“BACKFLIP: A Comparison of Emerging Non-Fluoropolymer-Based, Co-Extruded PV Backsheets to Industry-Benchmark Technologies”

Comparison of market-benchmark BACKsheet technologies to novel non-FLuoro-based co-extruded materials and their correlation and ImPact on PV module degradation rates (BACKFLIP)

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Present, Future, and Technical Project Motivations

Historically, most backsheets made with laminated PET core. Co-extruded polyolefin materials explored here.
- Pros: lower manufacture cost, simplifies RTI (no adhesives).
- Cons: may facilitate through-thickness cracking.
- Unknown: durability of new materials.

Country regulations may require fluorine-free backsheets:
- Contain no toxic materials.
- Preserve raw resources.
- Recyclable, lower carbon footprint.

- What to measure, how?
  - Critical characteristics and their correlation not fully established.
- How to age?
  - Connection between accelerated tests and field not established.

Connection between surface- and bulk-degradation is further compared, including:

- Surface morphology (microscopy) relative to surface roughness (gloss).
- Damage catalysis in MiMos vs. coupons (FTIR).
- Breakdown voltage in BS-6 (AAA) and other backsheets.

Recent references:
Thuis et. al., J PV, in press, https://doi.org/10.1109/JPHOTOV.2021.3117915.
Uličná, et. al., Proc Euro PVSEC Conf, 2021, 4CO.2.3
Materials and Test Conditions for the BACKFLIP Study

**Backsheets:**
- Benchmark (TPT, PPE, KPf).
- Known bad (AAA).
- Developmental (PO’s, APO).

<table>
<thead>
<tr>
<th>Arbitrary Index</th>
<th>Backsheet</th>
<th>Construction</th>
<th>Thickness [AVG±2 S.D.] (mm)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS-1</td>
<td>PO-1</td>
<td>Coextruded</td>
<td>0.35±0.01</td>
<td>In Development</td>
</tr>
<tr>
<td>BS-2</td>
<td>PO-2</td>
<td>Coextruded</td>
<td>0.35±0.02</td>
<td>In Development</td>
</tr>
<tr>
<td>BS-3</td>
<td>TPT</td>
<td>Laminate</td>
<td>0.32±0.01</td>
<td>Traditional (reference)</td>
</tr>
<tr>
<td>BS-4</td>
<td>APO</td>
<td>Coextruded</td>
<td>0.35±0.01</td>
<td>Recently developed</td>
</tr>
<tr>
<td>BS-5</td>
<td>PPE</td>
<td>Laminate</td>
<td>0.36±0.01</td>
<td>Contemporary</td>
</tr>
<tr>
<td>BS-6</td>
<td>AAA</td>
<td>Coextruded</td>
<td>0.33±0.02</td>
<td>Known Bad</td>
</tr>
<tr>
<td>BS-7</td>
<td>KPf</td>
<td>Laminate</td>
<td>0.29±0.00</td>
<td>Contemporary</td>
</tr>
</tbody>
</table>

**Accelerated aging:**
- Hygrometric (3x, including IEC 61215 “Damp Heat”) → $E_{a,eff}$.
- UV weathering (2x, IEC TS 62788-7-2) → $E_{a,eff}$.
- UV weathering (2x, custom) → effect of H$_2$O spray.

<table>
<thead>
<tr>
<th>Arbitrary Experiment Index</th>
<th>UV Irradiance (W·m$^{-2}$ at 340 nm)</th>
<th>MiMo Temperature (°C)</th>
<th>Chamber Relative Humidity (%)</th>
<th>Water Spray?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>85</td>
<td>85</td>
<td>N</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>65</td>
<td>85</td>
<td>N</td>
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<tr>
<td>3</td>
<td>0</td>
<td>45</td>
<td>85</td>
<td>N</td>
</tr>
<tr>
<td>a (A3)</td>
<td>0.8</td>
<td>69</td>
<td>20</td>
<td>N</td>
</tr>
<tr>
<td>b</td>
<td>0.55</td>
<td>59</td>
<td>20</td>
<td>N</td>
</tr>
<tr>
<td>c</td>
<td>0.55</td>
<td>62</td>
<td>~80%</td>
<td>Y</td>
</tr>
<tr>
<td>d (A2)</td>
<td>0.8</td>
<td>59</td>
<td>20</td>
<td>N</td>
</tr>
</tbody>
</table>

In Characterization
Specimens and Locations Characterized

- **Coupons**
  - Center
  - 17 cm

- **MiMos**
  - Center
  - Sun side
  - Corner
  - Air side
  - 17 cm
  - 1 cm x 15 cm (typical)
  - 4.5 cm (typical)
  - 5 cm (typical)

- **Mechanical tensile test**
  - Mechanical tensile test #2
  - Mechanical tensile test #3
  - Mechanical tensile test #4
  - Mechanical tensile test #5

- **SLAC: SAXS/WAXS +DSC**

- **Extra - aerobically aging expected - do not test**

- **Label (sticker)**

- **Mechanical tensile test**
  - VBD #1
  - VBD #2
  - VBD #3
  - VBD #4
  - VBD #5
  - VBD #6

- **Punch code:** symbol_symbol_symbol

- **FTIR**

- **•Same 3 replicate MiMos through each experiment.**
  - **•1 coupon·read point⁻¹·experiment⁻¹ (destructive tests).**
Accelerated Testing in the BACKFLIP Study

• **UV weathering** performed in high spectral fidelity Atlas “Weather-ometer” Xe lamp (ASTM D7869) chambers.

