Evaluation of Bifacial Modules and PV Technologies with Combined-Accelerated Stress Testing

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3. DTU Fotonik, Roskilde, Denmark
4. DuPont, Central Research and Development, Wilmington, USA
Bifacial modules taking increased market share

Need something transparent on the back

A-priori reliability concerns for bifacial module rear/substrate

<table>
<thead>
<tr>
<th>Glass</th>
<th>Polymeric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delamination due to constrained outgassing</td>
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<td>PID on back</td>
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<td>Delamination due to adhesion loss (non-EVA)</td>
<td></td>
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<tr>
<td>Stress on cells &amp; metallization</td>
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</tr>
</tbody>
</table>
Introduction to C-AST

"representation"

C-AST Chamber

Applies five factors of the natural environment:
- Heat
- Light (filtered Xenon), ~7.5% albedo
- Humidity
  - Condensing
  - Non-condensing
- Mechanical pressure
- System voltage

Stress levels & combination: per maximum in nature

In-situ Metrology: I-V, EL

Degradation

<table>
<thead>
<tr>
<th>Degradation</th>
<th>Mean Acceleration Factor (Tropical/Florida)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer layer polymeric of backsheet (temperature/irradiance)</td>
<td>17.3</td>
</tr>
<tr>
<td>Backsheet inner PET (Temperature/humidity)</td>
<td>426</td>
</tr>
<tr>
<td>Electrochemical degradation (corrosion)</td>
<td>14.1</td>
</tr>
<tr>
<td>Thermomechanical fatigue (PbSn solder)</td>
<td>23.5</td>
</tr>
</tbody>
</table>

- Spataru, S.; Hacke, P.; Owen-Bellini, M., (WCPEC-7) 2018
- Owen-Bellini, M. et. al. Progress in Photovoltaics: Research and Applications 29 (1), 2021
- Hacke, P. et al; Advanced Micro-and Nanomaterials for Photovoltaics (Elsevier) 2019
C-AST Cycle and its climate sequences

Notes:
- Temperatures indicated as $T_{\text{chamber}}$ ($T_{\text{module}}$)
- -1200 V System voltage applied to cell circuit only when irradiation is applied
- DML = Cyclic Dynamic Loading 1000 Pa equivalent
- SL = Static loading 2400 Pa equivalent
C-AST Experiment 1: Monofacial PERC: 2 encapsulants x 3 substrates

<table>
<thead>
<tr>
<th>Cell type</th>
<th>No. samples</th>
<th>Encapsulant</th>
<th>Substrate</th>
<th>Cycles C-AST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monofacial Mono-Si PERC</td>
<td>1</td>
<td>POE</td>
<td>transparent PVF</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>POE</td>
<td>glass</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>POE</td>
<td>white PVF</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>EVA</td>
<td>glass</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>EVA</td>
<td>white PVF</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>EVA</td>
<td>transparent PVF</td>
<td>4</td>
</tr>
</tbody>
</table>

Substrate: transparent PVF, glass, white PVF
### Sample set 1: Bifacial module constructions with monofacial PERC

#### Encapsulant type: Substrate type  
**Number of cycles in C-AST**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial EL ($I_{sc}$)</strong></td>
<td>4 cycles</td>
<td>4 cycles</td>
<td>4 cycles</td>
<td>2 cycles</td>
<td>2 cycles</td>
<td>2 cycles</td>
</tr>
<tr>
<td><strong>Breaks</strong></td>
<td>8</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td><strong>Final EL ($I_{sc}$)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Breaks</strong></td>
<td>39</td>
<td>45</td>
<td>134</td>
<td>69</td>
<td>13</td>
<td>114</td>
</tr>
</tbody>
</table>

NREL | 5
Sample set 1: Bifacial module constructions with monofacial PERC

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<tr>
<th>Encapsulant type: Substrate type</th>
<th>Number of cycles in C-AST</th>
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<tbody>
<tr>
<td>POE: T-PVF</td>
<td>4 cycles</td>
</tr>
<tr>
<td>POE: W-PVF</td>
<td>4 cycles</td>
</tr>
<tr>
<td>EVA: T-PVF</td>
<td>2 cycles</td>
</tr>
<tr>
<td>EVA: W-PVF</td>
<td>2 cycles</td>
</tr>
<tr>
<td>EVA: Glass</td>
<td>2 cycles</td>
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<td>EVA: W-PVF</td>
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</tr>
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<td>EVA: Glass</td>
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</table>

