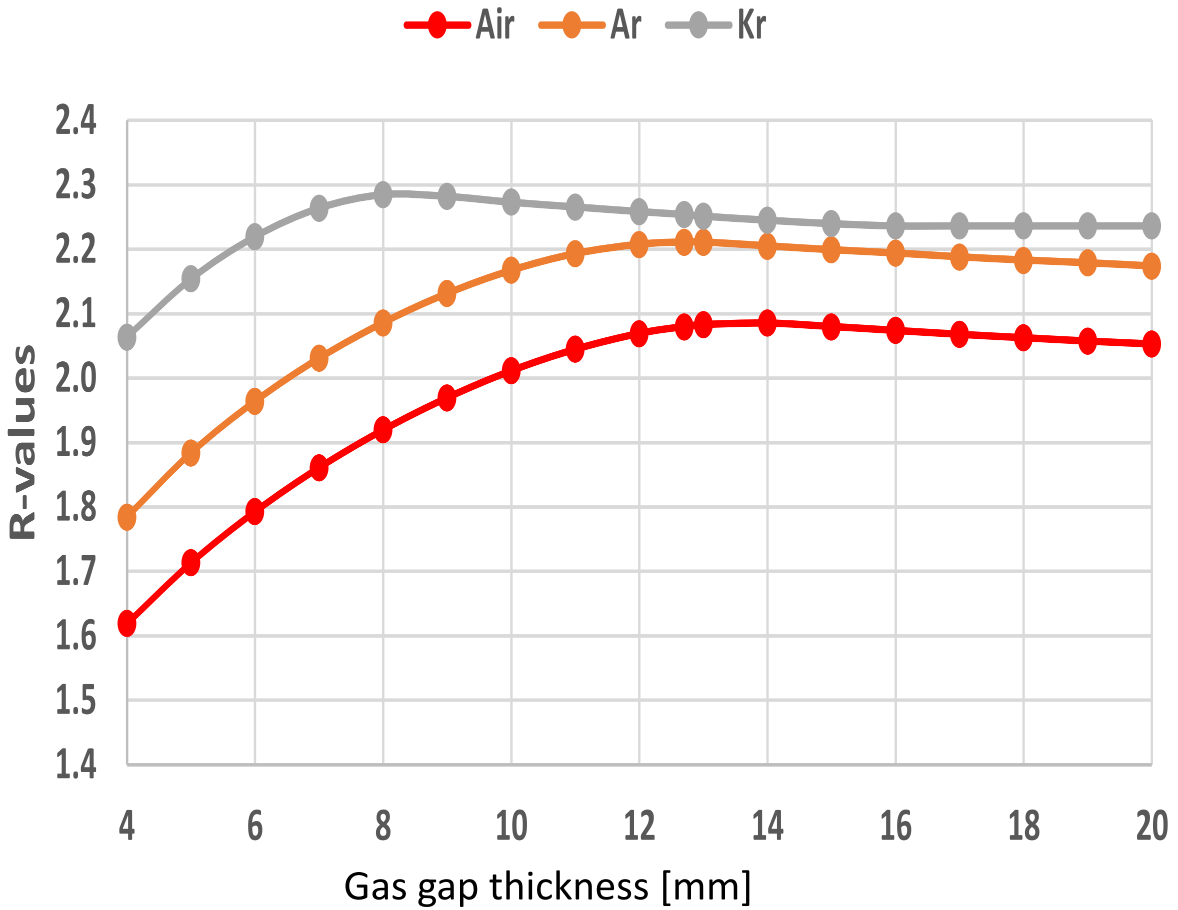
Power system

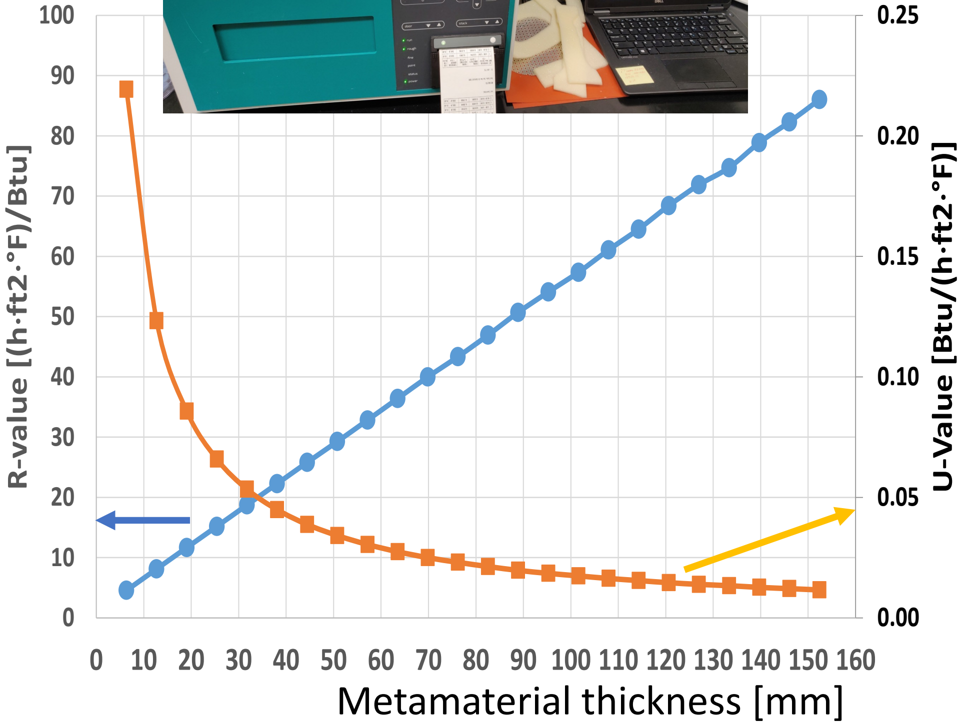
Energy justice

Consumer Benefits:
→Relative savings (household) \$500-2000 per year
→Extra benefits: comfort, sound proofing, condensation resistance…

Approach: gas vs (porous) solid IGU fillers

Towards ultra-high-R windows… IGU fillers?





