

Adding Some “Dirt” to “Clean” Energy: Applying Clay Nanocomposites in Solar Cells

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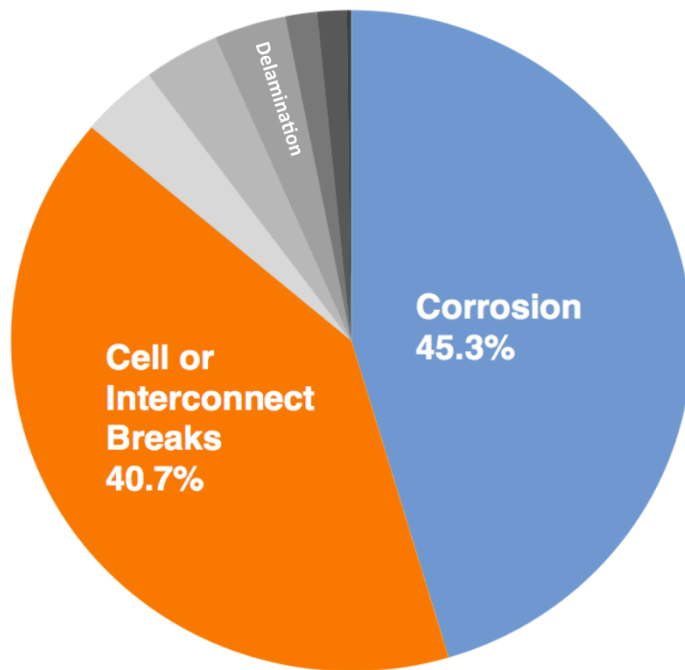
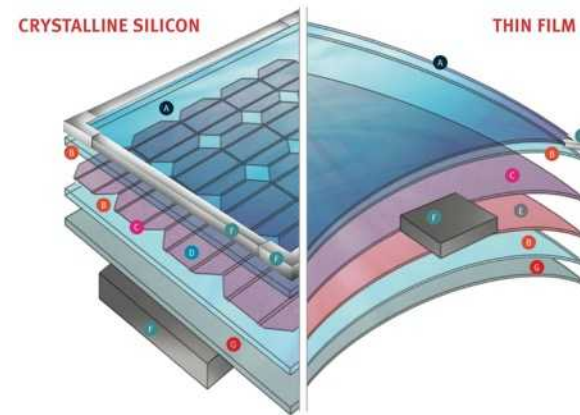
*Composites at Lake Louise 2017, Lake Louise, Alberta, Canada
November 12-16, 2017*



Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Degradation in PV Modules

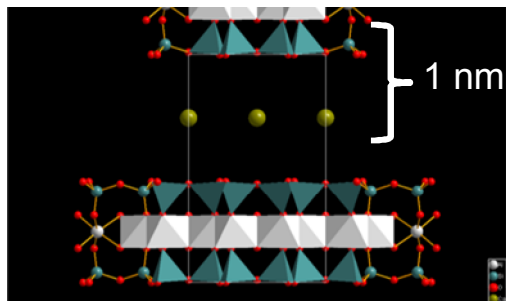
PV modules must be sealed against the environment using transparent, thin film encapsulants.



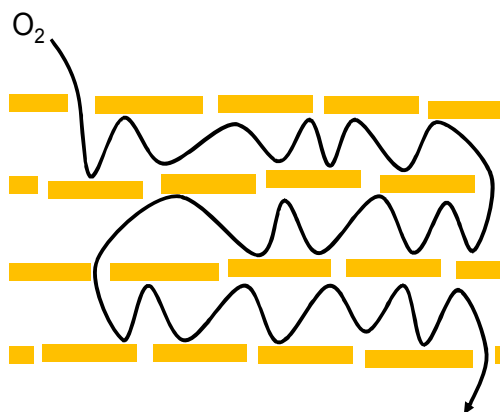
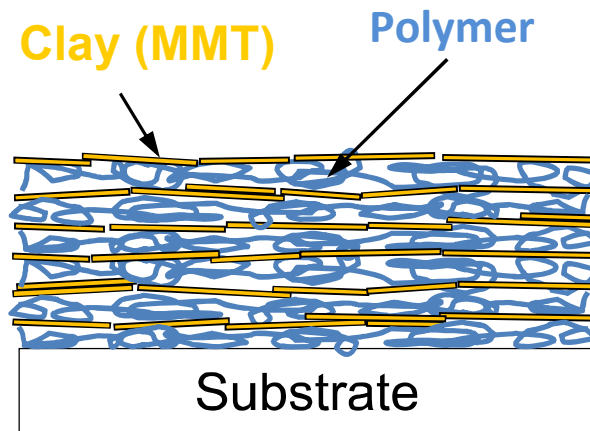
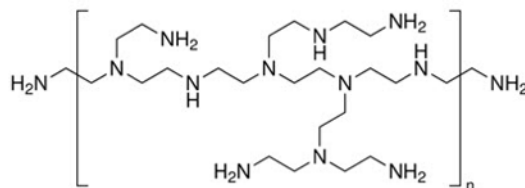
- Corrosion
- Cell/Interconnect Breakage
- Output Lead Problems
- Junction Box Problems
- Delamination
- Overheated Wires, Diodes, Terminal Strips
- Mechanical Damage
- Defective Bypass Diodes

Polymer Clay Nanocomposites (PCNs)

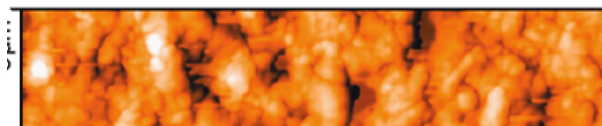
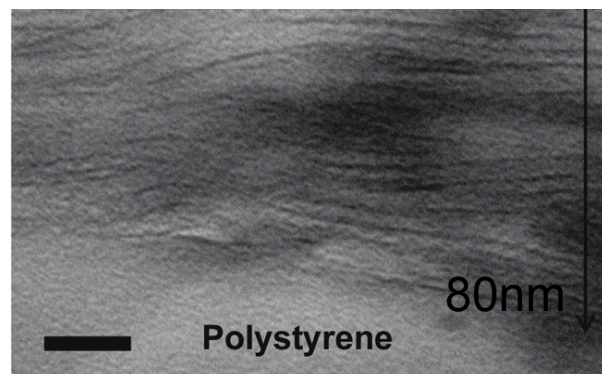
Montmorillonite (MMT)



Polyethyleneimine (PEI)



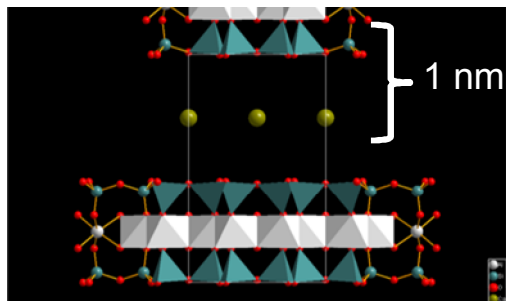
Highly organized layers of exfoliated clay and functional polymers make unique barrier thin films.



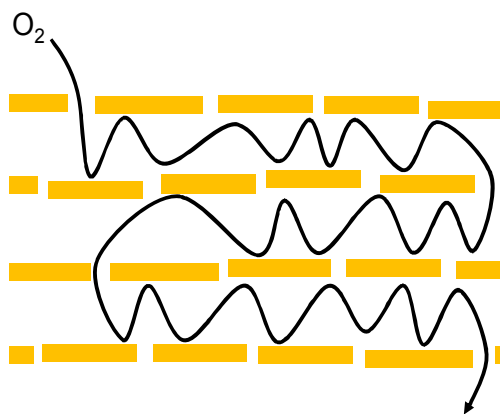
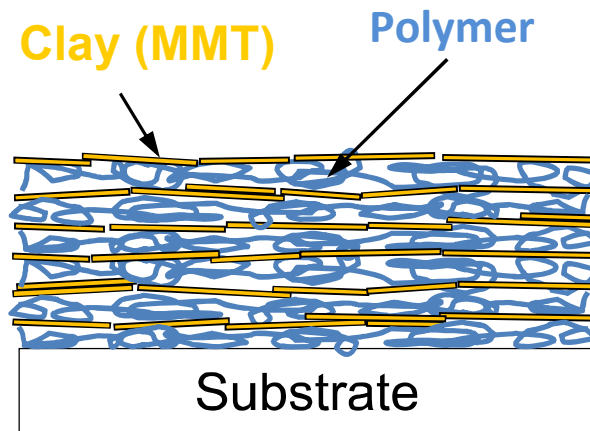
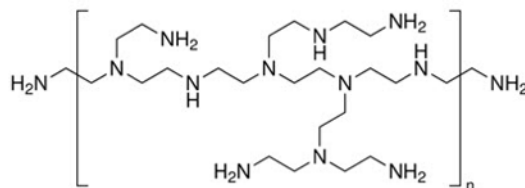
Nano Lett. **2010**, *10*, 4970--4974

Polymer Clay Nanocomposites (PCNs)

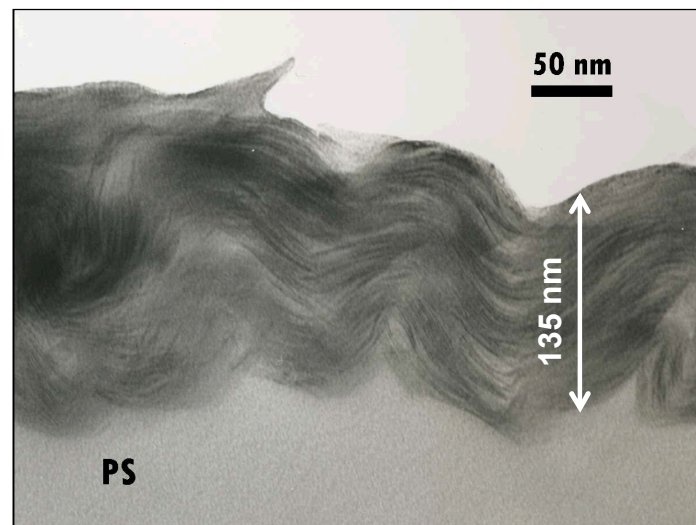
Montmorillonite (MMT)



Polyethyleneimine (PEI)



Highly organized layers of exfoliated clay and functional polymers make unique barrier thin films.



Motivating PCNs for PV

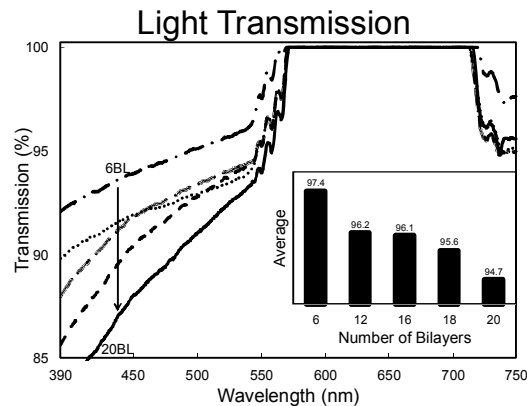


Why are these layer-by-layer PCNs attractive for PV Encapsulation?

