DuraMAT
Durable Module Materials Consortium

Project Updates and Progress at Sandia's Field Test Site

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Acknowledgements

William Snyder, Josh Stein
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David Miller, Soňa Uličná, Laura Schelhas, Rachael Arnold, Jimmy Newkirk, Emily Rago, Archana Sinha, Kent Terwilliger, Michael Thuis
NREL

Peter Pasmans, Chris Thellen
Endurans

Kristopher Davis, Dylan Colvin, John Sherwin
UCF & FSEC

Legacy: Ashley Maes, Naila Al Hasan, Karen Yang

DuraMAT Core Objectives

Central Data Resource

- Heterogeneous data – system performance, materials, etc.
- Accessibility
- Centrality
- Security
- Adaptability

Multi-Scale, Multi-Physics Modeling

- Publicly Accessible
- Experimentally Validated
- Bulk, Interfaces, Interconnects, and stressors modeled

Disruptive Acceleration Science

- Data-Driven
- Predictive
- Validated by outdoor tests
- Materials, modules, and systems

Fielded Module Forensics

- Identify module failure modes affecting field performance
- Multi-scale
- Multi-modal
- Practical
- Validated

Module Material Solutions

- Design, develop, and derisk materials
- Directly address reliability issues
- E.g. ECAs, backsheets, coatings, flex packaging, cell cracking, moisture barriers, etc.

Sandia Field Test Site

ABQ, NM
Climate Zone: Koeppen-Geiger BSk
(cold Steppe)

7 acres
50+ systems
300 kW
1100 modules

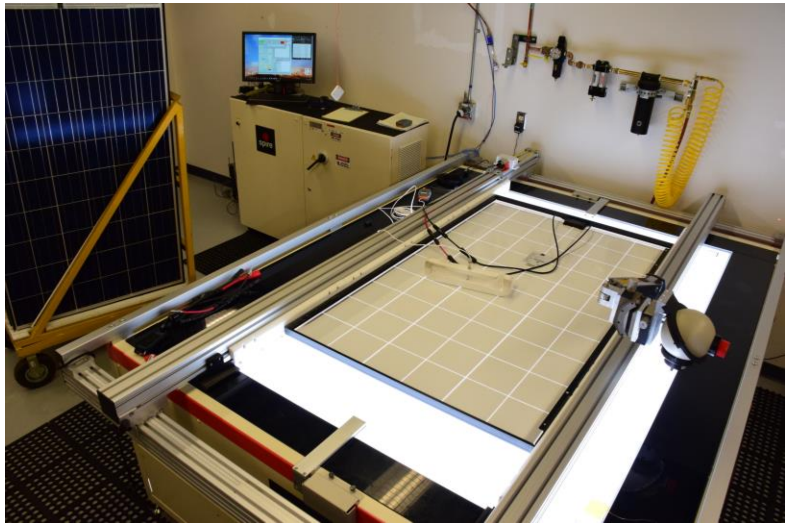
Sandia Field Test Site

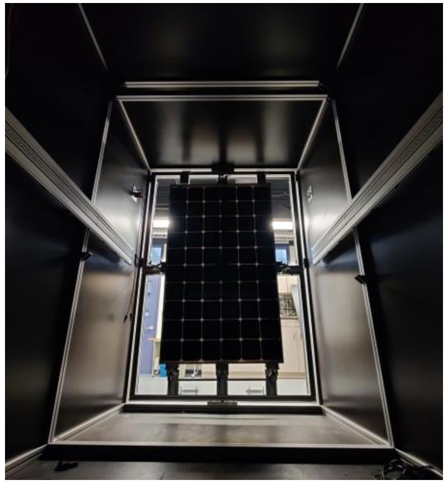
- Weather and solar irradiance summary
- Comprehensive Weather Platform
  - Primary and secondary trackers
    - DNI, GNI, diffuse, spectrum
  - Fixed orientation
    - GHI, Global Latitude, UV, spectrum
  - Non-irradiance
    - Ambient temperature, windspeed/direction (10m), barometric pressure, humidity, rainfall
- In-field Measurements
  - Plane-of-array pyranometer, reference cells
- Data Collection
  - 1s data rate
  - Written to database, GPS synchronized with other field measurements
- Other as needed
  - Rear-side irradiance for bifacial

All on-site calibrations traceable to the World Radiometric Reference via NREL Pyrheliometer Comparison

Module Characterization

- Electrical Performance – Solar Simulator
  - 1 Sun Flash Tester: Spire 4600SLP, Class AAA
  - Temperature Controlled Lab Flasher (TCLF) A+A+A+ Spire
- Co-located visual, electroluminescence (EL), infrared (IR), and UV fluorescence (UVF) imaging





DuraMAT Fielded Projects at Sandia

DuraMAT Module Library

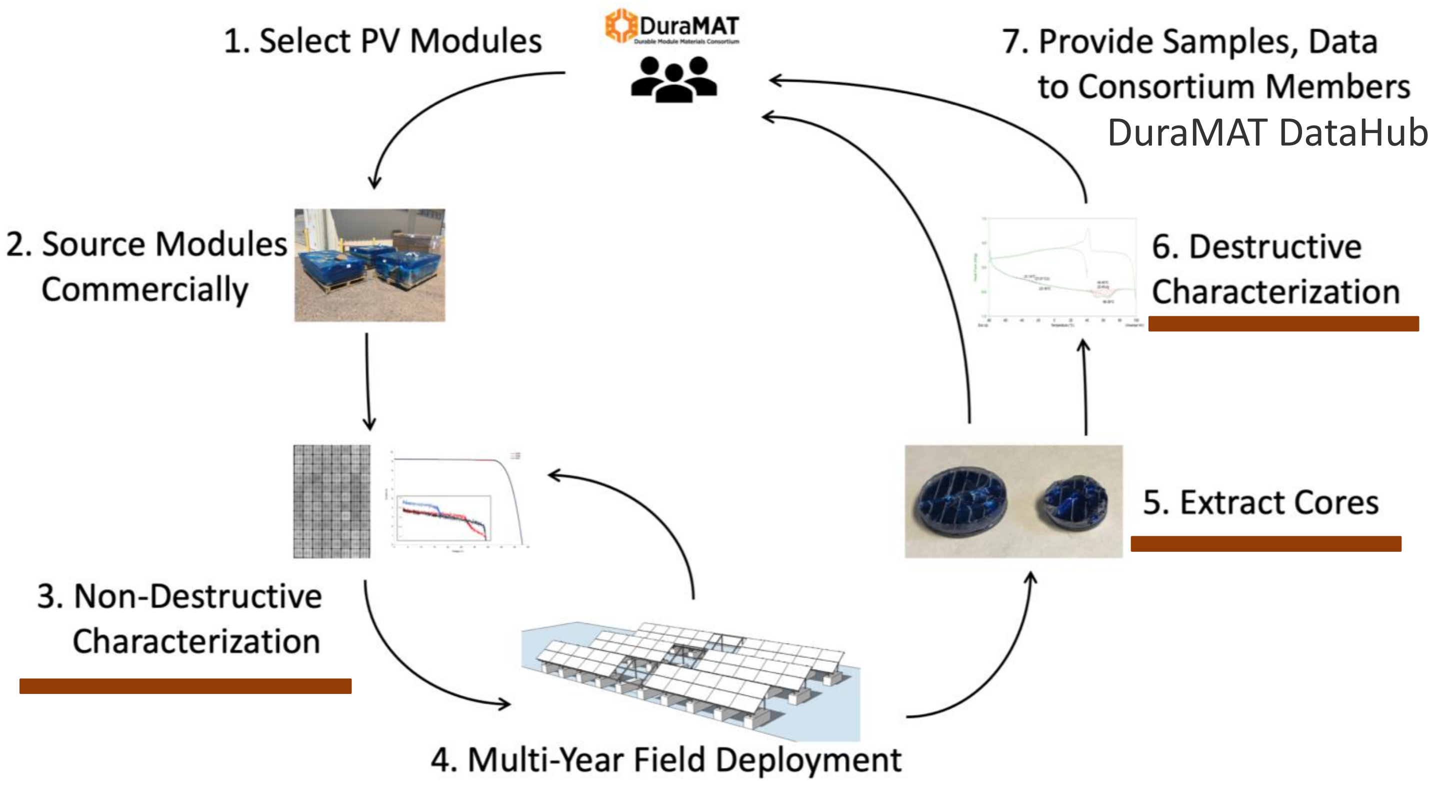
Characterize material degradation from natural aging in commercially available photovoltaic modules.

BACKFLIP

A comparison of market-benchmark and emerging non-fluoropolymer-based, co-extruded photovoltaic backsheets.

DuraMAT Module Library

Characterize material degradation from natural aging in commercially available photovoltaic modules.

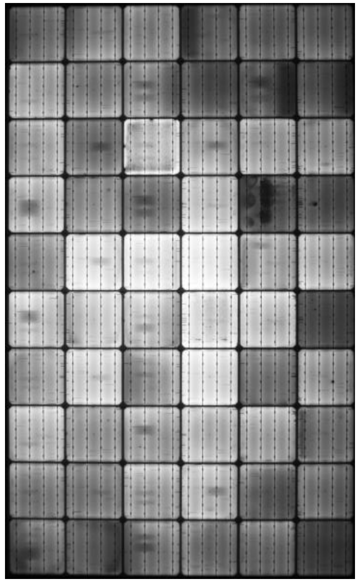


Manufacturer	Model	Cells	Cell Type	Inverter
Jinko	JKM270PP-60	60	Multi-Si	IQ7+
Canadian Solar	CS6K-300MS Quintech	60	Mono PERC	IQ7+
Hanwa Q Cells	Q.Peak-G4.1 300	60	Mono-Si	IQ7+
LG	LG320N1K-A5	60	Mono N-type	IQ7+
Panasonic	VBHN330SA17 HIT	96	HIT N-type	IQ7X
Mission Solar	MSE300SQ5T	60	Mono PERC	IQ7+
Itek*	350 SE	72	Mono P-type	PVI

** Installed one year delayed*

Non-Destructive Characterization

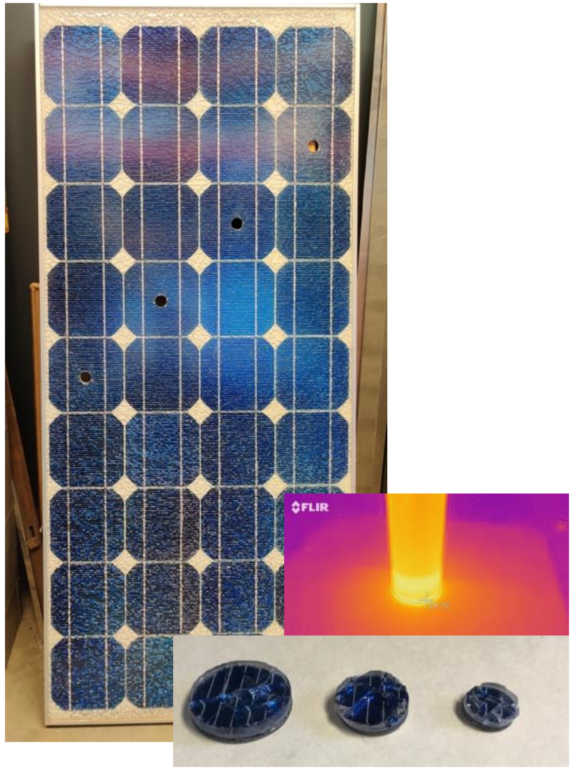
Module



Backsheet

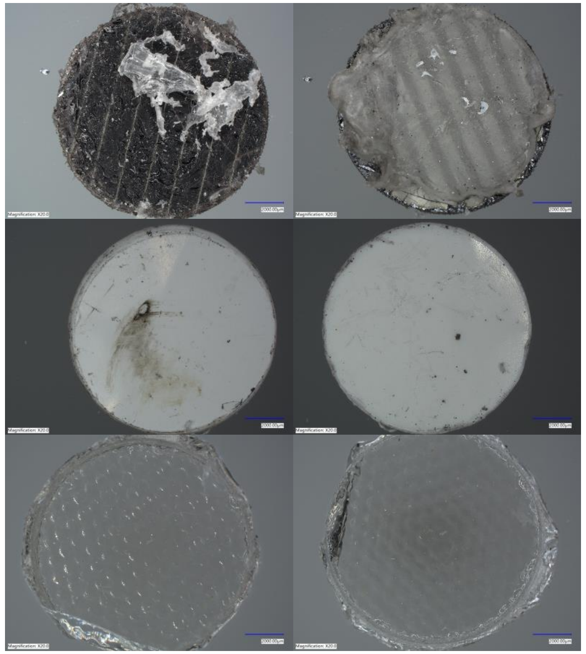
- Indoor light IV (flash testing)
  - YoY STC parameters
- Electroluminescence
- Visual
- FTIR
- Gloss
- Reflection Spectroscopy

Coring



- Modified CNC table
- Tight process control to avoid heating and sample damage
- 0.5 – 1” diameter samples

Destructive Characterization



- Optical imaging
- Raman Spectroscopy
- FTIR
- Differential Scanning Calorimetry (DSC)
- SAXS/WAXS (SLAC)

Electrical Performance

Non-Destructive: Module

Manufacturer	Rating, W	Initial	Year 1		Year 2		Year 3	
			Power, W	Rd, %/yr	Power, W	Rd, %/yr	Power, W	Rd, %/yr
Canadian Solar	300	300 ± 2	295 ± 1	-1.6	293 ± 1	-1.1	284 ± 2	-1.5
Hanwa Q Cells	300	302 ± 1	295 ± 1	-2.2	293 ± 1	-1.5	292 ± 1	-0.9
Itek	360	358 ± 1	351 ± 1	-2.2	339 ± 8	-2.2	-	-
Jinko	270	273 ± 1	268 ± 1	-1.8	264 ± 1	-1.6	260 ± 1	-1.4
LG	320	319 ± 1	316 ± 1	-0.9	314 ± 1	-0.8	311 ± 6	-0.7
Mission Solar	300	292 ± 1	289 ± 1	-1.0	286 ± 1	-1.0	282 ± 2	-1.0
Panasonic	330	330 ± 0	330 ± 1	0.0	328 ± 1	-0.3	324 ± 3	-0.5

- All fielded modules are brought inside annually for recharacterization
- Most modules display a 1-2%/year power degradation during the first year that stabilizes to ~ 1%/year in subsequent years
- Trends are consistent with expectations from larger arrays of the same modules on-site at Sandia

