PV Module Safety and Performance Standard Requirements in Extreme Environments

NIST/UL Workshop on Photovoltaic Materials Durability

December 13, 2019
Colleen O’Brien, UL
Manifestations of material durability...
UL Standards Development Addressing PV Market Needs

North American Leader

1986 – UL1703 PV Modules and Panels
1999 – UL1741 Inverters and Converters
1999 – SU 1279 Solar Collectors
2005 – UL 4703 PV Wire
2007 – SU 2579 Low Voltage Fuse Holders
2007 – SU 5703 Max Operating Temp
2008 – SU 8703 Concentrator PV Modules
2010 – UL 2703 Mounting Systems
2010 – SU 4248-18 Fuse Holders
2010 – UL 489B Circuit Breakers
2010 – UL 6703/A Connectors
2010 – SU 98B Dead-Front Switches
2011 – SU 1699B Arc Fault Protection
2011 – UL 3703 Solar Trackers
2011 – UL 3730 Junction Boxes
2011 – SU 508i Disconnect Switches
2011 – SU 9703 Wiring Harnesses
2012 – UL 4730 Name Plate Rating
2014 – UL 62109-1 Power Converters
2016 – UL 61215 Terrestrial PV Modules – series
2016 – UL 1741SA Advanced Inverter Testing
2016 – UL 9540 Energy Storage Systems and Equipment
2017 – UL 61730 PV Module Safety (harmonized)
2018 – UL 9540a Thermal Runaway Fire in BESS
2018 – SU 3741 PV Hazard Control

International Collaborator

2000 > 2010 > 2020

IEC 61215 Module Type Qualification - Series
IEC 61724 System performance monitoring
IEC 61730-1/2 Module safety
IEC 61853-1/2 Module performance
IEC 62093 BOS design Qualification
IEC 62109-1/2/3/4 Safety of Power Converters
IEC 62446 System commissioning and Inspection
IEC 62509 Battery charge controller performance
IEC 62548 PV array design requirements
IEC 62738 PV plant guidelines
IEC 62804 System voltage durability for modules
IEC 62938 Snow load testing
IEC 62947 Energy performance
IEC TS 60904-1-2 Measurement for Bifacial Modules
Safety and Performance Standards For *Typical* Environments

**Safety**
- Demonstrate non-hazardous failure conditions

**Performance**
- Achieve standard test conditions

**Compliance to Standards**
- UL 1703
- UL/IEC 61730
- IEC 62788-2 Back/front sheet
- New BiPV: UL 7103

**Durability**
- Performs under stress conditions

**Standards Based**
- Acc Life Test (ALT):
  - Temperature Cycle (TC)
  - Humidity-Freeze (HF)
  - Damp Heat (DH)
  - Dynamic Mech Load (DML)
  - Ultra-Violet (UV)

Possible updates based on:
- IEC 63209-2 Extended-stress testing
- IEC 62982 extended TC
- C-AST
### “Typical Environments” Assumed in PV Standards

<table>
<thead>
<tr>
<th>Factor</th>
<th>Standards Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>-40°C to +40°C</td>
</tr>
<tr>
<td>Module temperature</td>
<td>-40°C to +90°C</td>
</tr>
<tr>
<td>Wind load</td>
<td>2400 Pa (minimum test load)</td>
</tr>
<tr>
<td></td>
<td>1000 cycles x 1000 Pa dynamic mechanical load</td>
</tr>
<tr>
<td>Snow load</td>
<td>2400 Pa (minimum test load)</td>
</tr>
<tr>
<td>Corrosivity</td>
<td>Mild to moderate</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>Not typically addressed</td>
</tr>
<tr>
<td>Hail</td>
<td>25-75 mm hail, 7.53-39.5 m/s</td>
</tr>
<tr>
<td>Mounting</td>
<td>Fixed roof-mount, fixed or tracking ground-mount</td>
</tr>
</tbody>
</table>
Extreme Environments: High PV Temperatures
Hot climates or configurations that limit cooling

Basic Form of Equation

\[ T_{\text{module}} = \text{Irradiance} \times e^{(a+b \times \text{Wind Speed})} + T_{\text{ambient}} \]

Module to Cell Temperature

\[ T_{\text{cell}} = T_{\text{Module}} + \frac{G}{1000 \text{ W/m}^2} \Delta T \]