  17 cm MiMo size avoids shading between carousel rows. ⇒ ¼ cell MiMo’s used at NREL.
  Removable cables, with j-box end caps.

• **Hygrometric aging** performed in separate dark chambers.
The Specimen Temperature Was Verified for UV Weathering

- Xe sources emit UV, VIS, and NIR light ⇒ heating above chamber temperature likely.
- MiMos and coupons may achieve different temperatures.

Takeaways:
- Specimen temperature stabilizes ~15-30 minutes.
- Minimal (1-2°C) difference center and corner. → 17 cm specimens still small.
- Modest (up to 4°C) difference coupons and MiMos. → Absorptance of cell, geometry + heat transfer.
- Verified temperature will be used for Arrhenius analysis.
Grayness From EL Corroborates I-V Performance Change

• $\Delta P_{\text{max}}$ [MiMos] identified most damaging 85°C/85% RH experiment. Q: Can the degradation be verified, e.g. standardized EL images?

• *Imageio* and *NumPy* Python libraries can extract an average image grayness. Typically comparable (±<1%) of *ImageJ*.

Example: Sn-rich surface of soda-lime glass after A3 4000h.

• $\downarrow P_{\text{max}}$ in hygrometric aging quickly confirmed from grayness.

• $\uparrow P_{\text{max}}$ in UV weathering also confirmed in grayness. May result from glass corrosion (AR effect).

• Presently working to verify I-V:EL fidelity using *pvimage* package to crop to cell only.

Q: What damage mode(s) might be affecting MiMo durability?
Surface Integrity of **MiMo** Air Side Surface From Optical Microscopy

- BS-4, BS-6: biaxial mud crack geometry presumably results from misfit strain.
- BS-6: smaller incipient micro-cracks in 85°C/85% RH.
- BS-5: micro-cracking and delamination in 85°C/85% RH.

Comparison of surface morphology at 4000h (85°C/85% RH and A3) relative to unaged.
Changes in AVG[Gloss] BS-5, -6 Identified

• Greatest initial gloss: BS-5, -7, then -1, e.g. 85°.

• Gloss reduced BS-5 (greatly), -6 (slightly), at all incident angles in UV weathering, e.g., 60°.

• Gloss reduced (slightly) BS-6 throughout hygrometric aging, e.g., 60°.

• BS’s with low gloss value remain low (may seem less affected), all experiments.

• Air side: similar trends observed between MiMos (center & corner) and coupons (center).
Changes in $\Delta$[Gloss] of Backsheets Identified

- Base values (AVG) distinguish the BS’s; change ($\Delta$) distinguishes their degradation.

- Gloss reduced BS-5, at all incident angles in UV weathering, e.g., $60^\circ$.

- Gloss reduced BS-6 at all incident angles in UV weathering. Thermal activation observed through hygrometric aging, e.g., $60^\circ$.

- Other BS’s also distinguished for $\Delta$[gloss], e.g. in UV weathering.

- Spikes at read points observed, e.g. 1000 h. Compare MiMos and coupon results.
Gloss Confirms Surface Roughening for Artificial Aging

- Gloss: 100 = polished glass reference; 0 = matte.
- Decrease in gloss indicates roughening of the surface, e.g., texturing, erosion, or cracking.
  - Gloss immediately identifies BS-5.
  - Not obvious in microscope. More than meets the eye?
  - Gloss confirms BS-6 affected, both UV- and hygro-aging.

Regarding gloss measurements:
- Gloss might be another method to identify micro-scale cracking.
  - Optimize $\lambda$ and $\theta$ to feature size $\Rightarrow$ PV BS specific instrument & method.
    - (Obtain a gloss scale that might identify BS-4 after UV).
- Or- quantify surface roughness directly (profilometer, interferometer, etc).

https://www.sciencedirect.com/topics/chemical-engineering/gloss-measurement
Method of Comparing the Effect of Acetic Acid (MiMos vs. Coupons)

- Goal: verify adverse effects of acetic acid.
  (Possible catalyst that slowly escapes during aging.)
- Greatest concentration between cell and front glass.
  - Acid blocked from backsheet by cell. 😞
- Next most concentrated location: adjacent to cell. 😞
  - Double thickness EVA (source), far from MiMo edge. (Primary mass transport through BS).