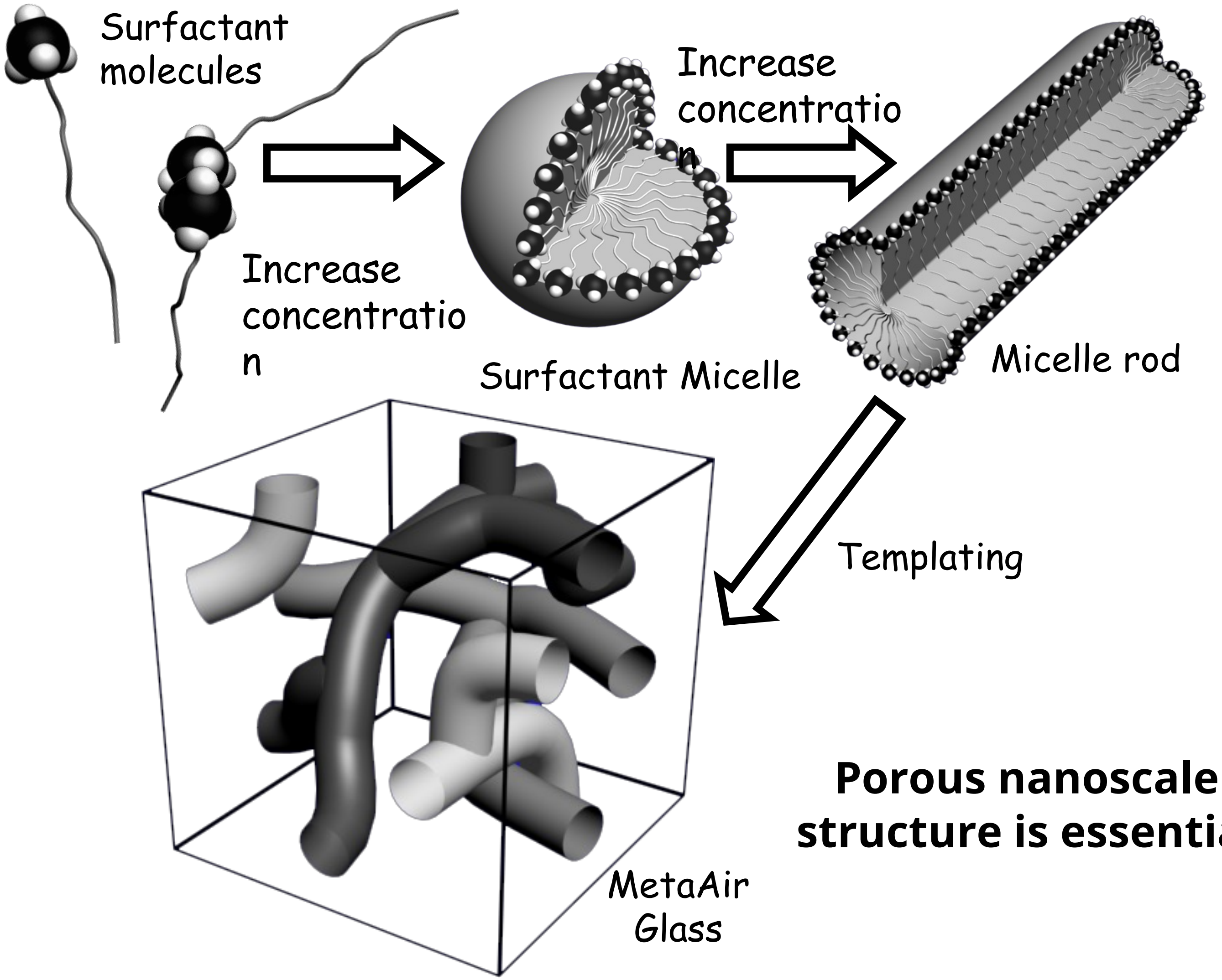
→**Convection for thick air/gas gaps!!!**

→**90% air, 10% solid shaped into porous tubes**

→**9-11mW/(Km), R-15/inch for our material**

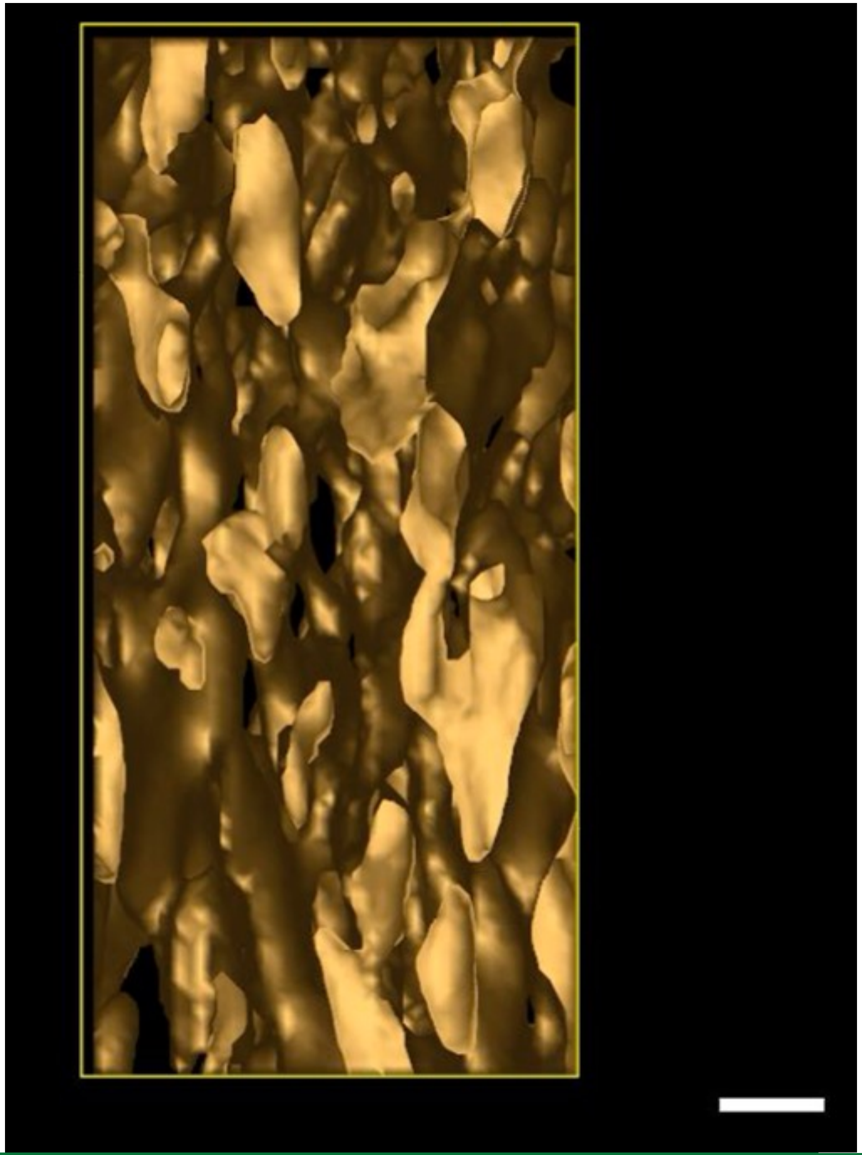
Approach: Templating mesoscale porous tube networks by lyotropic LCs