Electroluminescence

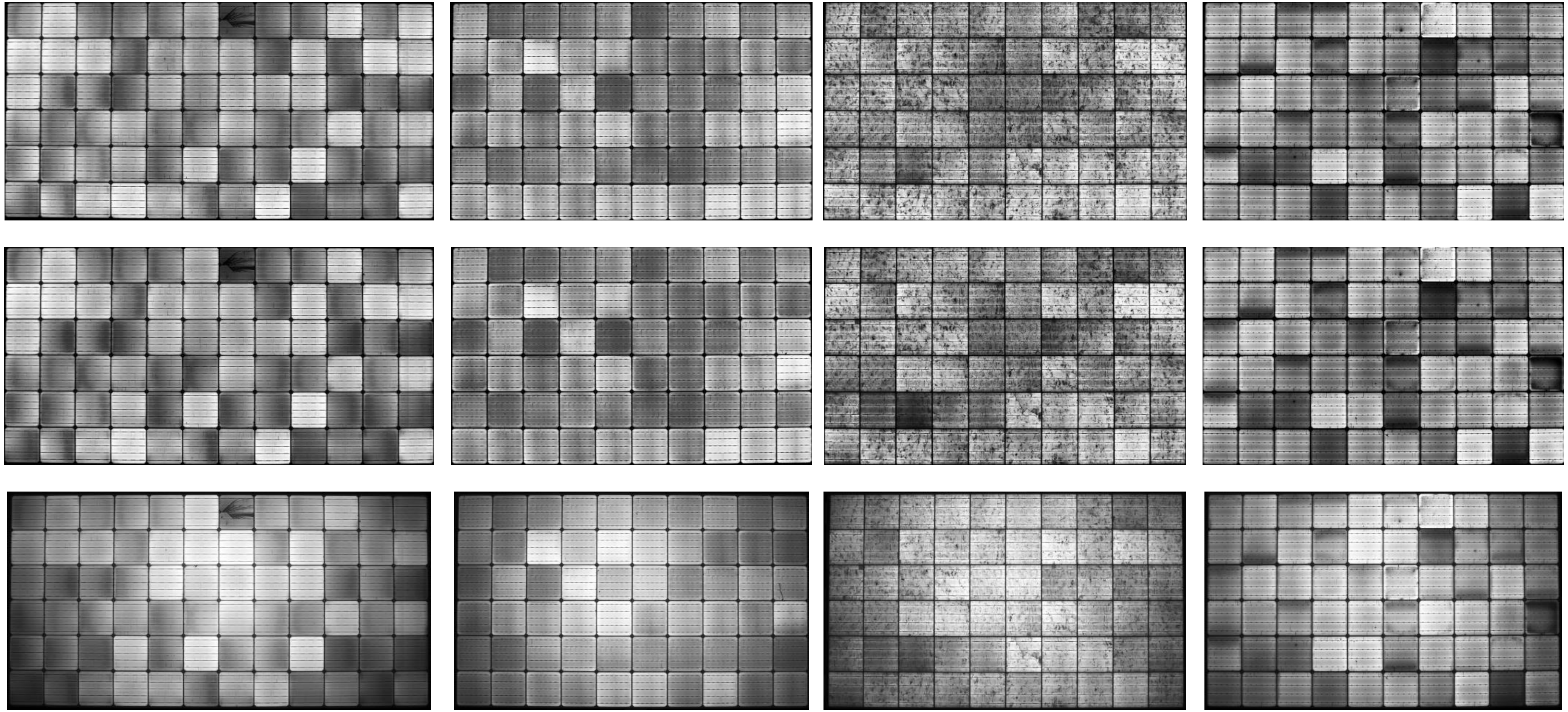
Non-Destructive: Module

Itek 4525 | Canadian 4156 | Jinko 4177 | Q-Cells 4141

2020

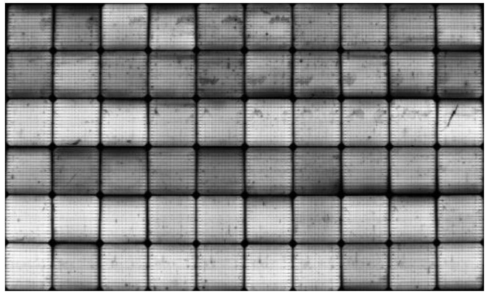
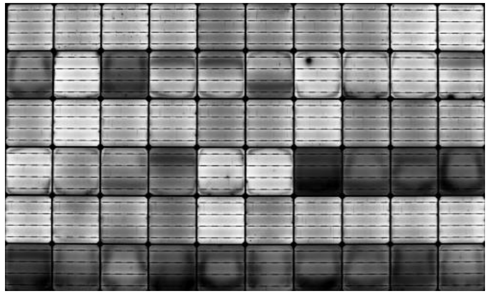
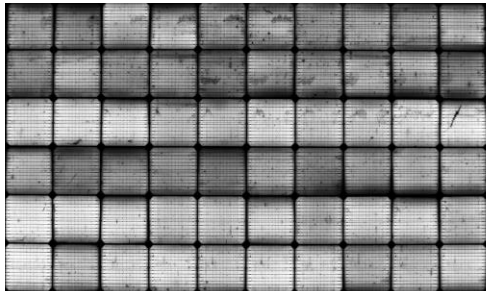
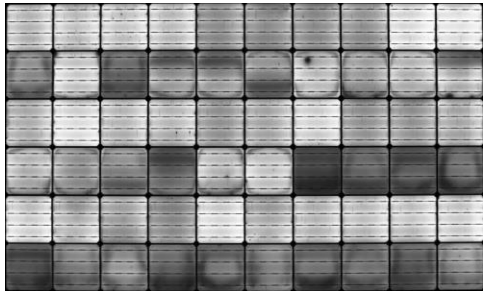
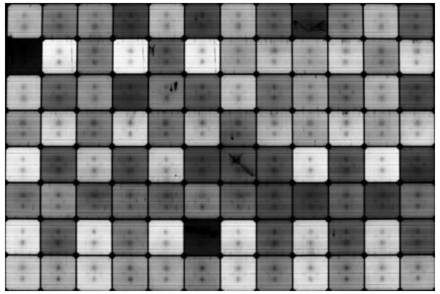
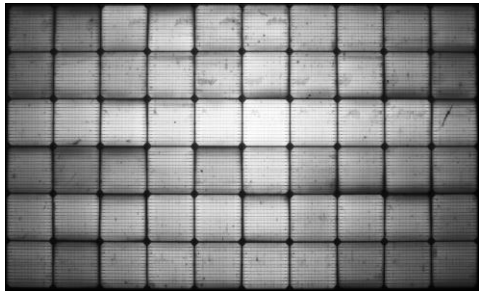
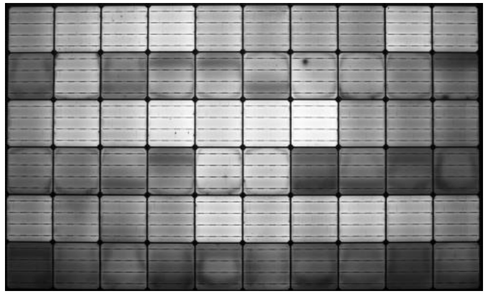
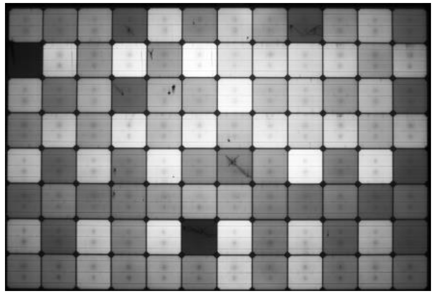
2021

2022



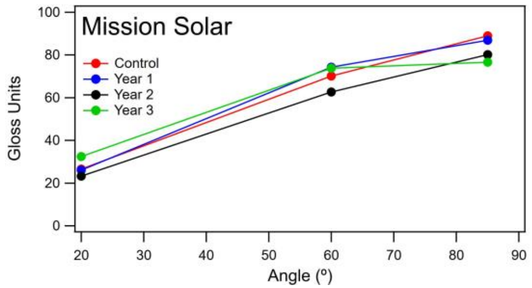
Electroluminescence

Non-Destructive: Module

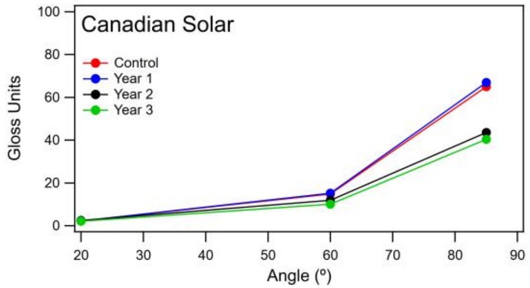
	LG 4166	Mission 4272	Panasonic 4189
2020			
2021			
2022			

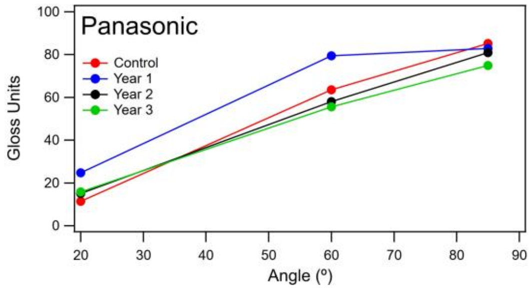
FTIR & Gloss

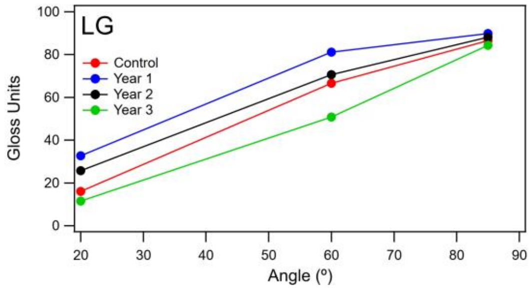
Non-Destructive: Backsheet

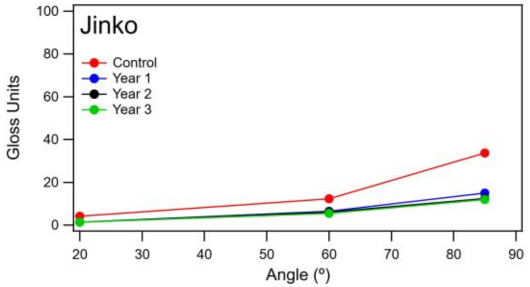


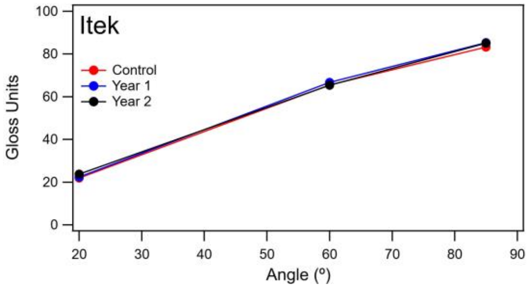
Agilent 4300 Handheld FTIR

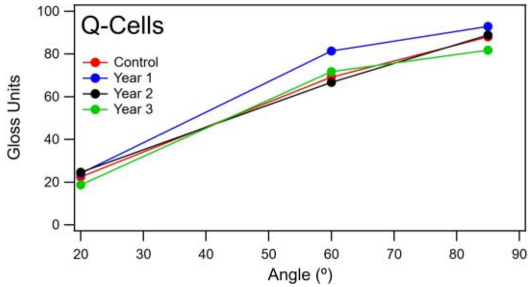












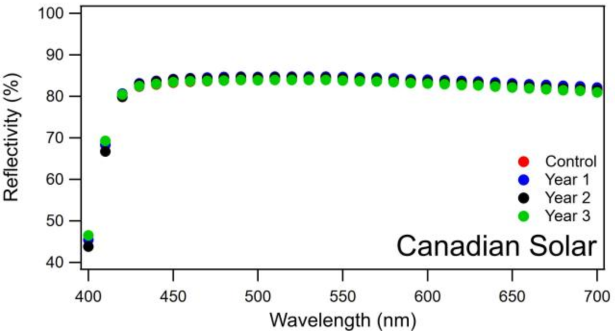
Pearson correlation was used to identify backsheets using known references

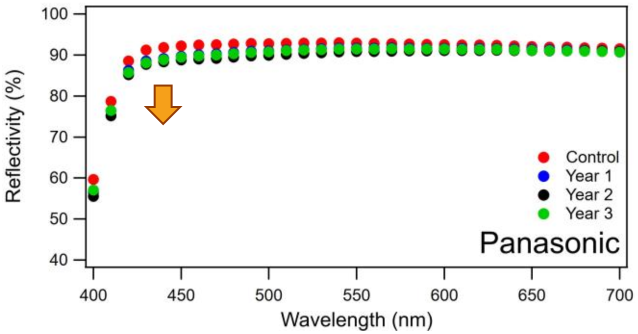
- Canadian (PVDF) and Jinko (TPT) display low gloss characteristics and reduction with aging
- PET modules show medium to high gloss
  - Minimal change with time

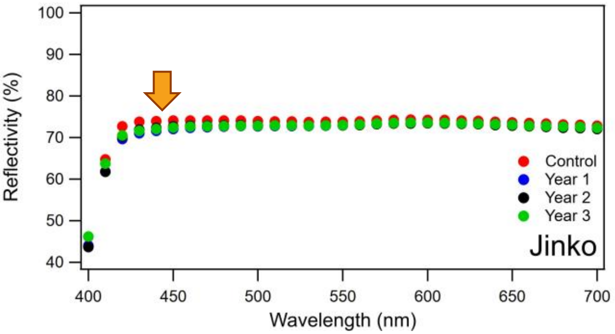
Gloss Range	Measurement	60°
High Gloss	20°	<10 GU
Semi Gloss	60°	
Low Gloss	85°	>70 GU

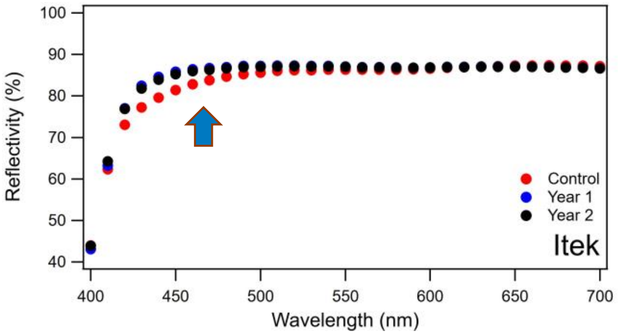
Reflectance and b*

Non-Destructive: Backsheet

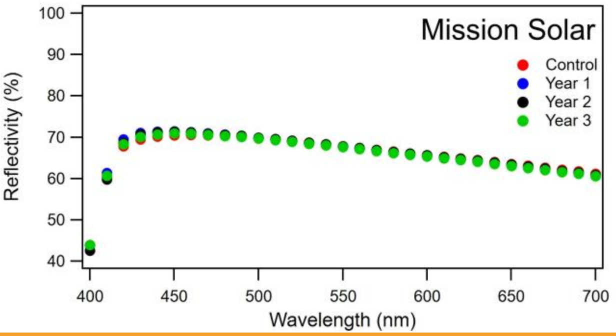


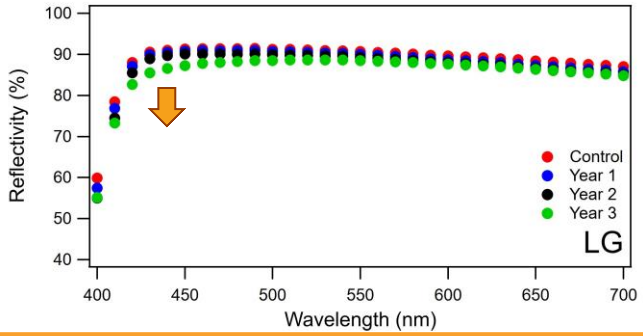


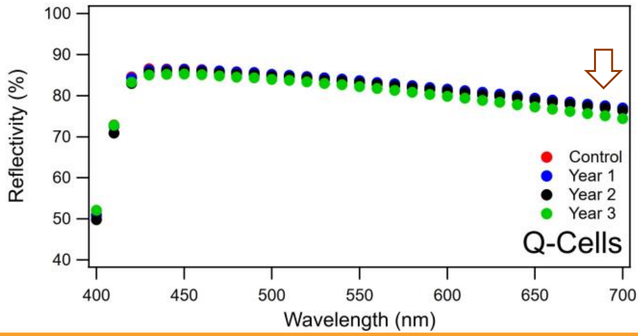




	b*			
	Control	Year 1	Year 2	Year 3
Canadian Solar	0.98	0.9	0.86	0.76
Jinko	0.38	1.31	0.89	1.03
Mission	-1.69	-2.53	-2.2	-2.18
Panasonic	0.95	1.76	1.88	1.82
Itek	4.3	2.11	2.36	
LG	0.04	-0.04	0.09	1.28
Q Cells	-1.66	-1.49	-1.43	-1.8

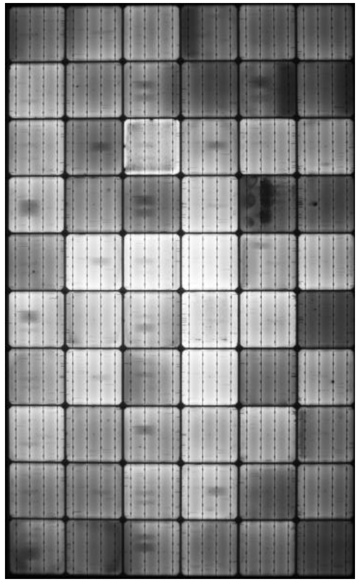






Non-Destructive Characterization

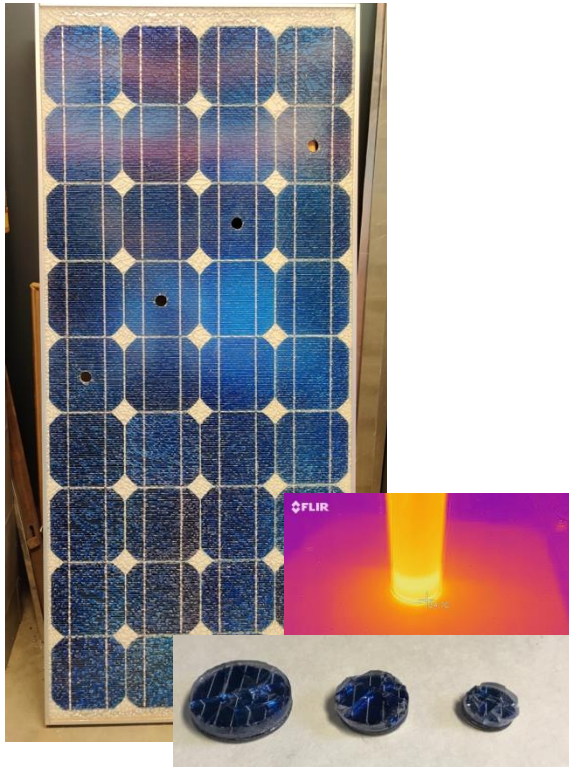
Module



Backsheet

- Indoor light IV (flash testing)
    - YoY STC parameters
- Electroluminescence
- Visual
- FTIR
- Gloss
- Reflection Spectroscopy