Empirically determined

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Mount</th>
<th>a</th>
<th>b</th>
<th>( \Delta T ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass/cell/glass</td>
<td>Open rack</td>
<td>-3.47</td>
<td>-0.0594</td>
<td>3</td>
</tr>
<tr>
<td>Glass/cell/glass</td>
<td>Close roof mount</td>
<td>-2.98</td>
<td>-0.0471</td>
<td>1</td>
</tr>
<tr>
<td>Glass/cell/polymer sheet</td>
<td>Open rack</td>
<td>-3.56</td>
<td>-0.0750</td>
<td>3</td>
</tr>
<tr>
<td>Glass/cell/polymer sheet</td>
<td>Insulated back</td>
<td>-2.81</td>
<td>-0.0455</td>
<td>0</td>
</tr>
<tr>
<td>Polymer/thin-film/steel</td>
<td>Open rack</td>
<td>-3.58</td>
<td>-0.113</td>
<td>3</td>
</tr>
</tbody>
</table>

\[ \text{Tgg open} \quad \text{Tgg roof} \quad \text{Tgp open} \quad \text{Tgp insulated} \quad \text{Tps open} \]

SAND2004-3535
Unlimited Release
Printed August 2004
Extreme Environments: High PV Temperatures

Model indicates open-rack modules in field at
~ 70ºC

Add Safety Margin of 20ºC
• 90ºC (matches UL 61730)

Add 20ºC to other constructions and mounting styles:

• Level 1 ~ Group at 90º-100ºC
• Level 2 ~ Group at 100º-110ºC

How do we apply Level 1 and Level 2?
# Extreme Environments: High PV Temperatures

## IEC TS 63126

<table>
<thead>
<tr>
<th>Standard</th>
<th>Test Ref</th>
<th>Test Name</th>
<th>Original Requirement</th>
<th>Proposal - Level 1</th>
<th>Proposal - Level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$T_{98%} = 70 ^\circ C$ or less</td>
<td>$T_{98%} &gt; 70 ^\circ C$ to $\leq 80 ^\circ C$</td>
<td>$T_{98%} &gt; 80 ^\circ C$ to $\leq 90 ^\circ C$</td>
</tr>
<tr>
<td>module level tests</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IEC 61215</td>
<td>MQT 09</td>
<td>Hot-spot endurance test</td>
<td>$50 \pm 10 \ ^\circ C$</td>
<td>$+10 ^\circ C$, $(60 \pm 10) ^\circ C$</td>
<td>$+20 ^\circ C$, $(70 \pm 10) ^\circ C$</td>
</tr>
<tr>
<td></td>
<td>MQT 10</td>
<td>UV preconditioning</td>
<td>$(60 \pm 5) ^\circ C$</td>
<td>$+10 ^\circ C$, $(70 \pm 5) ^\circ C$</td>
<td>$+20 ^\circ C$, $(80 \pm 5) ^\circ C$</td>
</tr>
<tr>
<td></td>
<td>MQT 11</td>
<td>Thermal cycling test</td>
<td>$(85 \pm 2) ^\circ C$</td>
<td>$+10 ^\circ C$, $(95 \pm 2) ^\circ C$</td>
<td>$+20 ^\circ C$, $(105 \pm 2) ^\circ C$</td>
</tr>
<tr>
<td></td>
<td>MQT 18</td>
<td>Bypass diode testing chamber</td>
<td>$(75 \pm 2) ^\circ C$</td>
<td>$+15 ^\circ C$, $(90 \pm 2) ^\circ C$</td>
<td>$+25 ^\circ C$, $(100 \pm 2) ^\circ C$</td>
</tr>
<tr>
<td></td>
<td>Part 1</td>
<td></td>
<td>$1.25 \times \text{Isc}$ for diode T</td>
<td>(1.4 \times \text{Isc}) for stress</td>
<td>$1.15 \times \text{Isc}$ for diode T</td>
</tr>
<tr>
<td></td>
<td>Part 2</td>
<td></td>
<td>$1.4 \times \text{Isc}$ for stress</td>
<td>(1.15 \times \text{Isc}) for stress</td>
<td>$1.4 \times \text{Isc}$ for stress</td>
</tr>
<tr>
<td>IEC 61730</td>
<td>MST 22</td>
<td>Hot spot endurance</td>
<td>$(50 \pm 10) ^\circ C$</td>
<td>$+10 ^\circ C$, $(60 \pm 10) ^\circ C$</td>
<td>$+20 ^\circ C$, $(70 \pm 10) ^\circ C$</td>
</tr>
<tr>
<td></td>
<td>MST 37</td>
<td>Material creep test</td>
<td>105 °C</td>
<td>no change</td>
<td>110 °C</td>
</tr>
<tr>
<td></td>
<td>MST 51</td>
<td>Thermal cycle</td>
<td>$(85 \pm 2) ^\circ C$</td>
<td>$+10 ^\circ C$, $(95 \pm 2) ^\circ C$</td>
<td>$+20 ^\circ C$, $(105 \pm 2) ^\circ C$</td>
</tr>
<tr>
<td></td>
<td>MST 54</td>
<td>UV test</td>
<td>$(60 \pm 5) ^\circ C$</td>
<td>$+10 ^\circ C$, $(70 \pm 5) ^\circ C$</td>
<td>$+20 ^\circ C$, $(80 \pm 5) ^\circ C$</td>
</tr>
<tr>
<td></td>
<td>MST 56</td>
<td>Dry heat conditioning</td>
<td>105 °C</td>
<td>no change</td>
<td>110 °C</td>
</tr>
<tr>
<td>component level tests</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IEC 62788-1-7</td>
<td>BST 9</td>
<td>Weathering (UV) ageing test</td>
<td>IEC TS 62788-7-2 (A3 cond.)</td>
<td>IEC TS 62788-7-2 (A4 cond.)</td>
<td>IEC TS 62788-7-2 (A5 cond.)</td>
</tr>
<tr>
<td>(encapsulant, performance)</td>
<td></td>
<td></td>
<td>IEC 62788-7-2 (A3 cond.)</td>
<td>IEC 62788-7-2 (A4 cond.)</td>
<td>IEC 62788-7-2 (A5 cond.)</td>
</tr>
<tr>
<td>IEC TS 62788-2*</td>
<td>BST 9</td>
<td>Weathering (UV) ageing test</td>
<td>IEC TS 62788-7-2 (A3 cond.)</td>
<td>IEC TS 62788-7-2 (A4 cond.)</td>
<td>IEC TS 62788-7-2 (A5 cond.)</td>
</tr>
<tr>
<td>(backsheet and frontsheet safety)</td>
<td></td>
<td></td>
<td>IEC TS 62788-7-2 (A3 cond.)</td>
<td>IEC TS 62788-7-2 (A4 cond.)</td>
<td>IEC TS 62788-7-2 (A5 cond.)</td>
</tr>
<tr>
<td>IEC 62852</td>
<td>5.2.1 h)</td>
<td>Marking, Upper Limit Temperature (ULT)</td>
<td>no requirement</td>
<td>95 °C</td>
<td>105 °C</td>
</tr>
<tr>
<td>IEC 62790</td>
<td>4.2.1 i)</td>
<td>Range of temperature (upper ambient temperature)</td>
<td>no requirement</td>
<td>95 °C</td>
<td>105 °C</td>
</tr>
</tbody>
</table>

