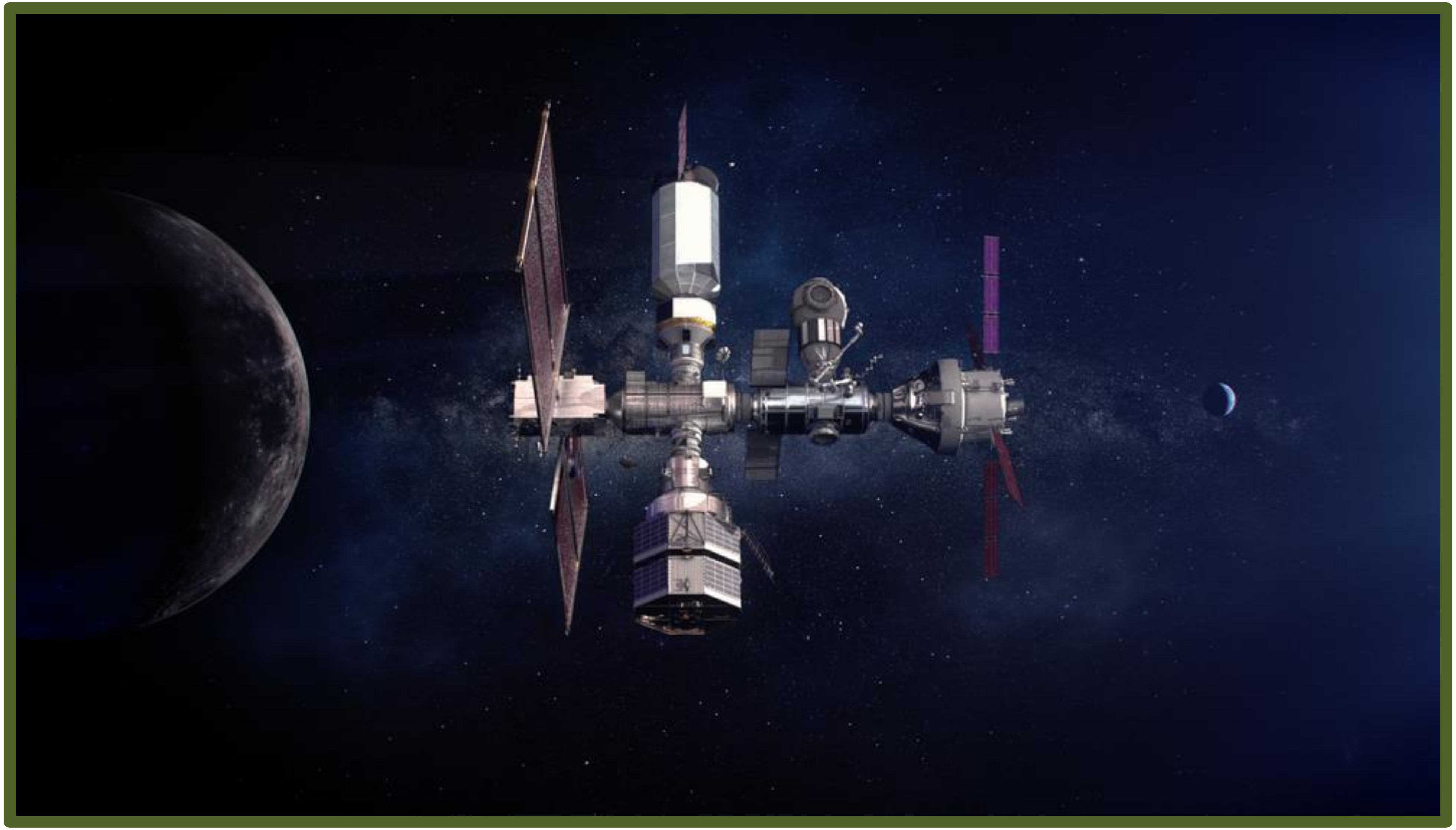
Powering the Next Frontier: Manufacturing Solar Cells in Space

Lyndsey McMillon-Brown, Ph.D.

NASA Glenn Research Center
Photovoltaics & Electrochemical Systems Branch
lyndsey.mcmillon-brown@nasa.gov

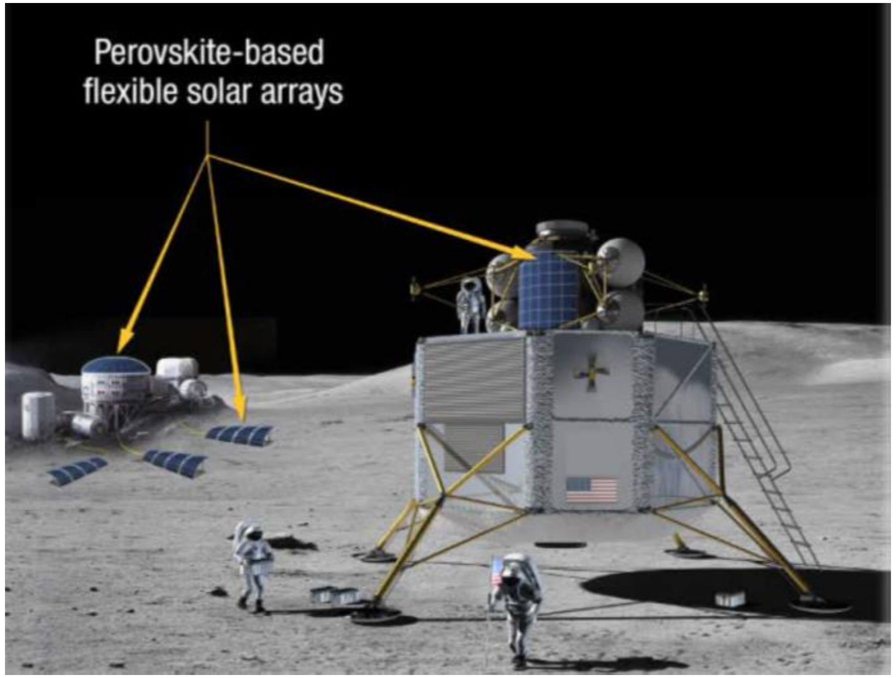
PV SPACE 23
July 5, 2023


ARTEMIS
HUMANITY'S RETURN
TO THE MOON



Powering Artemis

- NASA Strategic Gaps
  - Lunar Science Report https://www.nasa.gov/reports
  - Decadal surveys (2023-2033, National Academies)
- Agency Need: Lunar surface power is unlike most other space power. The need is for very large arrays, and significantly reduced cost. These goals are more readily met by perovskite thin films.

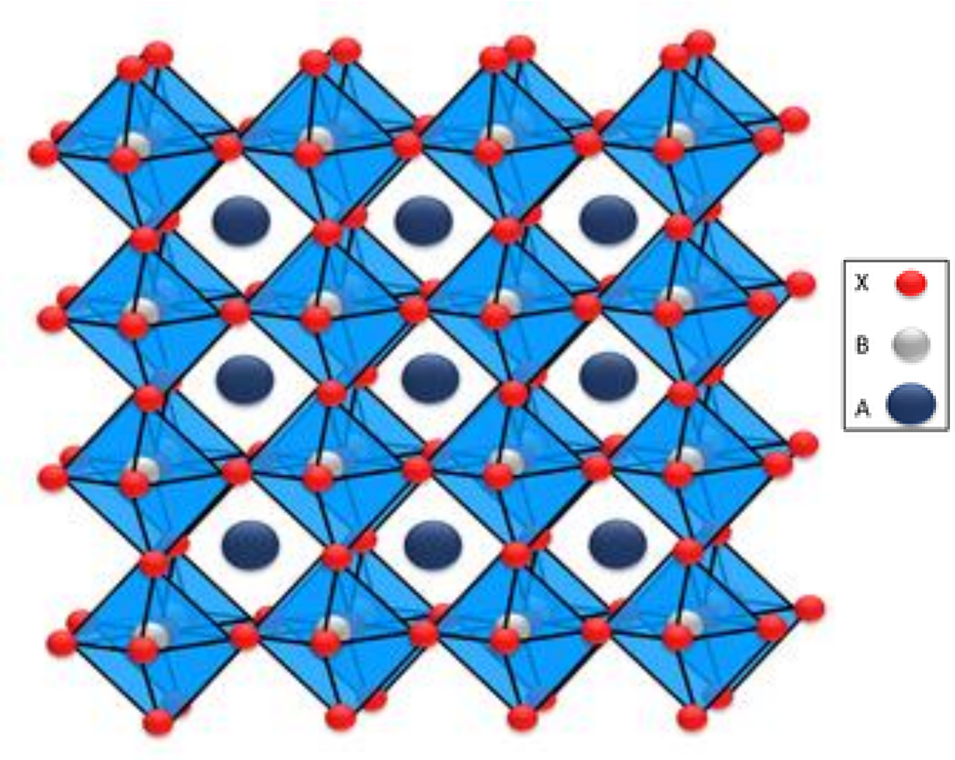


What is a perovskite?

ABX_3

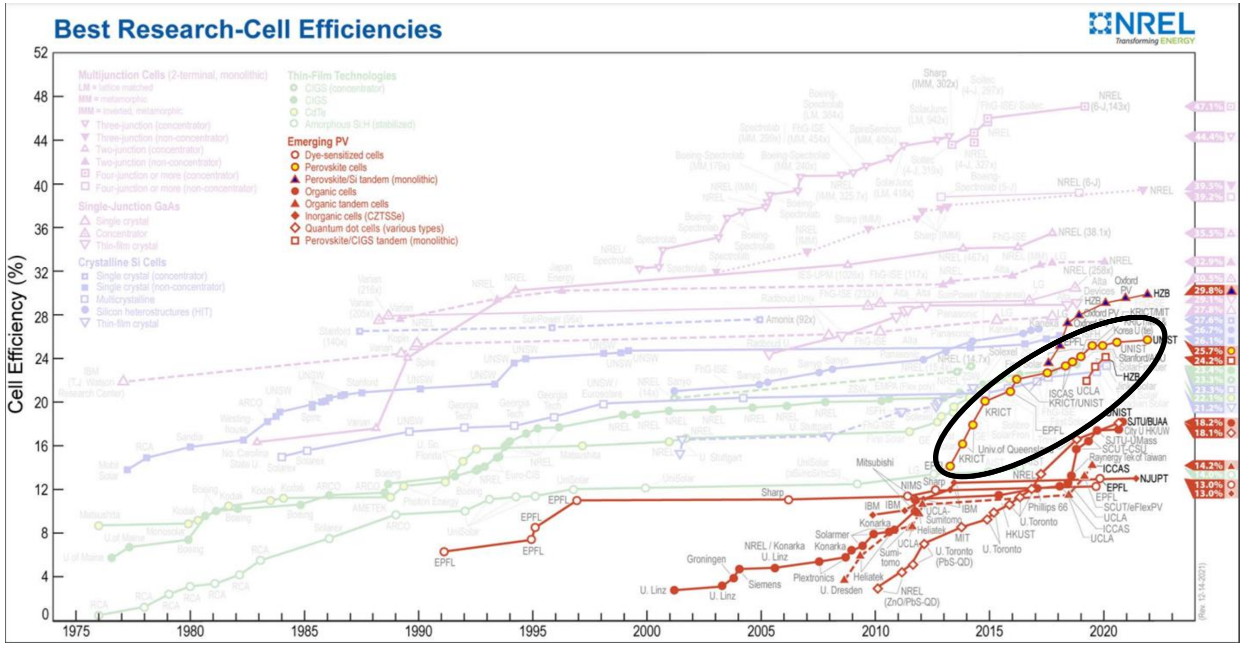
$(MA/FA)PbI_3$

- Material with the same crystal structure as mineral calcium titanium oxide ($CaTiO_3$)
- A and B are cations
- X is an anion that bonds to both
- For solar materials they're commonly hybrid organic-inorganic lead or tin halide based material
- Many elements can be combined to form perovskite structures
- The crystals can have a wide variety of physical, optical and electrical characteristics.



Motivation and Project Goals

- Perovskite-based photovoltaics
  - ✓ Thin Films (300 nm)
  - ✓ Radiation hardness
  - ✓ Defect tolerance
  - ✓ Liquid or vapor phase processable
  - ✓ Light weight
  - ✓ Low cost
- Stability challenges
  - Vacuum / thermal
  - Moisture / oxygen
- Compatible with in-space manufacturing



1 MW solar array can be printed while transporting 12 kg of condensed material to orbit.

- Demonstrate the feasibility of perovskite-based photovoltaics for applications in space
- Demonstrate durability at the research level in relevant environments (LEO, lunar)
- Technical Goal: the enabling of in space manufactured perovskite solar cells capable of a 100X decrease in cost/watt compared to the current state of the art.