Coring



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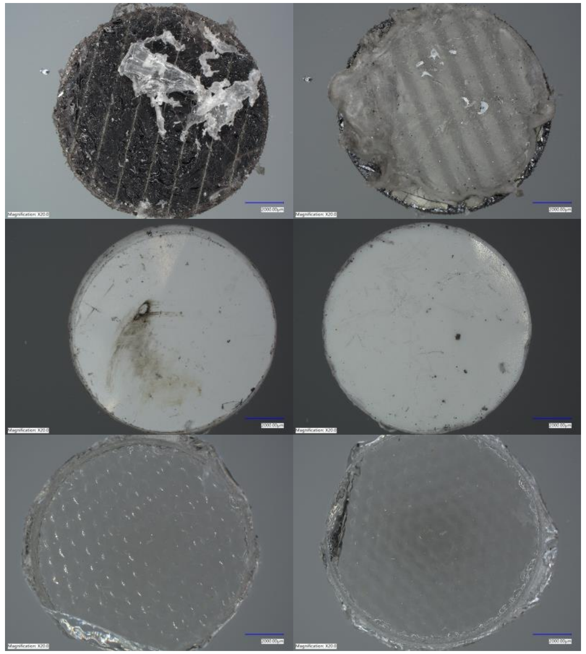
Destructive Characterization

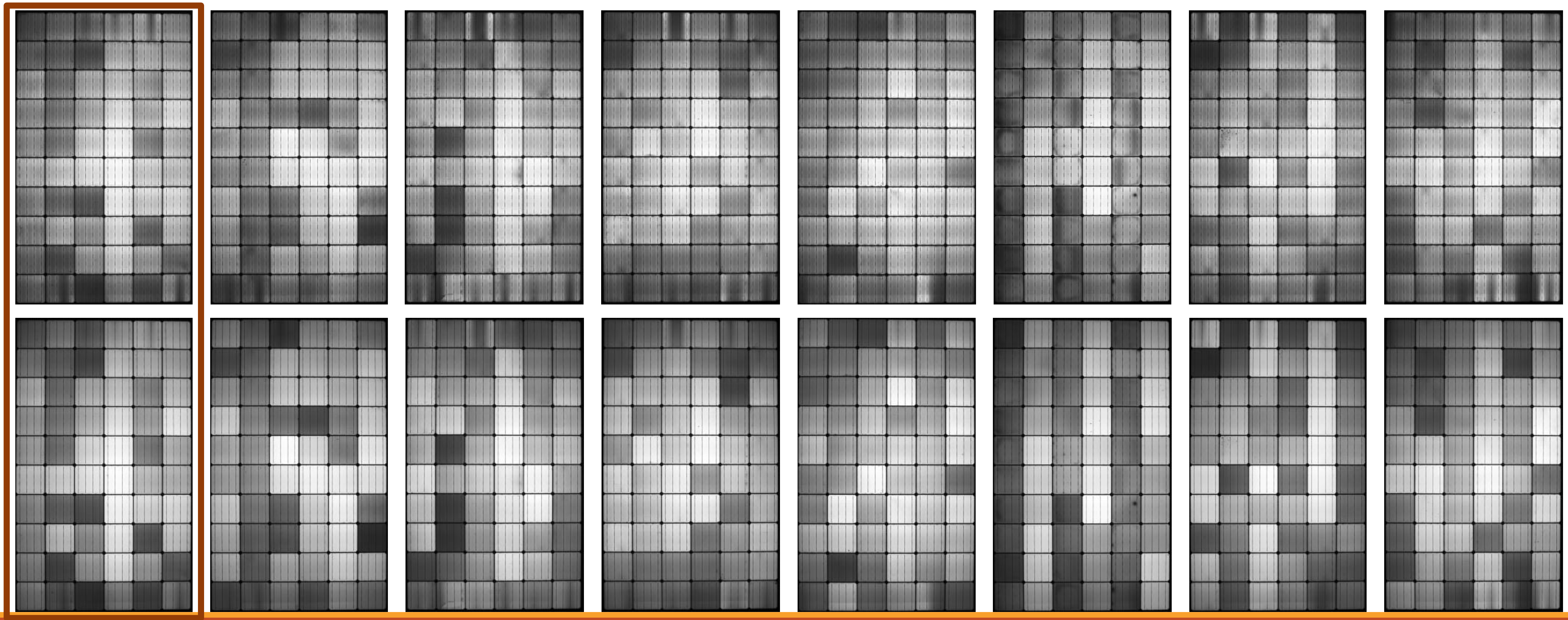


- Optical imaging
- Raman Spectroscopy
- FTIR
- Differential Scanning Calorimetry
- SAXS/WAXS (SLAC)

Coring Downselection

Mission Year 3

PVID	4250	4251	4252	4253	4268	4272	4274	4276
V_{oc} (V)	39.43	39.43	39.35	39.35	39.40	39.08	39.52	39.49
I_{sc} (A)	9.306	9.279	9.247	9.302	9.248	9.285	9.300	9.294