* - Following publication of IEC 62788-2-1, pass/fail requirements from this document shall be followed.
Extreme Environments: Wind Load

What governs wind load? Predominantly, three things:

- The site
- The system design
- The mounting system

Typical, flat-plate PV modules with typical frames are not one of the three governing factors.

Mechanical safety and performance of PV modules would *ideally* be addressed in conjunction with mounting system standards:

- UL 2703 (fixed), 3703 (trackers) – static/uniform mechanical Load tests, bonding tests
- IEC 62782 DML
Extreme Environments: Wind Load

Possible improvements to existing standards:
- IEC WG7 project just initiated, UL will participate
- Updates to 2703/3703

Mounting systems – CB verifies/report manufacturer specs:
- Deflections under maximum rated load / torques
- Static pressure coefficients and/or load ratings
- Dynamic response
  - Natural frequencies for all modes < ~10 Hz
  - Damping ratio for all modes < ~10 Hz
  - Dynamic amplification factors

PV modules
- Add nonuniform wind-load test (under consideration in WG2 and WG7)
- Verify allowable deflections and loads – designers then verify compatibility with mounting system
Extreme Environments: Snow Load

- Use test load of 1.5 x specified rating

- Also consider draft IEC 62938: non-uniform snow loading for PV modules
### Extreme Environments: Severe Corrosivity
### IEC 61701 Salt mist corrosion testing