Research Team

Dr. Lyndsey McMillon-Brown
Dr. Timothy J Peshek
Dr. Kyle Crowley
Dr. Kaitlyn VanSant
Jeremiah Sims
Tim Krause






UNIVERSITY OF CALIFORNIA MERCED

Prof. Sayantani Ghosh
Dr. William Delmas
Samuel Erickson

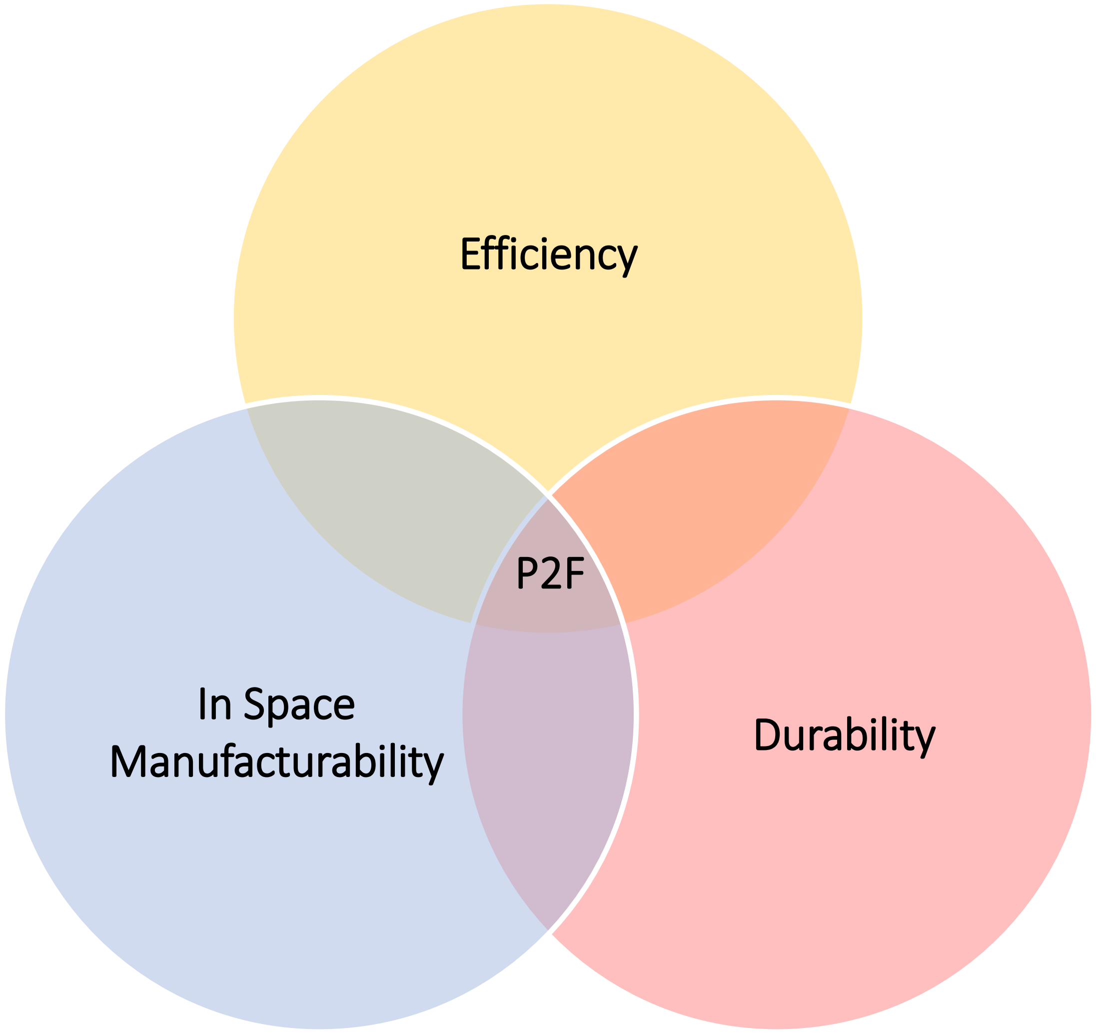


NREL

Dr. Joey Luther

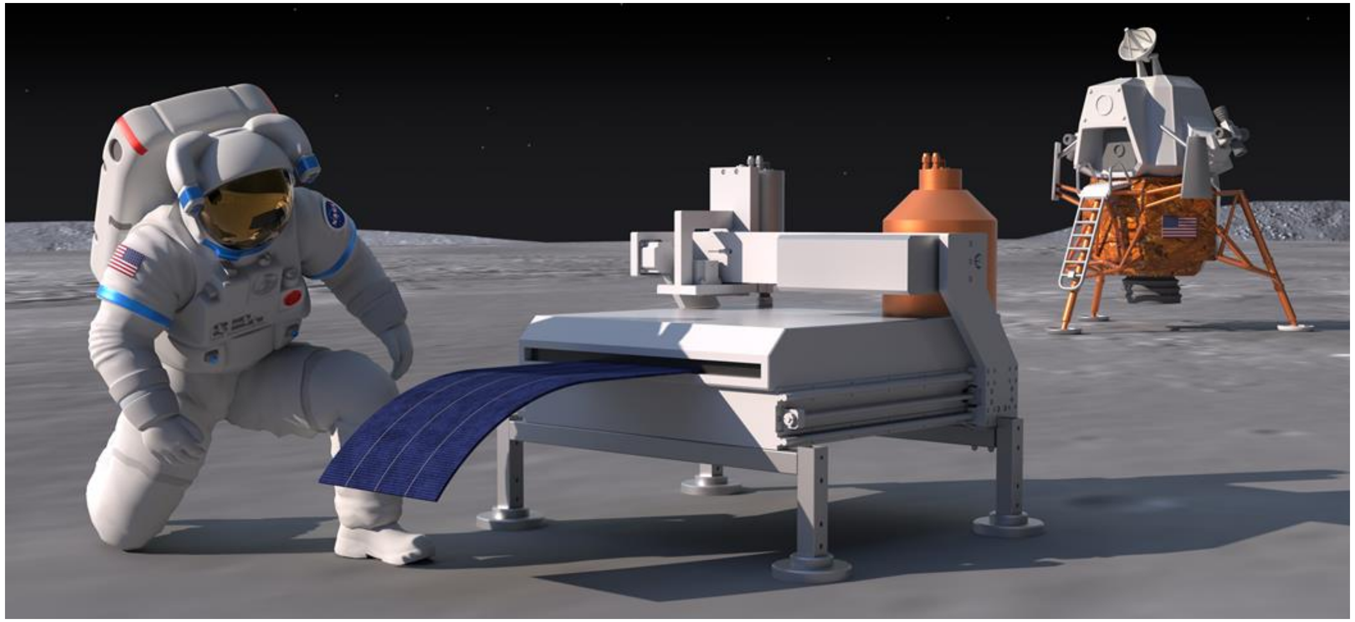
Path 2 Flight

- Durability
  - Atomic Oxygen
  - Temperature
  - Vacuum
  - Radiation (e^-, p^+)
  - Combined effects (MISSE)
- Efficiency
  - Materials Selection
  - Environmental effects
- In-Space Manufacturability
  - Physical Vapor Deposition
  - Thin film barrier layers
    - Thermal management
    - Radiation protection



What will it take to manufacture solar cells in space?

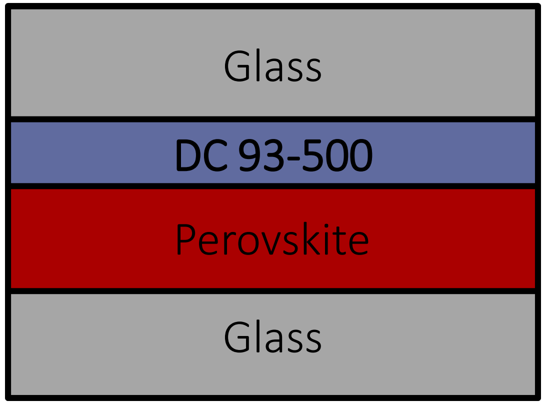
- Overcome thermal, vacuum, and humidity challenges
- Address radiation concerns
- Understand degradation modes resulting from space environment
- Find light weight space ready substrates
- Leverage the vacuum of space for deposition
- Leverage the sun to create high quality films

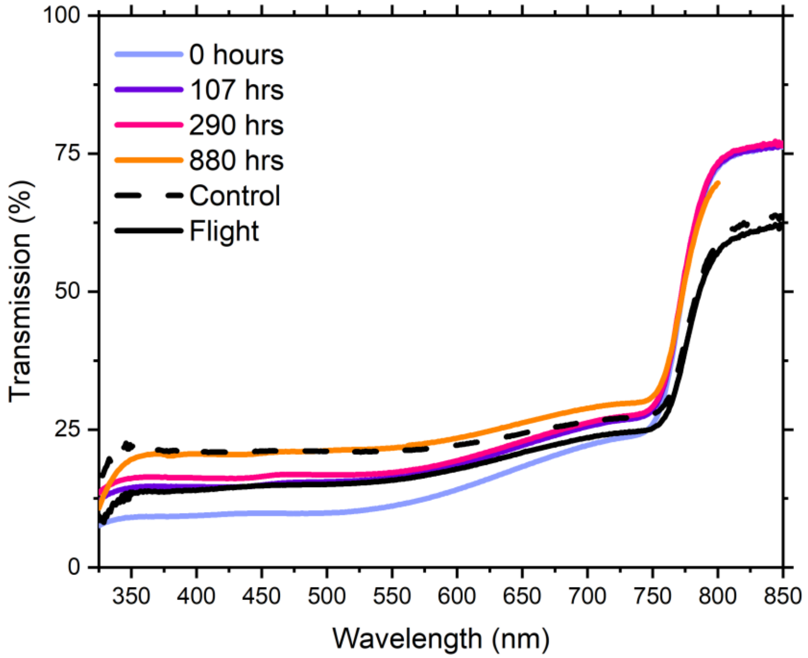


L. McMillon-Brown, et al. *ACS Energy Lett.* 2022, 7, 3, 1040–1042
https://doi.org/10.1021/acsenergylett.2c00276

Overcome Humidity Challenges

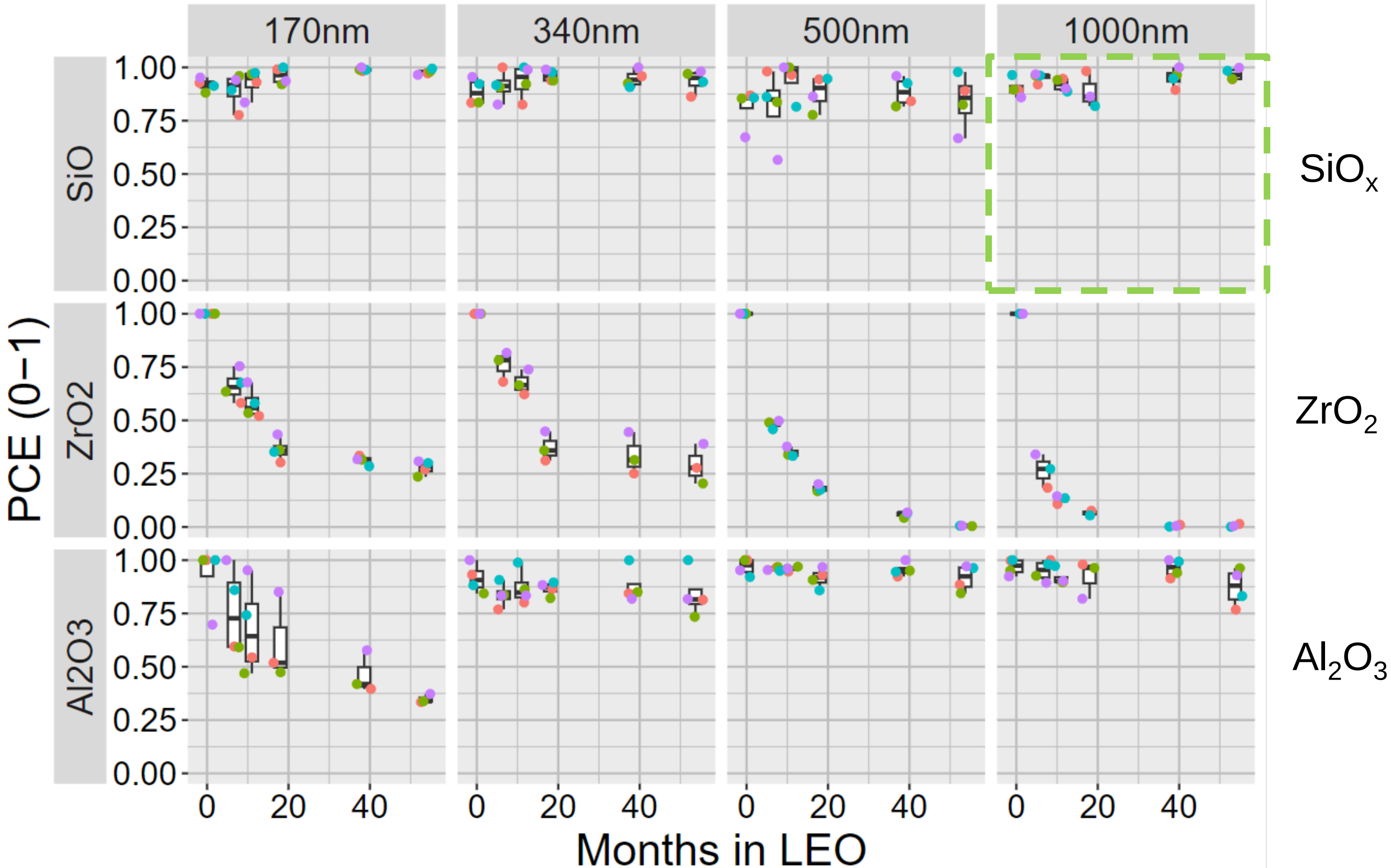
- AIAA S111 standards: 95% RH at 45 ℃ for 1500 hr
- $MAPbI_3$ perovskite active layers exposed for 880 hr. at 30 ± 5 ºC and 95% RH



