Welcome to Oerlikon Solar

Stress tests and failure modes of thin film silicon photovoltaic modules
Ivan Sinicco – Head of Module Technology

Durability of Thin Film Solar Cells - EMPA Academy
Dübendorf ZH, 4th of April 2012
**Agenda**

1. About Oerlikon Solar
2. How a PV module is designed?
3. What should be the module durability?
4. Accelerated stress tests
5. Failure Modes
6. Manufacturing Consistency and Reliability/Durability Implications
Oerlikon Solar at a glance

- A leading supplier of manufacturing solutions for thin film silicon modules
- More than 870 MW contracted to date
- Approx. 650 employees including 300 scientists and engineers as well as 200 global customer personnel
- R&D investments of more than MCHF 200 in last 4 years

Serving 13 locations in 9 countries
Milestones in Oerlikon Solar’s history

- PV lab at IMT
- VHF PECVD deposition
- Oerlikon founds own R&D lab
- 1st equipment sale (Schott Solar)
- 1st Micromorph® turnkey production line contract
- TUV certification for Micromorph®
- 1st Micromorph® technology patent
- 1st functional 1.4 m² a-Si module
- PV lab at IMT
- Oerlikon founds own R&D lab
- 1st equipment sale (Schott Solar)
- 1st Micromorph® turnkey production line contract
- TUV certification for Micromorph®
- Launch of ThinFab™ € 0.50/Wp
- Champion cell 11.9% efficiency
- 10% efficiency average
- 1st ThinFab™ sold
- Record module with 154 peak W and 10.8% efficiency
- Technology roadmap to 12% efficiency
- 1st customer in commercial production
- Launch of 2nd Gen. ThinFab™ € 0.35/Wp
- Record Cell with 12.5%
- Concept & product
- Commercialization & mass production
- Opportunity identification

Durability of Thin Film Solar Cells - 2012
How a PV module is designed?

- Design proposal
- DFMEA
- IP
- Sourcing
- Compliance to standards
- Test & qualification procedures
- EHS analysis
- Develop initial prototype
- Start material and interface testing
- Finalize feasibility study
- Market feedback
- Conclude tests at module level
- Define EQ requirements
- Supplier evaluation
- Prepare modules for certification
- Process range definition
- Certification obtained
- Engineering lot in mass production
- Re-test engineering lot
- Release BoM & design freeze
- Design process specs
- Design material specs
Module Reliability and Durability

The Bathtub Curve
Hypothetical Failure Rate versus Time

- Infant Mortality
- Decreasing Failure Rate
- Normal Life (Useful Life)
- Low "Constant" Failure Rate
- End of Life Wear-Out
- Increasing Failure Rate

Time

Durability (t)
(once the «killing parameters» are defined)

Module Design only

Bad Module Design
Bad Process
Somehow covered by IEC (NOT 100%) ➔ a design to failure model is missing...

Off-spec materials
Faulty process control

Polymers 2012, Cologne
What should be the PV Module Durability?

The energy produced is not depending ONLY on the efficiency:

\[ E \alpha \eta \times t \]

Where \( t \) is the time that an usable efficiency is delivered (durability).

A bit more realistic is the equation below

\[ E(t) \alpha \eta(t) \times t \]

and further

\[ E(t, \phi, \lambda, SV, MS) \alpha \eta(t, \phi, \lambda, SV, MS) \times t \]
What should be the PV Module Durability?

All topics above were still too academical…

At the end, what really matter is price!

\[
\text{LCOE} = \frac{\text{Total Life Cycle Cost}}{\text{Total Lifetime Energy Production}}
\]

Source: The drivers of Levelized Cost Of Electricity for utility scale pv (Sunpower)
What should be the PV Module Durability?