<table>
<thead>
<tr>
<th>Corrosivity Classification of module location</th>
<th>Location Characteristics</th>
<th>One-year Mass loss range (g/m²) of bare steel coupons</th>
<th>60068-2-52 Test Method achieving similar one-year corrosivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 (testing per this document not necessary)</td>
<td>--</td>
<td>--</td>
<td>&lt;10</td>
</tr>
<tr>
<td>C2 (testing per this document not necessary)</td>
<td>≥ 10</td>
<td>&lt;25%</td>
<td>10-200</td>
</tr>
<tr>
<td>C3</td>
<td>≥ 10 2 to 10 2 to 2</td>
<td>≥ 25% &lt;25%</td>
<td>200-400</td>
</tr>
<tr>
<td>C4</td>
<td>&lt; 2</td>
<td>≥ 25% &lt;25%</td>
<td>400-650</td>
</tr>
<tr>
<td>C5</td>
<td>&lt; 2</td>
<td>≥ 25%</td>
<td>650-1500</td>
</tr>
<tr>
<td>CX</td>
<td>offshore</td>
<td>--</td>
<td>1500-5500</td>
</tr>
</tbody>
</table>

Percentage time of wetness (ToW) is defined as the number of hours during the year at which the RH is at 80% or higher and the temperature is greater than 0°C, divided by the total hours in a year. This is defined in ISO 9223, but the tool uses a more complex model based on hourly RH measurements in the climate database.
# PV Module – Performance (Dust and Abrasion)

<table>
<thead>
<tr>
<th>Description</th>
<th>Standard</th>
<th>Test Elements</th>
<th>Pass/Fail Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEC 60068-2-68 :1994</td>
<td>Environmental testing - Part 2: Tests - Test L: Dust and sand Note: more appropriate for sealed enclosures</td>
<td>Informative Report</td>
</tr>
</tbody>
</table>
|                      | IEC 62788-7-3 under development | • Measurement procedures for materials used in photovoltaic modules  
• Part 7-3 Materials and coatings for photovoltaic modules or similar solar devices: Abrasion test methods for environment facing surfaces | TBD                              |

TBD = To Be Determined
Extreme Environments: Hail

- Module manufacturer specifies desired hail test conditions (Table 3, IEC 61215)
- UL verifies compliance
- Designer assess site-specific risk of exceeding test conditions (AHJ, insurance provider, other stakeholders may require specific level of hail resistance)
- Testing in excess of standard requirements can be done, if desired

### Table 3 – Ice-ball masses and test velocities

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Mass (g)</th>
<th>Test velocity (m/s)</th>
<th>Diameter (mm)</th>
<th>Mass (g)</th>
<th>Test velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>7.53</td>
<td>23.0</td>
<td>55</td>
<td>80.2</td>
<td>33.9</td>
</tr>
<tr>
<td>35</td>
<td>20.7</td>
<td>27.2</td>
<td>65</td>
<td>132.0</td>
<td>36.7</td>
</tr>
<tr>
<td>45</td>
<td>43.9</td>
<td>30.7</td>
<td>75</td>
<td>203.0</td>
<td>39.5</td>
</tr>
</tbody>
</table>
Extreme Environments – “New” Applications

New and innovative products - no existing standards:

Custom review needed to assess safety and performance requirements, taking into account safety and performance risks (hazard-based safety engineering, HBSE).

Examples:

Floating PV
- Shock / electric shock drowning
- IP ratings of PV and BOS
- Chronic soiling, heating, shade (IEC TS 63140)
- Site specific cyclic loading, fatigue
- Corrosion
- O&M safety risks
- Reliability of floats and moorings
Extreme Environments – “New” Applications

PV pavers – sidewalk applications
- Immersion risk, impact on reliability, safety
- Slip risk
- Cyclic compressive loads (high heels)
- Maintenance – shoveling, salt/sand

PV thermal hybrid
- Thermal shock
- Thermal cycling
- Extreme temperatures
- PV integration – mechanical securement, chemical compatibility, grounding
- Failsafe design in prolonged leak
- Industry demand for field retrofits based on limited or testing for adding new modules to certifications
## Summary - Standards Considerations for Extreme Environments

<table>
<thead>
<tr>
<th>Factor</th>
<th>Extreme Environment Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>Increase temperature per IEC TS 63126</td>
</tr>
<tr>
<td>Module temperature</td>
<td>Increase temperature per IEC TS 63126</td>
</tr>
</tbody>
</table>
| Wind load       | **Updates needed:**  
|                 | • Assess impact of mounting system (deflections, dynamic amplification)  
|                 | • Non-uniform load                                                  |
| Snow load       | 1.5 x load; IEC 62938 (non-uniform)                                |
| Corrosivity     | IEC 61701                                                           |
| Abrasion        | Reference IEC 62788-7-3 (draft); DIN EN 1096-2-2012; ASTM D968-17   |
| Hail            | Verify compliance with site requirements or get insurance / modify test |
| Mounting        | Custom hazard based assessment needed to determine requirements.    |
Thank you