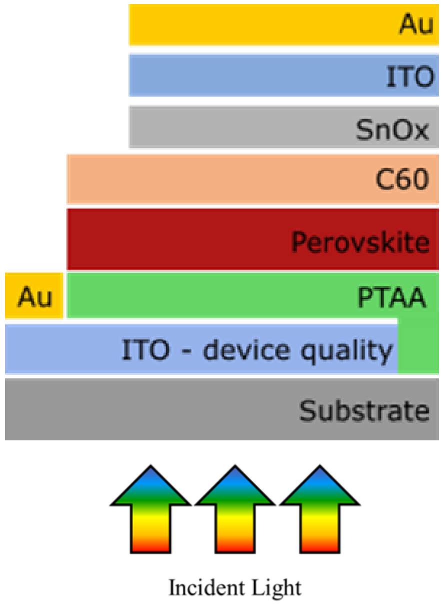


No detectable changes in chemical stoichiometry of encapsulated samples across 880 hours of damp heat (30 ºC and 95% RH).

Enduring Atomic Oxygen



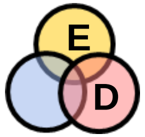
Kyle Crowley



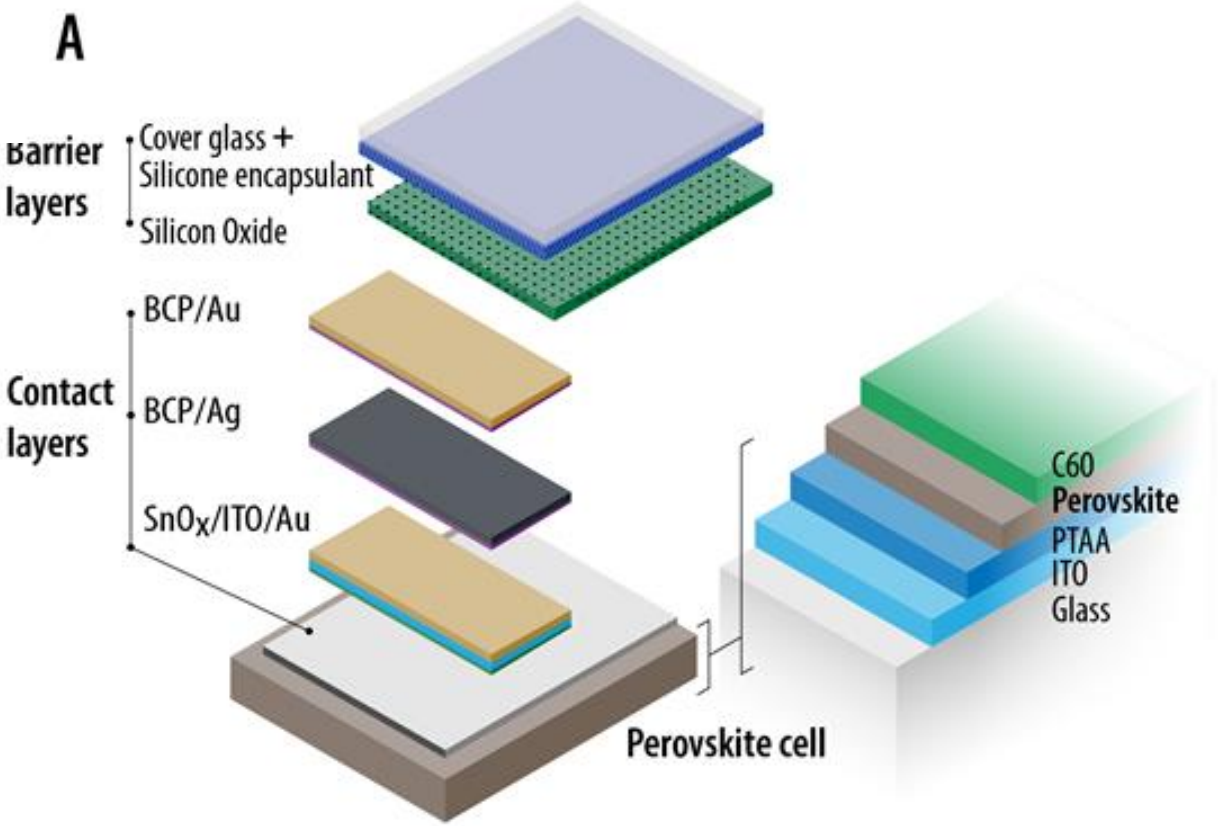
Designed thin film layers capable of protecting the devices against AO fluence equivalent to 5 years in LEO. We have also exposed these devices to electron irradiation.

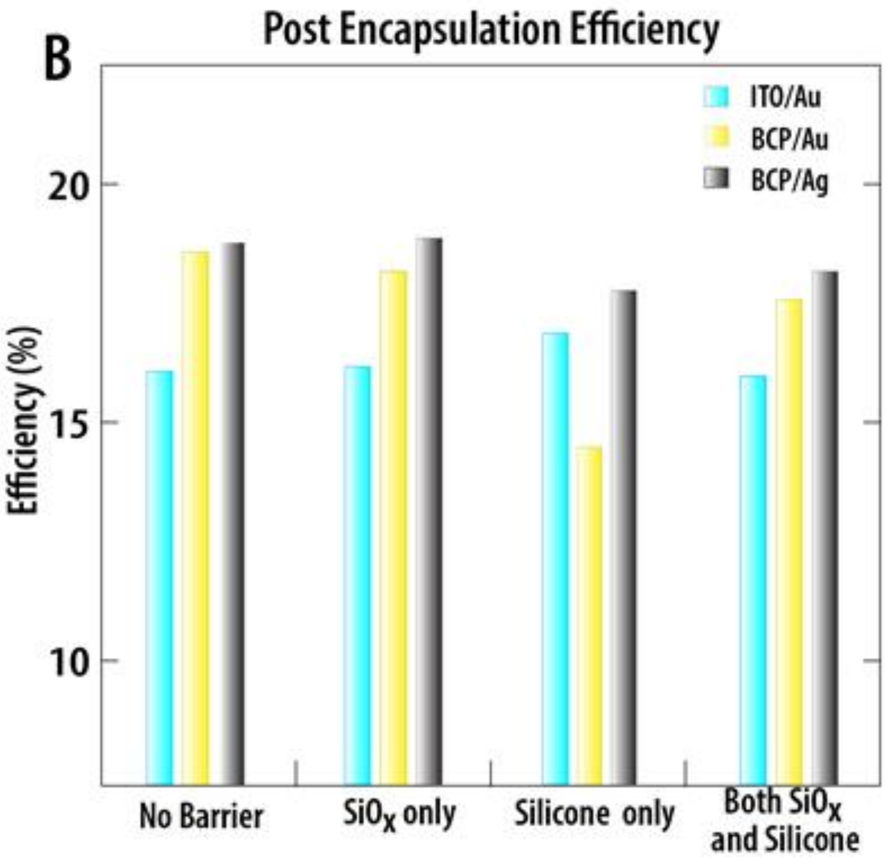
K. Crowley, et al. *In preparation*.

Thermal and Vacuum Stability



Perovskite = $Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}Pb(I_{0.83}Br_{0.17})_3$



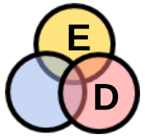


Kaitlyn VanSant

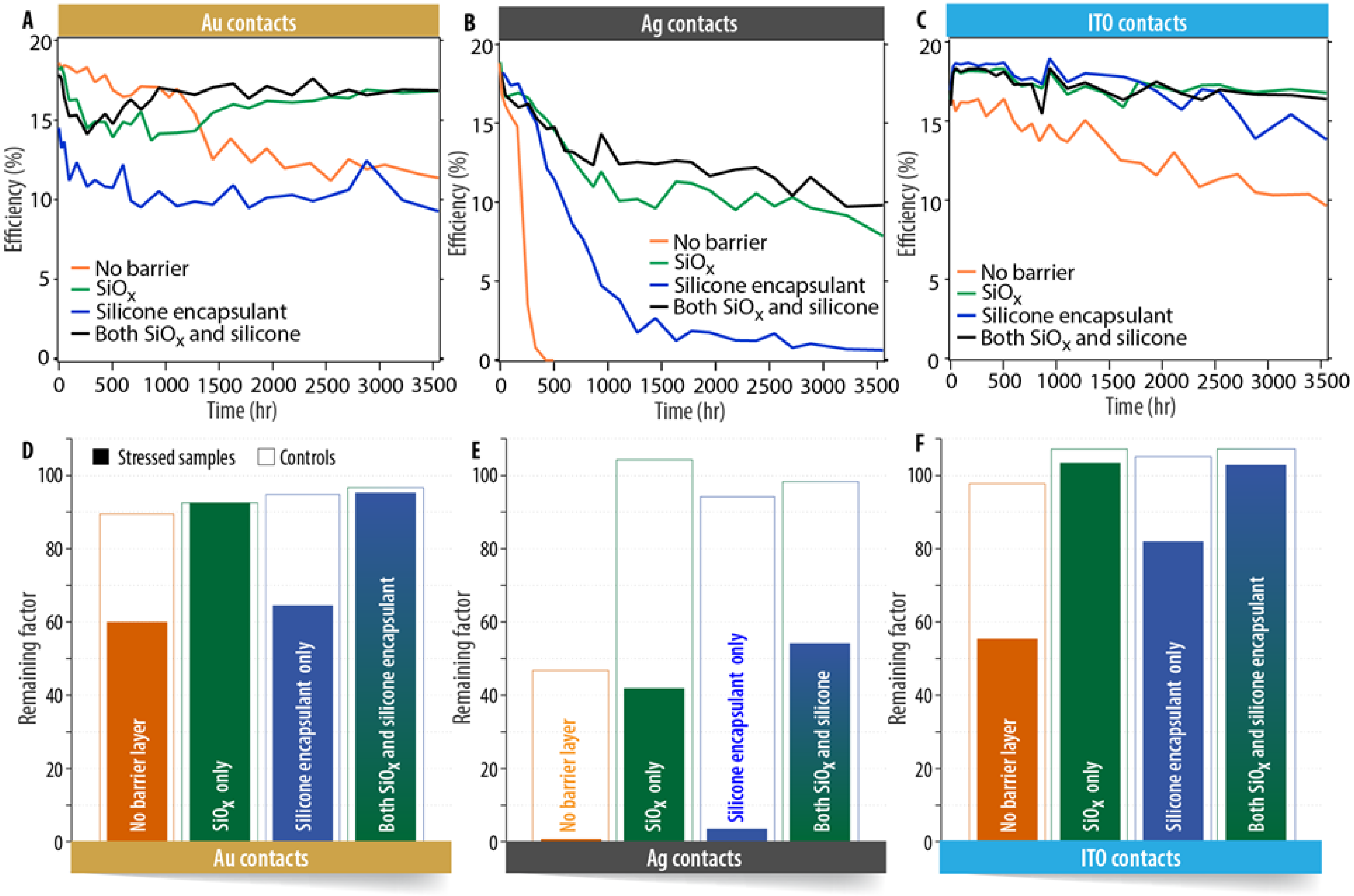
Demonstrated thermal and vacuum stability in contacts for more than 3600 hours.