Surfactant self-assembly



Porous nanoscale structure is essential

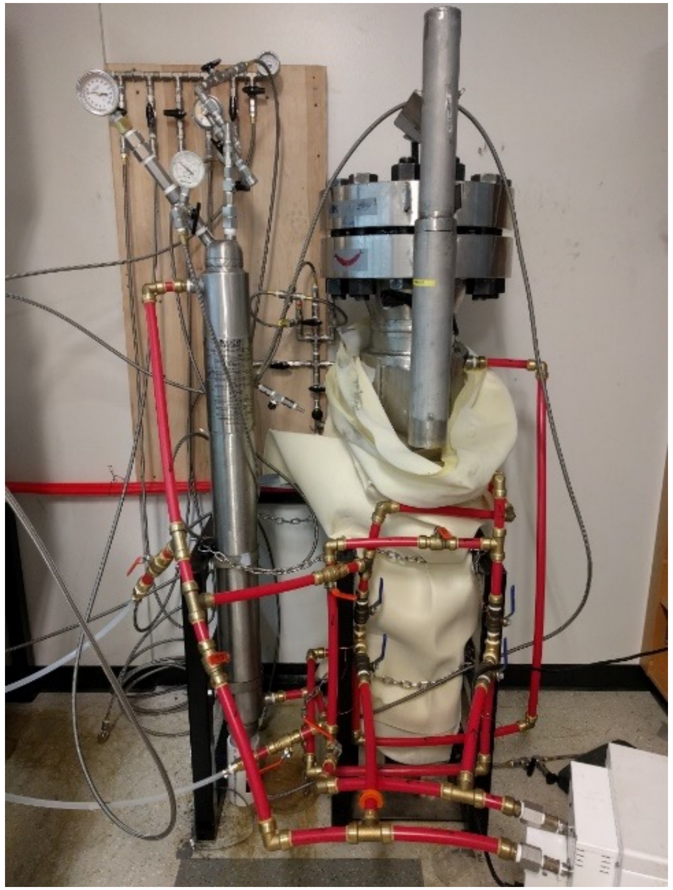
3D TEM tomography



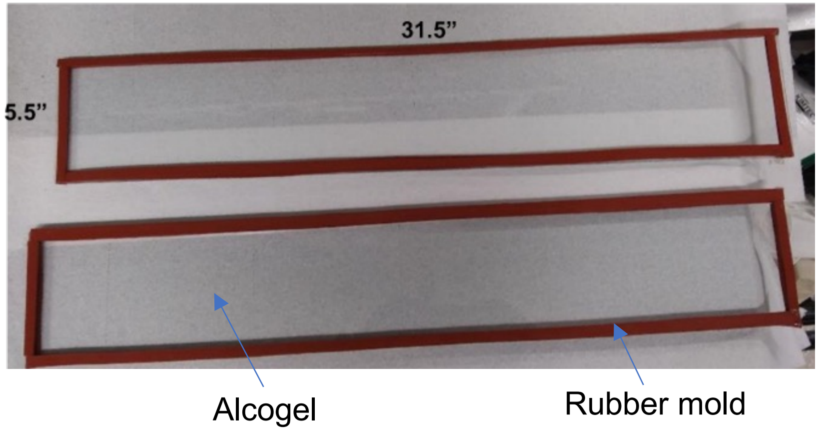
Approach: Drying to obtain nano-porous analogs of glass

MMM Samples Fabrication

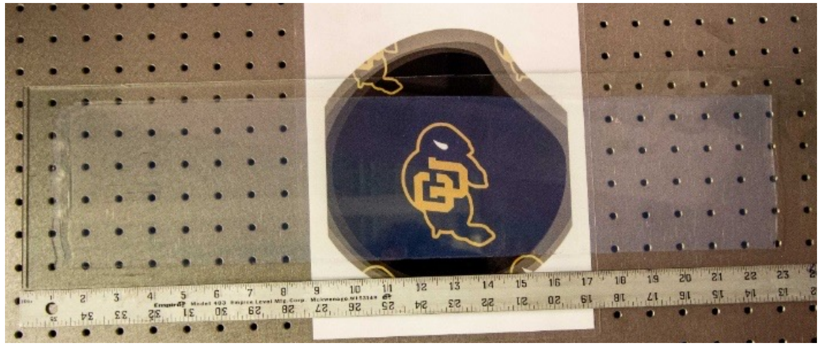
Supercritical drying of MMM samples



Preparation of MMM samples

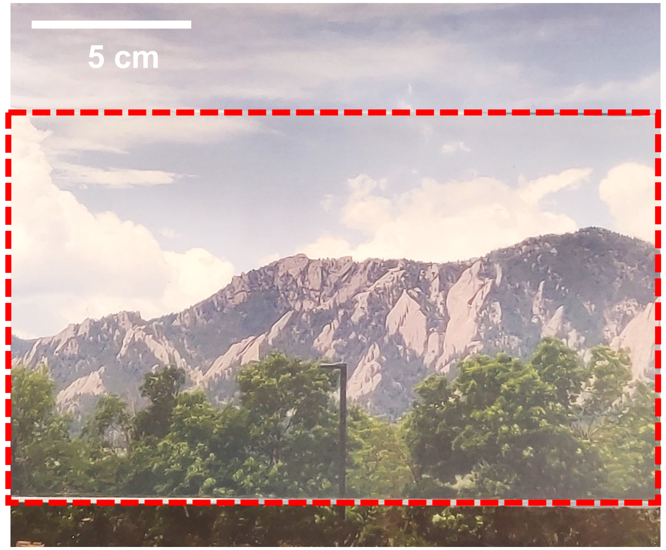


Fabricated square-foot MMM sample



- New procedure for drying MMM samples using supercritical fluid extractor was developed
- Curing and solvent exchange of large area samples developed
- drying procedure and solvent recycling