LCoE as basic reference point:

LCoE = f(financial costs, taxes, inflation rate, BOS price, Module price, Location, EY, Module durability, System depreciation, System degradation rate)

Cost structure installed system:

- ca 35%
- ca 35%
- ca 30%
## Back to Reality

### Possible environmental conditions on the Planet Earth

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. ambient temperature</td>
<td>58°C</td>
</tr>
<tr>
<td>Min. ambient temperature</td>
<td>-67°C</td>
</tr>
<tr>
<td>Max. ΔT/24h = 103°C, ΔT/1min = 20°C</td>
<td></td>
</tr>
<tr>
<td>Highest average ΔT/24h</td>
<td>ca 30°C</td>
</tr>
<tr>
<td>Max. yearly average UV (280nm – 400nm) on horizontal surface</td>
<td>ca 185KWh/m2</td>
</tr>
<tr>
<td>Pressures up to:</td>
<td></td>
</tr>
<tr>
<td>static</td>
<td>10kPa</td>
</tr>
<tr>
<td>dynamic</td>
<td>4kPa</td>
</tr>
<tr>
<td>Hail up to 200gr</td>
<td></td>
</tr>
<tr>
<td>rH up to 95% @ 35°C</td>
<td></td>
</tr>
<tr>
<td>Basic ambient → PH 11 (near salted roads, farms, sea)</td>
<td></td>
</tr>
<tr>
<td>Acid ambient → PH 3 (industry, highway..)</td>
<td></td>
</tr>
<tr>
<td>System Voltage:</td>
<td>1000V, 1500V…+</td>
</tr>
<tr>
<td>Several possible mounting configurations</td>
<td></td>
</tr>
</tbody>
</table>

In those conditions the PV Module **must** deliver electric energy with minimal performance losses!

http://www.ncdc.noaa.gov

Durability of Thin Film Solar Cells - 2012
Accelerated Stress Tests

Typical field failure modes:

- Broken interconnects
- Corrosion
- Delamination or loss of elastomeric properties of lamination foil
- Solder failures
- Broken Glass
- Hot Spots
- Ground faults
- Junction box and connection faults
- Structural failures
- By-pass diode failure
- Arcing
- Electrochemical corrosion / or delamination of TCO
- Electro migration of chemical species
- Faulty edge deletion
- Shunts at laser scribes
- Shunts at absorber impurities

→ Developing accelerated stress tests that replicates the failure mode observed in the field is the only chance to determine module durability without waiting 20+ years
Accelerated Stress Tests

History of Accelerated Testing (or better; Qualification Testing)

• JPL Block Buys I-V (1975 – 1981) → Crystalline Si

• European Community Specifications 501 to 503 (1981 – 1991)

• SERI IQT → Modifications to a-Si (Thin Film) (1990)

• IEEE 1262 → All technologies included (1995 – 2000)

• IEC 61215 → Crystalline Si (ed1 – 1993)
  (ed2 – 2005)

• IEC 61646 → Thin Film (ed1 – 2005)
  (ed2 – 2008)

From: History of Qualification Standards; J. Wolgemuth
### Accelerated Stress Tests

**JPL Block buys**

<table>
<thead>
<tr>
<th>Test</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Cycles</td>
<td>100-40 to +90°C</td>
<td>50-40 to +90°C</td>
<td>50-40 to +90°C</td>
<td>50-40 to +90°C</td>
<td>200-40 to +90°C</td>
</tr>
<tr>
<td>Humidity</td>
<td>70°C, 90% 68 hrs</td>
<td>5 cycles 40 to 23°C 90%</td>
<td>5 cycles 40 to 23°C 90%</td>
<td>5 cycles 54 to 23°C 90%</td>
<td>10 cycles 85 to -40°C 85%</td>
</tr>
<tr>
<td>Hot Spot (intrusive)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 cells 100 hrs</td>
</tr>
<tr>
<td>Mechanical Load</td>
<td>100 cycles ± 2400 Pa</td>
<td>100 cycles ± 2400 Pa</td>
<td>10000 ± 2400 Pa</td>
<td>10000 ± 2400 Pa</td>
<td></td>
</tr>
<tr>
<td>Hail</td>
<td></td>
<td></td>
<td></td>
<td>9 impacts ¾&quot; ~ 45 mph</td>
<td>10 impacts 1&quot; ~ 52 mph</td>
</tr>
<tr>
<td>High Pot</td>
<td>&lt;15 µA 1500 V</td>
<td>&lt; 50 µA 1500 V</td>
<td>&lt; 50 µA 1500 V</td>
<td>&lt; 50 µA 2*V&lt;sub&gt;s&lt;/sub&gt;+1000</td>
<td></td>
</tr>
</tbody>
</table>

From: History of Qualification Standards; J. Wolgemuth
Accelerated Stress Tests

JPL Block buys led to dramatic improvements – can we learn from this?