K. VanSant, et al. *ACS Appl. Energy Mater.*, accepted.

Thermal and Vacuum Stability



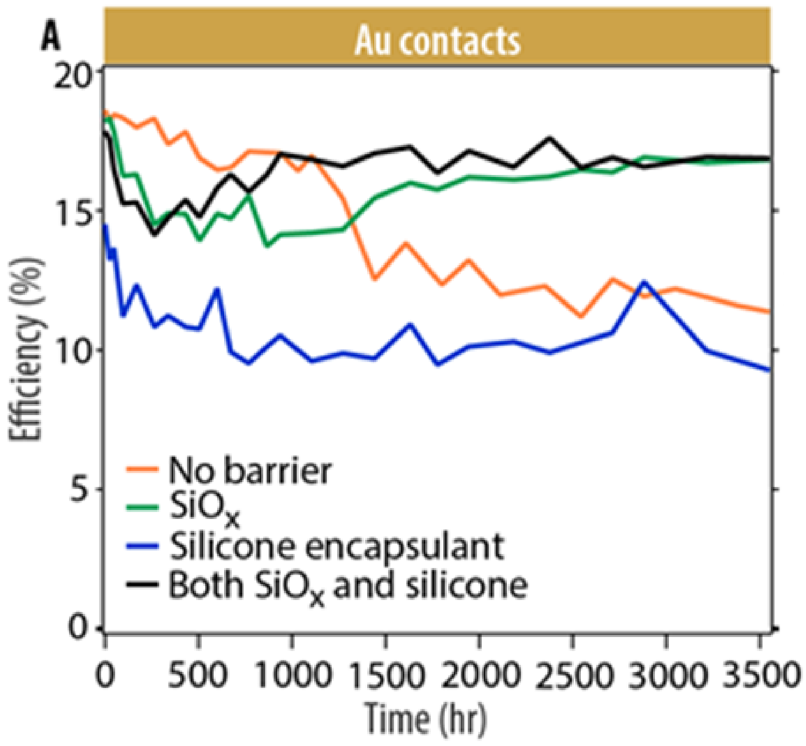
75 ℃ (± 5 ℃)
1– 2 x 10^{-2} Torr

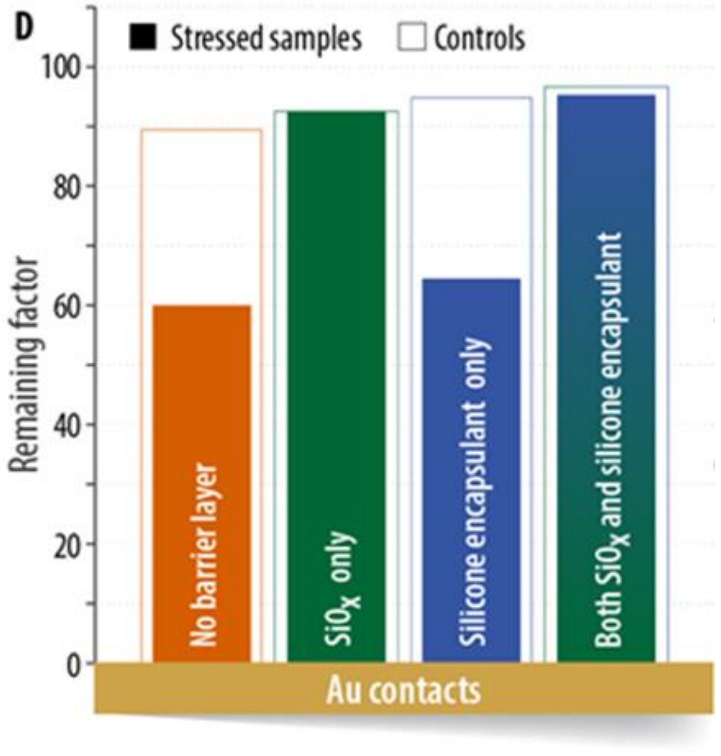


Kaitlyn VanSant

K. VanSant, et al. *ACS Appl. Energy Mater.*, accepted.

Thermal and Vacuum Stability – Au Contacts



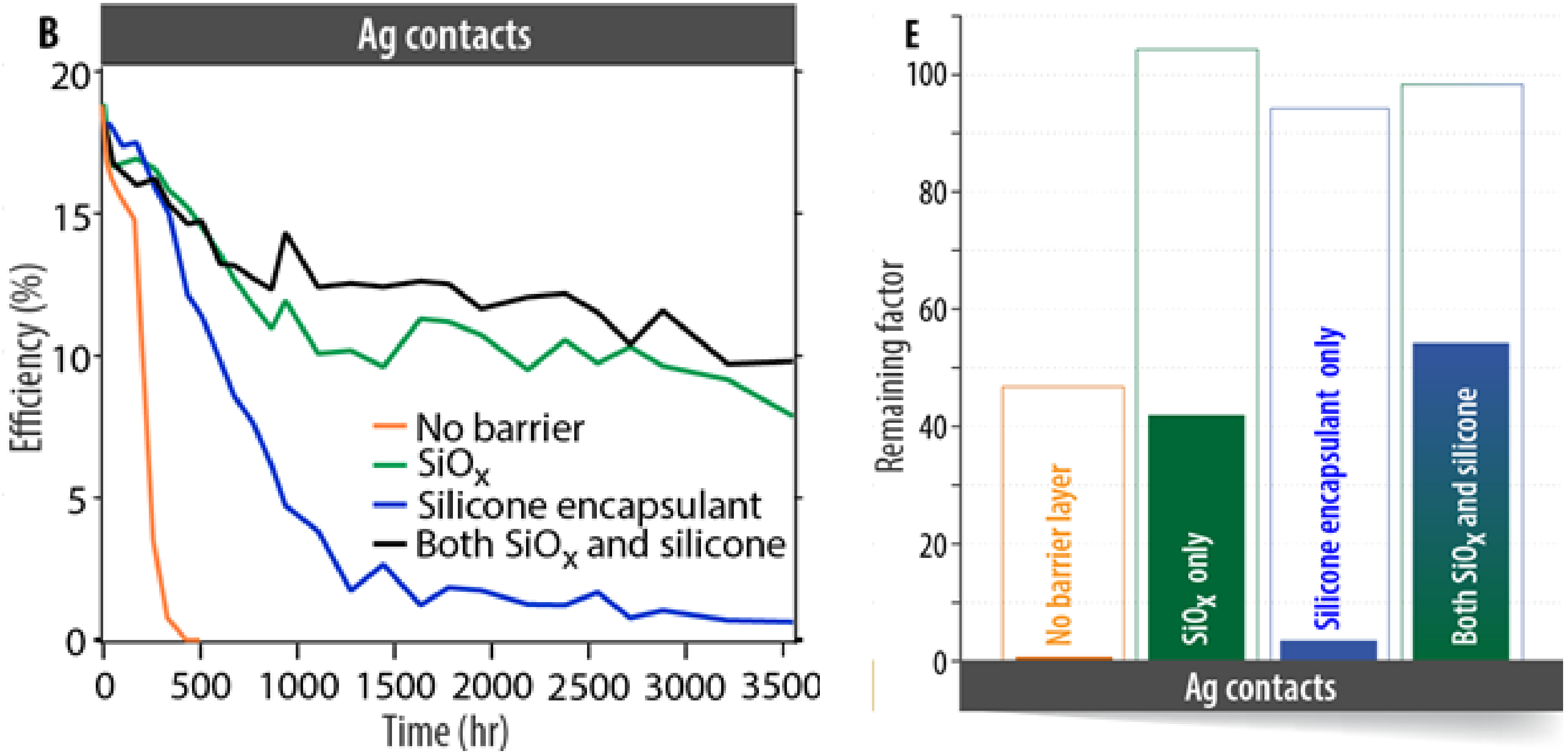


Kaitlyn VanSant

- Au-contacted cells with a barrier layer exhibit a 2 - 4% drop in average efficiency (absolute) within the first 100 hours.
- Au-contacted cells with both SiO_x and the silicone encapsulant/ cover glass begin to recover after ~300 hours
- Au-contacted cells with SiO_x alone generally begin to recover after ~500 hours.

K. VanSant, et al. *ACS Appl. Energy Mater.*, accepted.

Thermal and Vacuum Stability – Ag Contacts

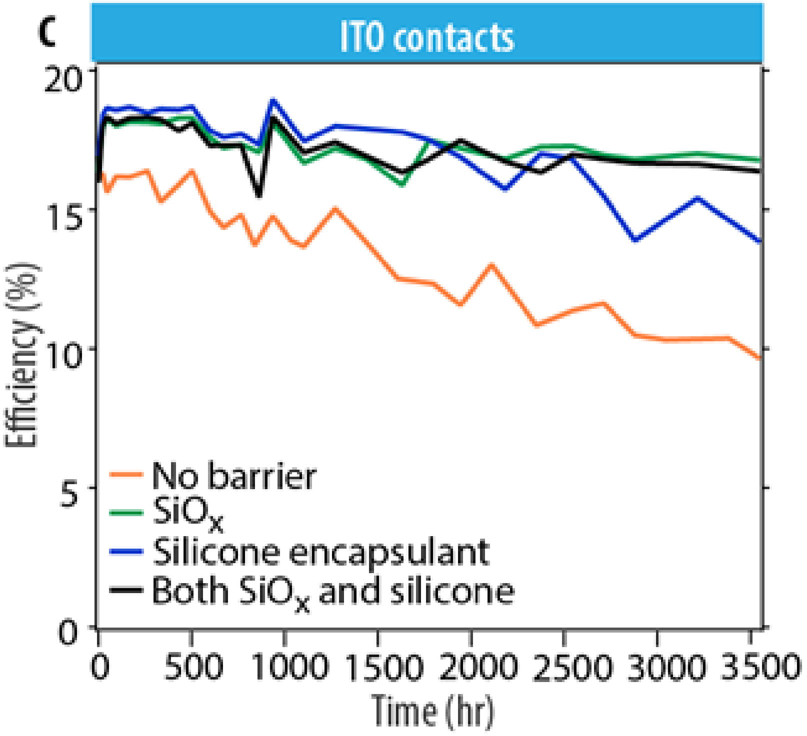


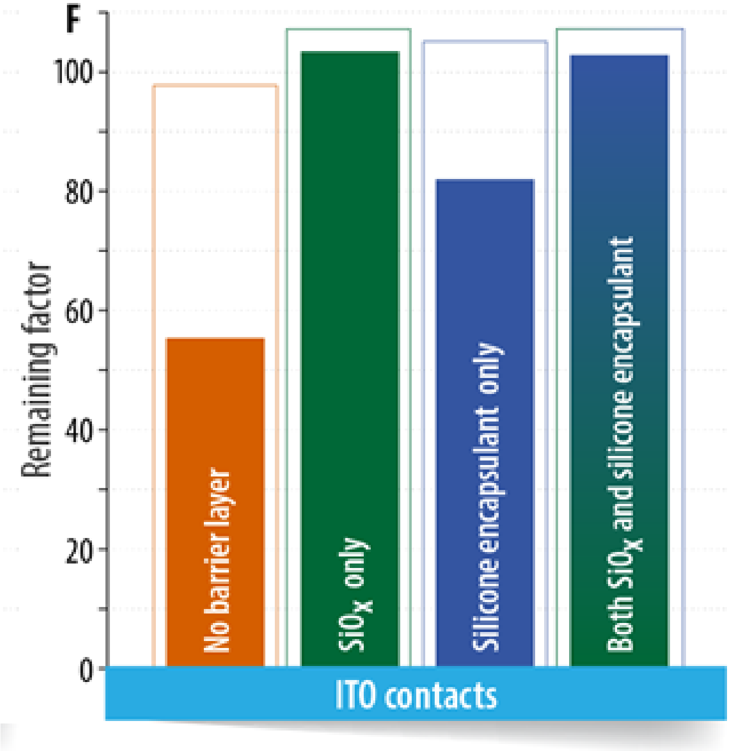
Kaitlyn VanSant

- Ag-contacted cells without barrier layer and with silicone encapsulant fail completely
- Ag-contacted cells with SiOx only and with both SiOx and the silicone encapsulant/cover glass exhibit steady degradation over the course of stress testing.
- Failure of the Ag-contacted cells is likely due to interaction between Ag and the perovskite layer, resulting in degradation related to AgI formation.