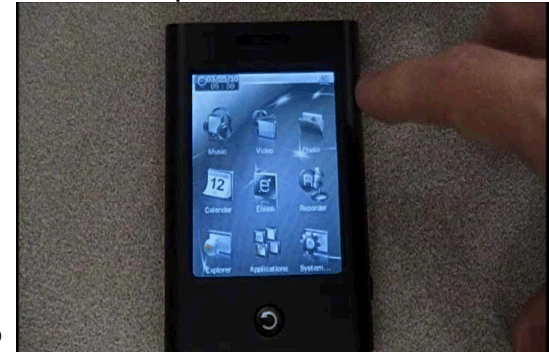
Important qualities for Encapsulants:

- Optical transparency
- Water/oxygen repellent
- Adhesive
- UV-stable
- Inexpensive (materials, processing, environmental)
- Tough but flexible

Optical Transparency of PCN Barrier Films



20BL Deposited on Touchscreen



Gas barrier properties

EVA*: O₂ (90% RH): ~2000-10,000 cc/m²/day
H₂O (RT): ~7 g/m² day

PCN thin films: 0.093 cc/m²/day (100% RH)
H₂O (RT): ~0.65 g/m² day

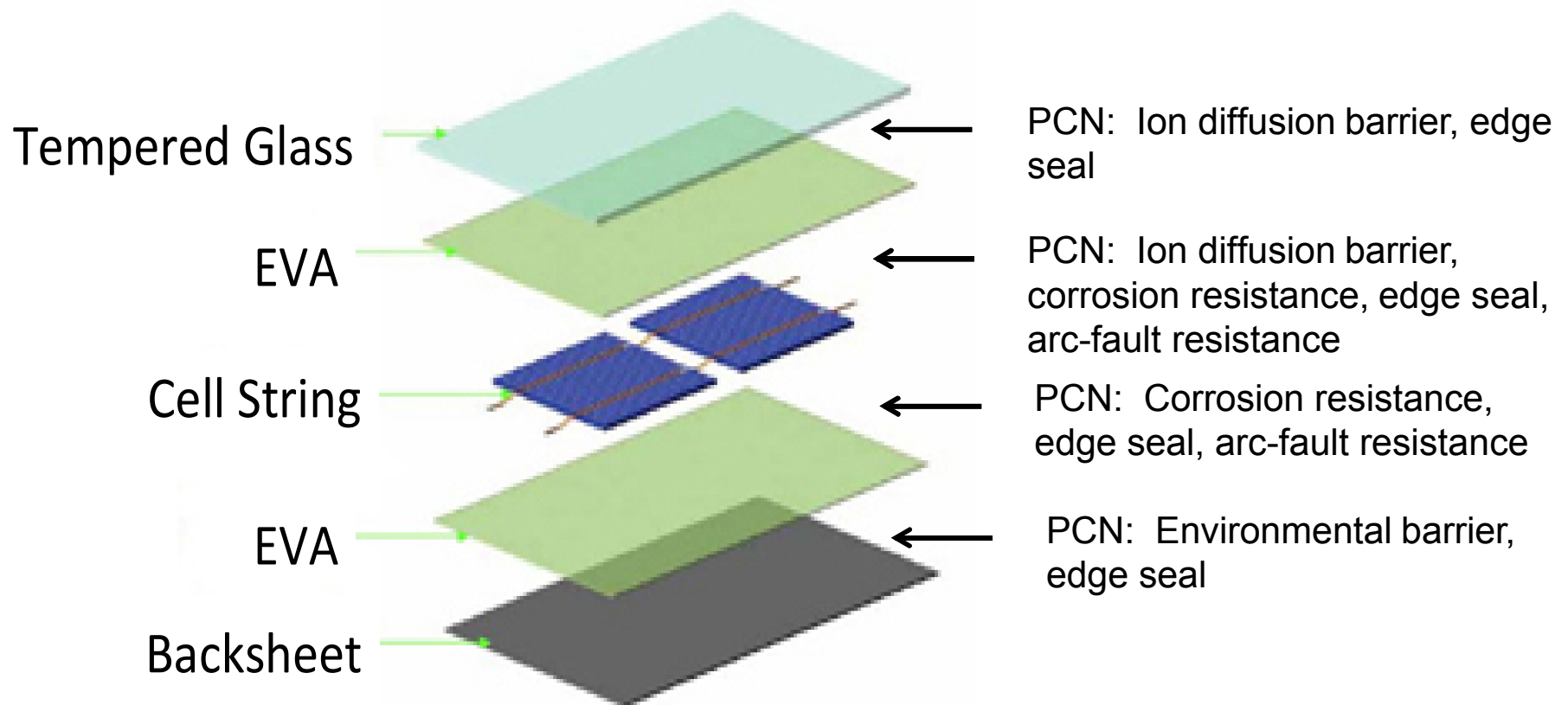
*EVA Data based on reports from Dow Chemical (1998), Dupont (2001), and NREL (2008).

Cost: Commercial Montmorillonite (~\$0.50/kg)
Commercial Polyethyleneimine (\$1-10/kg)

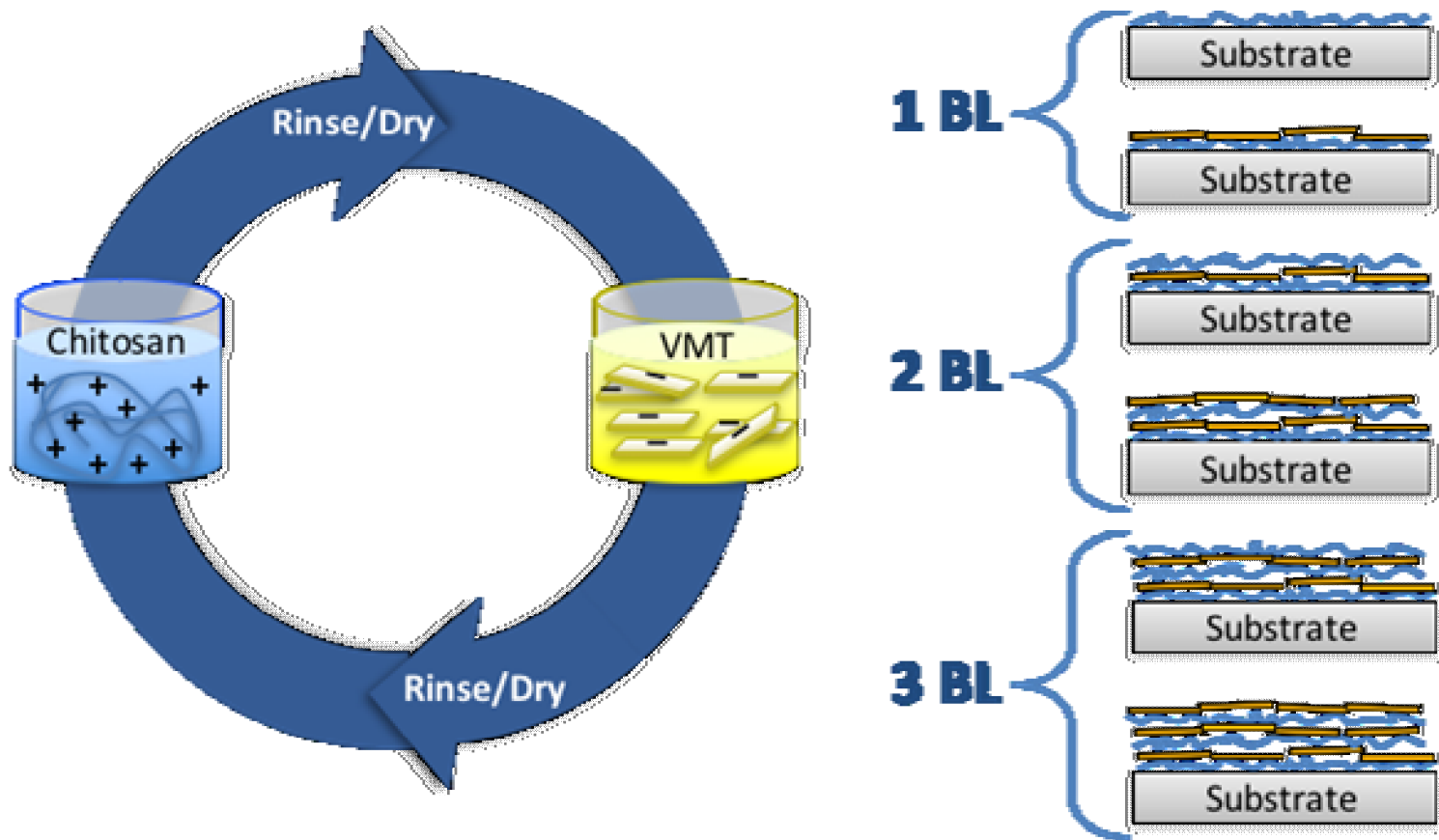
50¢ of clay will cover ~2 soccer fields, 40 layers thick!

PCN Integration Strategy

PCNs can be integrated into multiple locations within a cell to provide diverse benefits

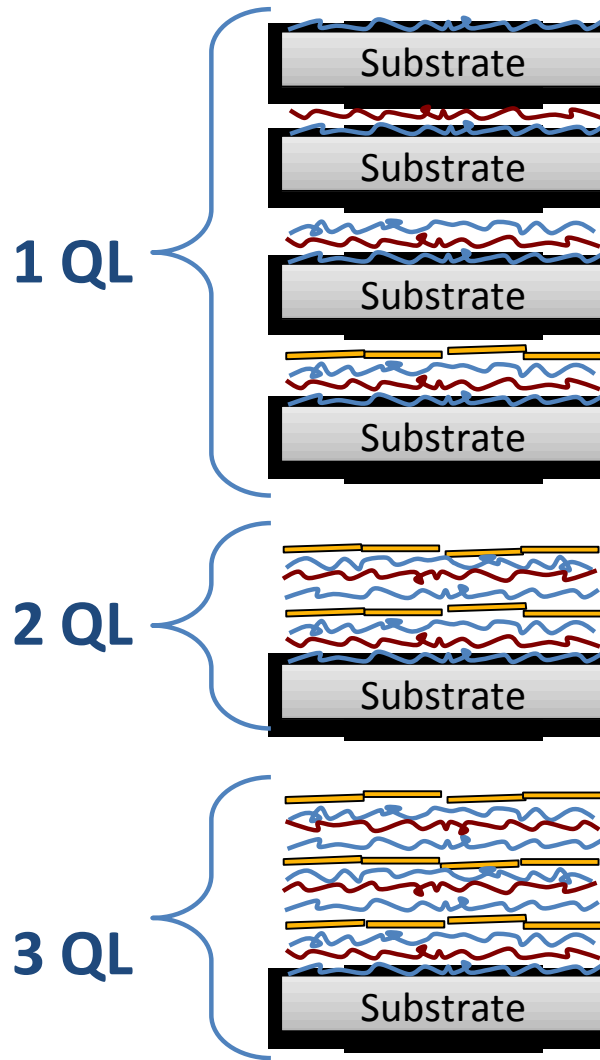
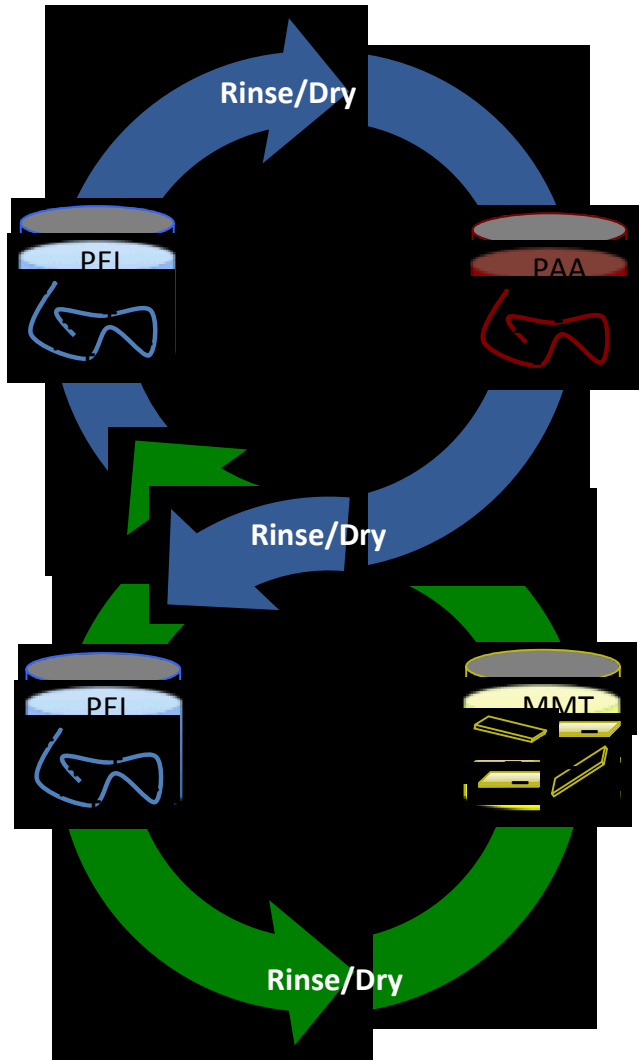