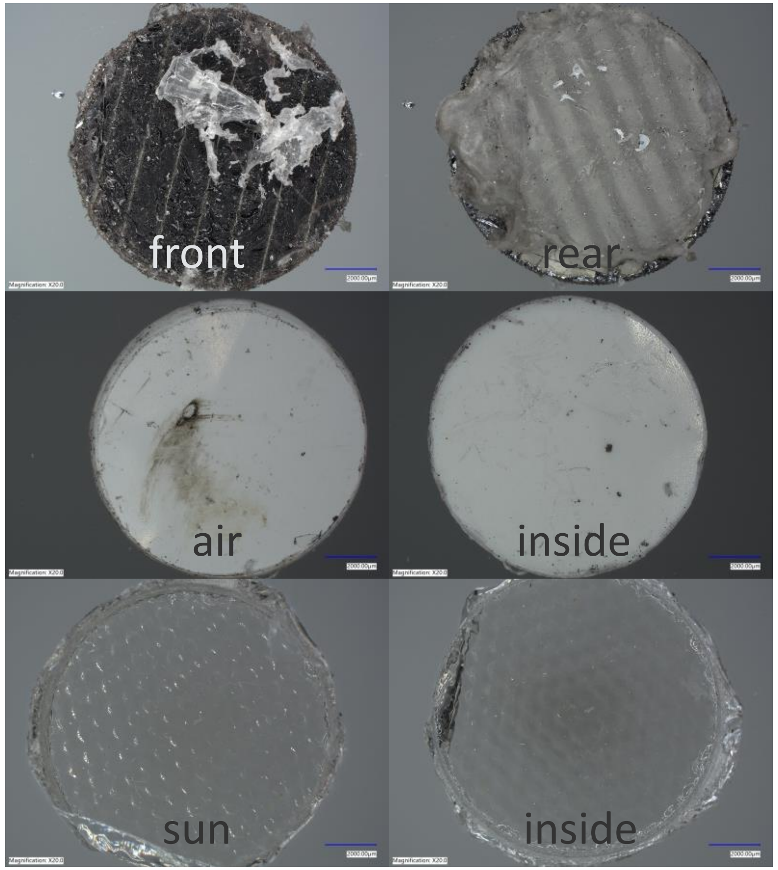
High Current

Low Current

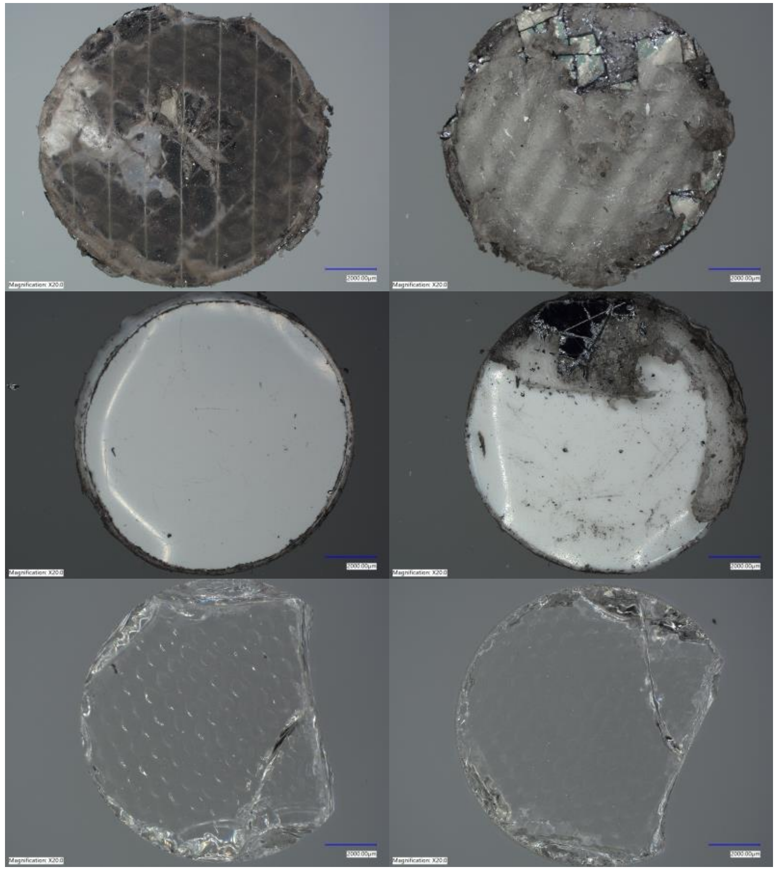
Core Dissection Example

Q-Cells

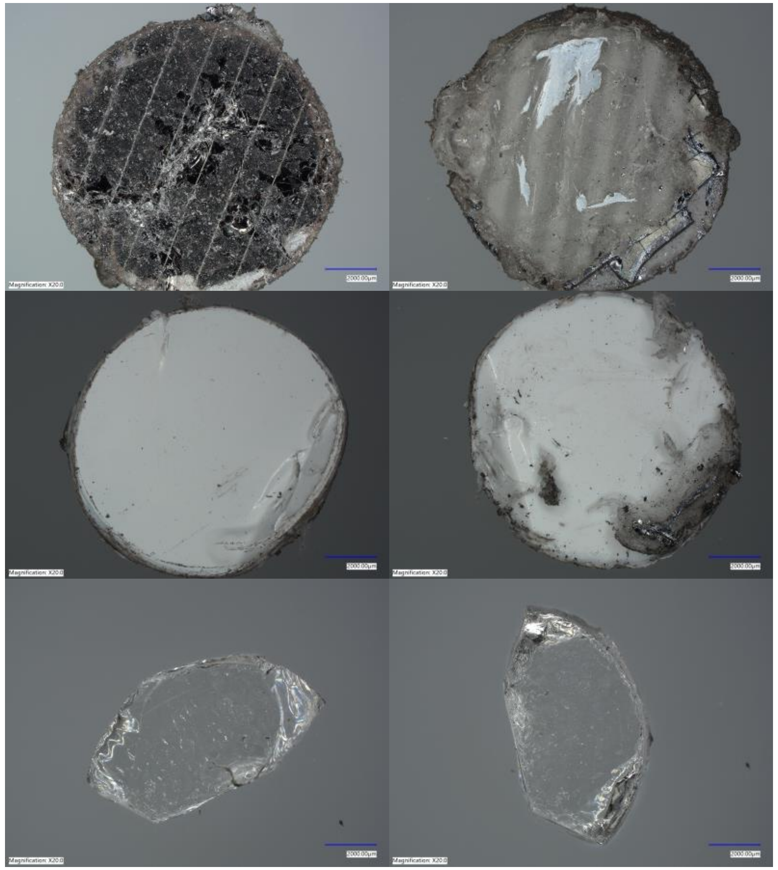
Control



Year 1



Year 2

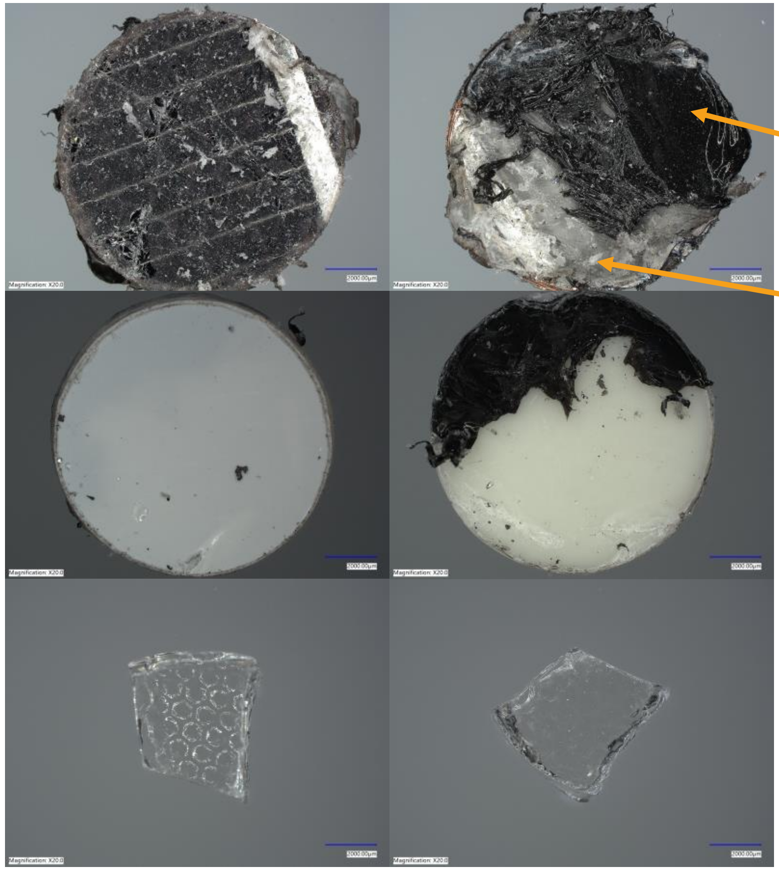


**similar: Jinko, Canadian, Itek*

Core Dissection

Some notable features

Mission - Control

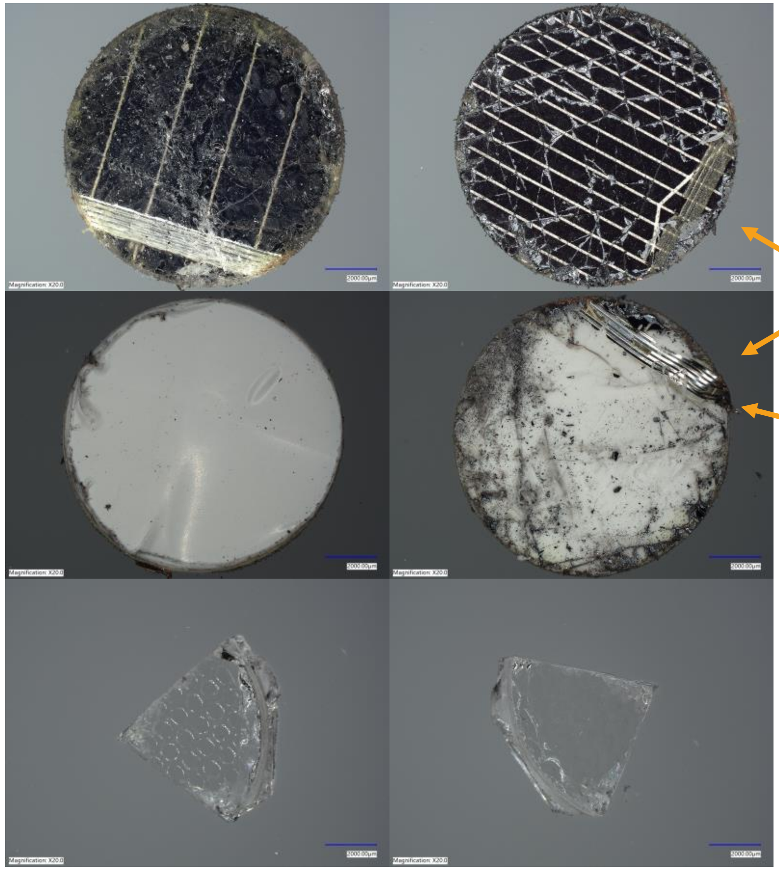


Black encapsulant

Clear encapsulant

*similar: LG

Panasonic - Year 2

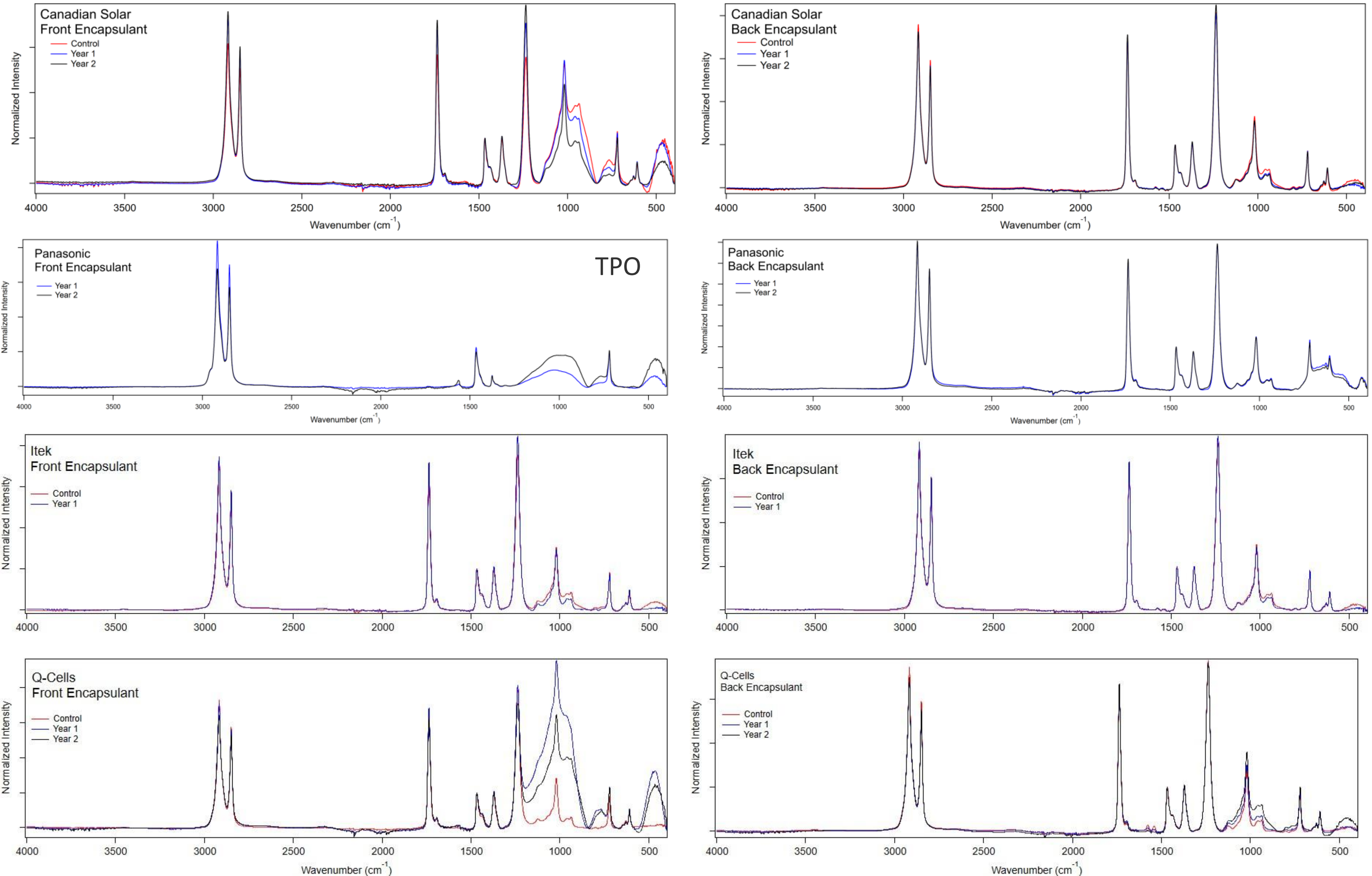


Extremely thin back encapsulant

Ribbon pressed deep into backsheet

FTIR

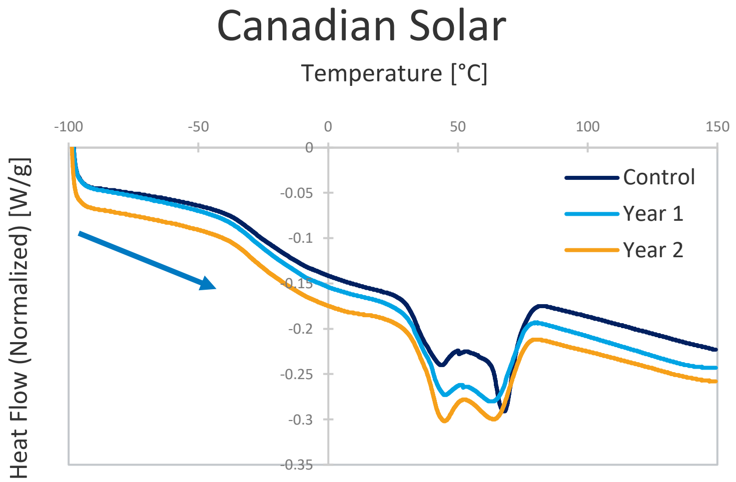
Front Encapsulant and Rear Encapsulants

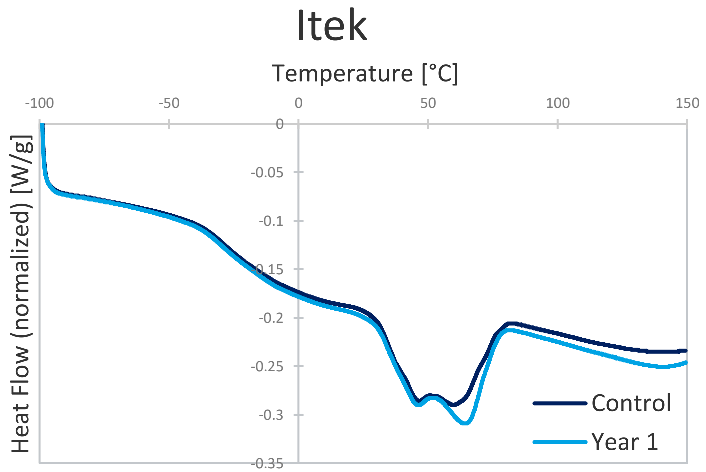


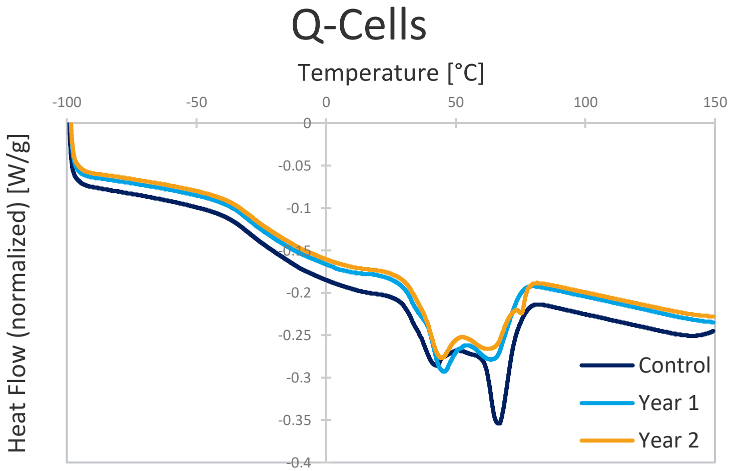
- Most modules feature EVA front and rear encapsulants
- Panasonic used TPO front and EVA rear
- Rear encapsulants were generally stable
- Front EVA from some modules showed broader, more intense peaks in the range of 1090 – 800 cm^{-1} that varied with year of sampling
  - Indication of silane adhesion promoters, EVA oxidation and/or glass contamination

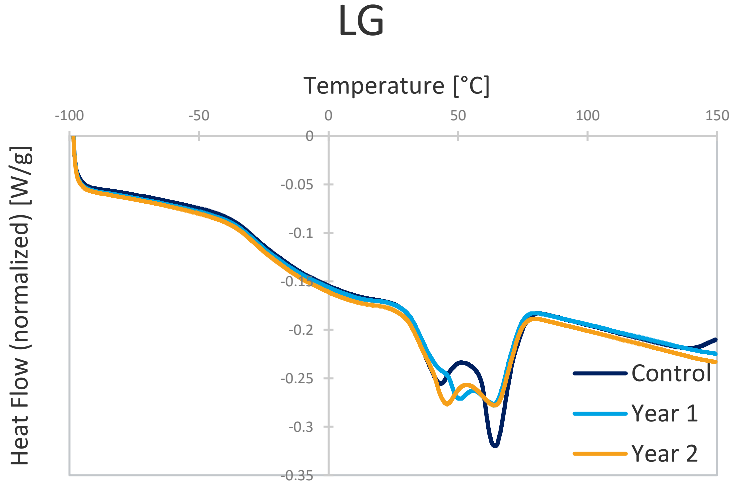
DSC First Heating

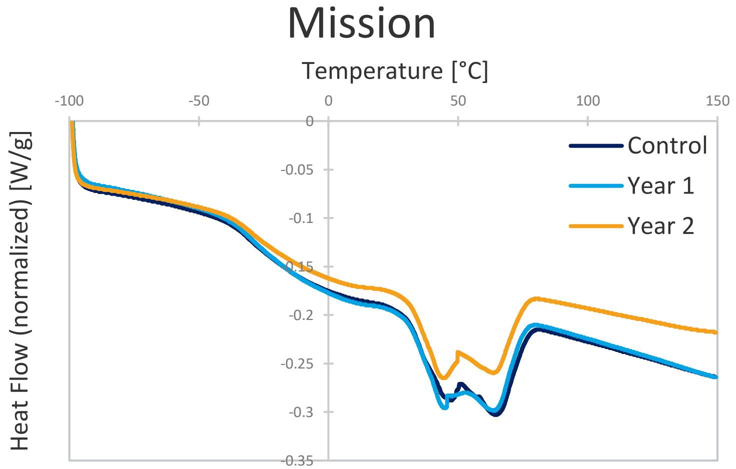
Front Encapsulant







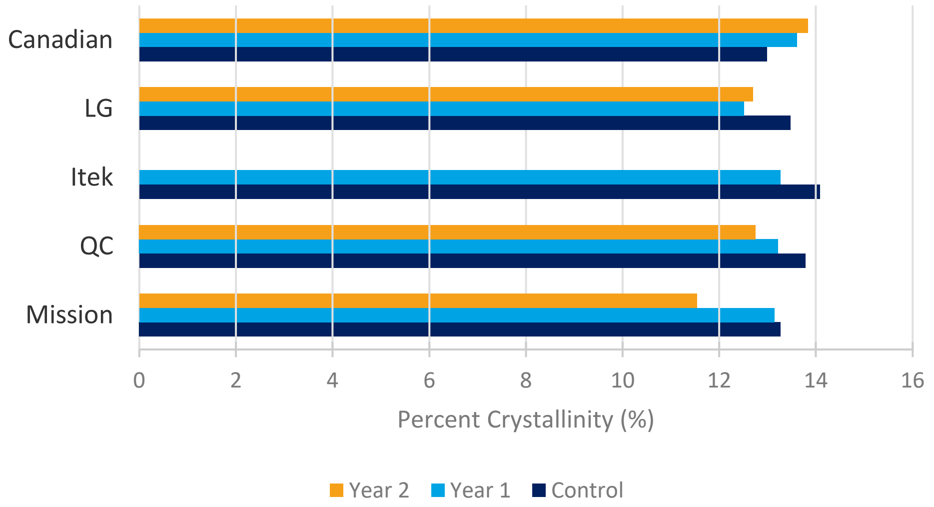


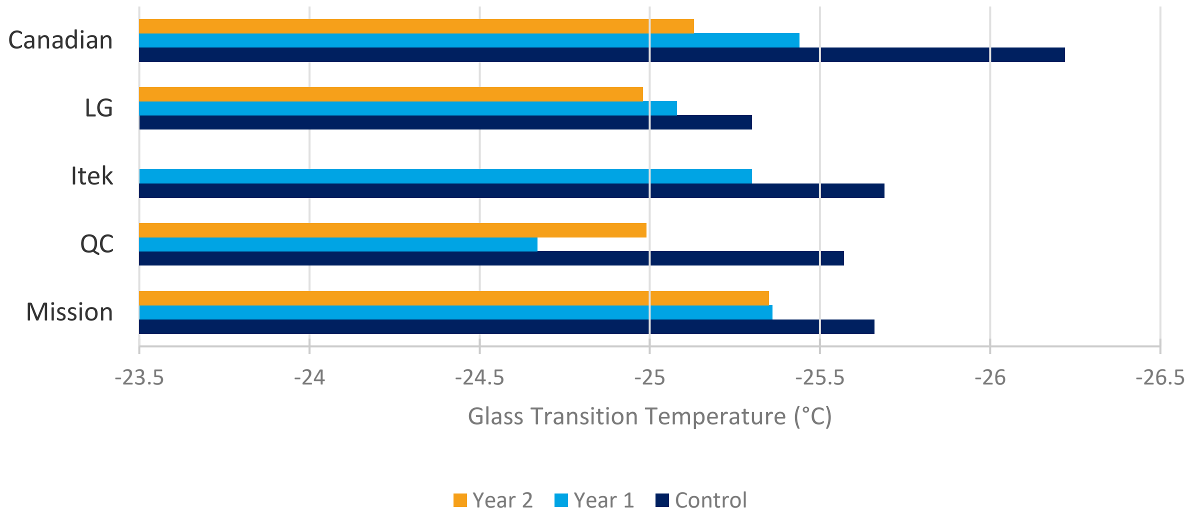


DSC First Heating

Front Encapsulant

$$X_c(\%) = \frac{\Delta H_{MP}}{\Delta H_{100}} \cdot 100\%$$

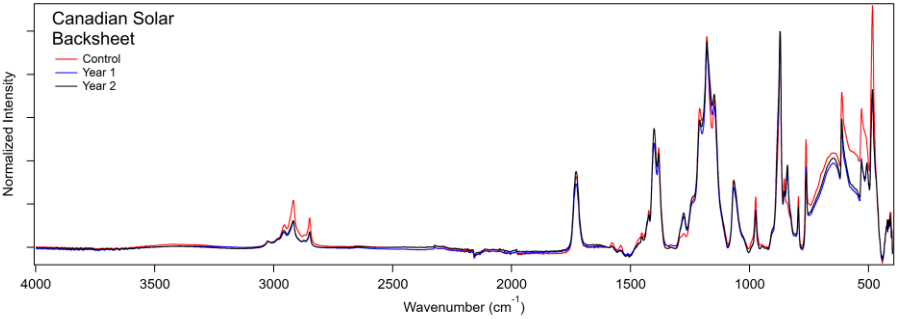


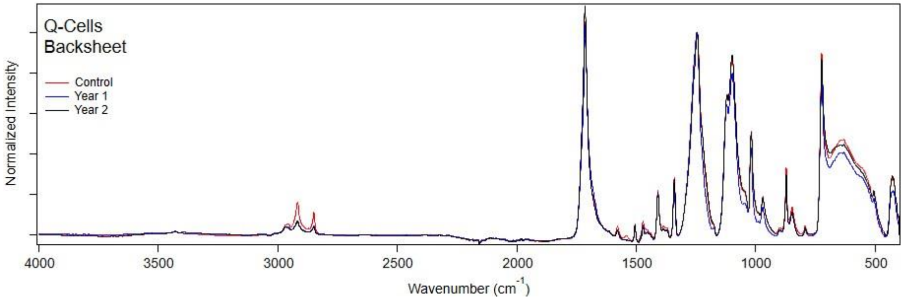


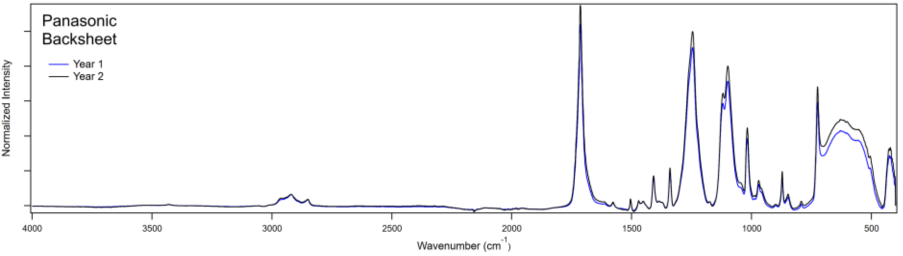
- Percent crystallinity decreased a small amount YoY (except Canadian)
- Glass transition temperature (T_g) decreased a small amount YoY