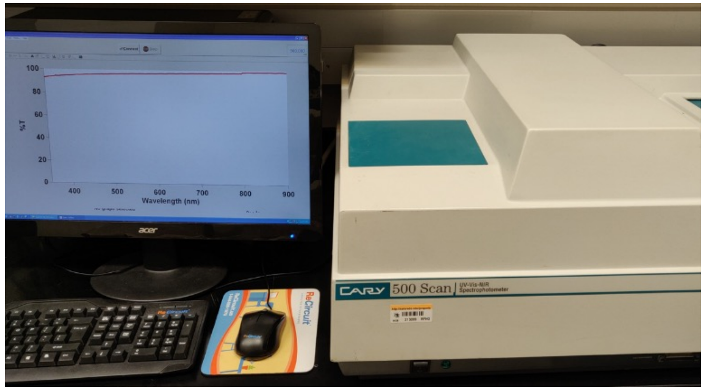
MMM sample



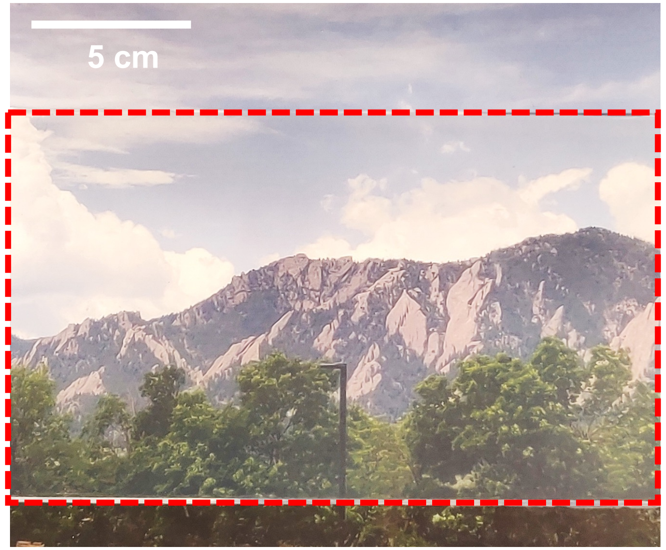
Approach: Meeting stringent requirements for transparency and haze