Layer-by-Layer Deposition of Polymer-Clay Nanocomposites



Using layer-by-layer (LBL) assembly, molecular composites barrier films can be produced on macroscopic scales.

QuadLayer Assembly



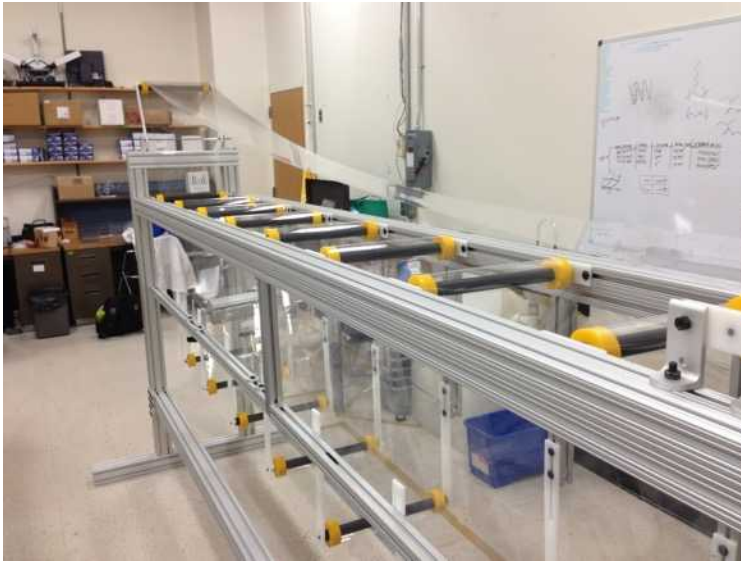
QuadLayer assemblies involve not only polymer-clay interactions, but polymer-polymer interactions.

These secondary polymer interactions significantly affect PCN properties!

Robot Automation of Deposition: “Big Dipper”



PCN Processing Scalability

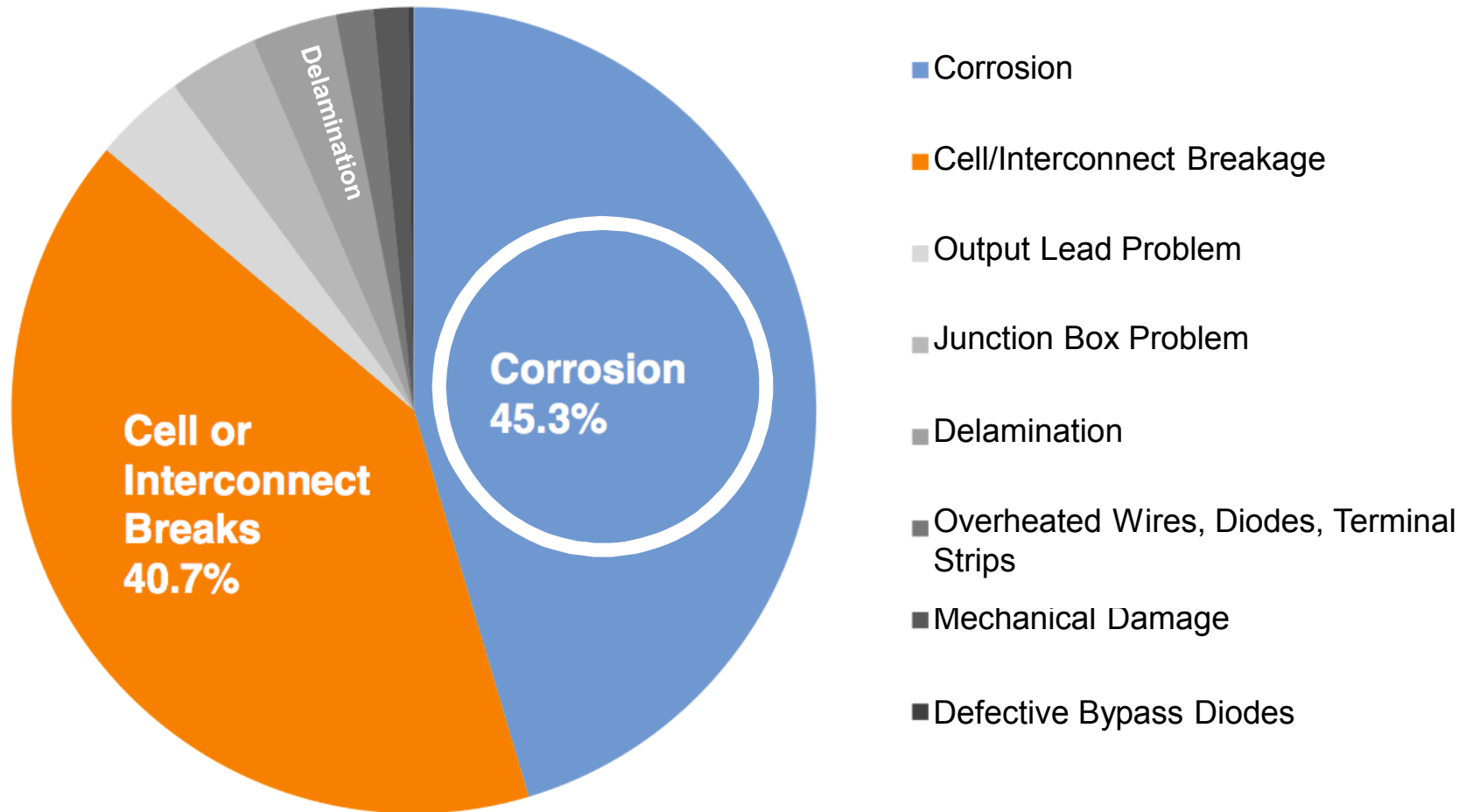


60ft of EVA
coated by reel-
to-reel process
at TAMU (Prof.
J. Grunlan)

TAMU Reel to Reel system capable of 11" x 50' of coating.

- Suitable for lamination onto coatings for:
 - Nature Power 3W and 5W Modules (single crystal Si, < 8"x 12")
 - Uni-Solar US-3 (amorphous Si, ~8"x 11")

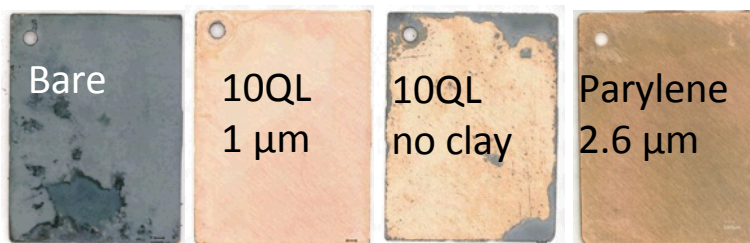
Tackling PV Corrosion



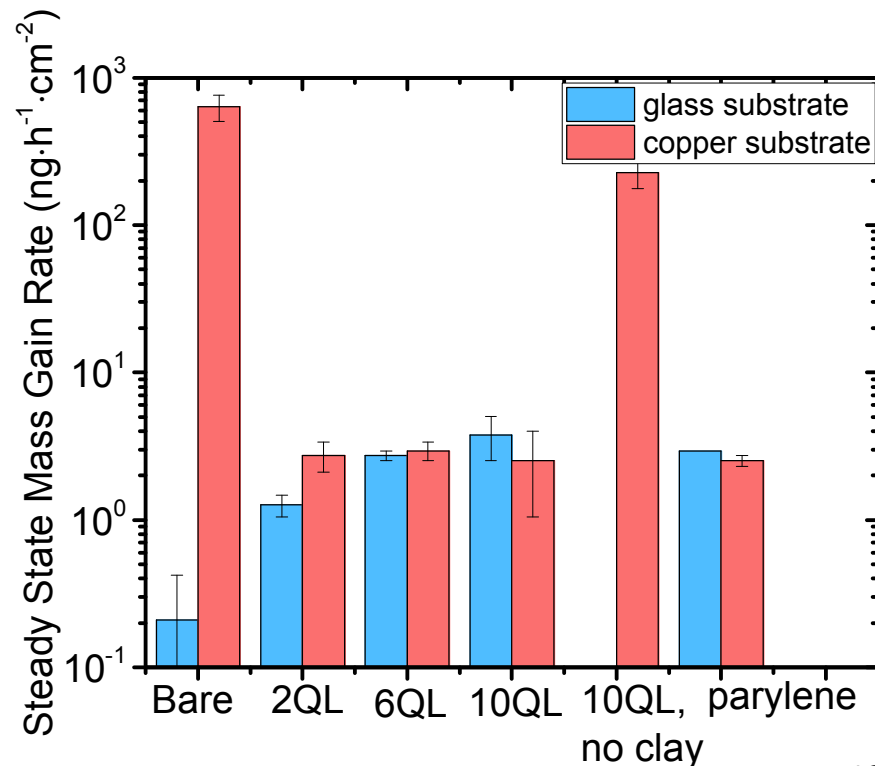
PCNs as PV Corrosion Barriers

Copper coupons were coated with quadlayer PCNs and exposed to an aggressive H_2S -based corrosive atmosphere. Visual analysis and quantitative mass gain (from CuS_x) formation PCN coatings are as effective or *more effective than thicker parylene* coatings.

Incorporation of clay in the coating is vital to film integrity and performance.