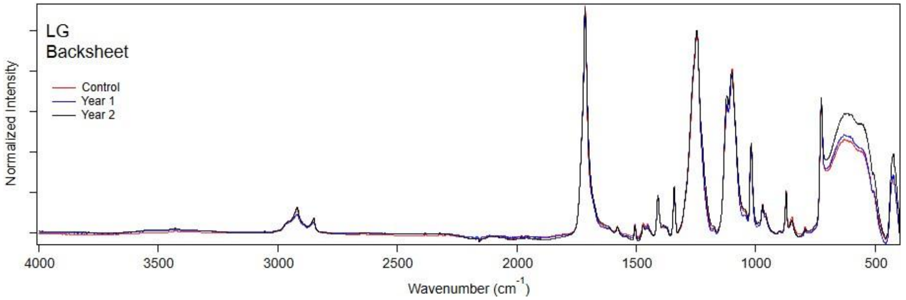
FTIR

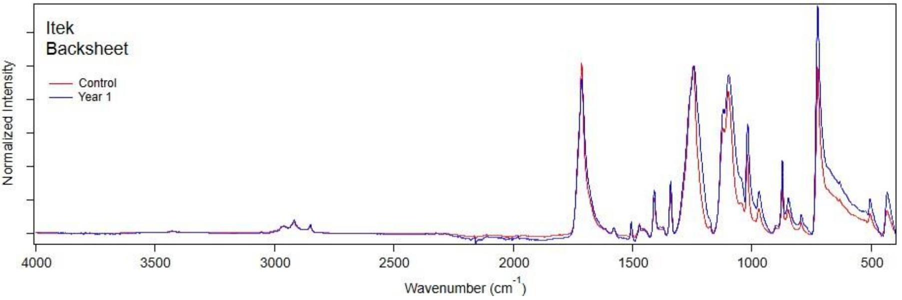
Backsheets

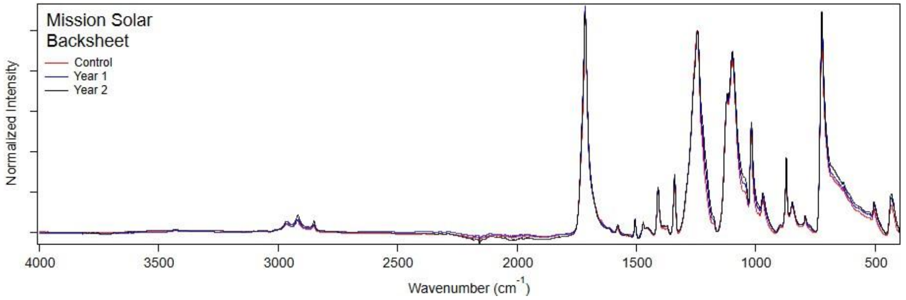












Manufacturer	Backsheet
Canadian Solar	PVDF
Q Cells	PET
Mission Solar	PET
Panasonic	PET
LG	PET
Jinko	TPT
Itek	PET

Little to no change over time

Status and Final Steps

- Year 3 cores were extracted last week
  - Remaining characterization to be completed
- Sharing on the DuraMAT DataHub
- Remaining fielded modules transitioned to maintenance mode
- Developing fielded characterization tools to monitor materials aging (handheld Raman, N-IR, FTIR, ARC imaging, etc.)
- Documentation and reporting

DuraMAT Fielded Projects at Sandia

DuraMAT Module Library

Characterize material degradation from natural aging in commercially available photovoltaic modules.

BACKFLIP

A comparison of market-benchmark and emerging non-fluoropolymer-based, co-extruded photovoltaic backsheets.

BACKFLIP

Market and novel backsheets selected.
Coupons and MiMo's prepared.

Accelerated Aging
-hydrolytic
-photolytic

Field Aging
-New Mexico: hot/dry
-Florida: hot/humid

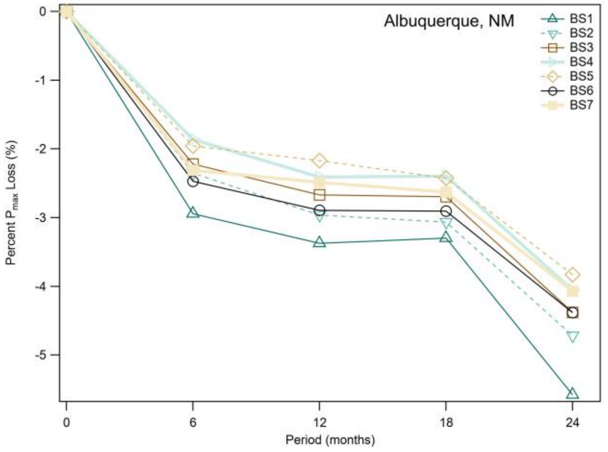
Materials characterization and analysis.

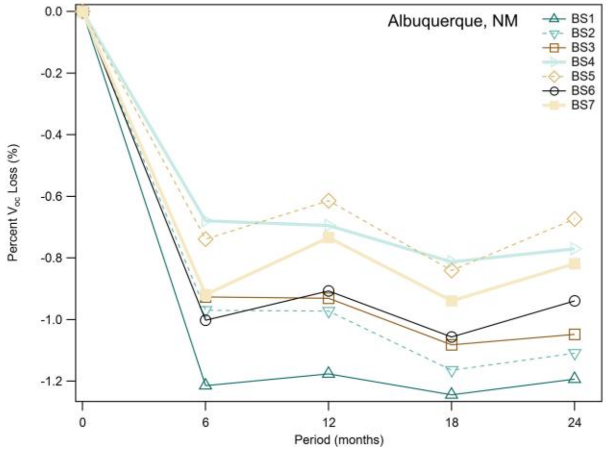
Arbitrary Index	Backsheet	Construction
BS1	PO-1	Co-extruded
BS2	PO-2	Co-extruded
BS3	TPT	Laminate
BS4	APO	Co-extruded
BS5	PPE	Laminate
BS6	AAA	Co-extruded
BS7	KPf	Laminate

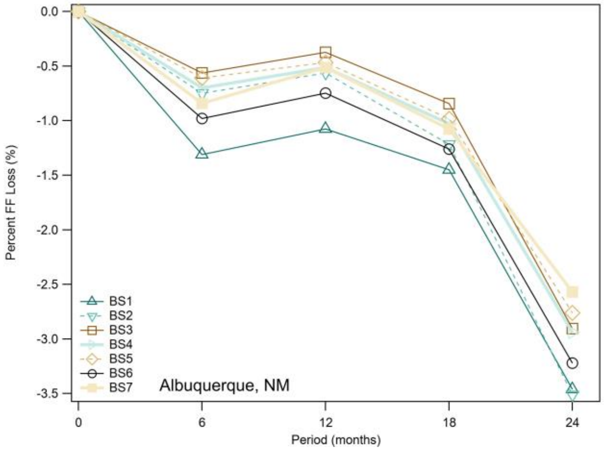
PO-based: BS1, BS2, BS4
PA-based: BS6
PET-based: BS3, BS5, BS7

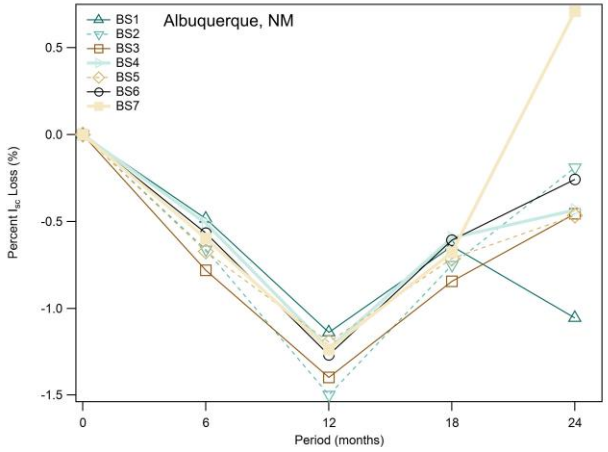
Electrical Performance

Albuquerque, NM





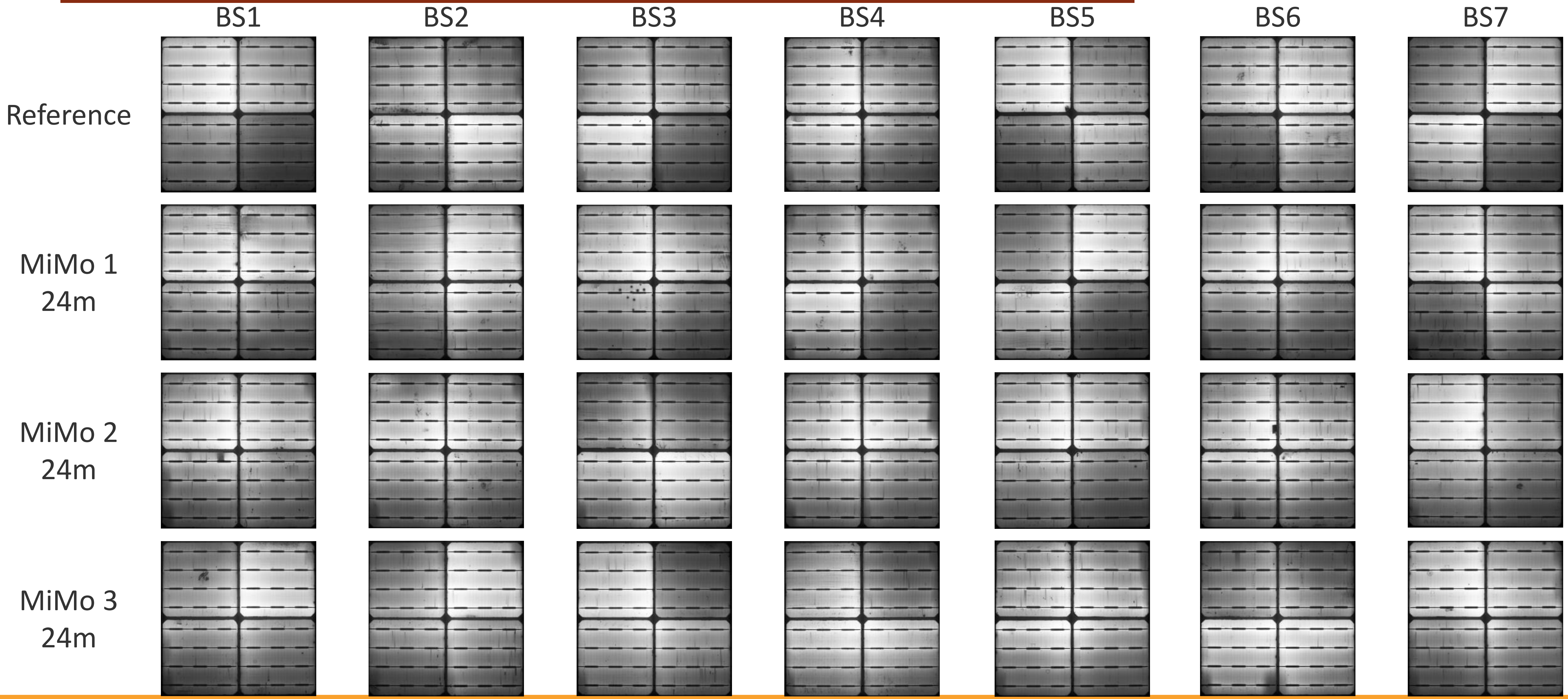




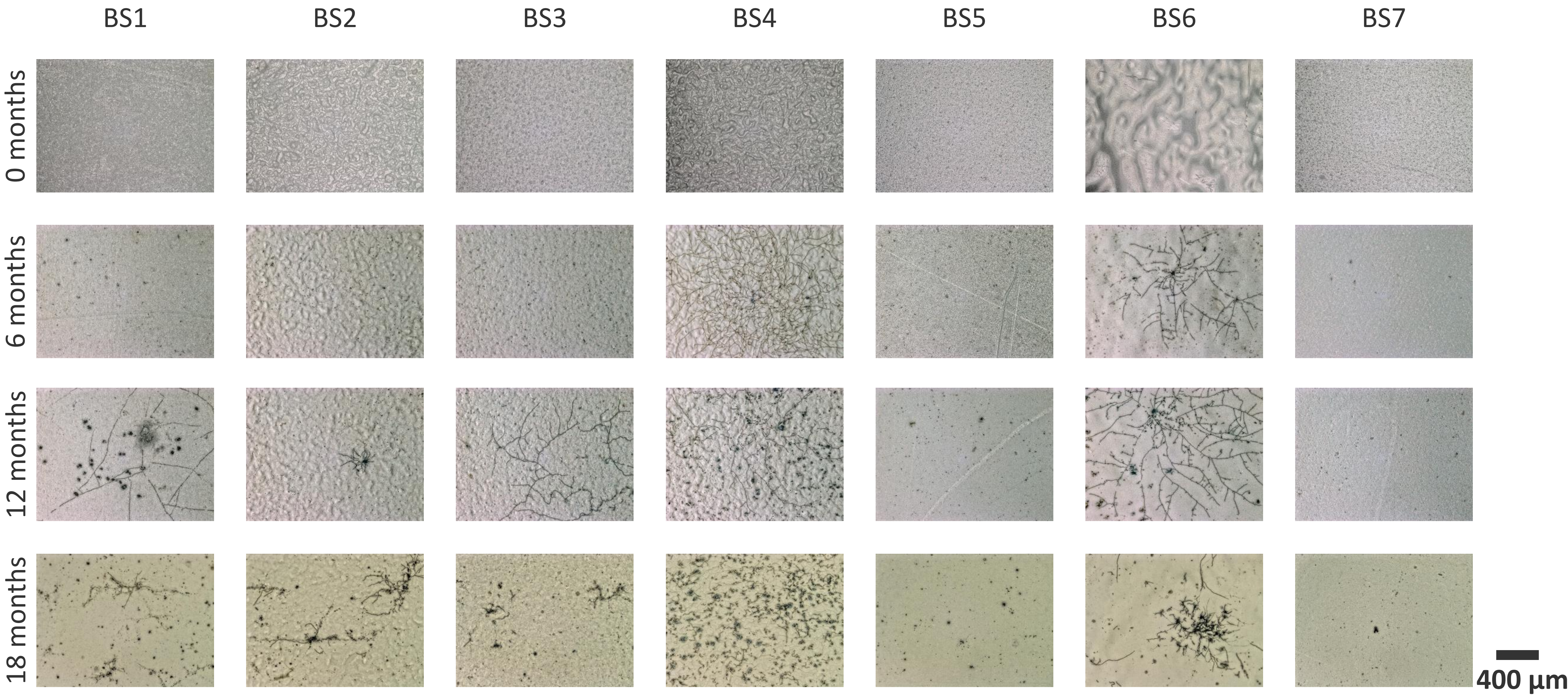
- Similar and moderate performance degradation for all backsheets fielded in ABQ, NM
- Ongoing analysis of FL modules
- Final comparison to accelerated