Optical properties of MMM samples

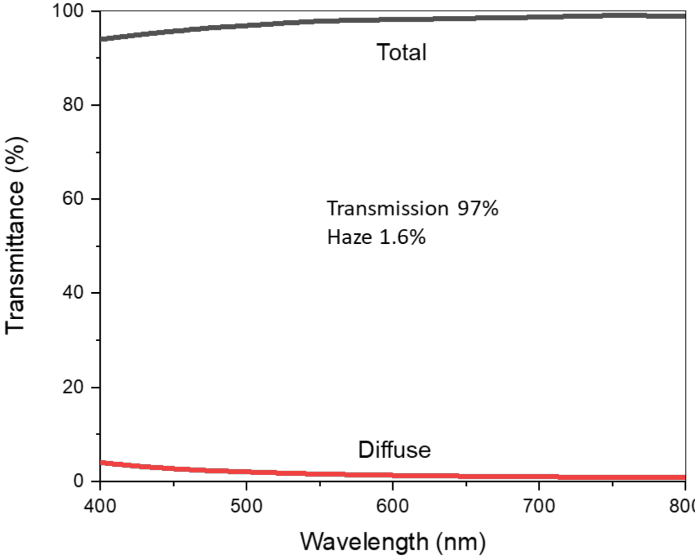
Cary 500 Scan UV-Vis-NIR spectrometer



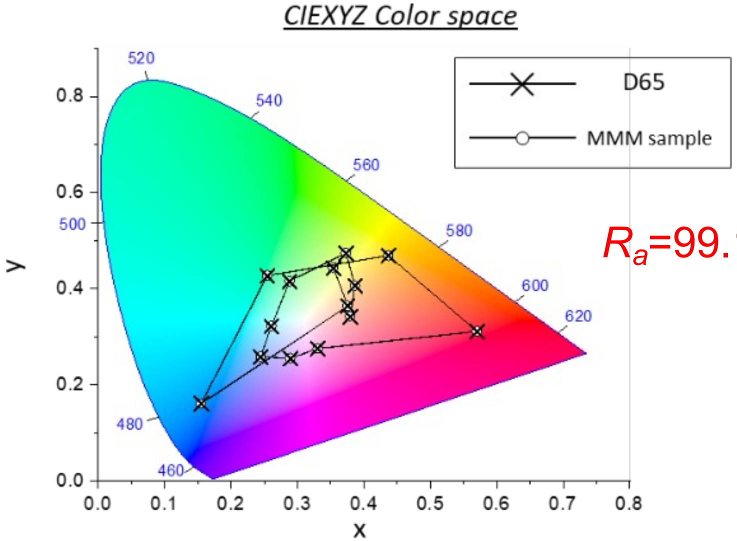
MMM sample



Visible light transmission of fabricated MMM samples



Color space diagram for fabricated MMM samples



R_a=99.1%

Total visible light transmission: T_{vis}= 97%

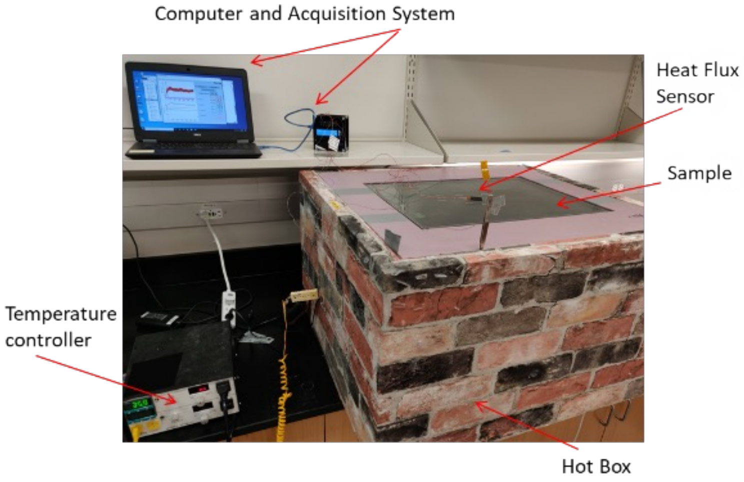
Haze: 1.6%

Color rendering index: 99.1%

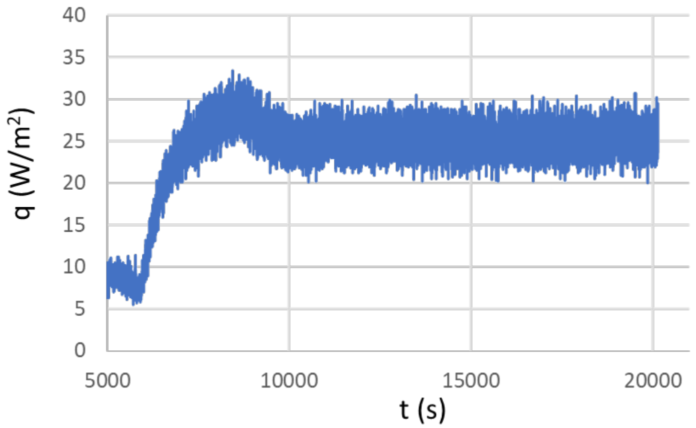
- High color rendering index of 99.1% shows that MMM does not affect the optical performance of IGUs, which will be limited by the used glass and low-e coatings