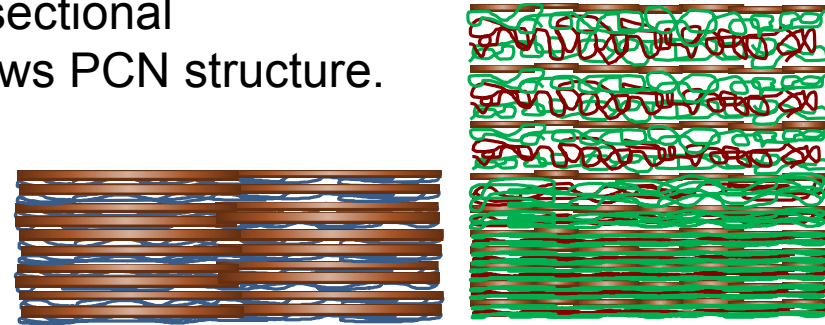
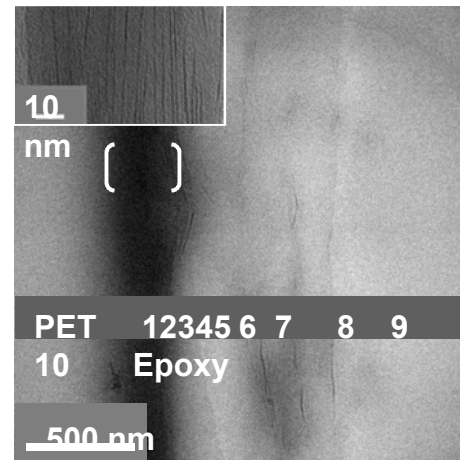
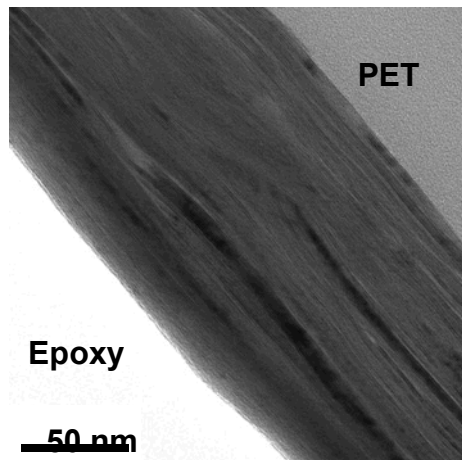
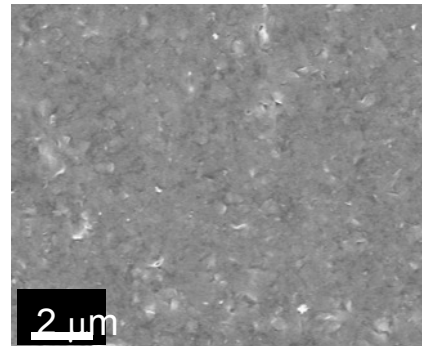
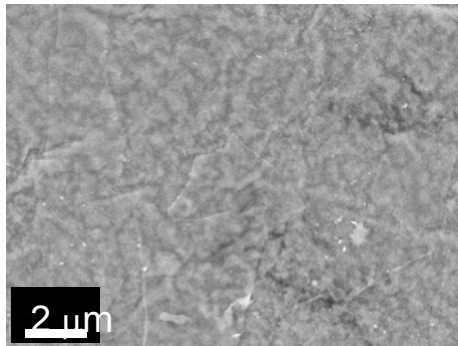


Copper coupon appearance after 800 hours exposure to corrosive H_2S environment.

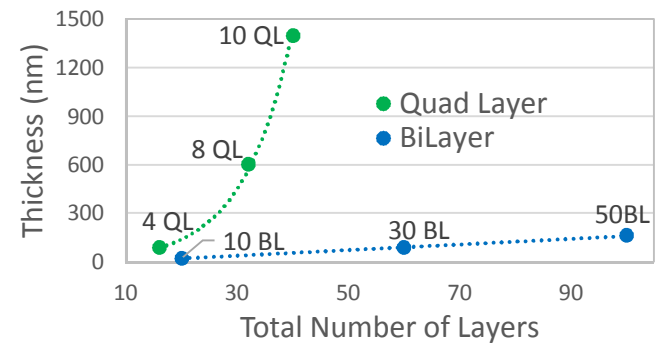


PCN Characterization

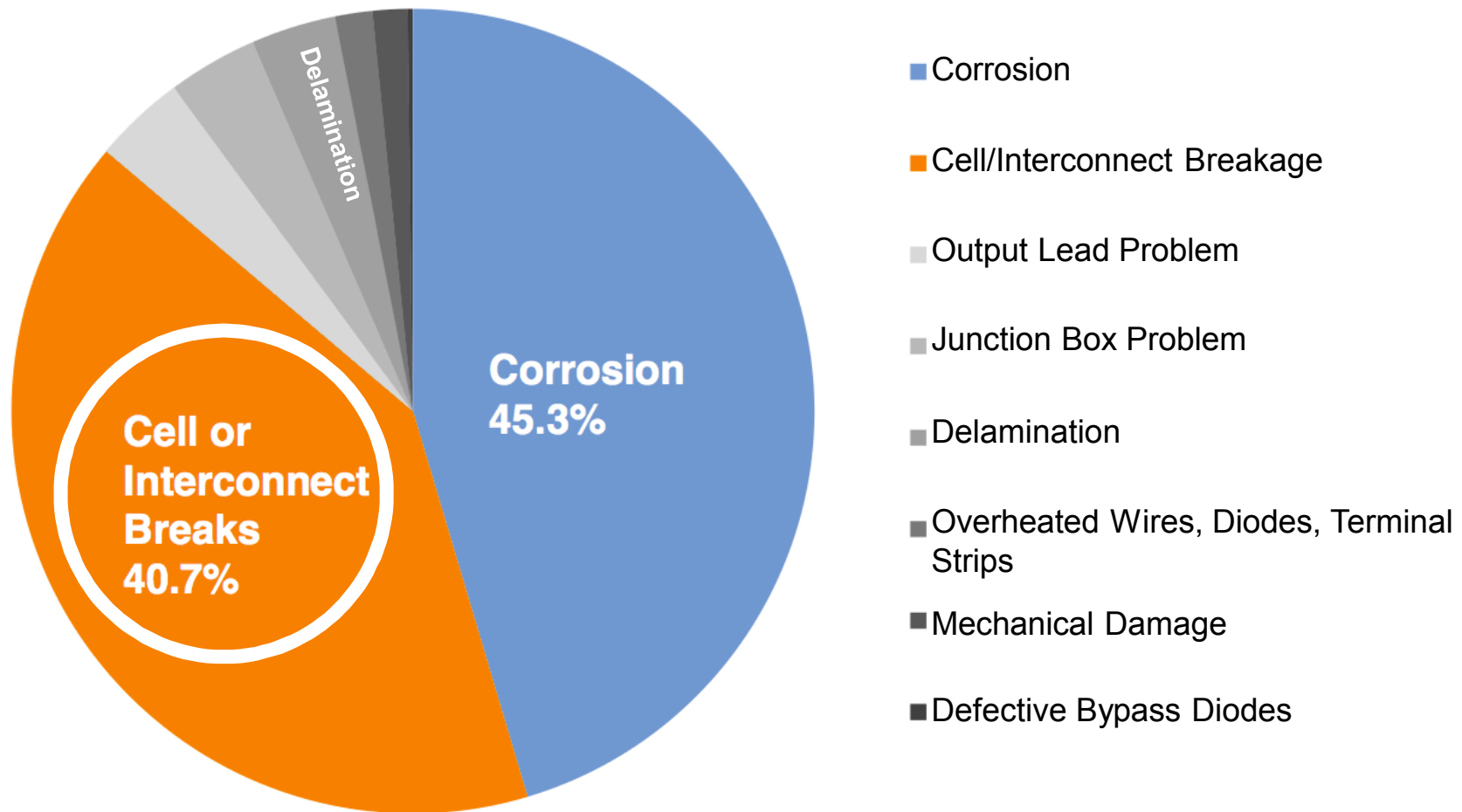
Scanning Electron Microscopy (above) and X-sectional Transmission Electron Microscopy (below) shows PCN structure.



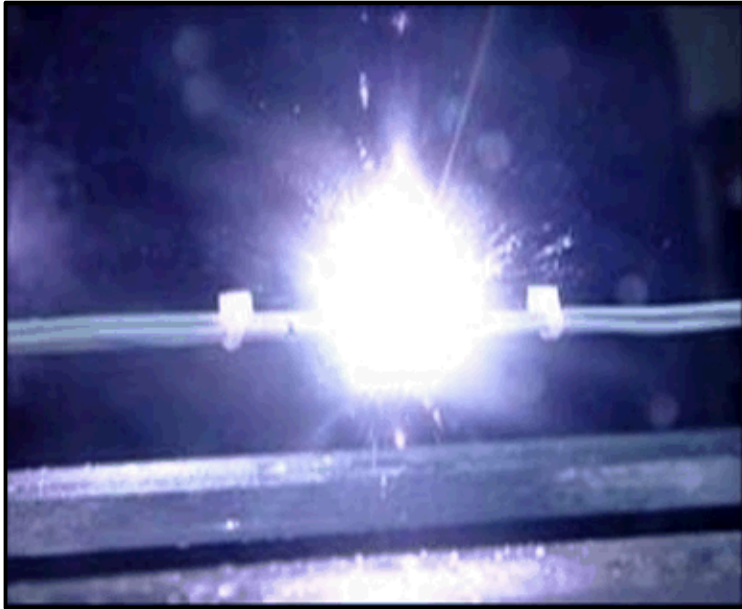
Although bilayers grow "linearly" quadlayers grow in an "extra-linear" fashion, forming thick polymer layers near the top of the films.