Electroluminescence

Albuquerque, NM

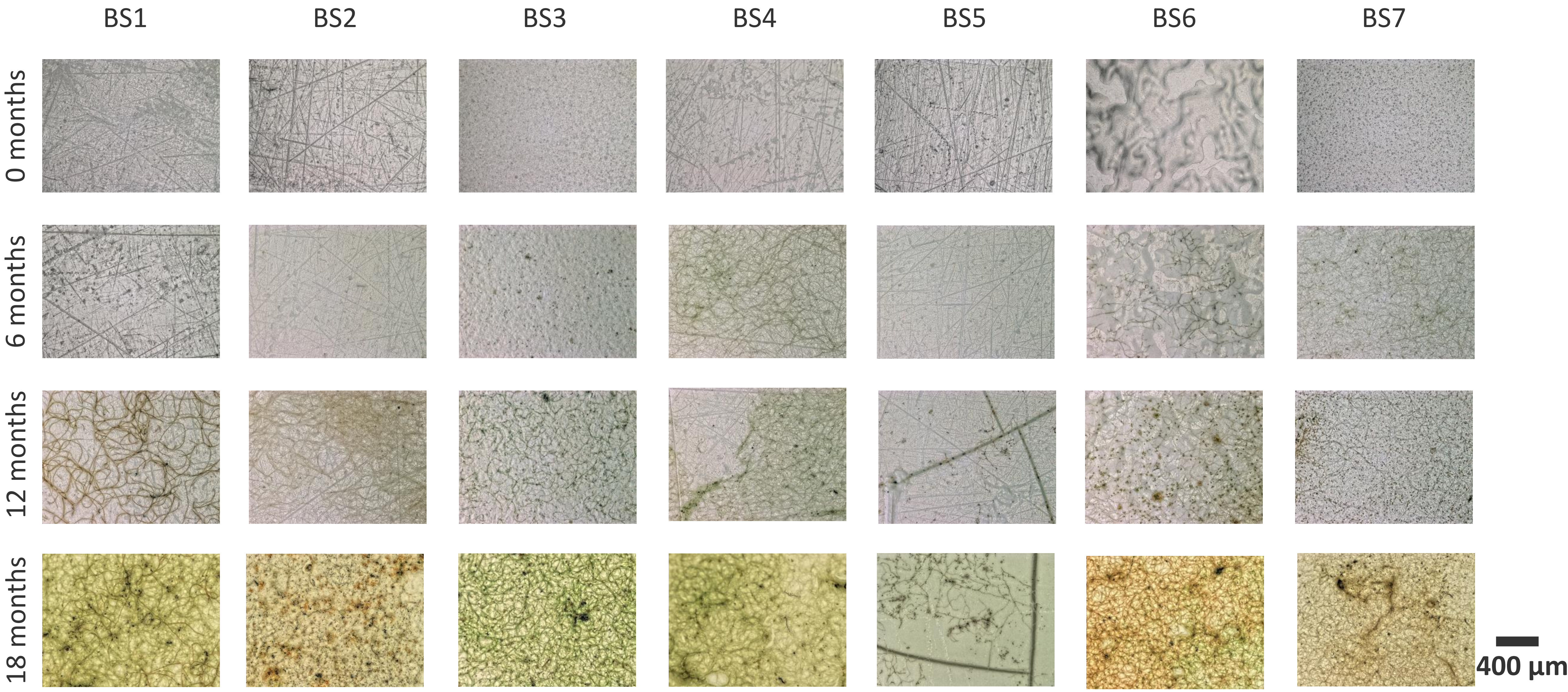


Keyence - air side
Cocoa, FL

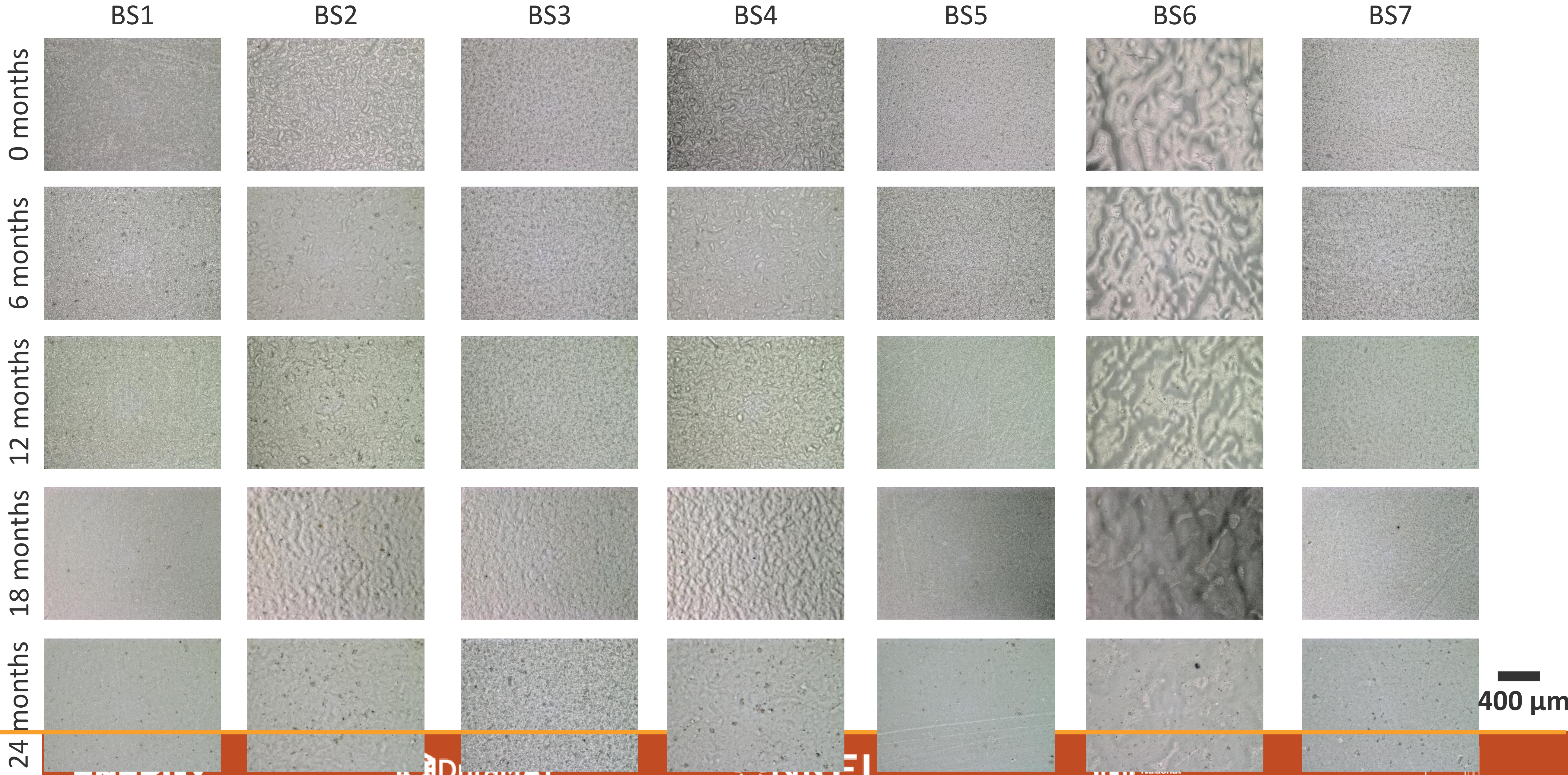


U.S. DEPARTMENT OF ENERGY
DuraMAT
NREL
Sandia National Laboratories
BERKELEY LAB

Keyence - sun side
Cocoa, FL



Keyence - air side
ABQ, NM



Keyence - sun side
ABQ, NM

BS1 BS2 BS3 BS4 BS5 BS6 BS7

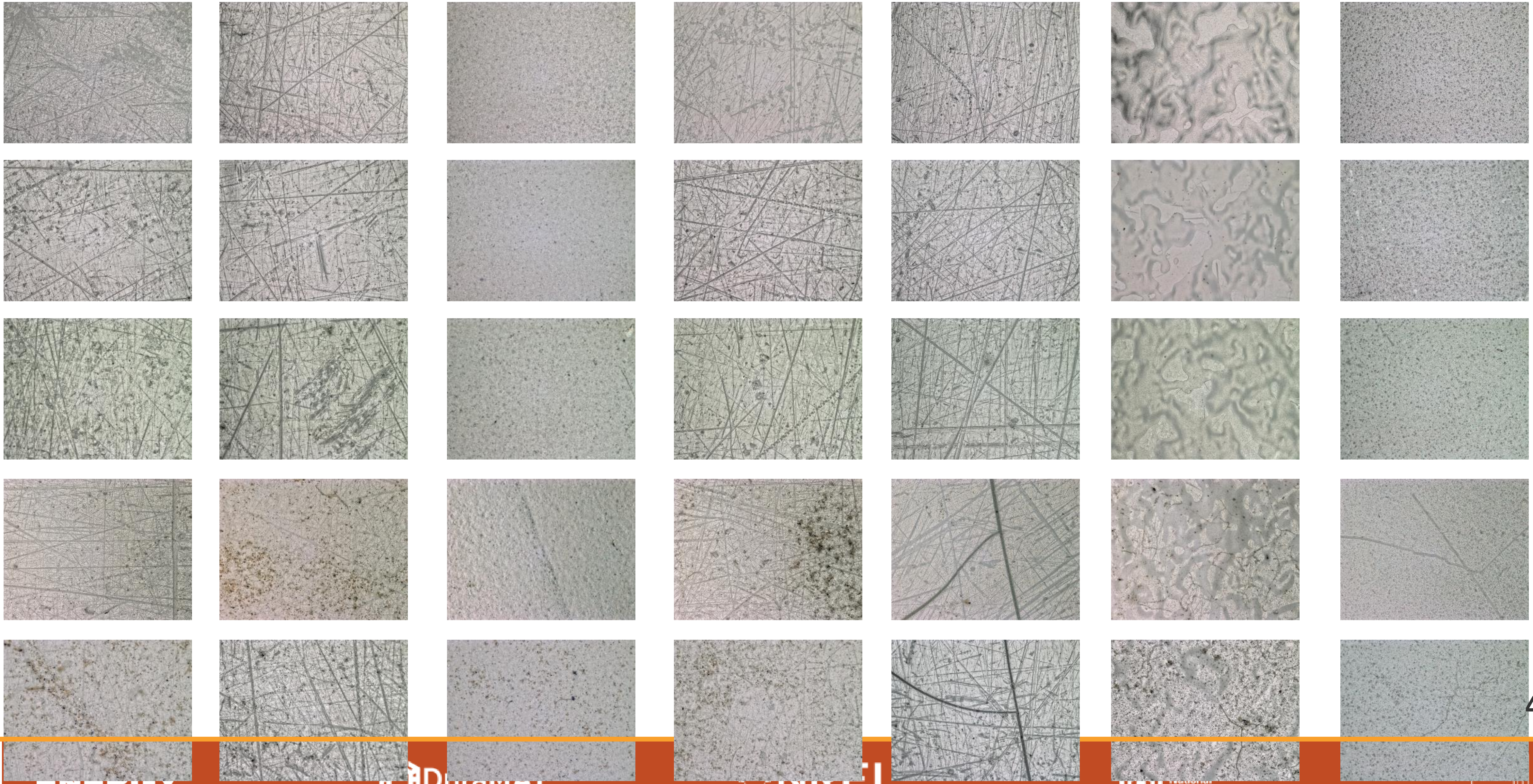
0 months

6 months

12 months

18 months

24 months



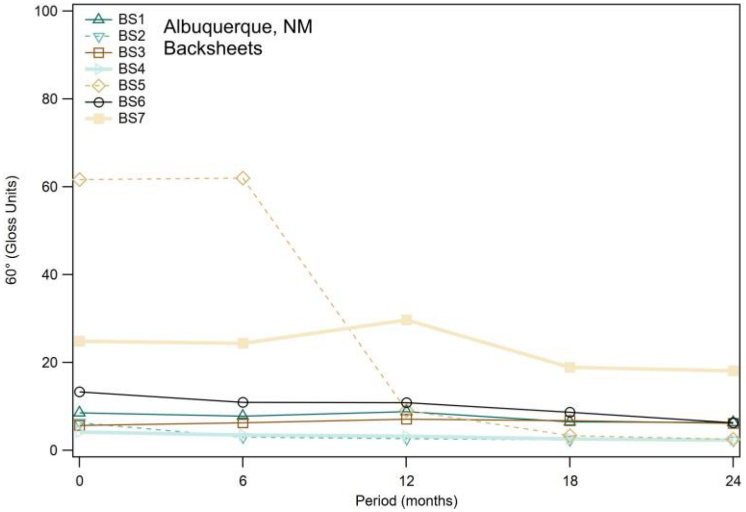
400 µm

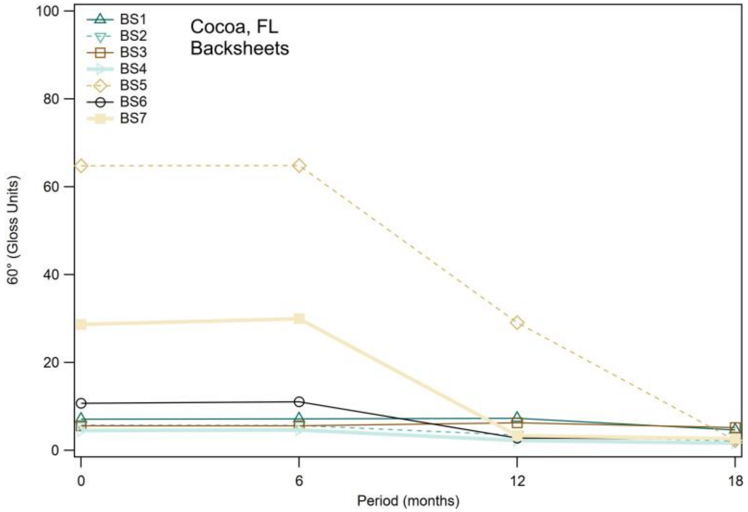
Gloss

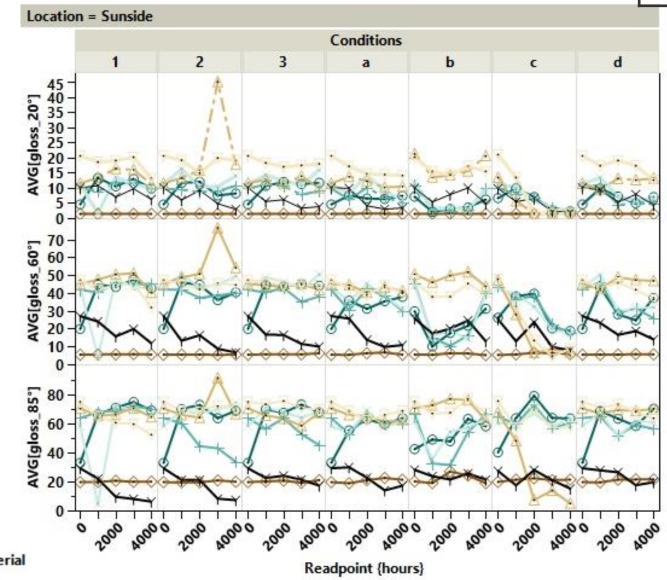
Albuquerque, NM and Cocoa, FL

1	85°C, 85%
2	65°C, 85%
3	45°C, 85%
a	0.8W/m², 65°C, 20%
b	0.55W/m², 57°C, 20%
c	0.55W/m², 65°C, ~80%
d	0.8W/m², 55°C, 20%