(Negligible fill factor and power loss with the monofacial PERC)
Gridfinger breaks

X-Ray Topography, thin-plate theory and finite element analysis

Slauch, IM and coworkers 48th IEEE: PVSC 2021

Finite element analysis of stress-strain in copper interconnects in -40 °C/85 °C temperature cycling

Kraemer, F. and Wiese, Microelettr. Rel., 55 (5) 2015

glass-glass modules show higher stresses in Si and interconnects than in glass-backsheet modules – 3x the gridfinger breaks –

- Highest mechanical loads appear in the glass–glass assembly
- The maximum accumulated plastic strain of some elements in glass-glass reaches double that of glass back sheet assembly

- 2 mm glass/glass have 200 % to 300 % higher stress than 2mm Glass/Backsheet modules
- Glass/glass exhibit higher bending induced cell stresses during module fabrication

2 mm GGEVA
2 mm GGPOE
2 mm GBEVA
2 mm GBPOE

Top 0.1% 1st Principal Stress Values (MPa)

\[
\begin{array}{c|c|c|c}
\text{Glass/Glass} & \text{max} & \text{median} & \text{min} \\
\end{array}
\]
### C-AST Experiment 2: Bifacial PERC: 2 encapsulants x 2 substrates

**Four cell mini modules**

<table>
<thead>
<tr>
<th>Cell type</th>
<th>No. samples</th>
<th>Encapsulant</th>
<th>Substrate</th>
<th>Cycles C-AST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bifacial Mono-Si PERC</td>
<td>1</td>
<td>EVA</td>
<td>transparent PVF</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>POE</td>
<td>transparent PVF</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>EVA</td>
<td>glass</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>POE</td>
<td>glass</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>POE</td>
<td>glass</td>
<td>n/a (ex-situ testing)</td>
</tr>
</tbody>
</table>

**Substrate:**
- transparent PVF
- glass
Overview of potential-induced degradation polarization (PID-p) on rear of bifacial PERC

When and where does it happen

- Rear of bifacial PERC (undoped, sensitive to dielectric charge state) \(^1\)
- Occurs most in EVA-glass back modules \(^1\)
- Negative system voltage (builds up + charge in dielectric) \(^2\)
- Generally correlated to high leakage current \(^1\)
- Degradation greater under low light or dark \(^3\)
- Recovery under light soak because of SiNx photoconductivity and annihilation of charge \(^2-4\)
- Recovery under opposite system voltage polarity \(^5\)

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1 Luo, W and coworkers, Progress in Photovoltaics: Research and Applications 2018, 26 (10), 859-867.
5 Swanson and coworkers, proceedings 15th International PVSEC, 2005.
Standard test conditions flash testing

Glass/EVA back

Glass/EVA front

-40°C, 35% RH, DML x 6 (45 m), 18 h

Spring (2 d)

-40°C, 35% RH, DML x 6 (45 m), 18 h

Dead of winter (18 h)

High desert (7 d)

30 kWh/m²

40 kWh/m²
**PID results**

**Glass back with EVA encapsulant** sample shows most significant loss in $I_{sc}$ and $V_{oc}$ from the rear in bifacial PERC.

- Glass/EVA module construction
- -1200 V system voltage applied
- Seen with highest leakage current
- Degradation under low light conditions (Spring: 800 W/m² 35 °C)
- Recovery with elevated irradiation
- Recovery under opposite polarity
From IEC 61215:2021 series
PV Module design qualification and type approval

85 °C, 85 % relative humidity, 96 h ± Vsys (dark)

Standard calls for 2 kWh/m² on rear to eliminate “polarization artifacts”

PID-polarization seen in C-AST Spring, so polarization may not be an “artifact”
**PID results**

Glass back with EVA encapsulant sample shows most significant loss in $I_{sc}$ and $V_{oc}$ from the rear in bifacial PERC.

- Glass/EVA module construction
- -1200 V system voltage applied
- Seen with highest leakage current
- Degradation under low light conditions (Spring: 800 W/m² 35 °C)
- Recovery with elevated irradiation

**Module type would be susceptible to PID in the field (Spring conditions)**

IEC 61215:2021 has a 2 kWh/m² rear light soak that may hide PID-p in PERC.