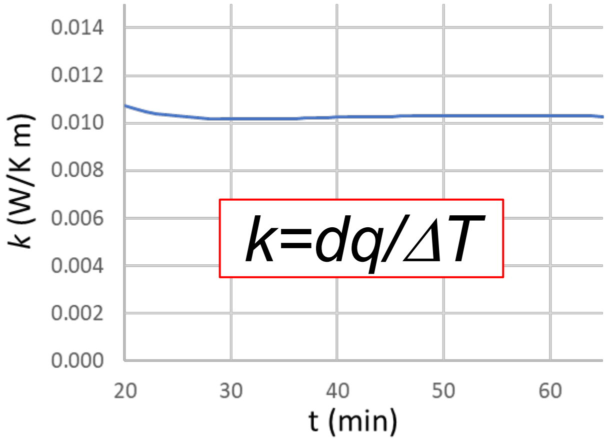
Approach: Thermal characterization

Thermal properties of MMM samples



Heat Flux Measurements

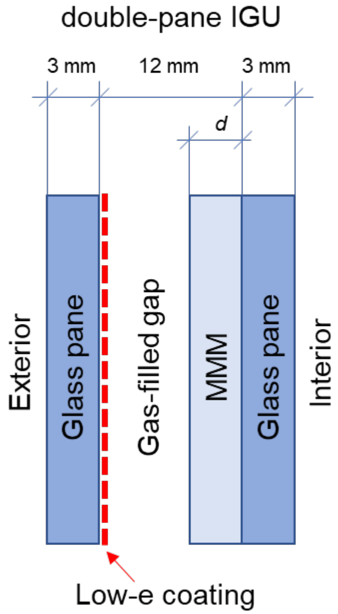


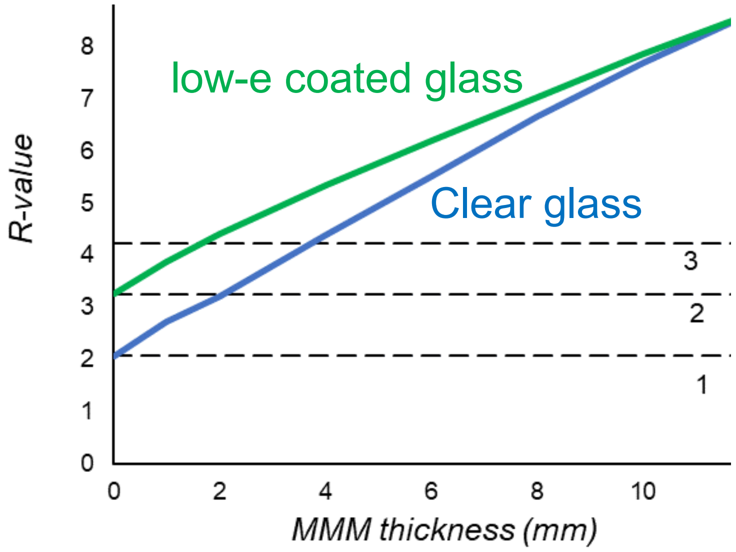


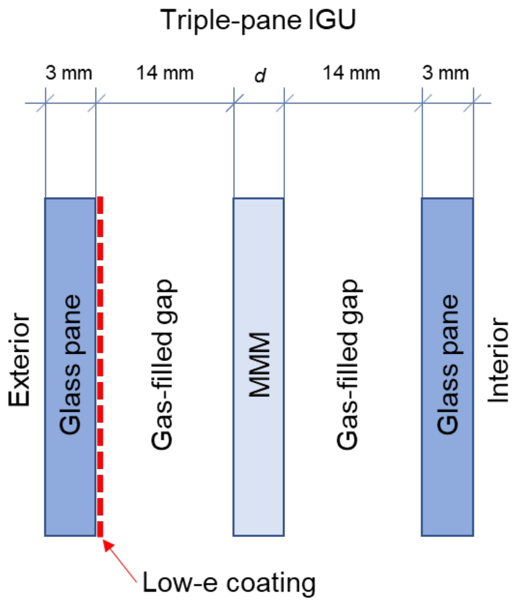
Heat Flow Meter Netzsch 446

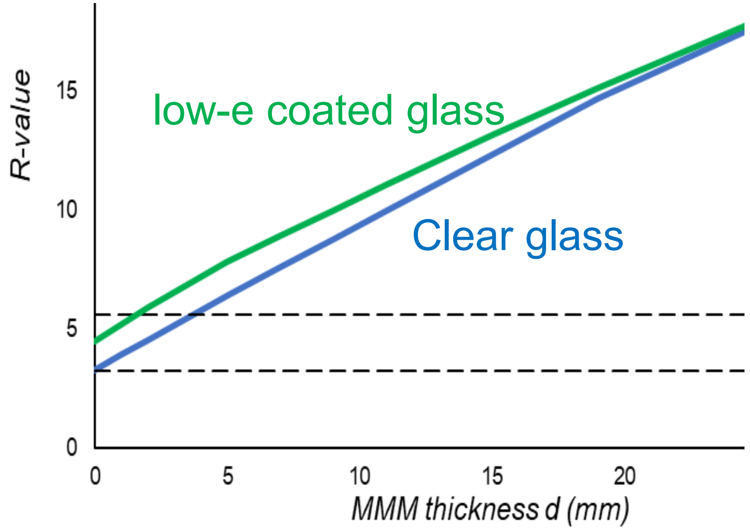
Thermal conductivity k	*9-11 mW/(K·m)*
R-value for 3-12 mm	*1.5-7.6*
R-value per inch	*12.9-16*

Progress and Future Work: Designing & Fabricating Square-foot IGUs

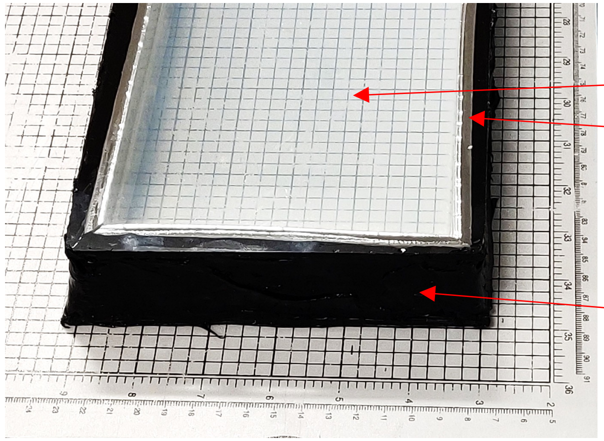


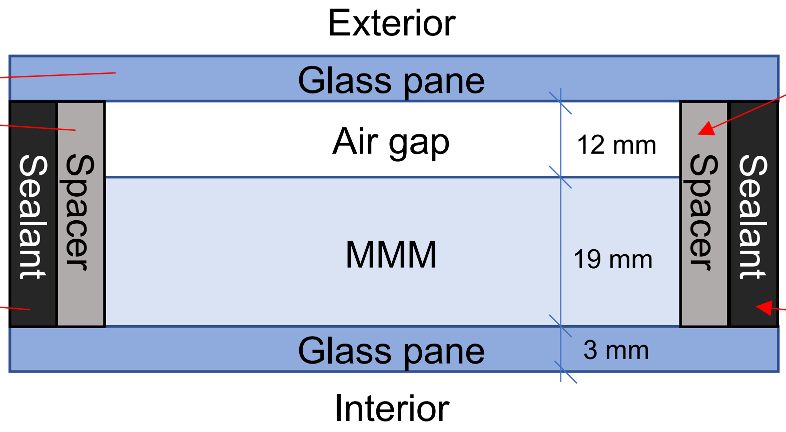






IGU Fabrication from MetaAir and Clear Glass (no coatings)

