Typical Photovoltaic Backsheet Failure Mode Analysis and Comparison Study with Accelerated Aging Tests

Aug. 5th, 2016

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Backsheet Materials Are Critical to Solar Module Durability and Performance

*Backsheets protect PV modules from many hazards*

- **Ultra Violet (UV)**
  - Transmitted
  - Reflected

- **Temperature**
  - Peak
  - Cycling
  - Hot spots

- **Moisture**
  - Humidity
  - Precipitation
  - Condensation

- **Corrosive Environment**
  - Atmospheric chemicals
  - Ammonia
  - Marine/coastal environment

- **Electrical Damage**
  - Shock
  - Shorting

- **Physical Threats**
  - Abrasion (sand)
  - Impact (installation, debris)
Materials are Best Assessed by Looking at Outdoor PV Performance

Photovoltaic modules are exposed to a wide range of stress conditions (UV, temperature, moisture, thermal cycling, and internal voltage) simultaneously or sequentially;

Current IEC standards are very mild and mostly are single stress condition at levels below those experienced in the field

“Long-term outdoor exposure is the ultimate test for all module components, material quality and manufacturing quality.”

DuPont Collaborated with Downstream Stakeholders to Assess PV Systems, Modules, and Materials in the Service Environment

- Inspected > 60 solar installations in NA, EU and AP by early 2015
- Age of 0-30yrs
- Including >200MW & 1.5 million solar panels

Components visual defect ratio

- Cell, 24%
- Backsheet, 9%
- Encapsulant, 4%
- Mismatch, 1%
- Others, 1%
- Defects not detected, 59%

41% of inspected modules have visual defects

Backsheets defect ratio

- FEVE, 11%
- Tedlar® PVF 1%
- PET, 30%
- PVDF, 58%

IEEE PVSC (New Orleans, 2015, A. Bradley et al)
Tedlar®-based Backsheets - Field Proven Under All Climates in China

Overall power loss rate average 0.55%/year

Arid Climate
- 24 yrs, 93.0% power
- 17 yrs, 86.7% power
- 20 yrs, 92.3% power

Temperate
- 27 yrs, ~90% power
- 23 yrs, 86.9% power

Tropical/subtropical
- 14 yrs, 92.5%
- 18 yrs, 88.2% power
- 23 yrs, 88.2% power
- 11 yrs, 92.5%

Overall power loss rate average 0.55%/year
Different Climates Present Different Environmental Stresses

<table>
<thead>
<tr>
<th>Climate</th>
<th>Weather station</th>
<th>Annual irradiation [MJ/m²]</th>
<th>25yrs UV on module rear side* [kWh/m²]</th>
<th>Annual average temperature [°C]</th>
<th>Annual average humidity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arid</td>
<td>Dunhuang, Gansu</td>
<td>6560</td>
<td>273</td>
<td>10.8</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>Lasha, Tibet</td>
<td>7598</td>
<td>317</td>
<td>4.5</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Urumqi, Xinjiang</td>
<td>5519</td>
<td>230</td>
<td>4.5</td>
<td>54.8</td>
</tr>
<tr>
<td>Tropical and Subtropical</td>
<td>Sanya, Hainan</td>
<td>5944</td>
<td>247</td>
<td>24.3</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>Guangzhou, Guangdong</td>
<td>4234</td>
<td>176</td>
<td>20.4</td>
<td>74.7</td>
</tr>
<tr>
<td>Temperate</td>
<td>Beijing</td>
<td>4912</td>
<td>204</td>
<td>11.9</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>Dongtai, Jiangsu (Seashore)</td>
<td>5019</td>
<td>209</td>
<td>15.1</td>
<td>76.5</td>
</tr>
</tbody>
</table>

Note*: 1) assume 5% UV ratio in solar irradiation and 12% albedo from ground surface; 2) 1 kwh/m² = 3.6 MJ/m²
Field Case: Tedlar® TPT Backsheet at Fire Lookout Station in Yunnan (Subtropical)- 20 years with no performance issues

• Tedlar® TPT backsheet appearance good after 20yrs field exposure;
• Metal frame has serious corrosion.

Junction-box yellowed and brittle; lid is missing.