Tackling PV Corrosion



Arc Fault Hazards in Photovoltaics



<http://jlelectrics.com.au/products/>



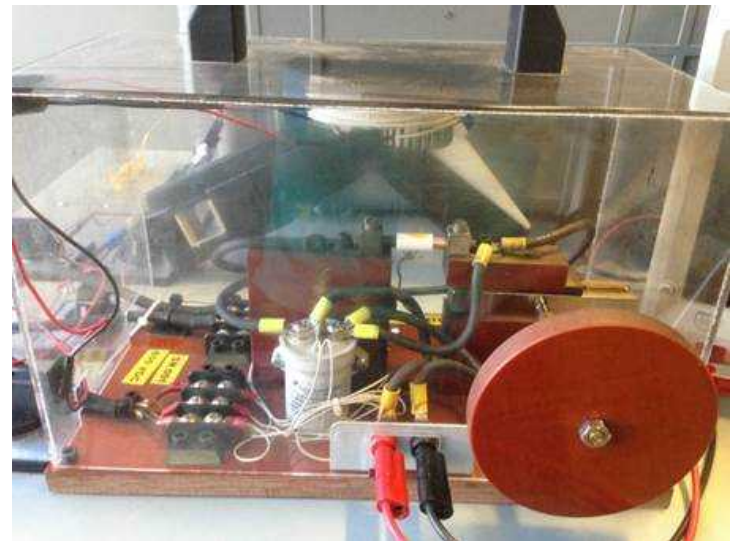
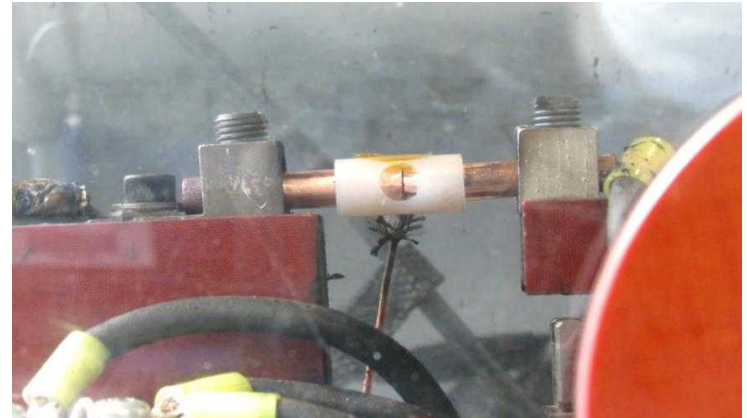
Image provided by Sean Hearne

*Interconnect corrosion/breakage can lead to high energy arc faults.
Resulting fires are a serious threat to equipment, property, and personnel!*

Arc Fault Flammability Testing

SNL-Developed Arc-testing:

- Controlled arc generation
- Time to smoke
- Time to flame

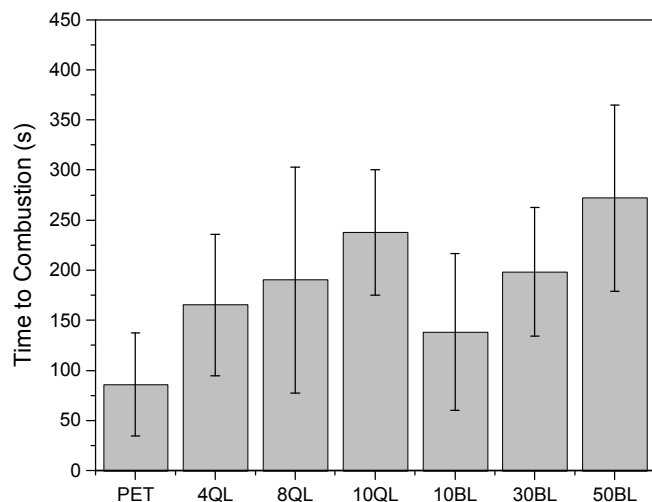


A Simulated Arc Fault



Quantifying Arc Fault Flammability Resistance

PCN films clearly improve the arc-fault flammability resistance of polymer substrates for 200W arcs.



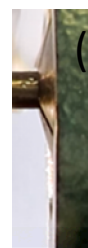
PCN films increase the time taken to ignite a coated polymer sheath with a 200W electrical arc.



(a) Arc start



(b) 145 s



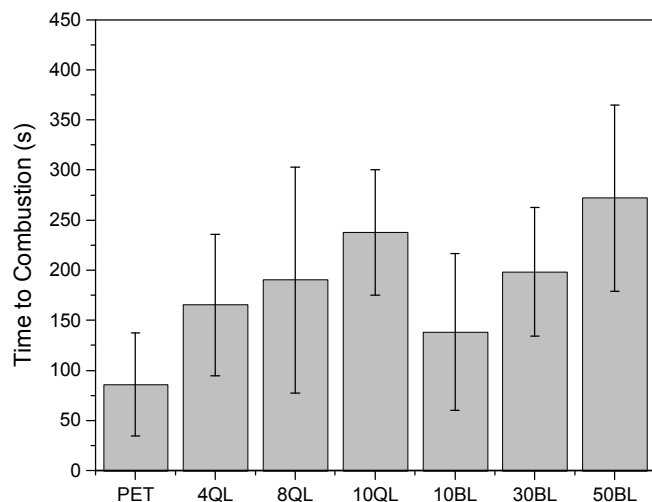
(c) 153 s



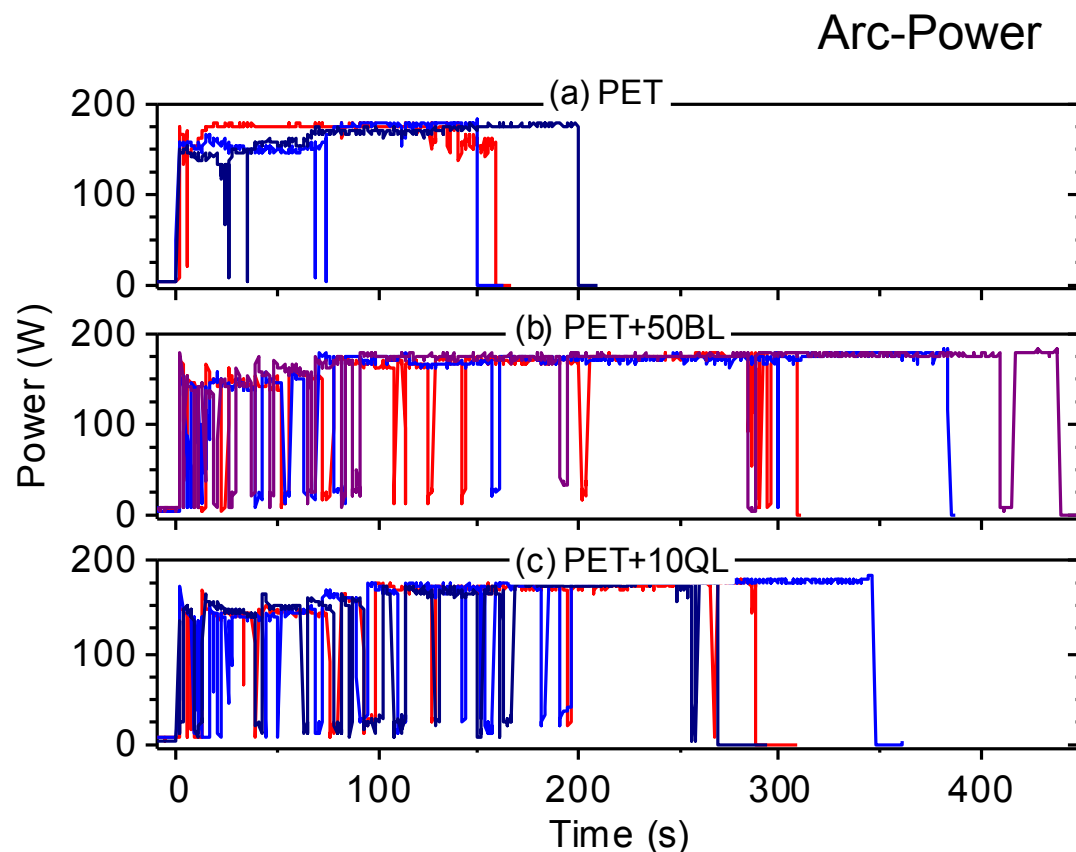
(d) 195 s

Quantifying Arc Fault Flammability Resistance

*PCN films also promotes arc **extinction**, meaning that arc-flammability is not only delayed, but the arc itself can be extinguished!*

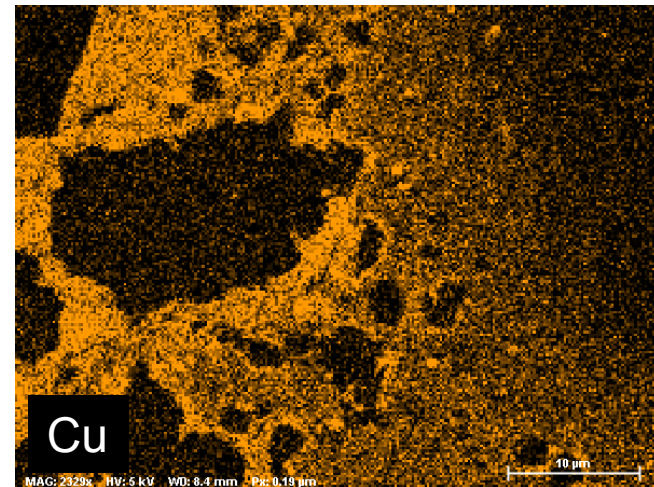
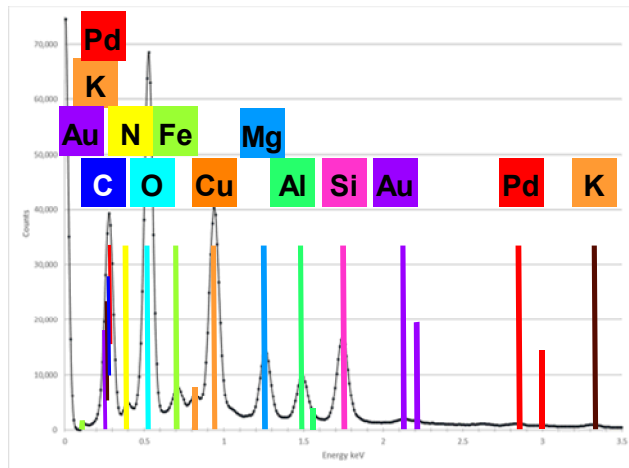
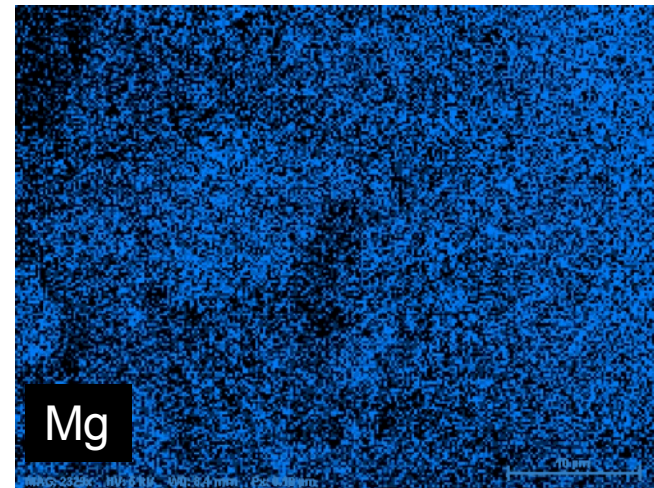
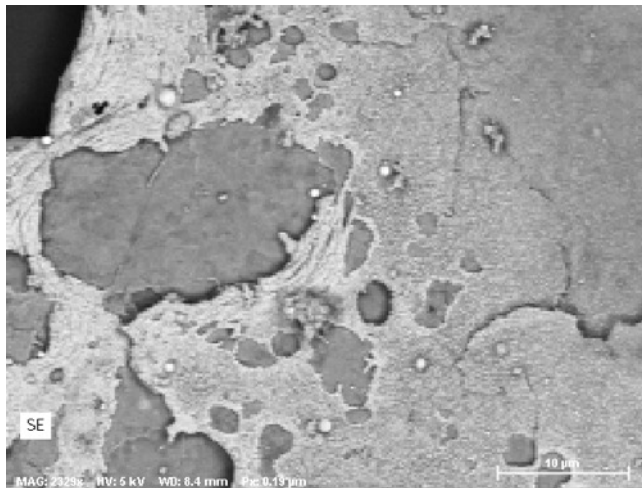