- One study claimed (Whipple, 1993):
  - Pre-Block V: 45% module failure rate
  - Post-Block V: <0.1% module failure rate

- Primary differences for Block V included:
  - 200 instead of 50 thermal cycles
  - Humidity freeze
  - Hot spot test

From: History of Qualification Standards; J. Wolgemuth
Test Sequences for IEC 61646 Qualification

Related to Performance
Test Sequences for IEC 61730 Qualification

Related to Safety
## Failure Modes and IEC Stress Tests

<table>
<thead>
<tr>
<th>IEC</th>
<th>Accelerated Stress Test</th>
<th>Failure Mode</th>
<th>Issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.11</td>
<td>Thermal Cycles</td>
<td>Broken Interconnect</td>
<td>Performance / Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solder Bond failures</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Junction Box Adhesion</td>
<td>Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Module Connection Open Circuits</td>
<td>Performance / Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open Circuits leading to Arching</td>
<td>Performance / Safety</td>
</tr>
<tr>
<td>10.13</td>
<td>Damp Heat</td>
<td>Corrosion</td>
<td>Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Delamination of Laminate</td>
<td>Performance / Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Adhesion and Elasticity of Polymeric Materials</td>
<td>Performance / Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Junction Box Adhesion</td>
<td>Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inadequate Edge Deletion</td>
<td>Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glass Corrosion</td>
<td>Performance</td>
</tr>
<tr>
<td>10.12</td>
<td>Humidity Freeze</td>
<td>Delamination of Laminate</td>
<td>Performance / Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Adhesion and Elasticity of Polymeric Materials</td>
<td>Performance / Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Junction Box Adhesion</td>
<td>Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inadequate Edge Deletion</td>
<td>Safety</td>
</tr>
<tr>
<td>10.1</td>
<td>UV Test</td>
<td>Delamination of Laminate</td>
<td>Performance / Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Adhesion and Elasticity of Polymeric Materials</td>
<td>Performance / Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cell Performance</td>
<td>Performance / Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Junction Box Adhesion</td>
<td>Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ground fault due to Backsheet</td>
<td>Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Polymer discoloration (more substrate configuration)</td>
<td>Performance / Safety</td>
</tr>
<tr>
<td>10.16</td>
<td>Mechanical Load</td>
<td>Broken Interconnect</td>
<td>Performance / Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solder Bond failures</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Broken Glass</td>
<td>Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Structural Failures</td>
<td>Safety</td>
</tr>
<tr>
<td>10.9</td>
<td>Hot Spot Test</td>
<td>Hot Spots</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weak Cell / Region</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shunting</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Broken Glass</td>
<td>Safety</td>
</tr>
<tr>
<td>10.17</td>
<td>Hail Test</td>
<td>Broken Glass</td>
<td>Safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solder Bond failures</td>
<td>Performance</td>
</tr>
<tr>
<td>10.18</td>
<td>Bypass Diode Thermal Test</td>
<td>Bypass Diode Failures</td>
<td>Safety</td>
</tr>
<tr>
<td>MST 26</td>
<td>Reverse Current Test</td>
<td>Weak Cell / Region</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shunts</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Broken Glass</td>
<td>Safety</td>
</tr>
</tbody>
</table>
Accelerated Stress Tests (modeling example)

Key to model the lifetime of a PV Module (once the kind of stresses that the device will suffer are well defined) is the knowledge of the acceleration factors (A_F) caused by each stress factor. Several models can be used to determine the acceleration factors. One of those is the so called Arrhenius factor which deals with temperature factors:

\[ \text{Rate} \propto e^{-\frac{E_a}{kT}} \]

With this model is possible to model degradation rates by using characteristic temperature \( T_{eq} \) associated with a time averaged degradation rate

\[
T_{eq} = \frac{E_a}{k \ln \left( \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} e^{-\frac{E_a}{kT(t)}} \, dt \right)}
\]

The Peck Model is an extension of the Arrhenius model where the humidity is added and can be used for modeling modules under Damp Heat conditions (even Biased conditions).

\[ \text{Rate} \propto [rH]^n \times e^{-\frac{E_a}{kT}} \]
Accelerated Stress Tests

$T_{eq}$ Varies by Location and Mounting Configuration

Mounting Configuration: ±10°C
Location: ±15°C
Activation Energy: ±10°C
Total Range: ±30°C

Accelerated Stress Tests

Thermal Acceleration Depends on Mounting and Environment

- Environment: 10X to 100X
- Mounting: 10X to 100X
- Activation Energy: 10 X to 1000X

- Overall there is a 10,000X variability in degradation rates.