**Glass/EVA module construction**

- $+1000 \text{ V} \ 60^\circ \text{C} \ 96 \text{ h (faces grounded)}$  
  → PID recovery

---

**Stage**

- Standard test conditions flash testing

<table>
<thead>
<tr>
<th>Sample</th>
<th>Substrate</th>
<th>Encapsulant</th>
<th>Coulombs</th>
<th>Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>39B</td>
<td>T-PVF</td>
<td>EVA</td>
<td>1.37</td>
<td></td>
</tr>
<tr>
<td>39F</td>
<td>T-PVF</td>
<td>EVA</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>40B</td>
<td>T-PVF</td>
<td>POE</td>
<td>2.15</td>
<td></td>
</tr>
<tr>
<td>40F</td>
<td>T-PVF</td>
<td>POE</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>41B</td>
<td>Glass</td>
<td>EVA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41F</td>
<td>Glass</td>
<td>EVA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>42B</td>
<td>Glass</td>
<td>POE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>42F</td>
<td>Glass</td>
<td>POE</td>
<td></td>
<td></td>
</tr>
</tbody>
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**NREL | 13**
Light-induced degradation (B-O complex) basics

Herguth, A. 33rd EU PVSEC (2017)
Light-induced degradation (B-O complex) basics

A new POE/glass module under sun → dark heat → sun
A new POE/glass module under sun → dark heat → sun

State A ‘annealed’ (inactive)
- Destabilization
  - T: >200°C

State B ‘degraded’ (active)
- Redegradation
  - T: >200°C

State C ‘regenerated’ (inactive)
- Regeneration
  - T: >1000 W/m²

Standard test conditions flash testing

Sample | Substrate | Encapsulant | Coulombs cycle
-------|-----------|-------------|----------------
39B T-PVF | EVA | 1.37
39F T-PVF | EVA | 0.35
40B T-PVF | POE | 2.15
40F T-PVF | POE | 0.19
41B Glass | EVA |
41F Glass | EVA |
42B Glass | POE |
42F Glass | POE |
A new POE/glass module under sun → dark heat → sun

State A: ‘annealed’ (inactive)
- Destabilization: T > 200°C
- Regeneration: T < 100°C

State B: ‘degraded’ (active)
- Degradation: T > 20°C
- Redegradation: T > 200°C

State C: ‘regenerated’ (inactive)
- Redegradation: T > 1000 W/m²

<table>
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<th>Encapsulant</th>
<th>Coulombs cycle</th>
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<tr>
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<tr>
<td>40B</td>
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<tr>
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<td>Glass</td>
<td>POE</td>
<td></td>
</tr>
</tbody>
</table>
A new POE/glass module under sun → dark heat → sun
Regeneration not stable

Lim, B
“prolonged illumination at elevated temperature always resulted in renewed degradation”
From IEC 61215:2021 series PV Module design qualification and type approval

Front-end characterization

12 Modules
- MQT 01: Visual inspection
- MQT 08.1: Performance at STC (Followed by Gate No. 1)
- MQT 19.1: Initial Stabilization

≥10 kWh/m² 50 ±10 °C

Higher temperature, longer light exposures as with C-AST Tropical and High Desert might lead to LID destabilization, which won’t be seen in IEC 61215
A new POE/glass module under sun → dark heat → sun

Module type would be susceptible to LID in the field in high temperature operation. Issue would not be seen in IEC 61215:2021
## Summary of Results

### Reliability concerns for bifacial module rear/substrate
- **Up to 4 rounds combined-accelerated stress**

<table>
<thead>
<tr>
<th>Glass</th>
<th>Polymeric</th>
</tr>
</thead>
<tbody>
<tr>
<td>No delamination due to constrained outgassing</td>
<td>No discoloration and embrittlement → cracking (with polyvinyl fluoride)</td>
</tr>
<tr>
<td>PID on back</td>
<td>No PID on back</td>
</tr>
<tr>
<td>No delamination due to adhesion loss (non-EVA)</td>
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</table>

- *also*

- **C-AST Spring showed PID-polarization**
  - The 2 kWh/m² after the PID test per the IEC 61215 qualification test masks it
  - Installed modules in the field do not necessarily get rear light soaks

- **C-AST found destabilization of LID-regenerated, inactive state cells leading to power loss in the Spring cycle and ex-situ light soaks;**
  - Likely not findable in IEC 61215
Thank you

US Dept of Energy Awards
08565 – Reliability Evaluation of Bifacial and Monofacial Glass/Glass Modules with EVA and non-EVA Encapsulants
38259 – DuraMAT
38263 – PV Reliability R&D to Ensure a Scientific Basis of Qualification Test and Standards

Hosted at: Swiss NSF/ École Polytechnique Fédérale de Lausanne

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