36 cell monocrystalline-Si solar panels without apparent visual defect.
Field Case: Tedlar® TPT Rooftop Solar Farm in Beijing – low power loss, no backsheet degradation after 18 years

Total 11.8% ave. power degradation after 18yrs field service (0.65% annual)

No apparent Tedlar® thickness reduction in air side after 18yrs field exposure

Tedlar® PVF film shows no changes after 18yrs

TPT backsheet from the 18yrs fielded module retains 160.8% elongation and 92.1 Mpa tensile strength
Field Data for Non-Tedlar® Backsheets
Field case: Polyamide backsheet cracking in multiple sites at early stages in field

China

– Modules Installed 2012 in Arid climate
– Micro-cracks found in 2013
– Large amount of visual cracks found in 2016, mostly cracks along the ribbon
– Current leakage is a safety issue

Italy

– Modules Installed 2010
– In 2015, Micro-cracks, large cracks, delamination, corrosion from water ingress;
– Inverters tripped from current leakage.
Field Case: PVDF Backsheet Shows High Percentage of Cracking and Delamination after 4 years

- 4yrs solar farm in North American with 200 modules and 200KW installation;
- PVDF Backsheet cracking & delamination ranged from 21% to 85% (avg 57%);
- No PVDF film remaining on some backsheets.
Field case: PVDF Backsheet Show High Percentage Front Side Yellowing and power loss at Arid Ningxia Province

- 5yrs solar farm in north China- 5.2MW installation
- Around ~50% of PVDF Backsheet demonstrate front side yellowing. Similar results observed on 5 other countries across the world and all within 5yrs field service
- Average power degradation of these modules is ~11% (industrial spec is 5% within 5yrs).
Field case: PVDF Backsheet- Bubbling Issue and Power Loss at Shoreline of Subtropical Jiangsu Province after 5 years

- 5yr old solar farm in eastern China- 9.7MW installation
- Around 6.3% of PVDF Backsheets show bubble deformation (not due to hot spot)
- Power degradation of the modules with bubble deformation is 11%~14.7%.
Field case: PET Backsheet Shows High Yellowing after 4 years (Arid)

Solar farm in Inner Mongolia, north China - 4 yrs
Yellowness value b* of backsheet is as high as 8-10
Field case: PET Backsheet Peeled off and Yellowing after 9 yrs (Highland)

9yrs field module in Tibet, high inner layer yellowing

Airside PET peeled off, especially at cell gap areas

21um eroded from thick airside white PET with 9yrs field exposure in Tibet (2.3um/yr)
Field Sample Analysis: PET Backsheet of Tibet Module is Brittle and Molecular Weight Decreased

- **Molecular weight decreases**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core layer PET at cell shielding</td>
<td>19100</td>
</tr>
<tr>
<td>Core layer PET at cell space</td>
<td>12000</td>
</tr>
<tr>
<td>Outer layer PET at cell shielding</td>
<td>20400</td>
</tr>
</tbody>
</table>

- **Viscosity decreases**

<table>
<thead>
<tr>
<th>Sample</th>
<th>IV , dL /g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core layer PET at cell shielding</td>
<td>0.929</td>
</tr>
<tr>
<td>Core layer PET at cell space</td>
<td>0.693</td>
</tr>
<tr>
<td>Outer layer PET at cell shielding</td>
<td>0.800</td>
</tr>
</tbody>
</table>
Field case: Glass/Glass Module in Hainan with Zero Power Output, Busbar Wire Corrosion and Encapsulant Yellowing & Delamination (Tropical)- 15 yr

All busbar wires corroded

19yrs G/G module in Hainan. Serious electrical component corrosion and encapsulant yellowing
## Lab Testing: DuPont Recommends Sequential Aging Test to Better Simulate Field Stresses

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damp Heat 1000 hours → UVA 1000 hours → Thermal Cycling, 200X → UVA 1000 hours</td>
<td>Combines the most important stress factors in the field, appropriate for component, minimodule, or full-size module testing, our best recommendation</td>
</tr>
<tr>
<td>DH/TC exposure to assess backsheet cracking in full size modules</td>
<td>Combines two important stress factors in a shorter test not requiring expensive UV equipment. Appropriate for full-size module testing</td>
</tr>
<tr>
<td>ASTM G155 or SAE J1960 protocols in a Weatherometer Backsheet coupon or Minimodule</td>
<td>Combines UV and rainfall simulation, common weathering test conditions in commercially available weatherometer</td>
</tr>
</tbody>
</table>

**Rationale**

- Combines the most important stress factors in the field, appropriate for component, minimodule, or full-size module testing, our best recommendation.
- Combines two important stress factors in a shorter test not requiring expensive UV equipment. Appropriate for full-size module testing.
- Combines UV and rainfall simulation, common weathering test conditions in commercially available weatherometer.
## Comparison of Sequential Accelerated Test Results