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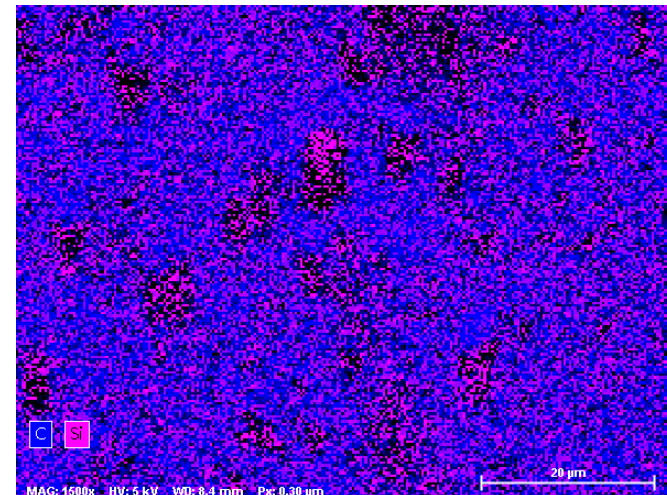
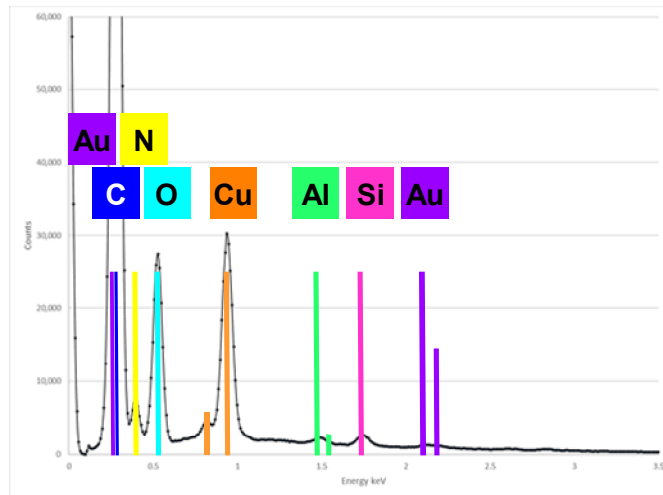
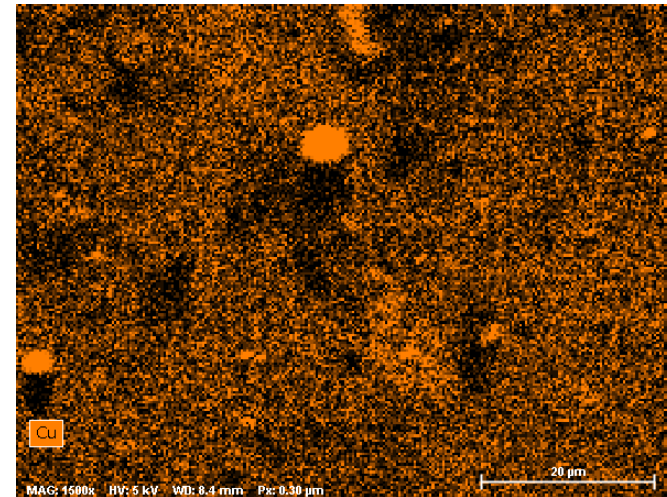
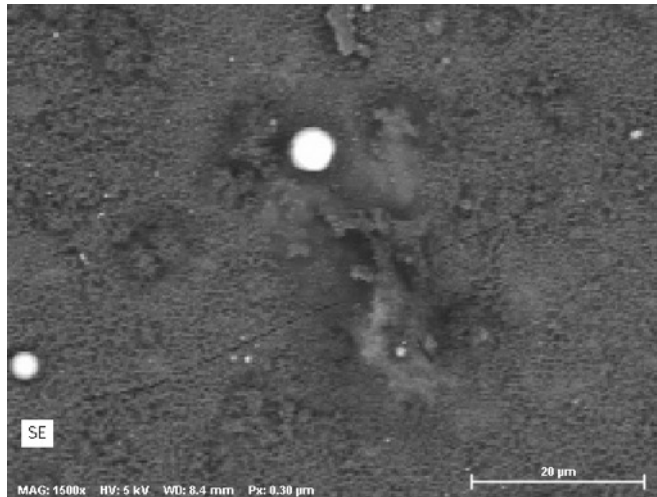
PCN Bilayers: Protective “Onions”

Bilayer PCN films “peel” away, providing multiple layers of protection



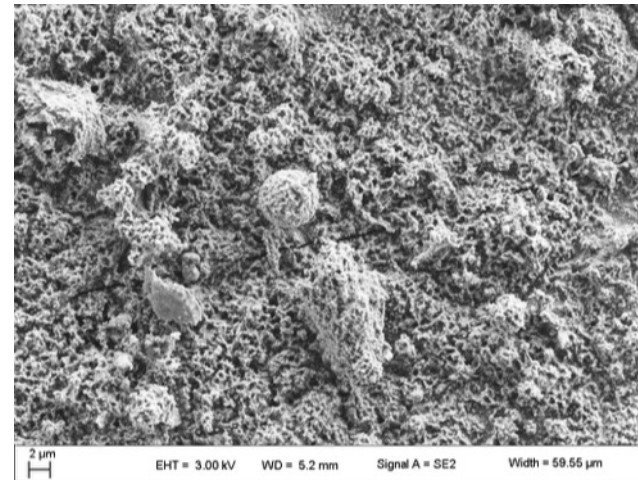
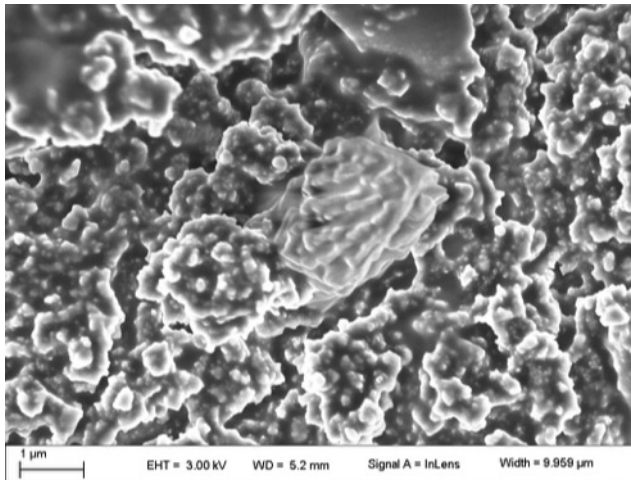
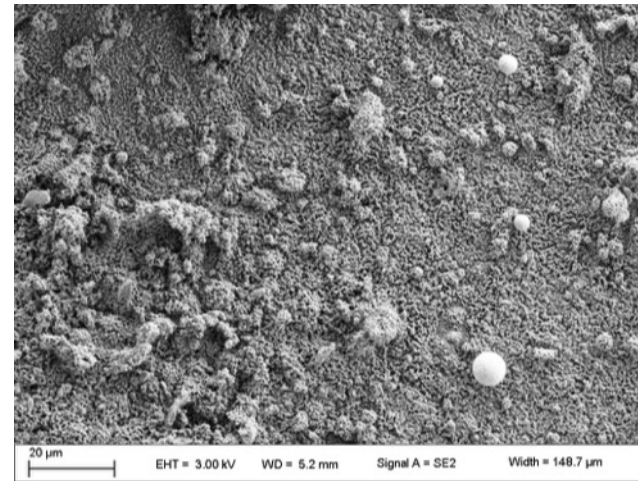
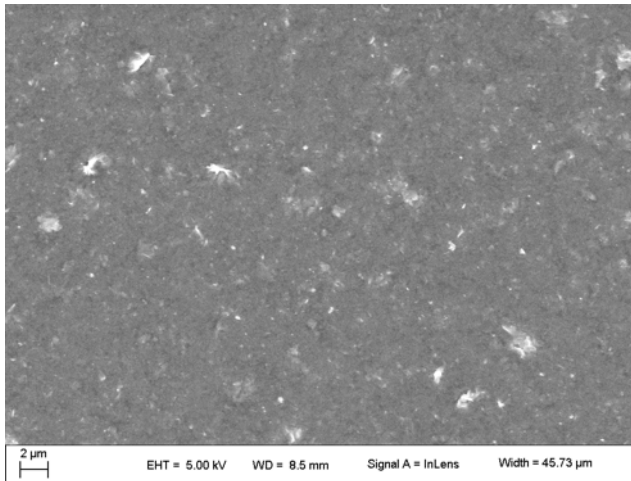
Quadlayer Arc-Fault Resistance

QL films also provide multiple layers of protection, but in a more disordered way



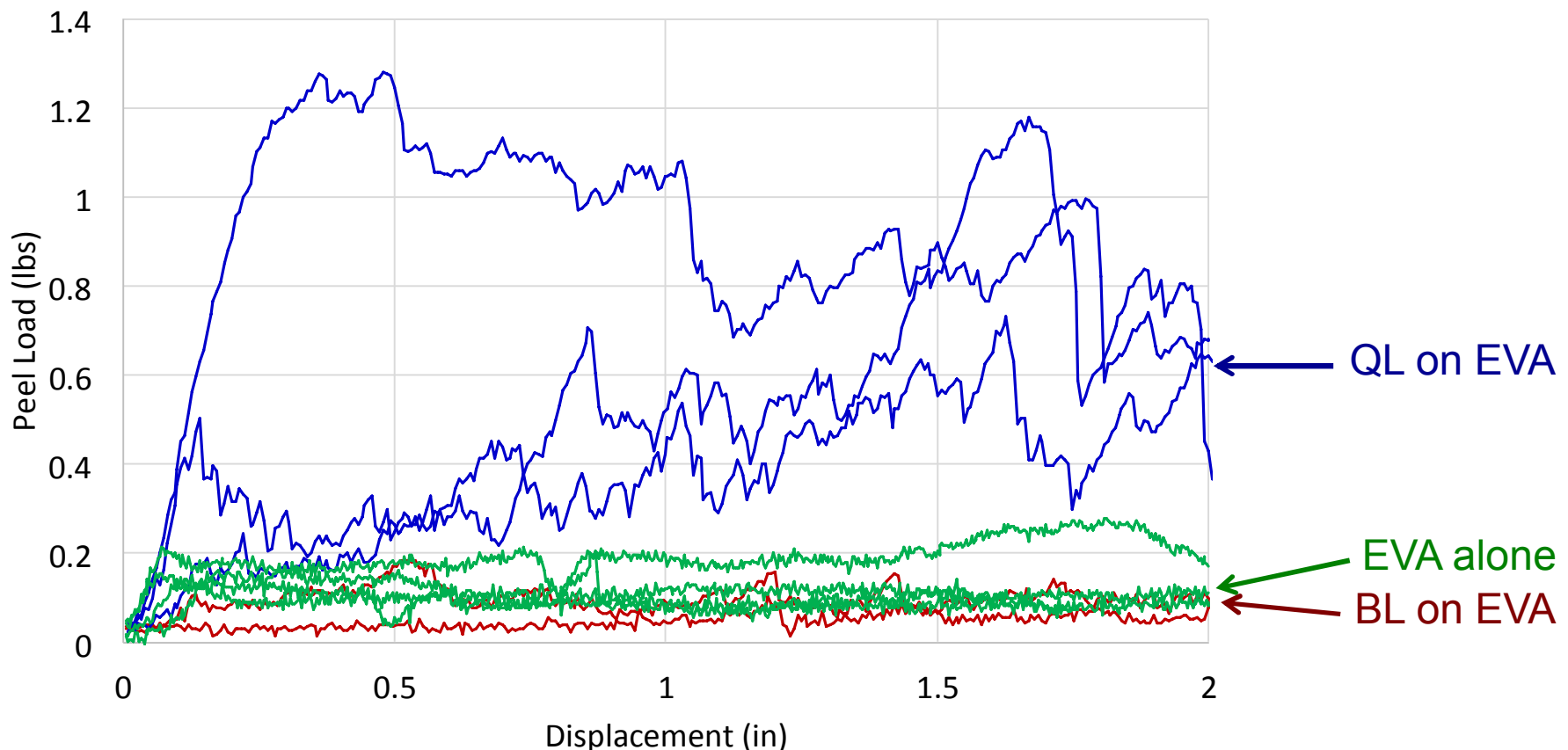
Quadlayer Film Morphology

QL films also provide multiple layers of protection, but in a more disordered way