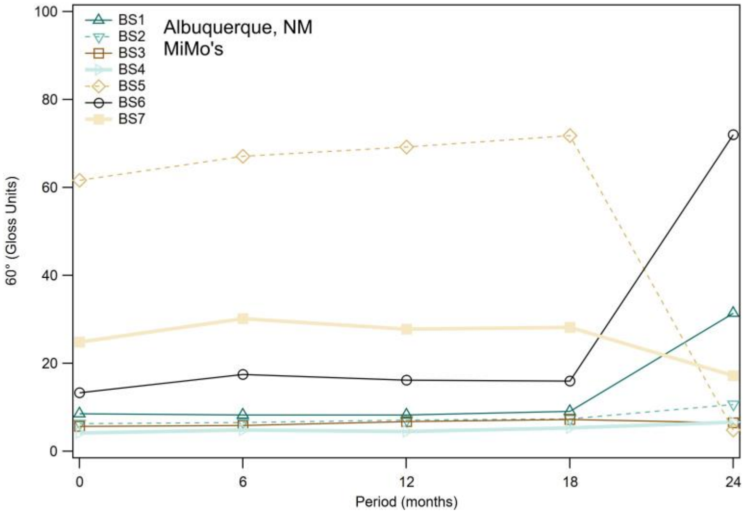
Backsheets

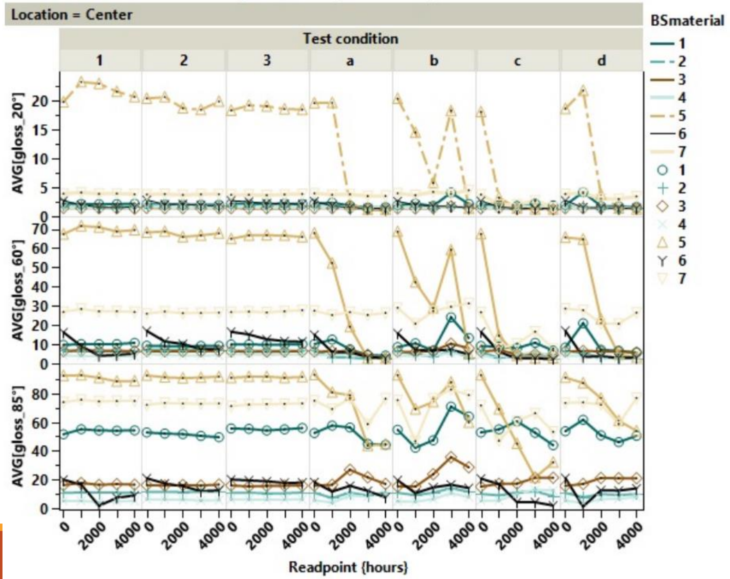






MiMo's

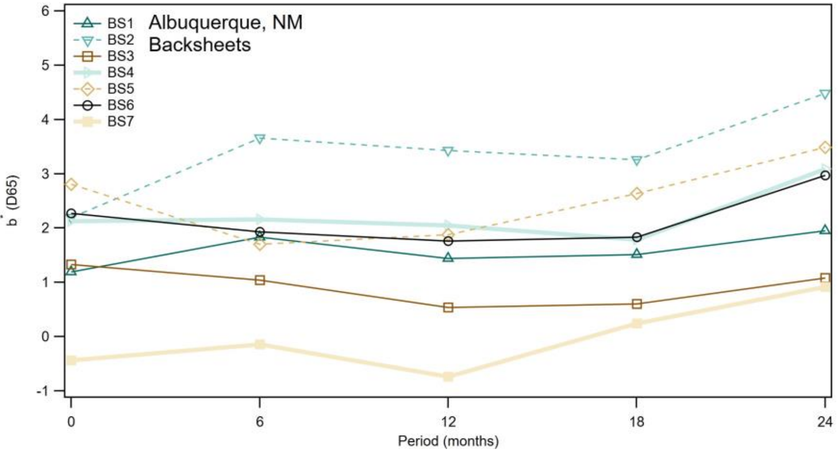


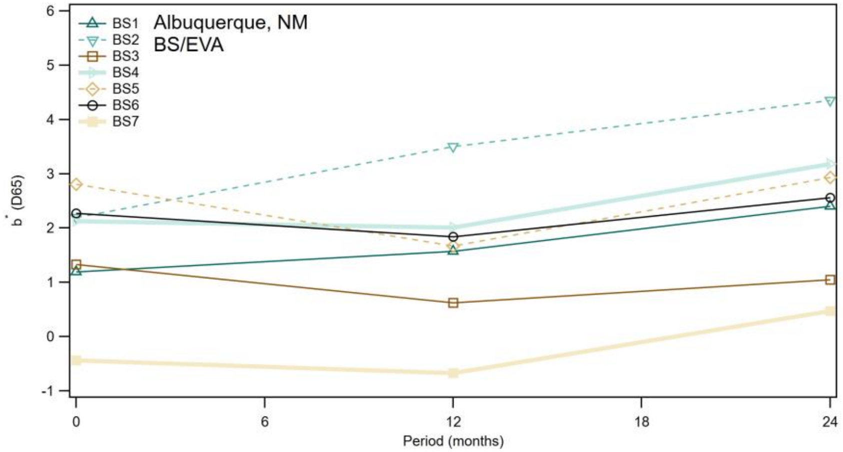


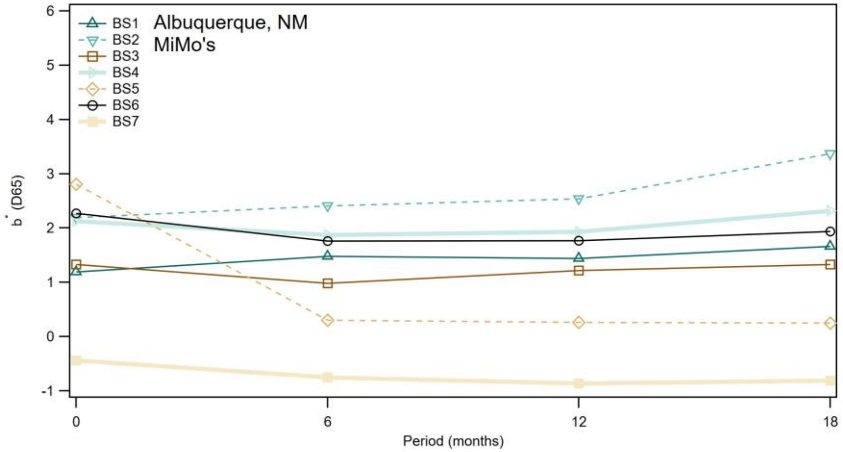
- Accelerated test samples saw great change for BS5
- Outdoor samples showed decrease in gloss for BS5 and BS7

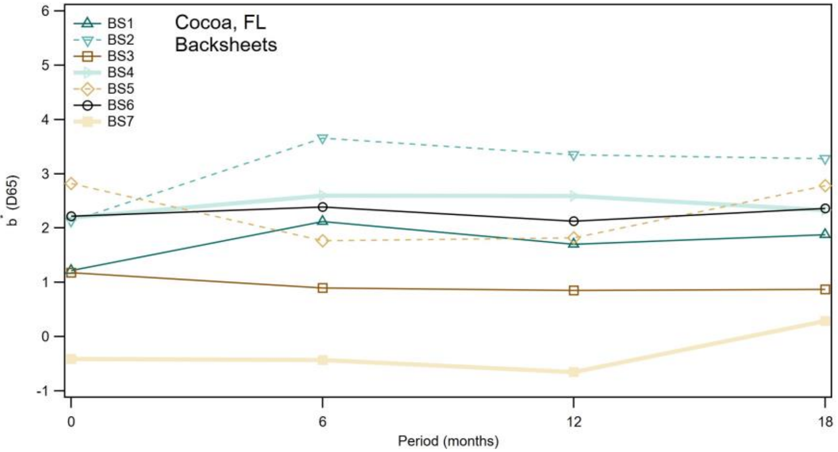
b*

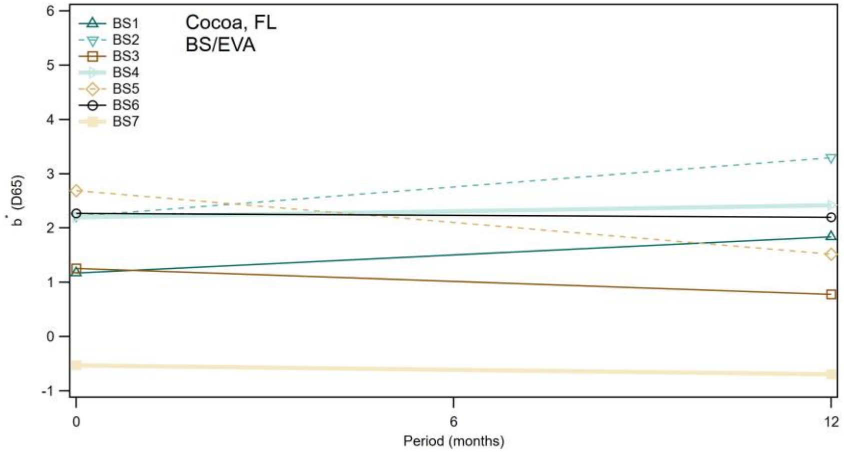
Albuquerque, NM and Cocoa, FL





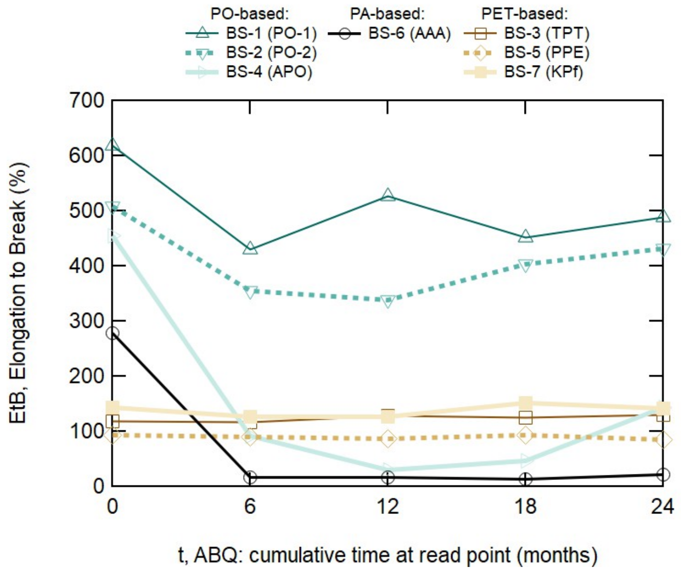


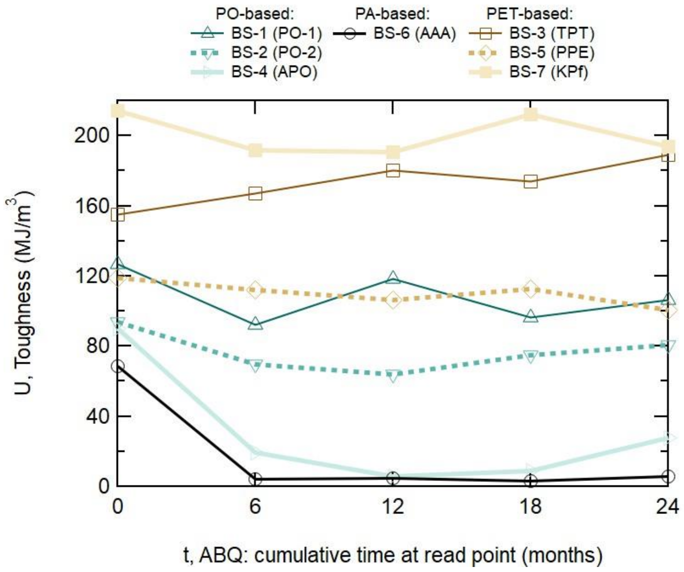


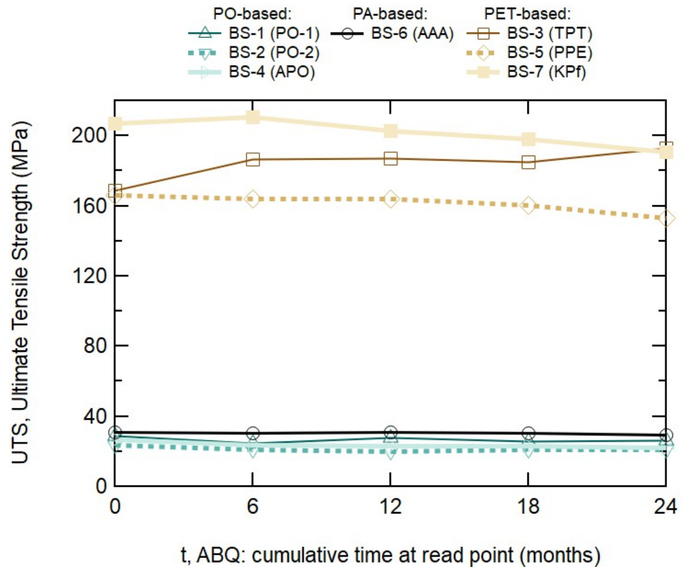


- Minimal change except for BS2 (increasing)
- Similar to accelerated test results