K. VanSant, et al. *ACS Appl. Energy Mater.*, accepted.

Thermal and Vacuum Stability – ITO Contacts



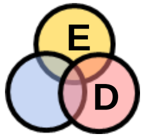


Kaitlyn VanSant

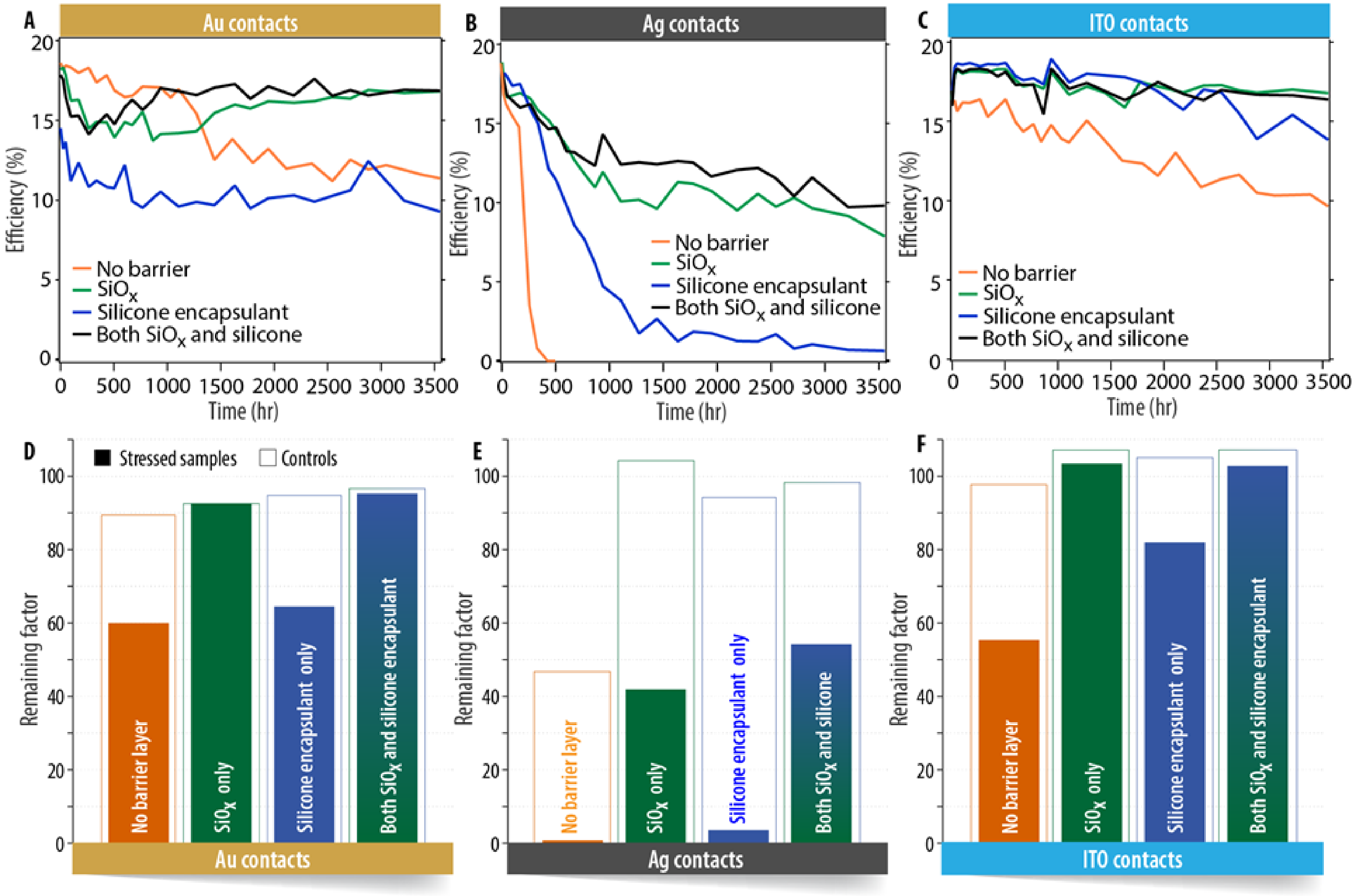
- ITO-contacted cells exhibit remarkable stability for all cells that include a barrier layer
- ITO-contacted cells cells exhibit an annealing effect within the first 48 hours that boosts the efficiency by ~2% (absolute)
- ITO-contacted cells with SiO_x only and SiO_x with silicone encapsulant stabilize at an efficiency 0.4% (absolute) higher than the initial efficiency after 3600 hours of thermal vacuum stress

K. VanSant, et al. *ACS Appl. Energy Mater.*, accepted.

Thermal and Vacuum Stability



75 ℃ (± 5 ℃)
1– 2 x 10^{-2} Torr

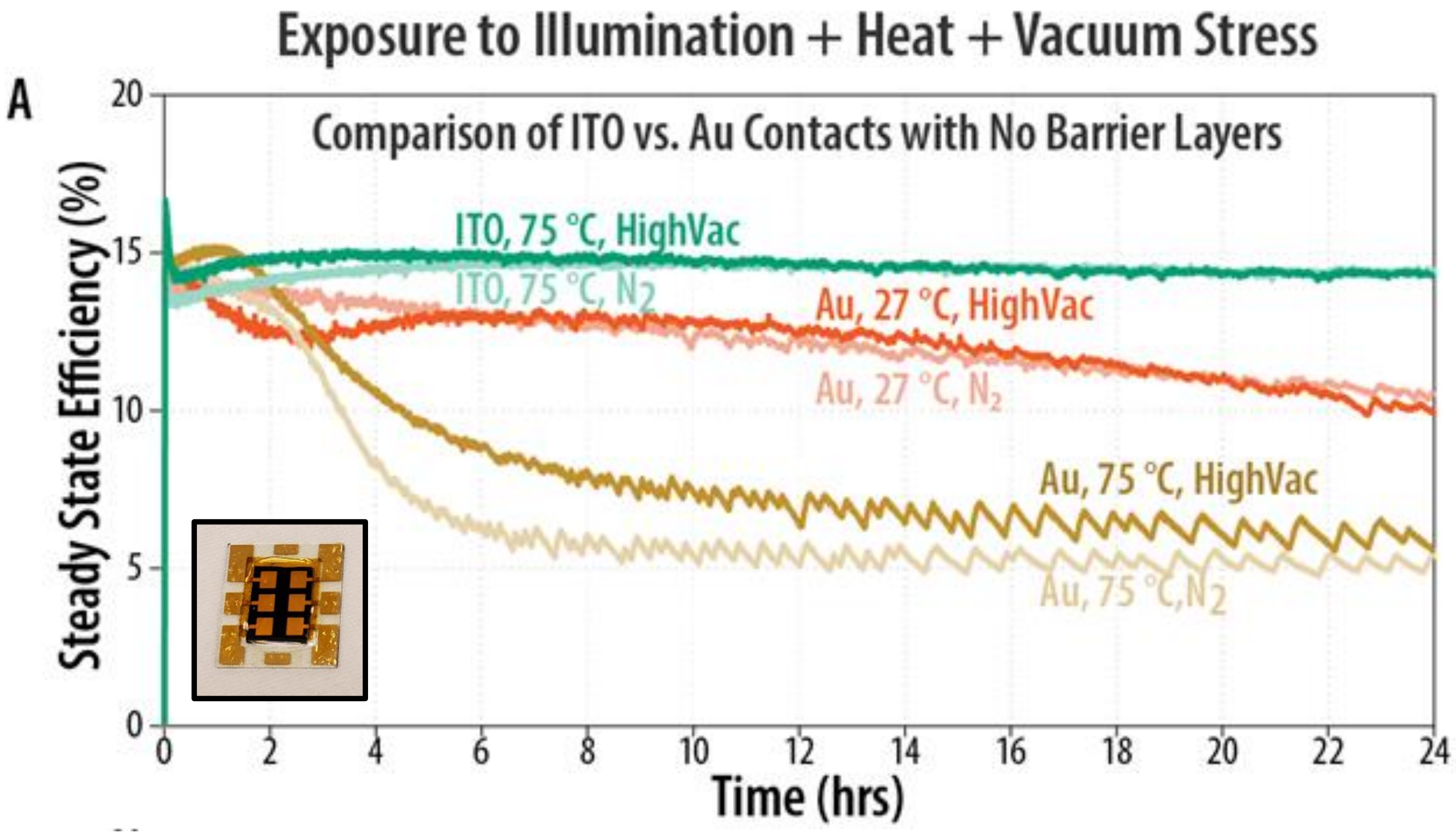


Kaitlyn VanSant

Both ITO and Au could be promising candidates when coupled with SiO_x or SiO_x + silicone encapsulant

K. VanSant, et al. *ACS Appl. Energy Mater.*, accepted.

Light, Thermal and Vacuum Stability



Kaitlyn VanSant

Time: 24 hr
Temperature: 348 K= 75 C
Pressure: High Vacuum = 2.3 x10^{-6} Torr
Light: AM0 Spectrum, 1000 W/m^2

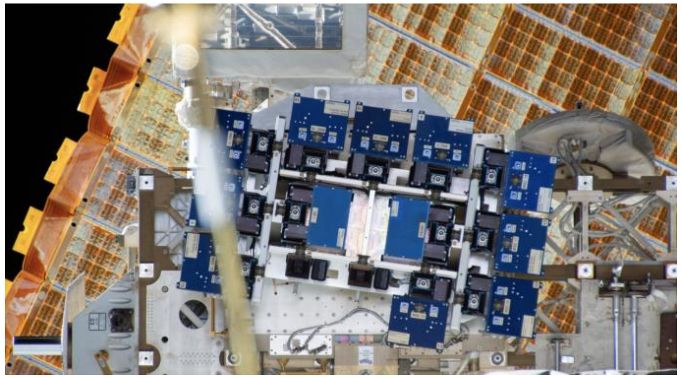
ITO Contacted cells are the most stable contact

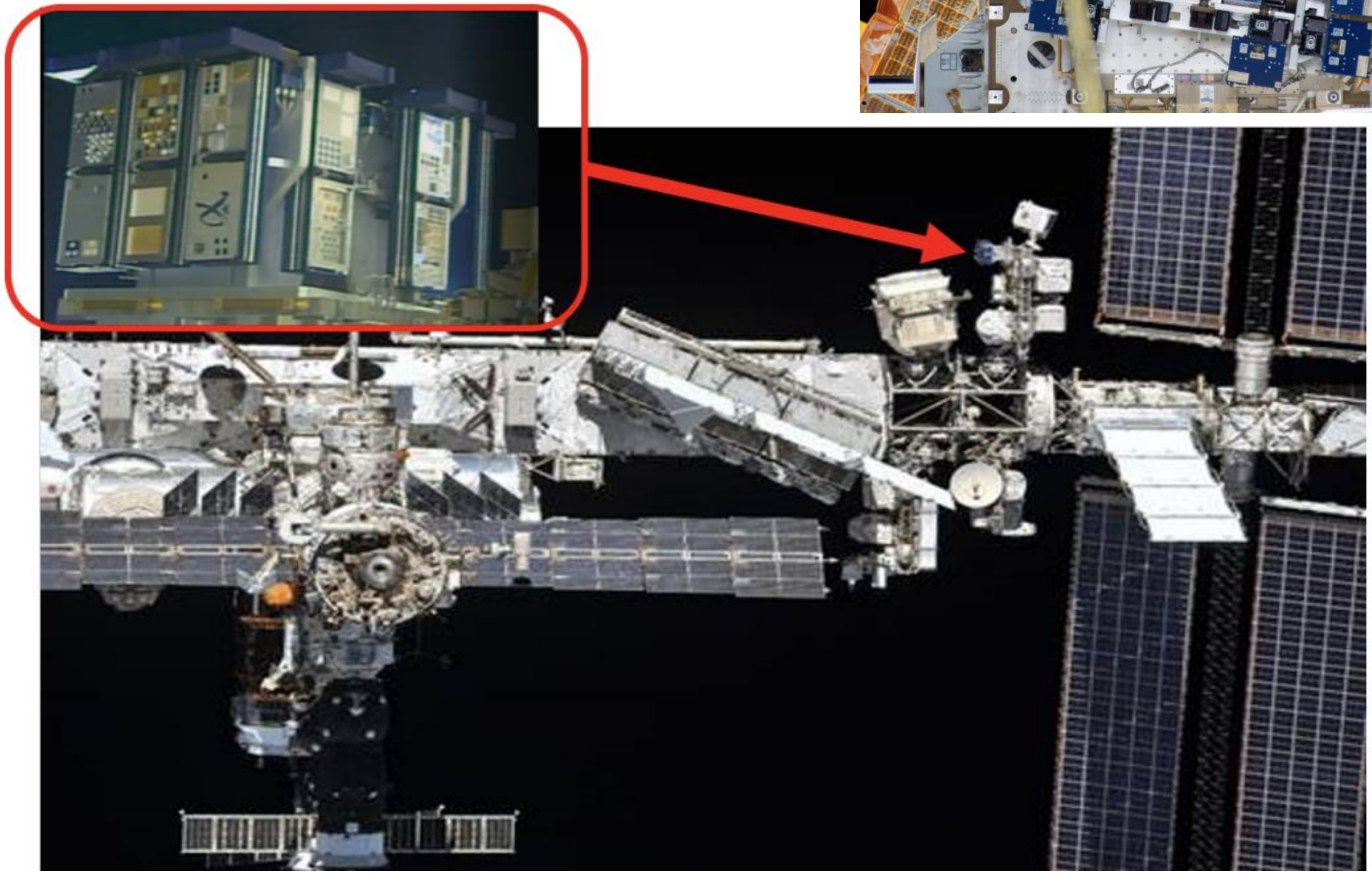
K. VanSant, et al. *ACS Appl. Energy Mater.*, accepted.