### Sequential Test Summary

<table>
<thead>
<tr>
<th>Test</th>
<th>Sequence</th>
<th>Measurement</th>
<th>Format</th>
<th>Unit</th>
<th>Double Sided Fluoro</th>
<th>Single-Sided Fluoro</th>
<th>Non-Fluoro</th>
<th>UVPET / HPET</th>
<th>UVPET / PET</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tedlar* PVF TPT</td>
<td>PVDF</td>
<td>FEVE</td>
<td>PET</td>
<td>PET</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tedlar* PVF TPE</td>
<td>PVDF</td>
<td>FEVE</td>
<td>In Test</td>
<td>In Test</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hydrolytically-stabilized</td>
<td>(Standard)</td>
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<tr>
<td>1</td>
<td>UVA1000-DH1000 2X(TC200-UVA1000)</td>
<td>Yellowing</td>
<td>Mini module</td>
<td>b*</td>
<td>0.8</td>
<td>0.6</td>
<td>0.2</td>
<td>Cracking (1)</td>
<td>Cracking (1)</td>
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<tr>
<td></td>
<td></td>
<td>Mechanical Loss-Cracking</td>
<td>Mini module</td>
<td>observe</td>
<td>OK</td>
<td>OK</td>
<td>Cracking (1)</td>
<td>Cracking (1)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>DH1000 2X TC200</td>
<td>Mechanical Loss-Cracking</td>
<td>Mini module</td>
<td>observe</td>
<td>OK</td>
<td>OK</td>
<td>Cracking</td>
<td>Cracking (1)</td>
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<tr>
<td>3</td>
<td>UVX-water spray-3000 hours</td>
<td>Yellowing</td>
<td>Backsheet</td>
<td>b*</td>
<td>0.1</td>
<td>0.2</td>
<td>0</td>
<td>Cracking</td>
<td>Cracking</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mechanical Loss-Elongation</td>
<td>Backsheet</td>
<td>% Elongation Loss</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>76</td>
<td>80.0</td>
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<tr>
<td></td>
<td>Outdoor Performance</td>
<td>Years in Field</td>
<td>Years</td>
<td>34</td>
<td>4</td>
<td>4</td>
<td>26</td>
<td>7</td>
<td>9</td>
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<tr>
<td></td>
<td>Field</td>
<td>Yelloing</td>
<td>Modules</td>
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<td>Modules</td>
<td>OK</td>
<td>OK</td>
<td>Cracking</td>
<td>Cracking</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Cracking also found in similar Sequential Test – 3rd party unpublished data
Sequential Aging Test 1 Shows Consistent Results with Field Failures

- Damp Heat 1000 hours
- UVA 1000 hours
- 1X, 2X, 3X
- Thermal Cycling, 200X
- UVA 1000 hours

**b* vs Cycle Number**

- Yellowing of PET Backsheet after sequential test
- Cracks in PVDF backsheet observed in fields
- Cracks in PVDF backsheet observed in field
- Crack profile of PVDF Backsheet after sequential aging test

- Yellowing of PET Backsheets observed in fields
- Cracks of PVDF film found along ribbon wires on Kpf backsheet after sequential aging test

DH 1000 hours – UVA 1000 hours (65 kW/sqm) – TC 200

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Sequential Aging Test 2 Shows Consistent Results with Field Failures

1x Humid Heat 1000 hours 3x Thermal cycling, 200X

PA backsheet shows cracks after DH1000 + TC200 test similar to cracks in field

4yrs PA backsheet cracked in field

Cracks in 1s PVDF backsheet (KPf) after DH1000+TC400 similar to cracks observed in the field

Cracks in KPE and KPf along ribbon wires after TC600 similar to cracks observed in the field

KPE, cracked  KPf, cracked  TPC, no crack
Sequential Aging Test 3 Shows Consistent Results with Field Failures

Yellowing in PET-based Backsheets

Fielded modules
15 year rooftop- yellowed PET backsheet

4 year ground mount-cracked polyester backsheet

Loss of Mechanical Properties in PET-based Backsheets
Conclusions

- Long-term field proven records are important verifications for solar module materials and components.
- Tedlar® PVF-based backsheets demonstrate superior durability and have been widely proven in all climates for 30+ years.
- PVDF-based backsheets crack, delaminate, and show front side yellowing and bubbling issues at early stage of field service. PET-based backsheets show cracking, yellowing and erosion loss in the field.
- Lab testing results using sequential test methods show consistent backsheet failure modes consistent with field findings and are highly recommended to identify and qualify materials.
- Different climates present different environmental stresses for solar modules. Select widely long-term proven materials for your module and solar farm designs to protect various module applications under any climate conditions.