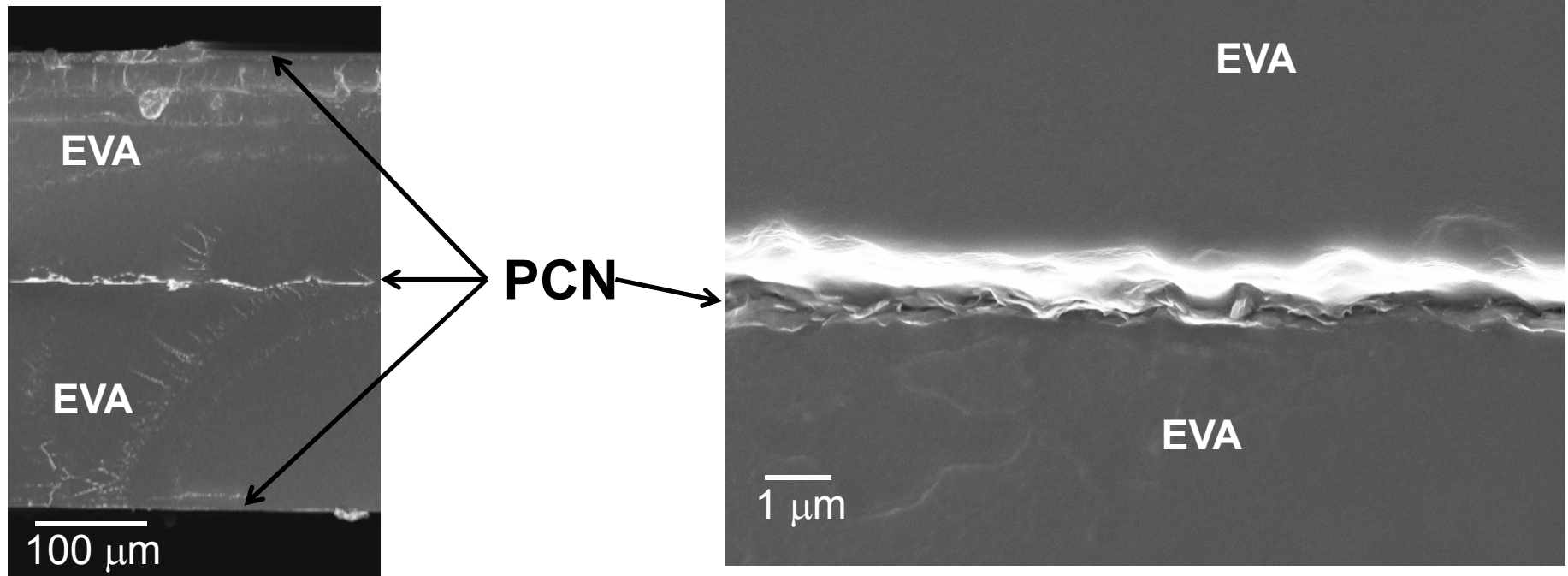
EVA Adhesion is Impacted by PCN

Preliminary evidence suggests that adhesive integrity of laminated EVA was retained or enhanced with PCN coatings.



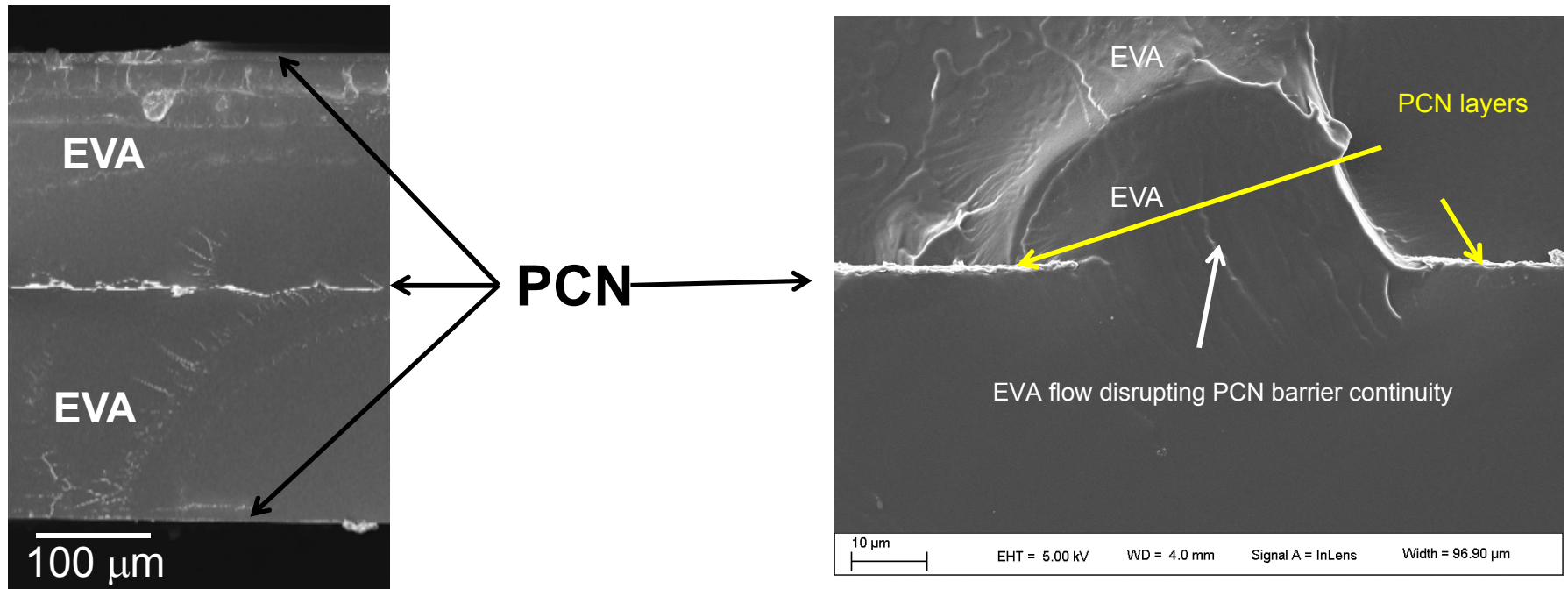
PCN/EVA Lamination

As suggested by the adhesion data, PCN-coated EVA can be laminated together...



PCN/EVA Lamination

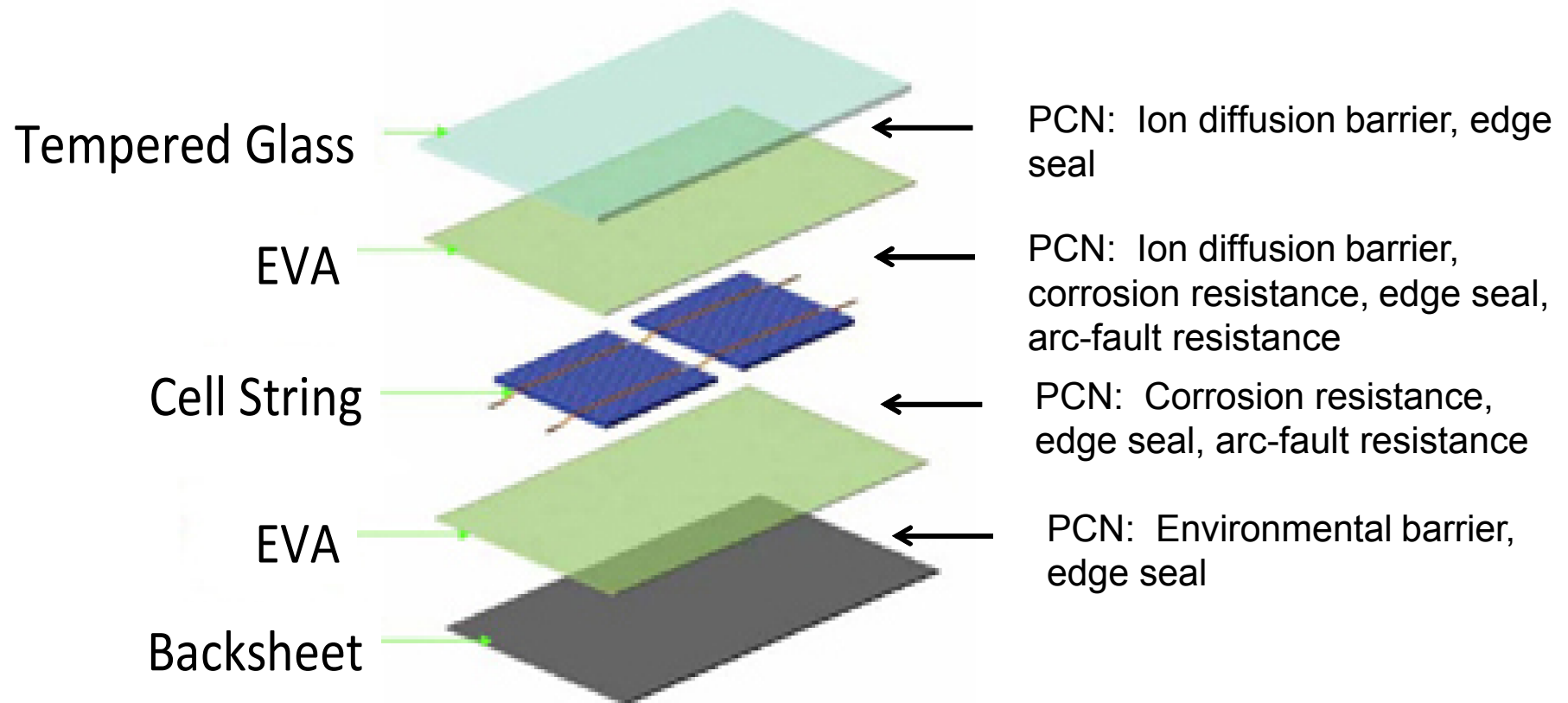
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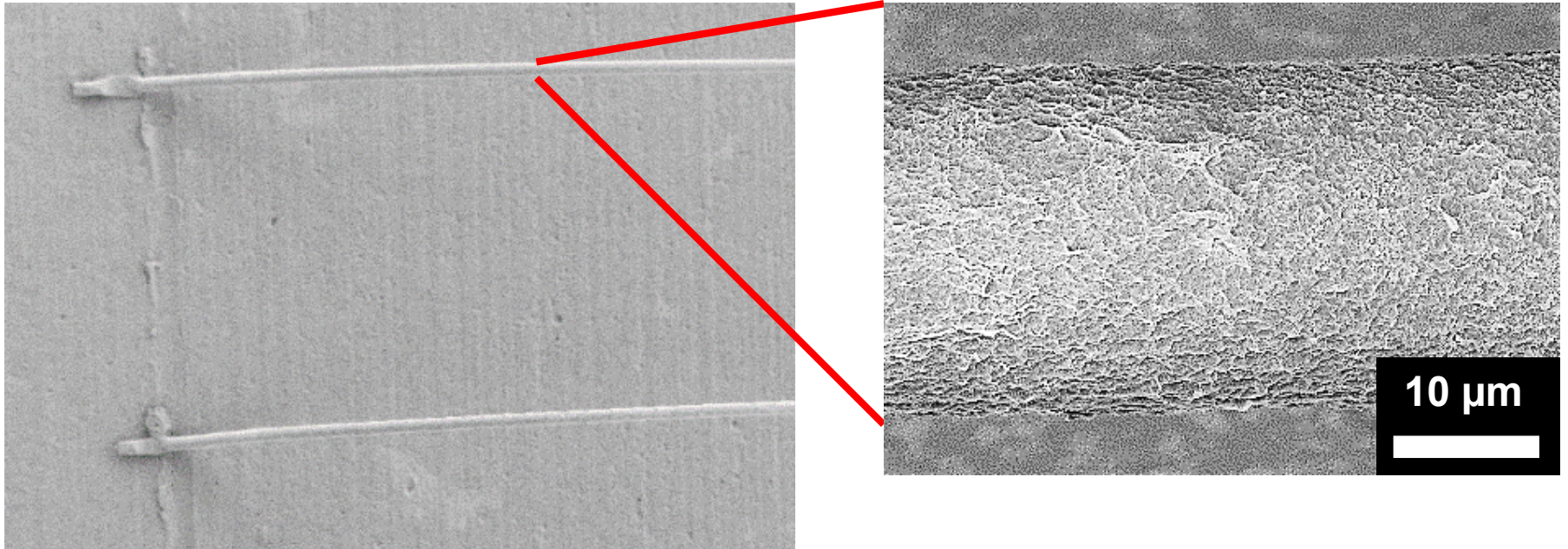
...but but the plastic flow the deforming EVA polymer disrupts the PCN barrier layer. This challenge limits the potential application of the PCNs on EVA encapsulants.