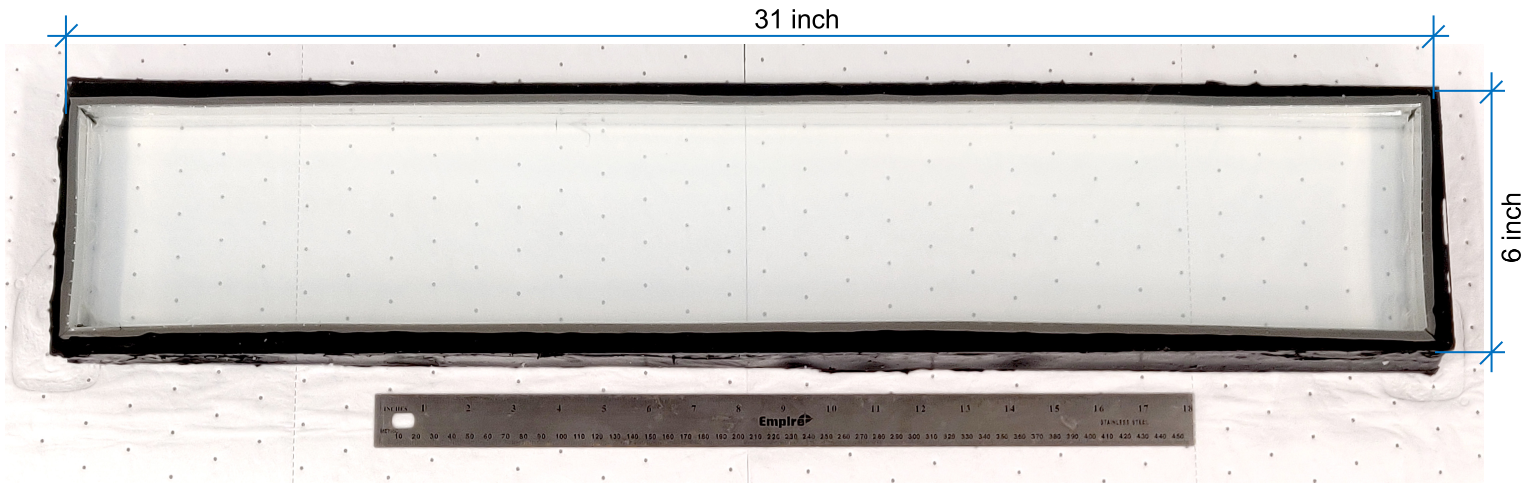




Super spacer for setting the gap

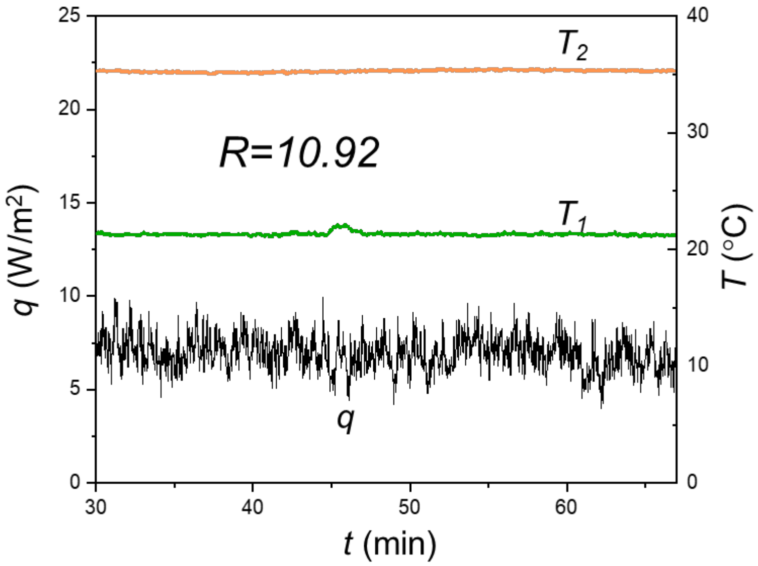
Silicone sealant for securing IGU edges

Progress and Future Work: R-11 large-area MMM-based IGU

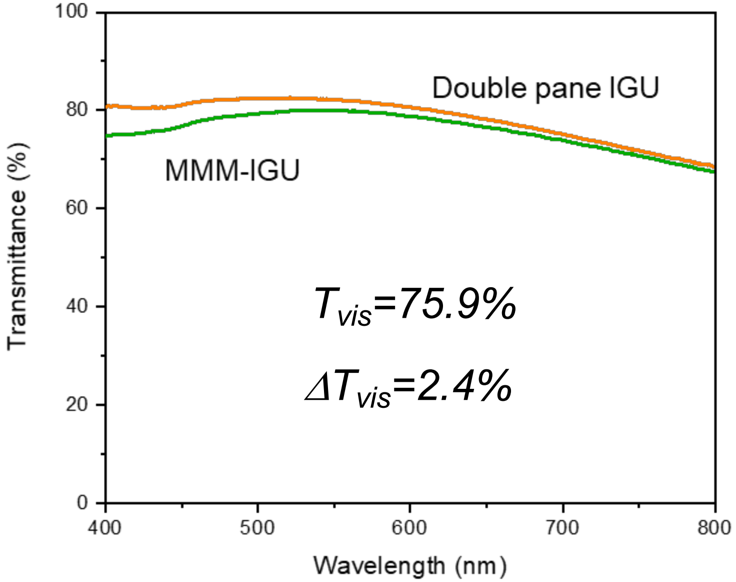


- Achieved R=10.92
- optical transparency < 3% lower than a double pane IGU with the same glass panes
- high color rendering index

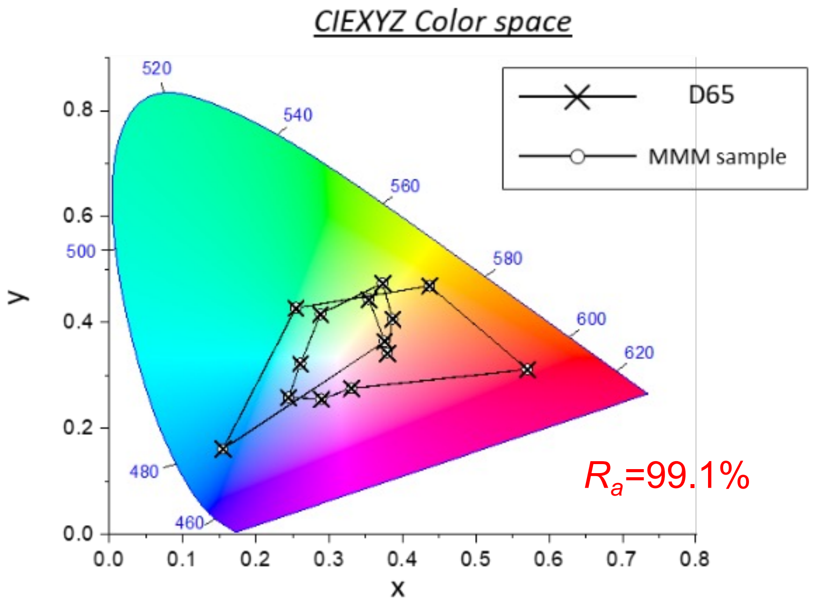
Thermal performance of MMM-based IGU



Optical performance of MMM-based IGU



Color space diagram for fabricated MMM samples



Progress and Future Work: switching to quasi-ambient drying

Ambient drying fabrication

We have been working using both ambient drying and critical point drying methods. These two methods are different in terms of chemistry, solvent exchange process, and cost of drying process

Critical Point Drying

- Better optical properties
- Can produce large composite MMMs by tiling lots of CPD dried MMMs together

1. Chemical formulation

2. Gelation at 55°C

3. Hydrogel

Wash and solvent exchange to ethanol

4. Alcogel

Supercritical point drying

5. MMM

Ambient Drying

- Cheaper and scalable
- highly insulating and mechanically strong MMMs

1. Chemical formulation

2. Gelation at 50-80°C

3. Hydrogel

Wash with water and solvent exchange to isopropanol

4. Alcogel

Solvent exchange to heptane, octane

5. Organogel

Ambient drying

6. MMM

Progress and Future Work: Accomplishments & Risks

- *Fabricated square-foot MMM samples with 97% visible transmission, low 1.6% haze, and a low thermal conductivity 11 mW/(K·m) and lower using supercritical drying*
- *Measured high color rendering index of 99.1% (required >95%) for fabricated MMM slabs*
- *Fabricated MMM-based IGUs with a glass-adhered MMM slab showing thermal performance of R=10.92*
- *Fabricated MMM samples using ambient drying method with T_{vis}=95.6% (required >90%)*
- *Fabricated MMM samples using low pressure subcritical drying method T_{vis}=97.1% (required >92%)*