IEC Qualification Tests are a pass/fail criteria only!

- Increase test duration (test to failure approach)
- Use higher stress levels (Note: Higher stress levels could generate failure modes not observed under real circumstances)
- Combined Stresses (i.e. add voltage to Damp Heat)
- Dynamical mechanical load (not present in IEC qualification and present in real life)
- Introduce Material Designed Tests to focus on material performance excluding complex degradation modes due to interfaces and cross reactions
- Change pass / fail criteria into trend determination
- Introduce pure thermal stress tests to identify potential failure modes associated to diffusion of elements and or chemical reactions
Relevant reaction / process that may impact module performance

<table>
<thead>
<tr>
<th>Glass or Polymer Superstrate</th>
<th>Soiling / Corrosion / Na E field Induced Migration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture / O2 (from edge), Cations / Anions</td>
<td>E field induced Migration (from glass)</td>
</tr>
<tr>
<td>TCO</td>
<td>Weak Cell / Shunt / Hot Spot</td>
</tr>
<tr>
<td>Absorber</td>
<td></td>
</tr>
<tr>
<td>TCO</td>
<td></td>
</tr>
<tr>
<td>Oxidation /corrosion / E field induced Migration / Ion catalyzed reactions /acidic attack from Polymer / bonding defect</td>
<td></td>
</tr>
<tr>
<td>Moisture / O2 inward diffusion, Na E field induced Migration / Photochem. Oxidative degrad. Reactions, Acidic Diffusion</td>
<td></td>
</tr>
<tr>
<td>Encapsulant</td>
<td></td>
</tr>
<tr>
<td>Cations / Anions Interdiffusion into Polymer / Adhesion / Delamination</td>
<td></td>
</tr>
<tr>
<td>Back Glass or Backsheet</td>
<td></td>
</tr>
</tbody>
</table>

Main drivers: T, rH, V, PH, UV, O₂, H₂O (vapor or liquid)
**Stressing Method**

- Light Soaking Visible (B,B,B)
- Light Soaking UV (UVA & UVB)
- Dynamical Mechanical Load (up to 8000Pa)
- Reverse Current Test
- Thermal Cycling (-60°C/+165°C)
- Humidity – Freeze (-60°C / 165°C/20%..95%)
- Damp Heat (30°C / 95°C/20%..95%)
- Biased Damp Heat (±1000V; ±4000V)
- Bake Test / Boiling test
- Module Breakage Test
- Chemical compatibility Test
- Outdoor

**Evaluation Method**

- Wet Leakage Current
- IV scanning (High & Low)
- Dark IV, EQE
- Spectral matching
- Electroluminescence
- IR
- FTIR; UVis
- SIMS; SEM; AFM; HSGC
- DSC; TGA
- Elemental chemical analysis
- Compressive Shear Test
- Pull Test; Ring-on-Ring Test
- TLM
- Visual Inspection (key!!)
Beyond IEC (increase test duration + trend line)

![Graph showing power relative to initial for sample A and sample b over DH hours, with an IEC limit]

IEC limit

- Power relative to initial
- DH hours
- Sample A
- Sample b
Beyond IEC (increase test duration + trend line)
Beyond IEC (increase test duration + trend line)
Beyond IEC (Example of OS modules design evolution)

Average survival (all technologies) according to IEC criteria
Damp Heat Acceleration Factors by Climate

SPR vs 3PM, DH @85% r.h. (in hours)

- SPR
- 1
- 2
- 3
- 4
- 5
- 6
- 7


"SPR" = SunPower internal reliability study of SunPower back-contact modules.

Florida
Las Vegas

30 yrs for SunPower Back-contact cells.
TLM Method - contacting resistance loss (initial)
TLM Method - contacting resistance loss (after 320 TC)
Beyond IEC (Biased Damp Heat)

Figure 1. Leakage current to ground, irradiance, calculated module surface relative humidity (RH), and module temperature over a one-day period in Florida. The module is horizontally mounted, the active layer is biased to scale logarithmically with irradiance to a maximum voltage of $-600 \text{ V}$ with the module leads connected to a load resistor to maintain approximately $P_{\text{max}}$. The leakage current is highest when morning dew is on the module face and the surface resistance (SR) is low (inset). When the module is dry, the current most closely follows the calculated module surface RH.