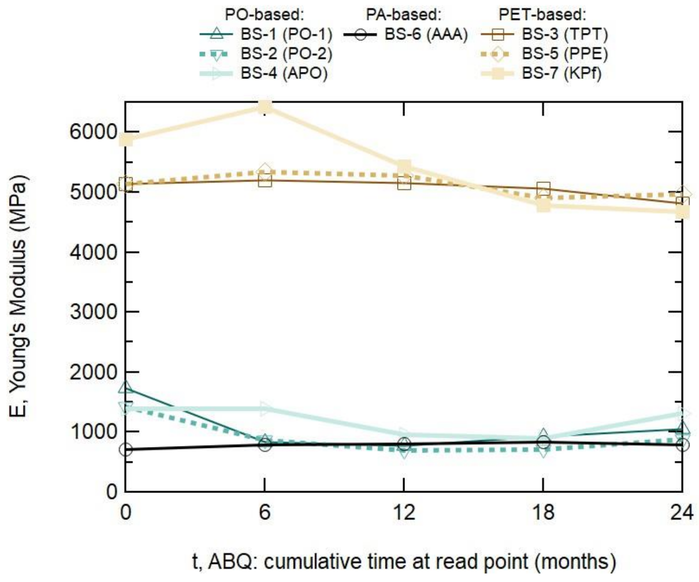
Tensile Test Results

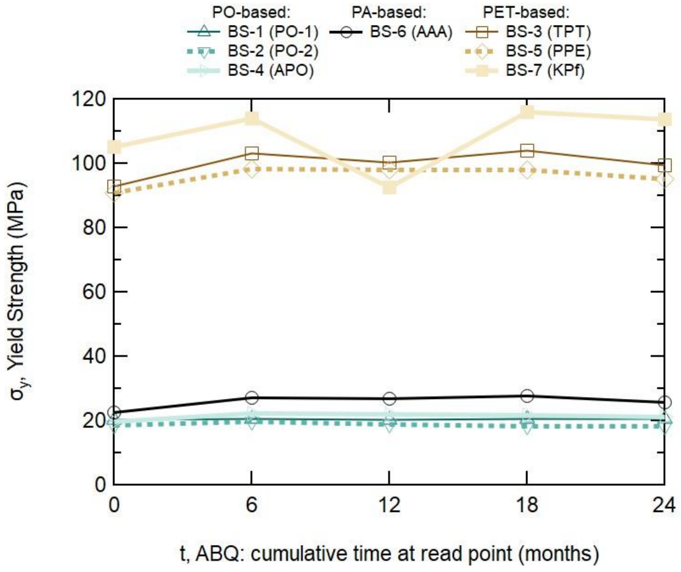


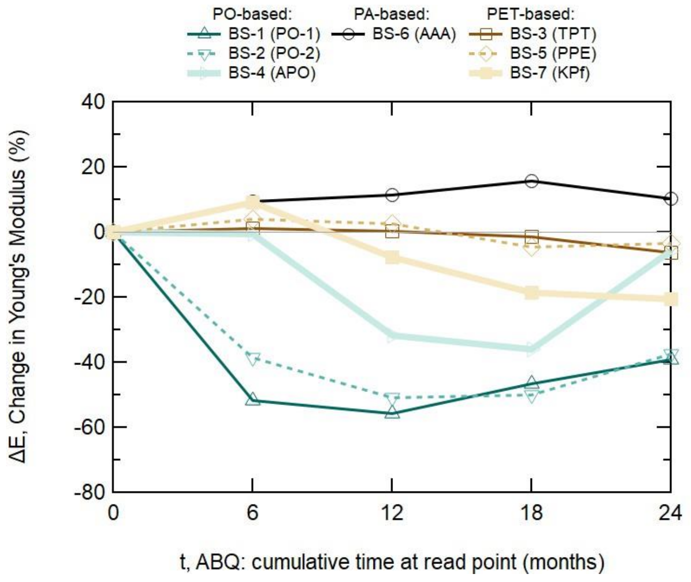




Tensile Test Results

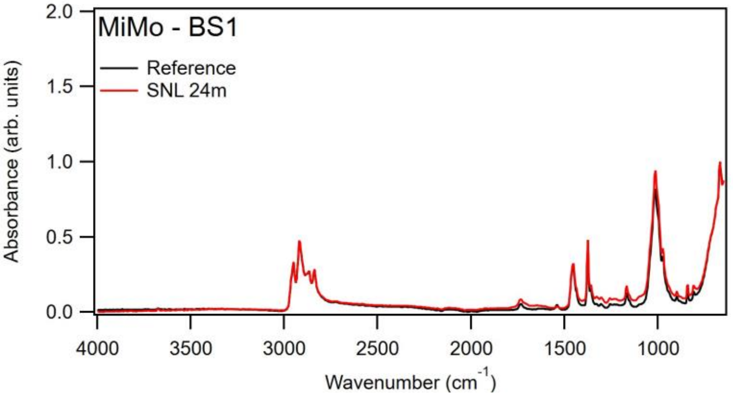


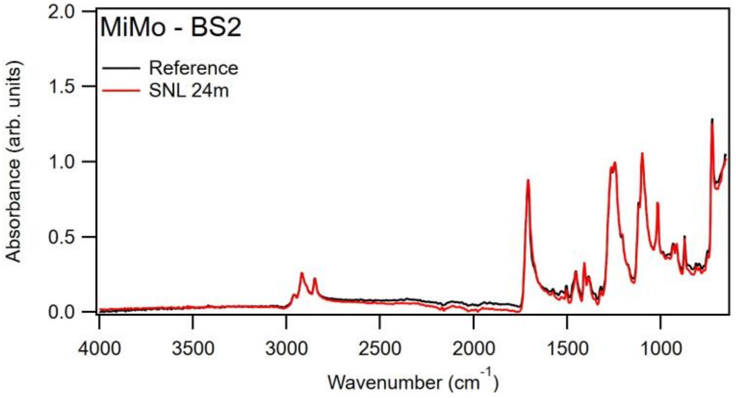


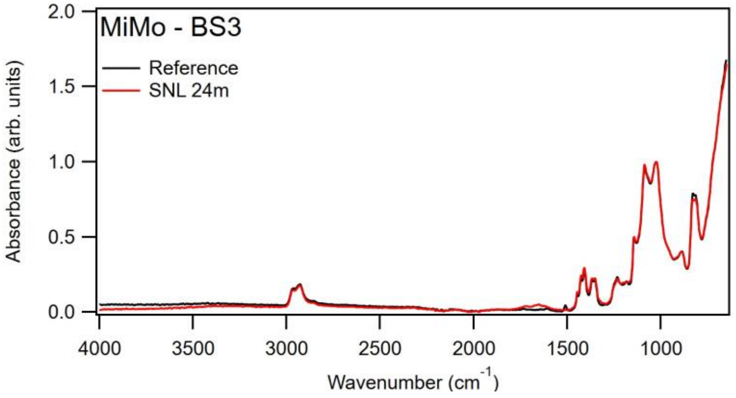


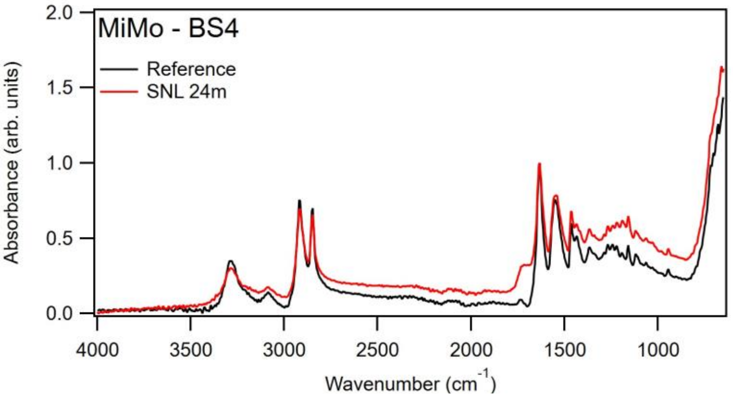
FTIR

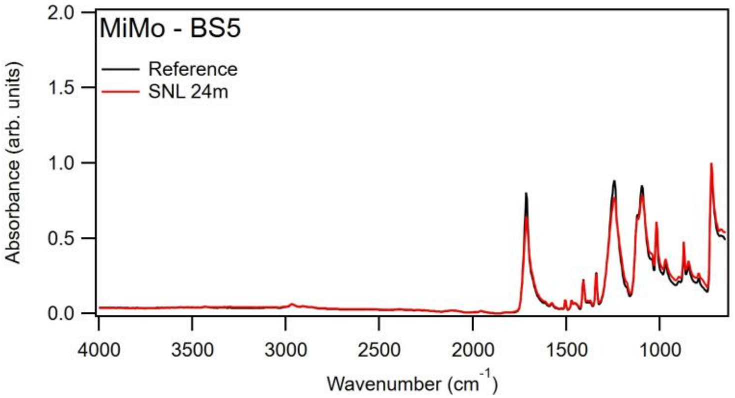
Albuquerque, NM and Cocoa, FL

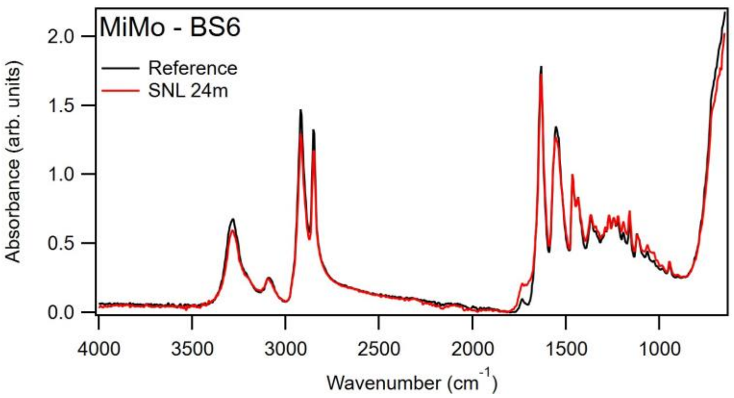


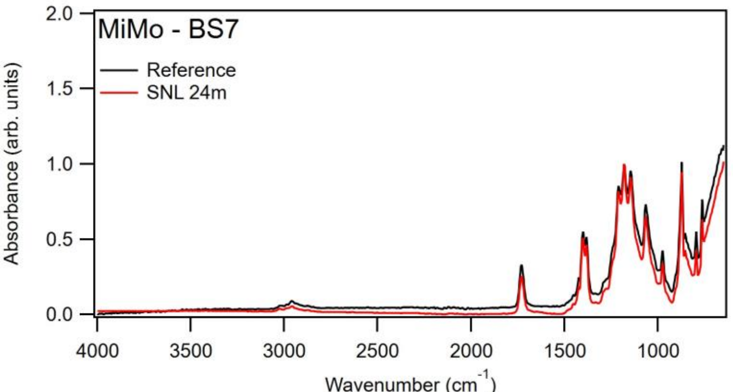










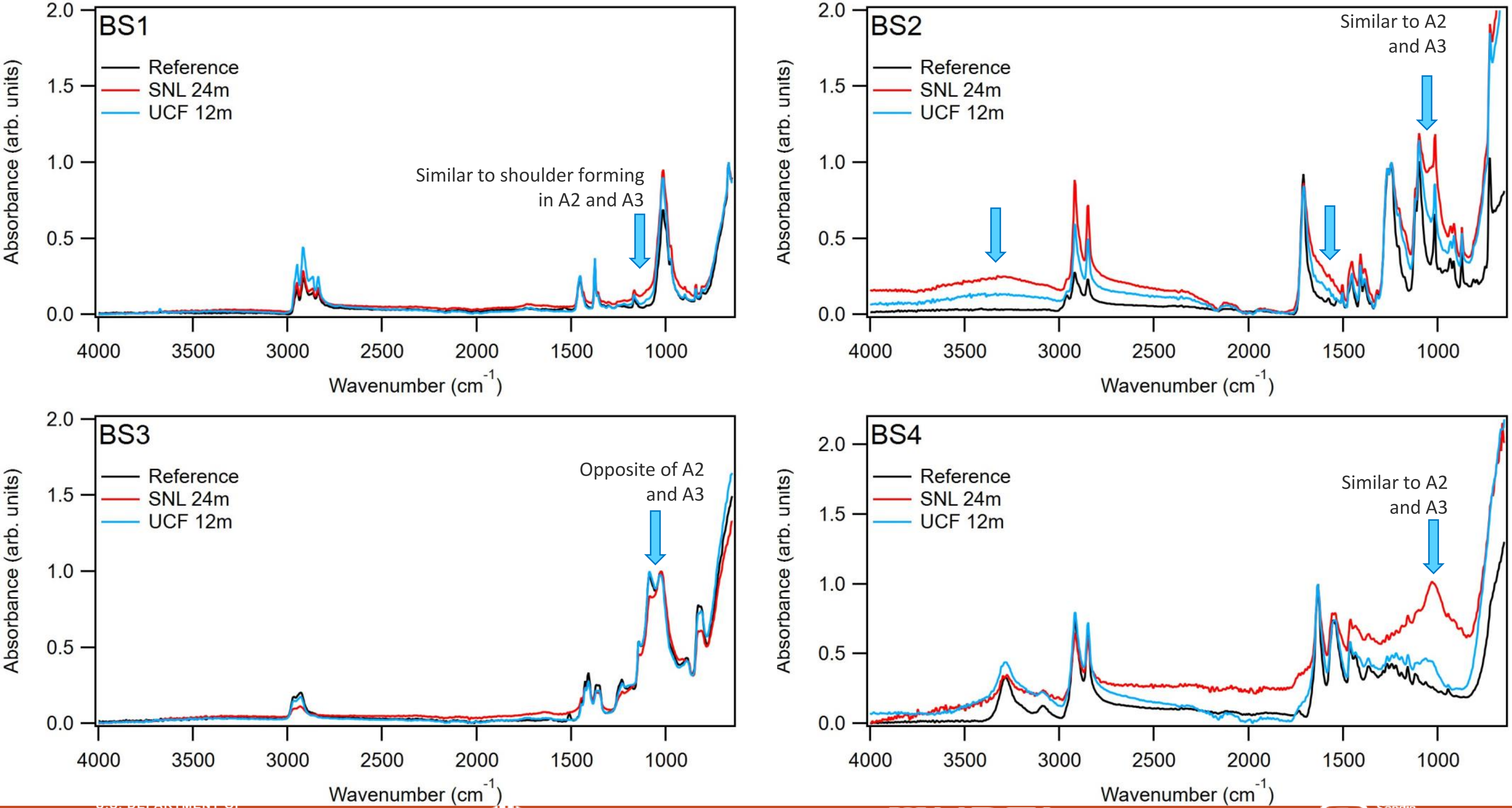


- Minimal changes to air side MiMo backsheets
- UCF samples to be studied

FTIR

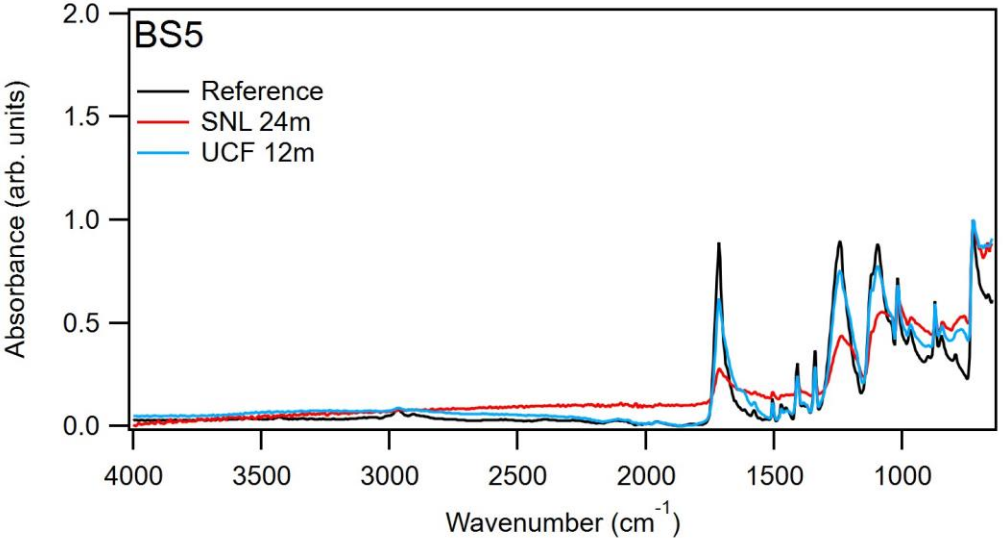
Albuquerque, NM and Cocoa, FL

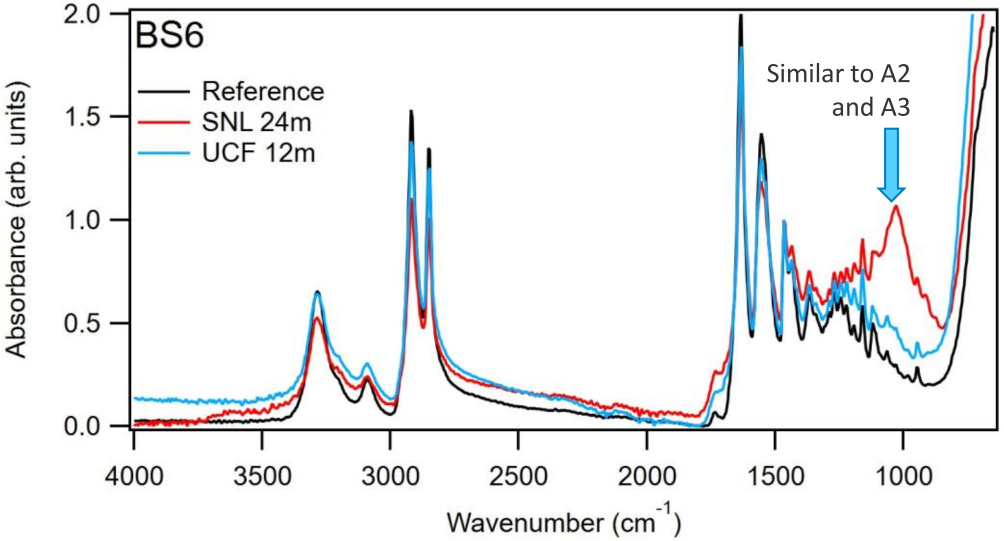
Accelerated (NREL):
A2: 0.8 W/m^2, 55°C, 20% RH
A3: 0.8 W/m^2, 65°C, 20% RH

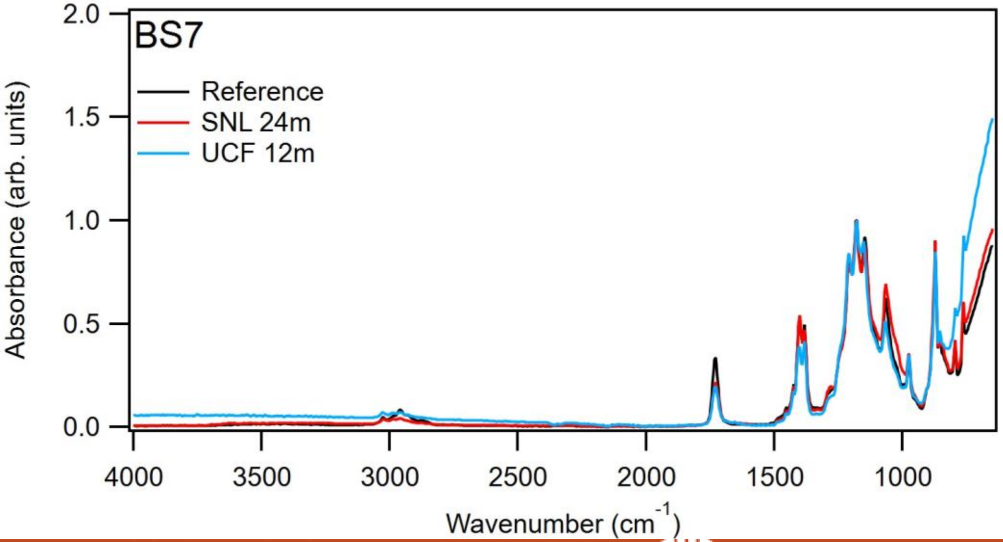


FTIR

Albuquerque, NM and Cocoa, FL







Status and Final Steps

- Accelerated tests revealed more prominent degradation for BS3, 5, and 7 (PET-based); hygrometric tests resulted in most degradation
- Comparing all accelerated and fielded results
  - FTIR so far showing connections between

- Sharing on the DuraMAT DataHub
- Submitting a SPARK proposal to further study degradation of all backsheet layers
- Documentation and reporting

Thank you!

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