Parameters of fabricated MMM samples and MMM-based IGUs

	Parameter/Metric	Target value	Achieved value	
1	Thermal conductivity of MMMs	<12 mW/(K×m)	11 mW/(K×m)	☑
2	R value of MMM-based IGU	≥10	10.92	☑
3	Visible light transmission of MMMs	>90%	97%	☑
4	Haze of MMMs	<2%	1.6%	☑
5	Color rendering index of IGU	>95%	99.1%	☑

➢ completed milestones due Q1-Q5 & will continue develop the technology to complete all technical goals, where we foresee no challenges that we cannot overcome

Progress and Future Work: Project Schedule & upcoming milestones

Milestone Number	Milestone	SOPO Task/ Subtask Number	Planned Completion Date	
1.1.1	Fabricate square-foot MMM samples with >92% visible transmission and a low thermal conductivity <12 mW/(K·m)	1.1	12/31/21	☑ 100%
1.1.2	Demonstrate/optimize MMM adhesion to glass by means of chemical bonding while retaining optical & thermal properties of the constituents showing neither visible delamination nor haze increase by >0.5%, nor transparency and thermal conductivity decrease by >1%	1.1	03/31/22	☑ 100%
1.2.1	Fabricate MMM-based IGUs with a middle pane made of free-standing or glass-adhered MMM slabs showing optical transparency < 3% lower than a double pane IGU with the same glass panes, and R-5 or better R values	1.2	07/31/22	☑ 100%
1.2.2	Fabricate a square-foot MMM-IGU with MMM between clear glass panes & 2-pane formfactor showing R-10 insulation or better, >80% visible transparency and >95% color rendering	1.2	10/31/22	☑ 100%
2.1.1	Determine parameters for optimal MMM drying with low-surface-tension solvents achieving haze <2%, color rendering >95% and transmission >90%	2.1	06/30/22	☑ 100%
2.2.1	Design large-scale square-meter, multi-pane subcritical or ambient drying apparatus	2.2	08/31/22	☑ 100%
3.1	Vessels machined & dryer assembled from home-built & commercial parts, which allows to fabricate a preliminary subcritical or ambient dried MMM sample showing >90% visible transmission and a thermal conductivity <15 mW/(K·m)	3.0	03/31/23	30%
3.2	Subcritical/ambient MMM dryer yields MMMs of high quality - similar to that with supercritical drying showing >92% visible transmission and a low thermal conductivity <12 mW/(K·m)	3.0	06/30/23	20%
4.1	Fabricate MMM-based triple-pane IGUs with middle panes made of free-standing or glass-adhered MMM slabs, showing visible transparency <7% lower than a double pane with the same glass panes, thermal insulation R-11 or better. Fabricate and characterize multiple-pane IGUs with more than three panes	4.0	04/30/23	20%
4.2	Design & fabricate MMM-based edge spacer for window frame insulation made from MMM thermal conductivity <12 mW/(K·m), and MMM-IGU with such MMM-spacer showing reduced thermal bridging in MMM-IGUs with MMM-spacers as compared to conventional ones	4.0	09/30/23	10%

Ongoing efforts, future plans & conclusions

→ **Quasi-ambient drying – perfecting procedures**

→ **Scaling thickness & lateral size simultaneously while keeping haze <1%**

→ **Reducing cost of production at scale to ~0.3 USD per square foot**

→ **Meta-Air-based IGUs may enable windows with wall-grade insulation**

→ **Increase the area of glazing within buildings 20X?**

Initial R&D to prove concept → Scaling & performance testing → Licensing, startup → Production/ distribution → Consumers

2022 | 2023-2024 | 2024-2025 | 2025 - 2028

Global area of windows now =

Increase 20X

Thank You

Performing Organization(s): University of Colorado Boulder

PI Name and Title: Professor Ivan I. Smalyukh

PI Tel and/or Email: ivan.smalyukh@Colorado.edu

WBS #, FOA Project # and/or any other Project #: DE-EE0009699

REFERENCE SLIDES

Project Execution

	FY2022				FY2023				FY2024			
Planned budget	340,226				329,329				320,445			
Spent budget	340,226											
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Q1 Milestone 1.1.1	◆											
Q2 Milestone 1.1.2		◆										
Q3 Milestone 2.1.1			◆									
Q4 Milestone 1.2.1				◆								
Q4 Milestone 2.2.1				◆								
Q1 Milestone 1.2.2					◆							
Current/Future Work												
Q2 Milestone 3.1						◆						
Q3 Milestone 3.2							◆					
Q3 Milestone 4.1							◆					
Q4 Milestone 4.2								◆				
Q1 Milestone 5.1.1									◆			
Q2 Milestone 5.2.1										◆		
Q3 Milestone 5.1.2											◆	
Q3 Milestone 5.2.2											◆	
Q4 Milestone 5.2.3												◆
Q4 Milestone 5.3.1												◆
Q4 Milestone 5.4.1												◆

- Go/no-go decision points are milestones in the end of FY 2022 (completed) and FY 2023

Team

- Prime Recipient: University of Colorado
- Agreement Number: DE-EE0009699
- PI: Prof. Ivan Smalyukh

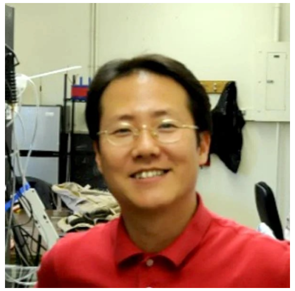
- NETL Technical Project Officer:

Dr. Coriana Hope Fitz & Dr. Marc Lafrance

- Project Team Members:

Dr. Eldho Abraham (100%), Dr. Taewoo Lee (50%), Dr. Vladyslav Cherpak (50%)

100%



50%

50%

- Past Project Team Members:

Dr. Cuiling Meng & Dr. Bohdan Senyuk (moved to new faculty jobs now)