In-Space Testing

D

- Materials International Space Station Experiment (MISSE 13, 15 and 16)
- Extended flight in Low Earth Orbit
  - Ionizing radiation
  - UV radiation
  - Atomic Oxygen
  - Vacuum
  - Thermal cycling

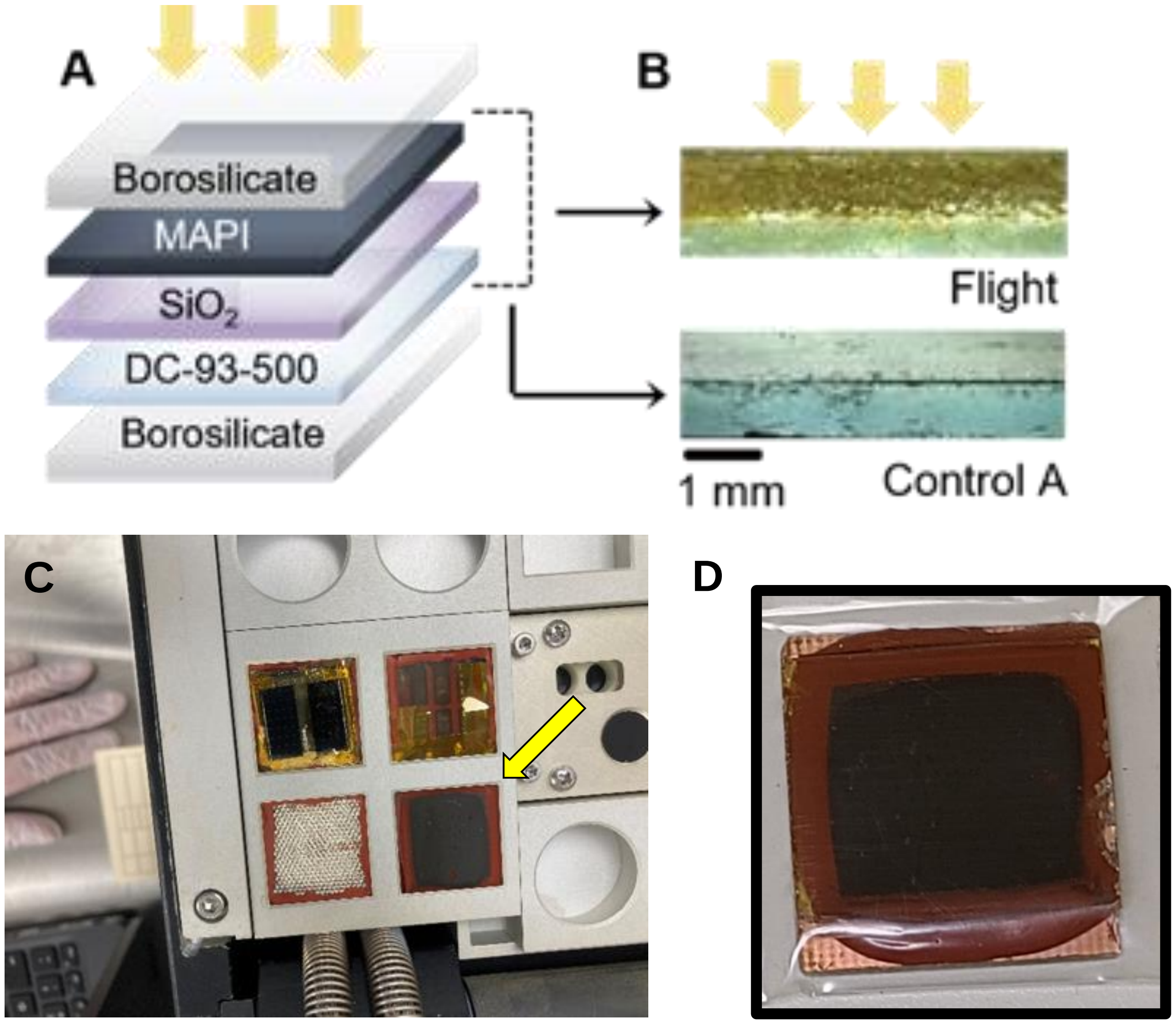




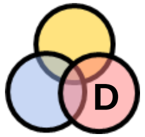
In-Space Testing Timeline

- Sample aligned in zenith direction
  - -20 º C ≤ T_{MIN} ≤ 0 ºC
  - 65 º C ≤ T_{MAX} ≤ 85 ºC
- Demonstrated success with $MAPbI_3$ film surviving 10 months in LEO.
- Effects of tensile strain on $MAPbI_3$ film caused by thermal cycling are reversable through PbI_2 inclusion healing with light soaking.

- Integrated October 2019
- Launched March 2020
- Landed January 2021
- Returned March 2021

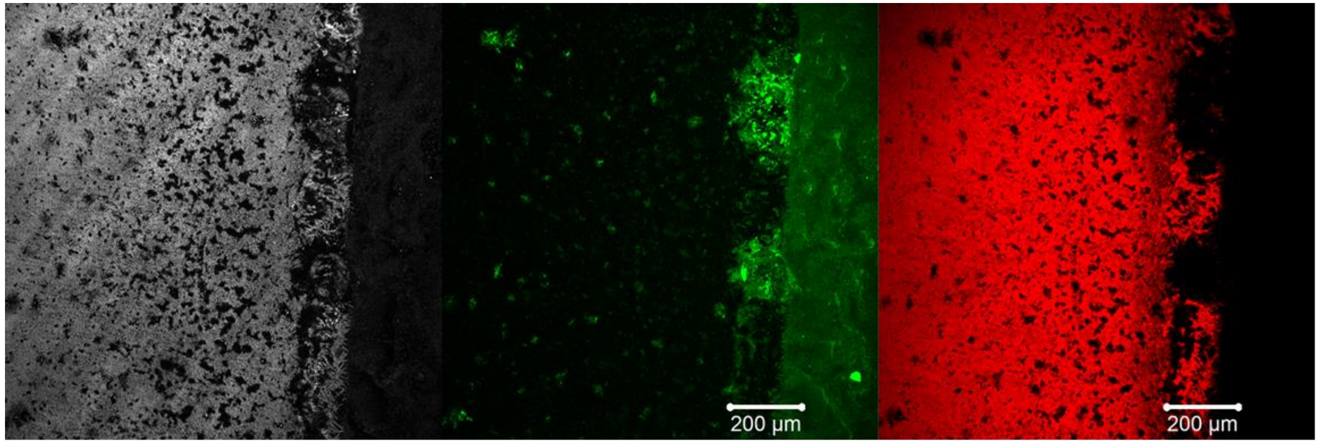


Ambient Comparison of Flight vs Ground



405nm excitation while collecting at:

- 400nm – 410nm (Sample reflection)
- 490nm – 530nm (PbI_2 Emission)
- 700nm – 800nm (MAPI Emission)

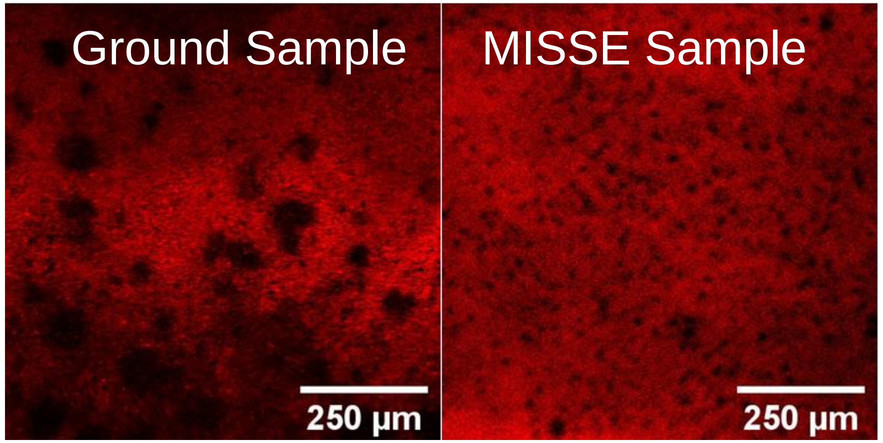


400nm-410nm Reflection | 490nm-530nm Emission | 700nm-800nm Emission

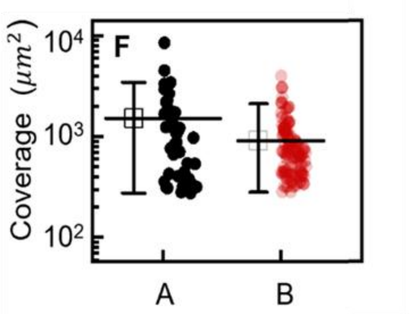
PbI_2 Region Analysis:

A. Grounds Sample
   - Total Area: 23%
   - Average Size: 1,100 μm^2

B. MISSE Sample
   - Total Area: 12%
   - Average Size: 900 μm^2

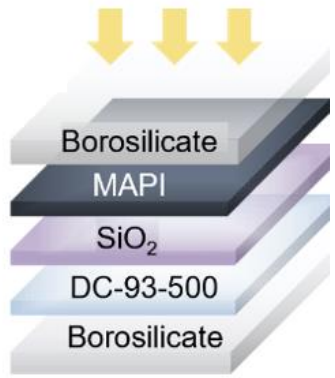


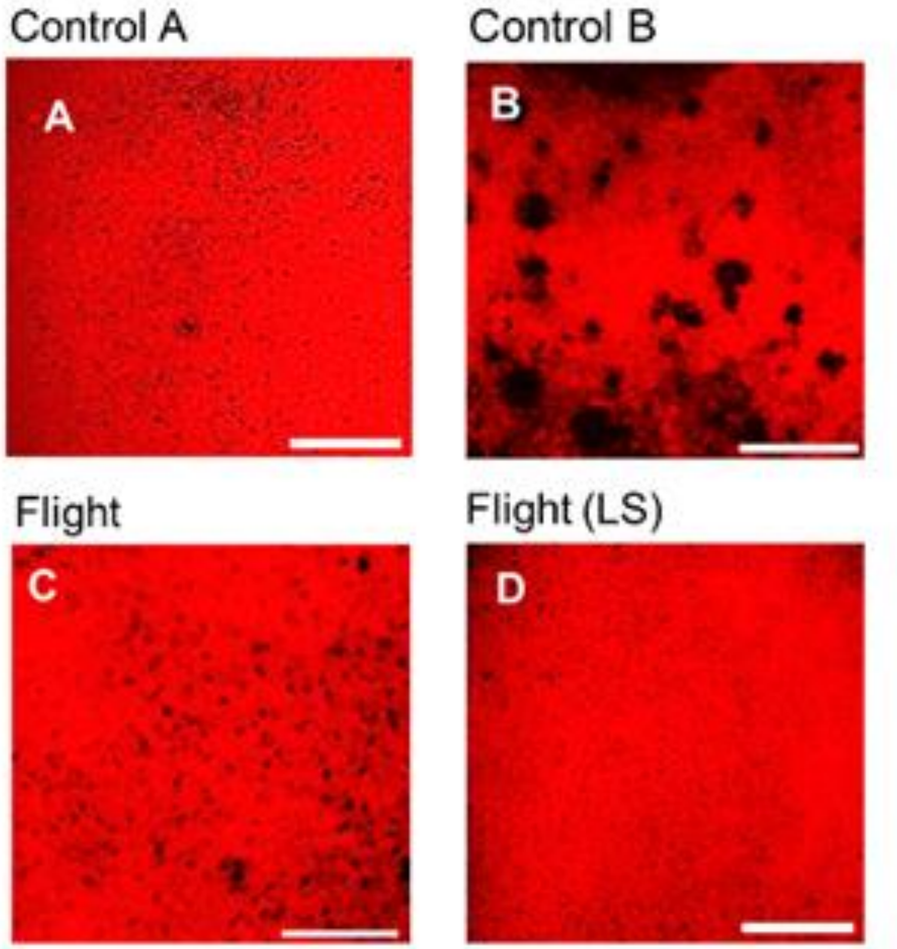
Average Size Of PbI_2 Regions

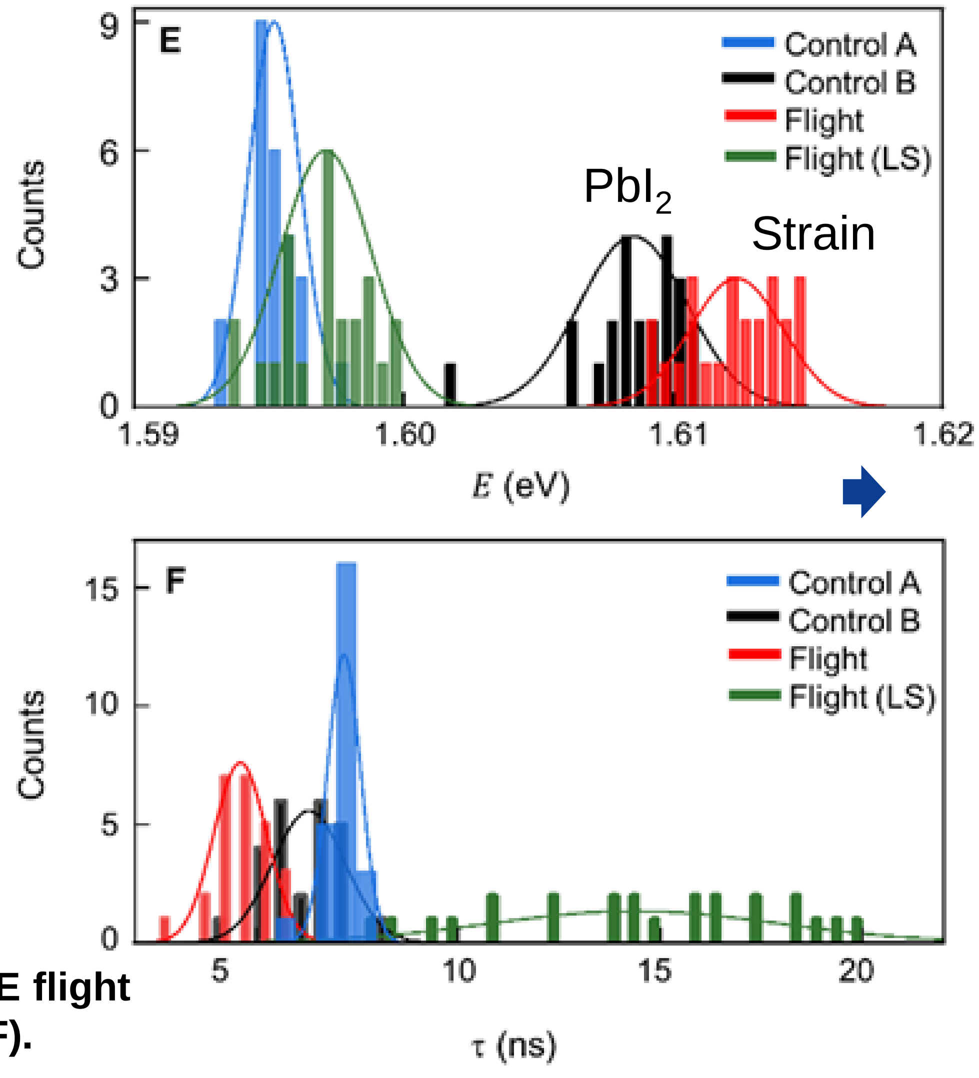


W. Delmas, et al. *Adv. Energy Mater.*, https://doi.org/10.1002/aenm.202203920

Ambient Comparison of Flight vs Ground





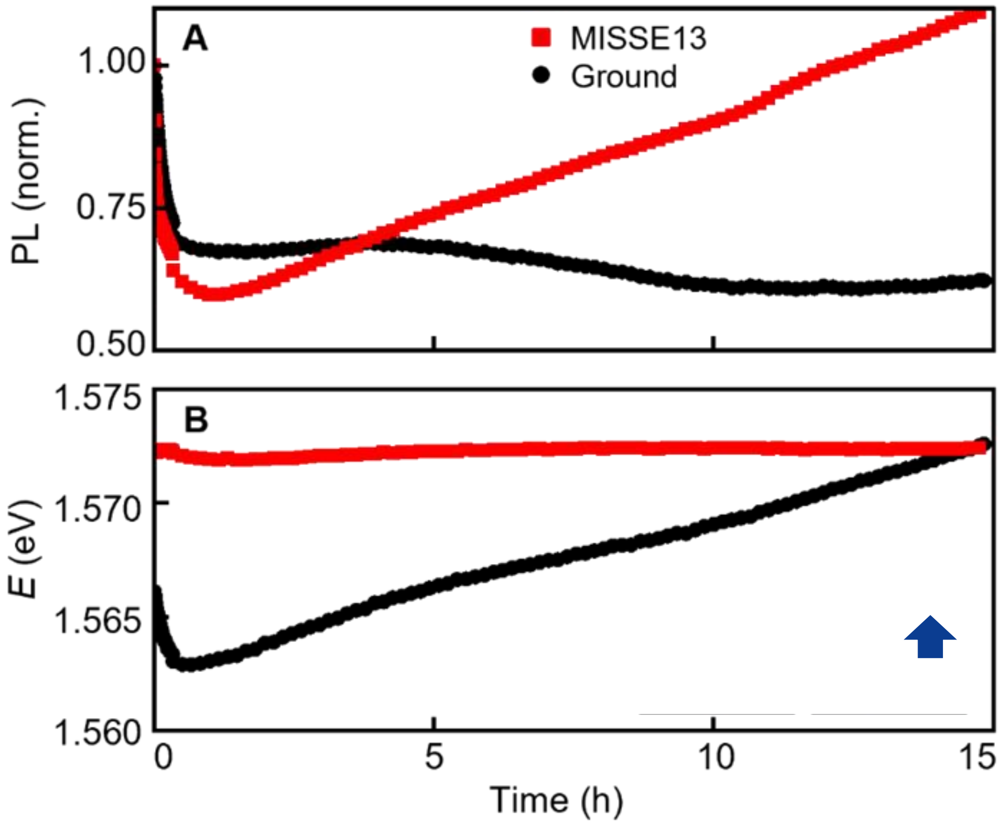


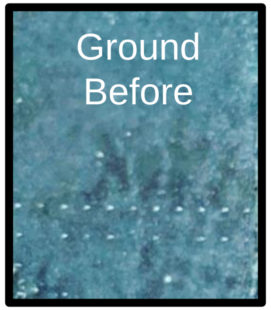
Thermal cycling under orbital conditions induced strain in sample (E). MISSE flight sample has higher density of small defects which leads to shorter lifetime (F). Conversion to PbI2 is not as preferred under orbital conditions.

W. Delmas, et al. *Adv. Energy Mater.*, https://doi.org/10.1002/aenm.202203920

Performance Stability

- AM 1.5 illumination for 15 hours
- First 30 mins
  - Both samples drop in PL intensity
  - Both samples red shift
- Remainer of illumination
  - Ground sample
    - Blue shift
    - PL Intensity remains stable
    - Completely degrades to PbI_2
  - MISSE
    - Photo brightens
    - Annealing of strain induced defects
    - No degradation observed



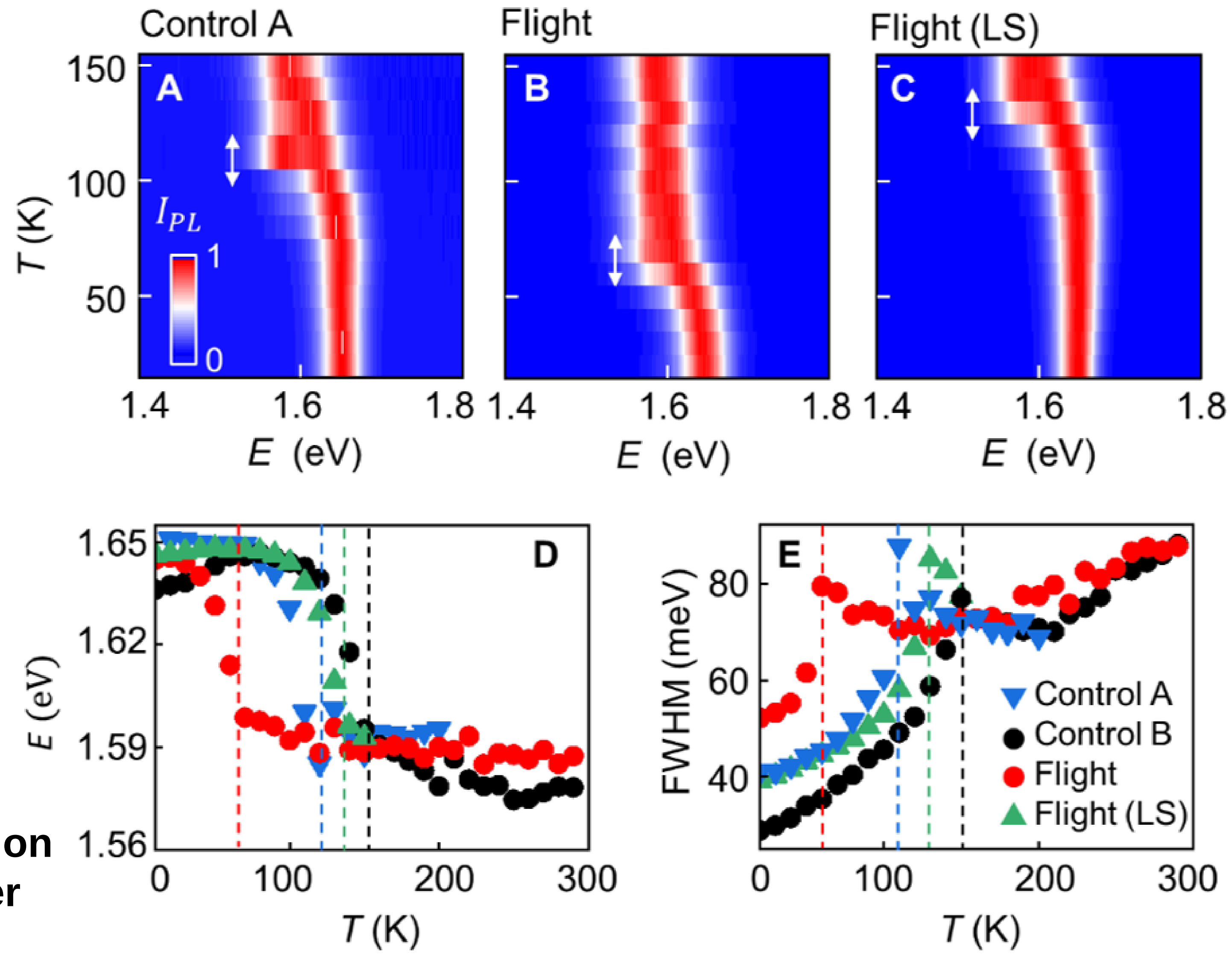


W. Delmas, et al. *Adv. Energy Mater.*, https://doi.org/10.1002/aenm.202203920

Structural Phase Transition

- Temperature dependent PL
  - PL emission intensity mapped as function of temperature *T* and emission energy *E*
- Peak emission energy and FWHM of PL emission plotted with T
- Dashed lines at T= T_C indicate flight and control samples have similar low temperature phase behavior except for suppressed T_C of flight sample prior to light soak.
- Typical T_C of MAPI 140-160 K