Compliant laminate → Extract 1 cm x 2 cm BS sample using box cutter.
Spectral Differences From FTIR of MiMos

- Changes observed, both BS-6 coupons and MiMoss: -3282, 2912 cm$^{-1}$. 1710 cm$^{-1}$. 1102 cm$^{-1}$.
- Notable peak enhancement at 1102 cm$^{-1}$ for all replicate MiMoss.
- Catalytic effect of acetic acid proposed: Lyu et. al., https://doi.org/10.1002/pip.3260.
- No other notable MiMo-specific differences observed, first 5 experiments.
Morphological Differences From FTIR of MiMos

- **85°C/85%**: core crumbled extracting PET BS’s!
  - Rank by damage: BS-5 (PPE) > BS-7 (KPF) > BS-3 (TPT).
  - 85°C/85%, c (H₂O spray): core also cracked for coupons.
  - Preliminary result: c (H₂O spray) more destructive than 85°C/85%.
  - **85°C/85% not field representative** (often 2000h > 200y, doi: 10.1109/PVSC.2013.6744112).

- BS-4 specimens readily extracted after 85°C/85%!
  - (BS + EVA) readily removed from front glass.
  - Not quantified, but suspect reduced interfacial adhesion.
  - MiMo sun side discolored with subsequent photobleaching.
  - see: [https://www.nrel.gov/docs/fy21osti/80362.pdf](https://www.nrel.gov/docs/fy21osti/80362.pdf)
  - Will c (H₂O spray) be damaging like 85°C/85%?
A Modest Effect of Aging Was Observed for $V_{BD}$ of BS-6 (AAA)

- $V_{BD}$ can only be consistently measured for BS-6, i.e. <100 kV.
- Possible reduction of $V_{BD}$ ($\alpha$) with aging.
- Decrease in variability ($\beta$) with aging.

- A modest reduction in $V_{BD}$ ($\alpha$) was previously observed in the development of the $V_{BD}$ test in IEC TS 62788-2.

Breakdown voltage ($\alpha$, scale parameter) and variability ($\beta$, shape parameter) of BS-6 through the most affecting of first 5 experiments.

BS-6 (unaged and after A3 2000 h), from: Miller et. al., SOLMAT, 2019, https://doi.org/10.1016/j.solener.2019.01.092
$V_{BD}$ Suggests Bulk Damage in Hygrometric Aging

- Failure function, “$F$”: 0% if all $V_{BD} > 100$ kV; 100% if all $V_{BD} < 100$ kV.

- No overt aging trend through **UV weathering**.
  - BS-6 (AAA) always measurable.
  - Surface (micro-cracking BS-4, BS-6; $\Delta$gloss BS-5, BS-6; FTIR BS-2, $-4$, $-5$, $-6$) vs. bulk ($V_{BD}$ no $\Delta$).

- $F$[remaining BS’s] increased through **hygrometric aging**.
  - Compare for $t > 2000$ h.
  - Surface (micro-cracking BS-5, BS-6; $\Delta$gloss BS-6) vs. bulk (cutting BS-3, $-4$, $-5$, $-7$; $V_{BD}$ all).
V_{BD}: Tailoring PV BS Performance; Verifying Surface & Bulk Connection

- $V_{BD} > 100$ kV suggests BS thickness could be reduced.
  - $h_{BS}$ presently based on DTI (legacy $h$), not $V_{BD}$ (verified performance).
  - Caution: effect of temperature or time not verified.

- Steady state aging invokes limited damage.
  - BS-6 (AAA) cracks in the field. Modest $\Delta V_{BD}$ here.
  - PPE (sun side) previously cracked from UV. Minimal $\Delta V_{BD}$ here.
  - Sequential- or combined-aging may better relate surface, bulk damage as well as identifying known-bads.
Remember from This Presentation

While verification of degradation is confirmed in additional characterizations, the connection between surface and bulk degradation remains limited:

• Gloss confirms surface roughening of PPE, AAA.
  - Standard equipment not optimized for PV BS’s. Other methods exist besides $\Delta$gloss.

• Catalytic effect acetic acid confirmed from AAA MiMos.
• Greatly accelerated PET core damage for $85^\circ$C/85% on extraction of:
  BS-3 (TPT), BS-5 (PPE), BS-7 (KPF) MiMos. MQT 13, H$_2$O spray not field-based tests.

• Modest $\Delta V_{BD}$ observed through indoor aging of AAA.
• Other BS’s: $V_{BD} > 100$ kV $>>$ 8 kV $\rightarrow$ BS’s thicker than needed.
• Minimal $\Delta V_{BD}$ steady state aging $\rightarrow$ more advanced-aging may help relate surface, bulk damage.
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Note: DSM Advanced Solar B.V. is now Endurans Solar Solutions B.V.

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If you have interest in UV weathering, see PVQAT TG5, e.g. https://www.pvqat.org/project-status/task-group-5.html
NREL, Sandia, SLAC and Endurans partner to:

- 0. Understand role of backsheets on the longevity of modules and impact on energy yield.
- 2. Compare specimens: unaged, artificially-aged, outdoor-aged.
- 3. + 4. Evaluate relative rate of degradation of commercial and experimental backsheets.
- 4 + 5. Evaluate predictive parameters ($E_{a,eff}$). Identify and correlate characteristics, accelerated tests of concern.