Figure 2. Application of voltage to the active layer of a PV module via the shorted leads. The leakage current is monitored by a voltmeter across a resistor R1 connected to ground. The voltmeter may be protected from overvoltage by a second resistor R2.
Beyond IEC (Biased Damp Heat)


G1

G2 (-4000V)
91.1% from initial power

G2
95.4% from initial power

G3 (90°C/95%RH)
100% from initial power
AF ≥ 2.3 (extended Peck Model)

A TF Si
B TF Si
C Benchmark CIGS
D TF Si
E TF Si
F Benchmark CdTe
G Benchmark Mono & Polycrystalline
H

Thin Film – Several manufacturers

The red indication corresponds the time range where the module had less than 80% of the initial power failure. Green color represents at least 80% from initial power. All @ -1000V if not marked.

See also:
Gossla, M., Hälker, T., Krull, S., Rakusa, F., Roth, F., & Sinicco, I.
Leakage Current and Performance loss of Thin Film Solar Modules. SPIE, San Diego (2010)

BDH hours
Beyond IEC (Biased Damp Heat)

EL example: Module F

928hrs BDH -1000V (51.1% $P_{ini}$)

Moisture Diffusion & TCO Corrosion

E Field Induced migration

EL example: Module H

800hrs BDH -1000V (60% $P_{ini}$)
Example of glass chemistry on reliability

- The leakage current of a PV Module is related to the module durability.
- The main contributor to leakage current on PV Modules is glass.
- Glass chemistry is key on glass resistivity (the better the insulation the lower the leakage current).

Modules in the field are subjected to voltages between cell and glass reaching the system voltage value in the worse case (and half of that in the best case) and this voltages are related to the way that the system is connected to the inverter. The biased damp heat test simulate such a situation.

FROM:

Leakage Current and Performance Loss of Thin Film Solar Modules

Mario Gossler*, Thomas Hälker, Stefan Krull, Fabia Rakusa, Florian Roth, and Ivan Sinicco
Oerlikon Solar Ltd., Hauptstrasse 1a, 9476 Trübbach, Switzerland
Chemical composition variation from float line to float line

<table>
<thead>
<tr>
<th>Sample</th>
<th>Glass (mol.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO₂</td>
</tr>
<tr>
<td>float 1</td>
<td>71.70</td>
</tr>
<tr>
<td>float 2</td>
<td>71.46</td>
</tr>
<tr>
<td>float 3</td>
<td>71.39</td>
</tr>
<tr>
<td>float 4</td>
<td>71.13</td>
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<td>float 5</td>
<td>71.91</td>
</tr>
<tr>
<td>float 6</td>
<td>73.49</td>
</tr>
<tr>
<td>float 7</td>
<td>69.98</td>
</tr>
<tr>
<td>float 8</td>
<td>72.04</td>
</tr>
<tr>
<td>float 9</td>
<td>71.99</td>
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<td>71.71</td>
</tr>
<tr>
<td>float 18</td>
<td>71.58</td>
</tr>
</tbody>
</table>
Glass / Foil interface after 1000 h DH 85/85 for a glass with low magnesia content

Figure 6: SEM micrographs taken from the glass- clear PVB interface of sample b (Glass type A) in figure 3 after delamination. (a) Crystallites formed by Ca/Na segregation from the glass bulk, penetrating into the clear PVB film. (b) Origin of the Ca/Na rich crystallites seen at the same position of the interface on the glass surface.

From: Analysis of the Glass- Clear PVB Lamination foil interface of Thin Film Laminates
Jens Günster\textsuperscript{a,b}, Stefan Krull, Fabia Rakusa\textsuperscript{a}, Florian Roth and Ivan Sinicco\textsuperscript{a}
Safety Integrity: Wet Leakage Currents

Wet Leakage Measurement

- Glass A
- Glass with low MgO
- Glass C

Generally, for Glass type C, the IEC limit is reached after 7000hrs.

Care must be taken when using accelerated stress tests.

Transmittance spectra of EVA field-exposed at Miyakojima

Active UV absorber formulated in EVA encapsulant is still remained even 17 years field exposed at Miyakojima.