Lamination “Incompatibility” is Not a Death Sentence for PCNs in PV

PCNs can be integrated into multiple locations within a cell to provide diverse benefits



PCN Application to Electronic Interfaces



Conformal 6QL film on simulated
metallic interconnect

PCNs can be effectively and conformally grown on the complex geometries of electronics found in PV systems.

Summary and Conclusions

PCNs can be scalably grown in several different configurations (BL, QL) on a variety of important technical materials (metals, ceramics, polymers) to address critical technical challenges in photovoltaics.

- Gas barrier
- Atmospheric corrosion inhibitor
- Arc fault flammability inhibitor/arc extinguisher

Thank you!

Funding for this work was provided by Sandia's Laboratory Directed Research and Development Program.

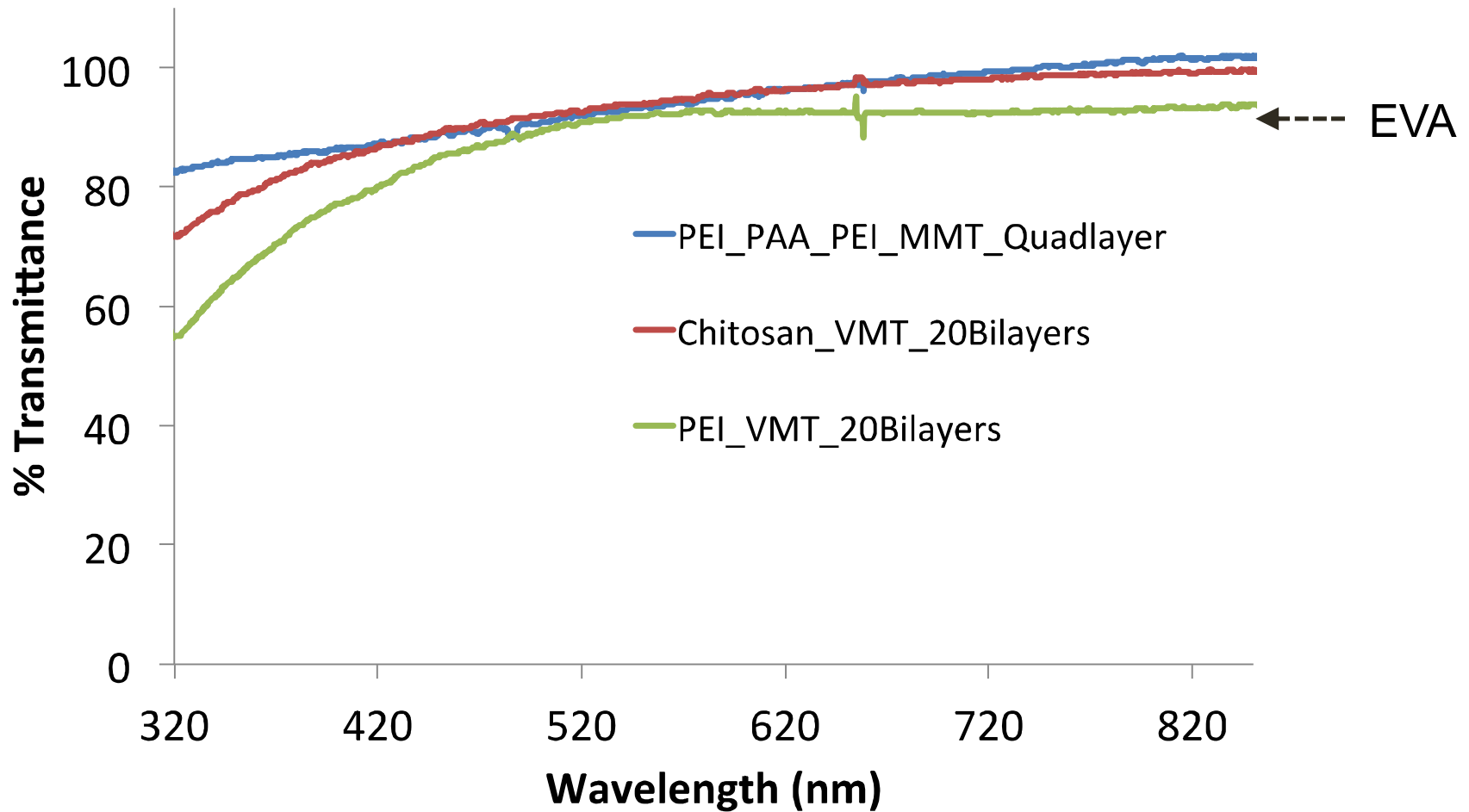


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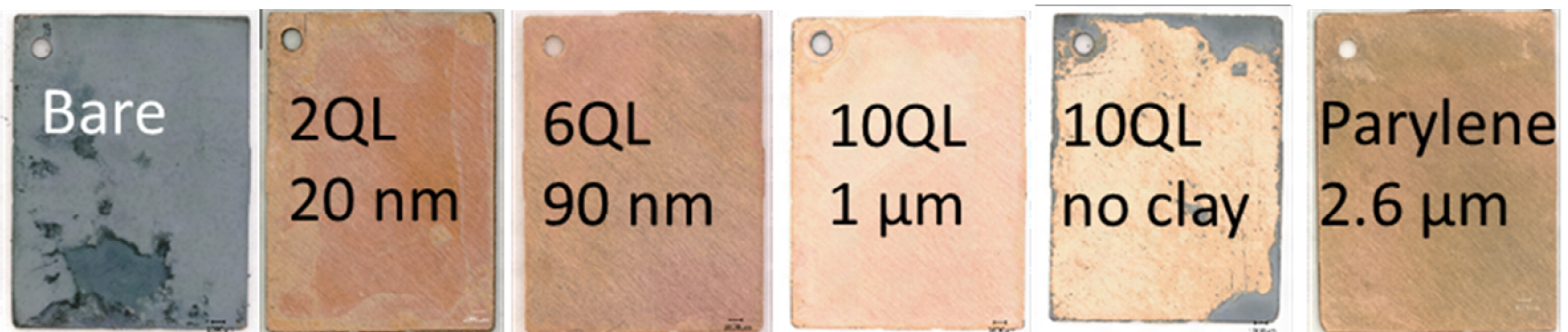


Backup Slides

Optical Transparency of PCN Thin Films



PCN-Coating Influence on copper coupons after H_2S -based atmospheric corrosion



Coated samples after 800 hours of exposure.

Why is this Important?

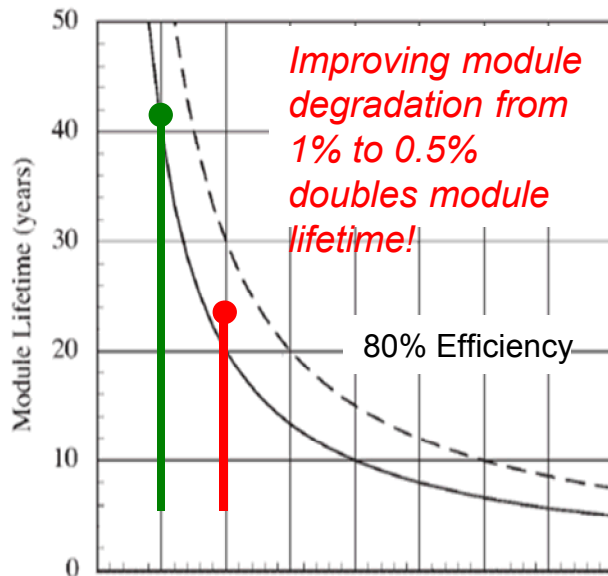
EC IAT Priority: “Renewable technologies combined with **reliable grid integration**, including generation technologies with **lower LCOE**, power electronics, storage, controls, and network cyber security.”

$$\text{LCOE (Levelized Cost of Electricity)} = \frac{\sum_{t=0}^T (I_t + O_t + M_t + F_t) / (1 + r)^t}{\sum_{t=0}^T S_t (1 - d)^t / (1 + r)^t}$$

K. Branker, et al. *Renewable and Sustainable Energy Rev.* (2011) **15**, 4470-448

LCOE is strongly dependent on device lifetime...and lifetime depends on module degradation!

Performance reduction over time is costly – the smaller the annual reduction in power, the higher the IRR



Project IRR



Annual reduction in power produced

Developing effective encapsulants is critical