$T_{C\ Flight}$	55 K
$T_{C\ Ctrl\ A}$	120 K
$T_{C\ Ctrl\ B}$	148 K

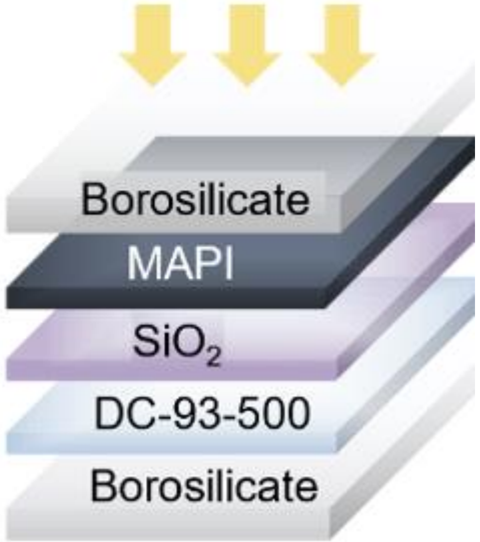


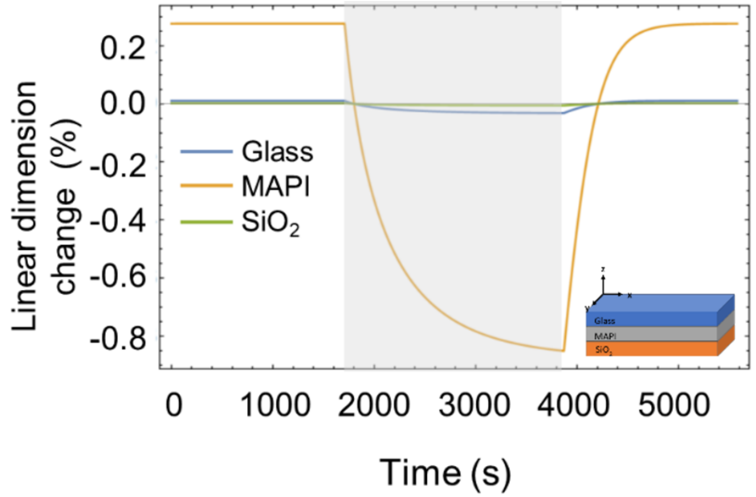
MISSE flight sample shows phase transition (tetragonal to orthorhombic) much lower than typical transition temperatures

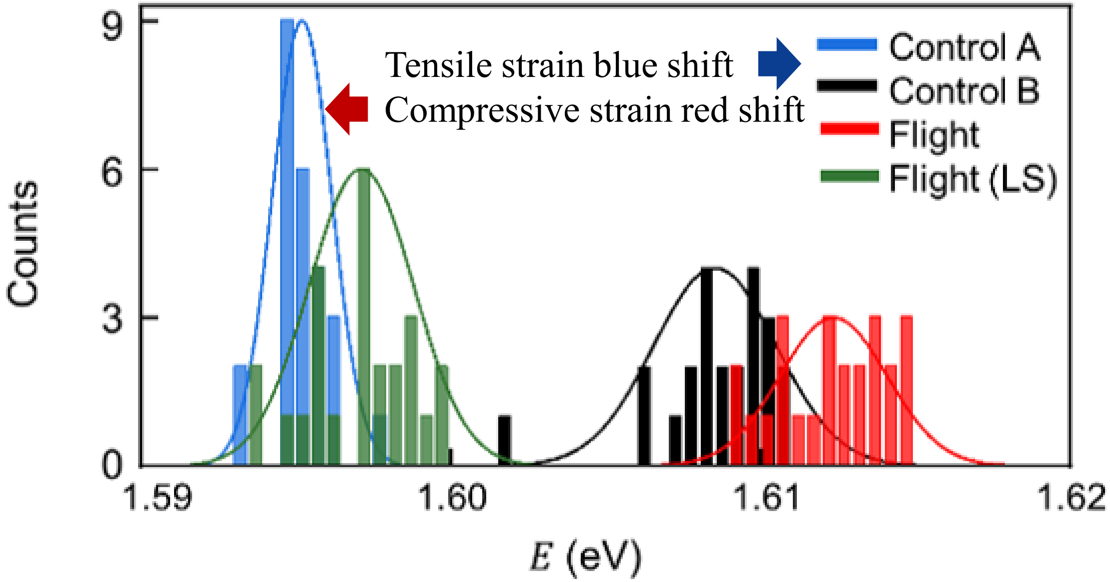
W. Delmas, et al. *Adv. Energy Mater.*, https://doi.org/10.1002/aenm.202203920

MISSE13 Lessons Learned

- No visual change in sample after 10 months in LEO
- 10 months in LEO induced tensile strain into the $MAPbI_3$ film
- Effects of strain on $MAPbI_3$ film caused by thermal cycling appear to be reversable through PbI_2 inclusion healing with light soaking.







W. Delmas, et al. *Adv. Energy Mater.*, https://doi.org/10.1002/aenm.202203920

Creating Standards for the Community

Collaborating with the field to determine how to make measurements in addition to how to make samples.

Joule CellPress

Article

Countdown to perovskite space launch: Guidelines to performing relevant radiation-hardness experiments

Ahmad R. Kirmani,[1,*] Brandon K. Durant,[2] Jonathan Grandidier,[3,4] Nancy M. Haegel,[1] Michael D. Kelzenberg,[4] Yao M. Lao,[5] Michael D. McGehee,[6] Lyndsey McMillon-Brown,[7] David P. Ostrowski,[1] Timothy J. Peshek,[7] Bibhudutta Rout,[8] Ian R. Sellers,[2] Mark Steger,[1] Don Walker,[5] David M. Wilt,[9] Kaitlyn T. VanSant,[1,7] and Joseph M. Luther[1,10,*]

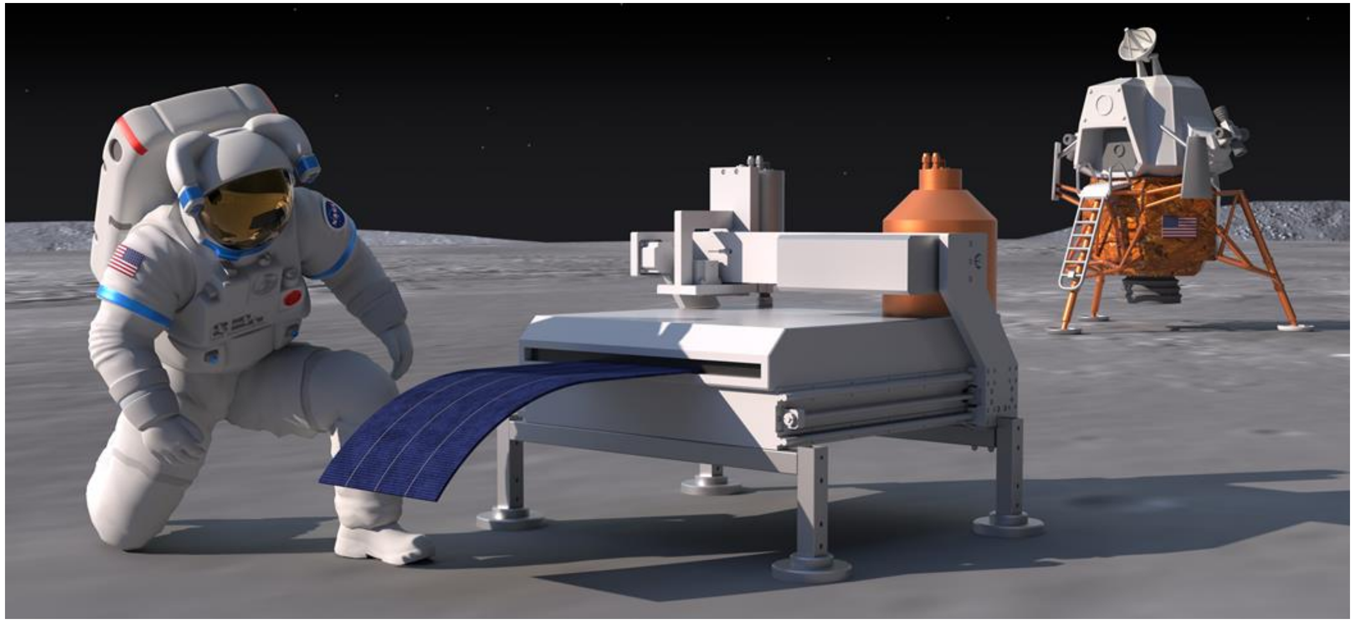
Technology	Proton Radiation Energy
III-V	1-3 MeV
Si	10 MeV
PVK	0.05-0.15 MeV

NREL NATIONAL RENEWABLE ENERGY LABORATORY
AFRL THE AIR FORCE RESEARCH LABORATORY
JPL Jet Propulsion Laboratory California Institute of Technology
NASA
Caltech
The UNIVERSITY of OKLAHOMA
UNIVERSITY of NORTH TEXAS
AEROSPACE

A. **Kirmani**, et al. *Joule. 2022*, 6, 5, 1015-1031 https://doi.org/10.1016/j.joule.2022.03.004

What will it take to manufacture solar cells in space?

- ✓ Overcome thermal, vacuum, and humidity challenges
- ✓ Address radiation concerns
- ✓ Understand degradation modes resulting from space environment
- ✓ Find light weight space ready substrates
- Leverage the vacuum of space for deposition
- Leverage the sun to create high quality films



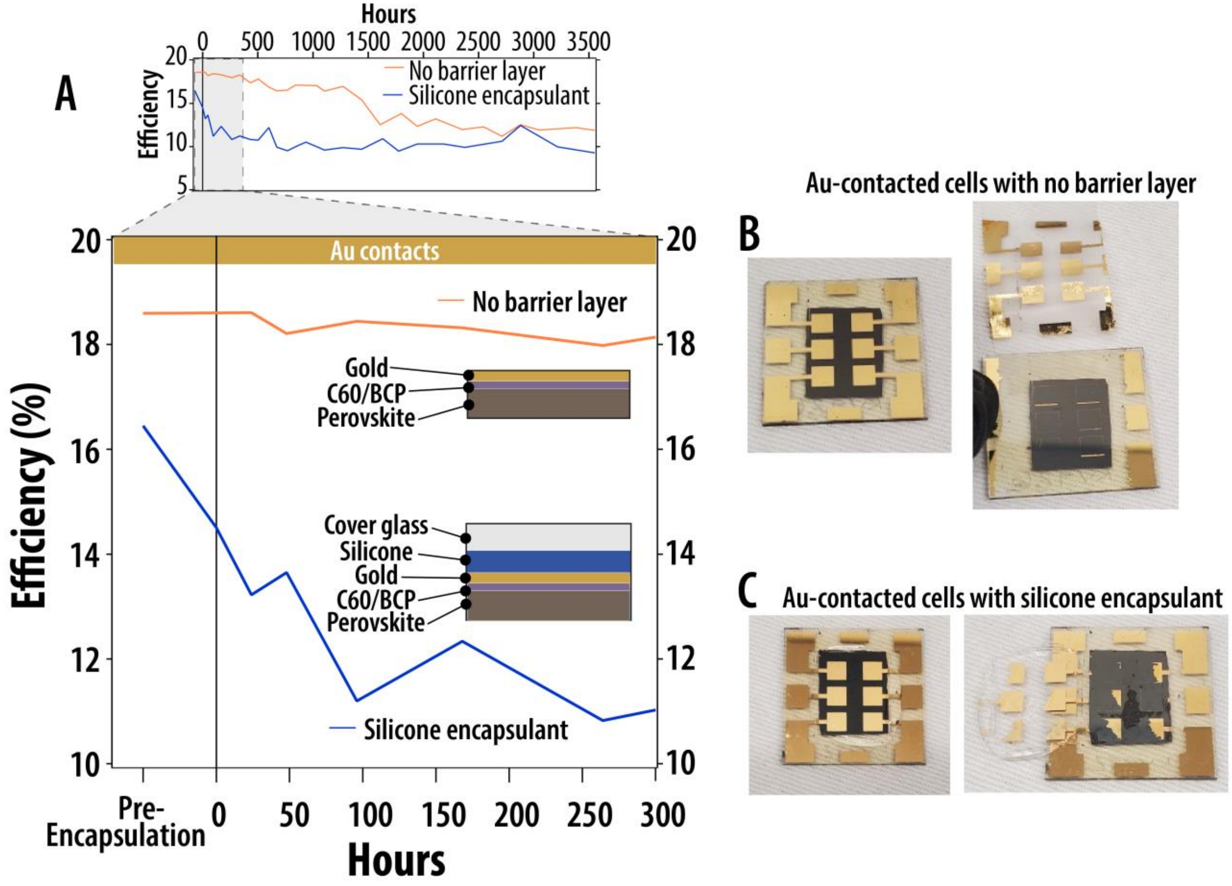
https://doi.org/10.1021/acsenergylett.2c00276

Thank you for your attention


SpaceX Falcon 9 rocket launching the Cargo Dragon spacecraft from NASA's Kennedy Space Center.

Impact of Silicone Encapsulant

- Peel test of samples with and without encapsulants
- Expect the sample to cleave at the weakest adhesion layer.
- With no barrier layer the Au peels off indicating the Au/BCP interface is the weakest
- With encapsulant the layer pulls off partial gold.
- The adhesion between the Au/Encapsulant and Au/BCP differ across the sample surface



The deposition of the encapsulant may slightly lift the Au from the cell surface as it cures, compromising the uniformity (and thus the conductivity) of cells encapsulated with the silicone encapsulant