From: Tsuyoshi Shioda
Mitsui Chemicals, Inc.
Mitsui Chemicals Tohcello Inc.
Care must be taken when using accelerated stress tests

Transmittance spectra of EVA aged by UV accelerated tests

From:
Tsuyoshi Shioda
Mitsui Chemicals, Inc.
Mitsui Chemicals Tohcello Inc.

Durability of Thin Film Solar Cells - 2012
Care must be taken when using accelerated stress tests

We evaluated 5 modules exposed at Miyakojima, and found that the maximum YI ranged from approximately 10 to 20.

We assumed that average of maximum YI change after 17 yrs field-exposure was 15.

From: Tsuyoshi Shioda
Mitsui Chemicals, Inc.
Mitsui Chemicals Tohcello Inc.
Care must be taken when using accelerated stress tests

YI change prediction for EVA-1 with Xenon light

Sample: EVA-1

17y at Miyakojima

60W/m²  BPT110°C
(300~400nm)

Exposed time [hr]

17 week

UV irradiation for 1 week corresponds roughly to field aged for 1 year.

From: Tsuyoshi Shioda
Mitsui Chemicals, Inc.
Mitsui Chemicals Tohcello Inc.
How to insure manufacturing consistency (or is the module successfully tested identical to the approved one)?

Quality

- Quality of a PV module is a balance between *module design, process control and material compliance*
- Once the module design is fixed process control and incoming material inspection/approval are the key element

⇒ *Only Fabs with an outstanding Process Control and clear material incoming inspection can afford the risk of warranties and reduce insurance costs (bankability)*
How the designed module is produced?

<table>
<thead>
<tr>
<th>Material control</th>
<th>Operation control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process control</td>
<td>Product control</td>
</tr>
</tbody>
</table>

- **Design specs**
  - Material specs available
  - Material specs check via incoming monitoring (fingerprint on sampling plan)
  - Supplier agreements
  - Storage and logistics clear

- **Are machines updated?**
  - How machines are monitored?
  - Down time impact clear?
  - Shelf life check
  - Process specs available
  - Process monitoring in place?

- **WPI are updated?**
  - Are operators well trained?
  - Are machine settings well adjusted?
  - Engineering lot successful?
  - Run process

- **Sampling testing plan according to sigma in place?**
  - Labeling according to design?
  - Warranties according to new design?
  - Packaging well considered?
  - Faulty product return plan in place?
  - After sales policy in place?
Implications on Module Reliability and Durability of non consistent manufacturing processes

The Bathtub Curve
Hypothetical Failure Rate versus Time

- Increased Failure Rate
- Decreasing Failure Rate
- Normal Life (Useful Life)
- Low "Constant" Failure Rate
- End of Life Wear-Out

Durability (t)
(once the measurement criteria is defined)

Due to off-spec materials
Faulty process control

Durability of Thin Film Solar Cells - 2012
How to insure manufacturing consistency? (or is the module produced identical to the approved one?)

The PV QA Task Force was formed last July and consists of six Task Groups;

**Task Group 1:** PV QA Guideline for Manufacturing Consistency  
(leader Ivan Sinicco)  
~200 volunteers

**Task Group 2:** PV QA Testing for Thermal and mechanical fatigue including vibration (leader Chris Flueckiger)

**Task Group 3:** PV QA Testing for Humidity, temperature, and voltage  
(leaders John Wohlgemuth and Neelkanth Dhere)

**Task Group 4:** PV QA Testing for Diodes, shading and reverse bias  
(leaders Vivek Gade and Paul Robusto)

**Task Group 5:** PV QA Testing for UV, temperature and humidity  
(leader Michael Köhl)

**Task Group 6:** Communication of PV QA ratings to the community  
(leader David Williams)

Summary

- Passing Certification Testing does not insure reliability and even less, **durability**

- Failure modes are related to:

  - **Module Design (cell included)**
    - (~ durability)
  - Where the modules are located
  - How the modules are installed
    - (~durability and reliability)
  - Quality of the used material (gases inclusive)
  - Effective process and environment control
    - (~reliability)

- To increase market confidence towards PV it is necessary to have a durable module design and adequate QA procedures at supplier and production sites

- To increase product bankability and reduce insurance costs (reducing so the financial risk) the points above MUST be correctly addressed and proactively informed to the policy makers
Three reasons to invest into THINFAB™

Competitive
Clean
Sustainable

Thank you for your attention!