The Principles of Weathering and How They Apply to Environmental Durability Testing of PV Backsheets

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Atlas - Introduction

Part 1
- Accelerated Weathering
- The Principles of Weathering

Part 2
- Solar Radiation on PV Backsheets
- Accelerated Weathering of PV Backsheet
- Recommendations for a Test Considerations

Summary and Conclusion
Atlas – The Beginnings 1915-1918

The history of Atlas’ predecessor goes back to the early 1900’s, however the current Atlas began in 1915 when the core carbon arc lamp lighting business was threatened by new high-power tungsten lamps. This led to textile dye fading experiments in 1915 in the back room and the development of the Solar Determinator in February 1918 as a result of the loss of German aniline dyes with the beginning of World War I and the switch back to less-lightfast natural plant dyes and the beginning of laboratory artificial sunlight testing.

- Concluding our 100th anniversary year in lightfastness and weathering testing equipment and services innovation and leadership.
Part 1: Primary and Secondary Weather Stress Factors

Solar radiation

- Heat / cold, temperature changes, shock
- Mechanical factors, e.g. wind; abrasion by sand, dust, hail
- Water: air humidity, rain, condensation, snow, ice
- Salt water, mist, acid rain
- Man-made and natural air pollutants, e.g. NOx, SOx, soot, NH3
- Oxygen, O3

Environmental ageing (microscopic)

Property change (macroscopic): function, appearance

Premature failure
# Weathering Test - Climatic Test

<table>
<thead>
<tr>
<th>Weathering Test</th>
<th>Climatic Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weathering Instrument, chamber, etc.</td>
<td>Climatic Chamber, Oven, Damp Heat Chamber, etc.</td>
</tr>
<tr>
<td>Light + Temperature + Water (Relative Humidity and Spray)</td>
<td>Temperature + Relative Humidity (no light)</td>
</tr>
</tbody>
</table>

Source: heckert solar.com

Caution: Parameters from climatic tests usually have to be changed when adding light to account for full-spectrum solar heating of test specimens. (Example: Damp Heat + 1 Sun)
General Polymer Degradation Mechanism

Polymer Autocatalytic Photo-oxidation Cycle

Dominated by photon energy

Dominated by O₂ availability

Dominated by heat

Dominated by heat, UV & Vis light

Note: Hydrolysis reactions not shown

Photons, especially UV *photoinitize* degradation, however much of the subsequent 2° free radical reactions primarily responsible for property degradation are *thermally* driven processes.
6 Basic Principles of Weathering Tests

1. Primary weather factors should be applied simultaneously to the specimens.
   – As in real life
   – Synergistic and interaction effects

2. Test parameters should include cyclic change and not steady state
   – As in real life
   – To induce mechanical stresses

3. Maximum stress levels should not be exceeded.
   – As in real life
   – Unless supported by data and knowledge.

4. The (laboratory) light source should resemble global solar radiation ("daylight") as closely as possible in the UV and VIS (and NIR) wavelength regions.
   – Especially in the UV cut-on region

5. The acceleration of a laboratory test should be limited to avoid distortion of the degradation mechanism(s).
   – Requires time and compromises
   – Rule of thumb < 10 x

6. "Black box" approach has proven to be useful because most environmental ageing processes are complex and usually not known in detail.
   – i.e. simulating the worst-case in-use conditions
No 1: Apply Primary Weather Factors Simultaneously

Weathering degradation often involves synergistic and interaction effects.

No 2: Change Test Parameters Cyclically

E.g., Test sequence according to automotive component testing standard DIN 75220

Steady-state conditions never exist in the real world

**Source:** Florian Feil, David Dumbleton: OPTIMIZING WEATHERING EXPERIMENTS FOR THE REPRODUCTION OF SIMULTANEOUS PHOTOCHEMICAL AND PHYSICAL DEGRADATION PATHWAYS, 6th European Weathering Symposium EWS. 11 – 13 September 2013. Bratislava, Slovak Republic.

DIN 75220:1992-11 Ageing of automotive components in solar simulation units
No. 3: Do not Exceed Maximum Stress Levels

Example: Glass Transition Temperatures $T_g$ (°C)

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_g$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene (atactic)</td>
<td>-20</td>
</tr>
<tr>
<td>Polypropylene (isotactic)</td>
<td>0</td>
</tr>
<tr>
<td>Poly-3-hydroxybutyrate (PHB)</td>
<td>15</td>
</tr>
<tr>
<td>Poly(vinyl acetate) (PVAc)</td>
<td>30</td>
</tr>
<tr>
<td>Polyethylene terephthalate (PET)</td>
<td>70</td>
</tr>
<tr>
<td>Poly(vinyl chloride) (PVC)</td>
<td>80</td>
</tr>
<tr>
<td>Poly(vinyl alcohol) (PVA)</td>
<td>85</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>95</td>
</tr>
<tr>
<td>Poly(methylmethacrylate) (atactic)</td>
<td>105</td>
</tr>
<tr>
<td>Poly(carbonate)</td>
<td>145</td>
</tr>
<tr>
<td>Polynorbornene</td>
<td>215</td>
</tr>
</tbody>
</table>

*The apparent rate of weathering often increases $> T_g$ in laboratory tests*

No. 4: Laboratory Light Must Match the Sun

Activation spectrum (photochemically effective irradiance):

$$F = E_{\text{eff}} = \int E_\lambda s(\lambda) \, d\lambda$$

Spectral sensitivity

Daylight spectrum

Poor solar spectral match containing unrealistic UV

Non-natural degradation resulting from the artificial test
No. 5: Acceleration is Limited

Back to the future?

- When there is not a simple single photolytic, hydrolytic or thermal degradation mechanism.
- When there are stress-interaction effects.
- Not all weathering stress factors can be accelerated at the same rate in tests.
No. 6: Use Black-Box Approach

• All organic materials undergo weathering due to combined effects of light, heat, and moisture in the presence of oxygen.
• Degradation mechanisms of polymers are complex and not fully understood

→ Use “black box approach” or – in other words – “agnostic testing”

Source: Nancy Phillips, Kurt Scott, David Burns. Quantifying PV module microclimates, and translation into accelerated weathering protocols. 2nd Atlas/NIST PV Durability Workshop, 14 November 2013. NIST, Gaithersburg, MD, USA.

For Standards:

C. “Agnostic Testing”
  ▪ Materials Independent
  ▪ Gives some confidence that a new product will work during its service life
  ▪ Example: encapsulants
    ▪ EVA, polyolefins, silicones, new ideas
    ▪ Anything that will work in the field should pass the test

  ▪ Philosophy: run at or near typical maximum values observed in the application
    ▪ Rule of thumb: limit acceleration to 10X
      ▪ 25 years → 2.5 years!
        ▪ Delta testing: Up to 10x; look for change, as opposed to a failure
        ▪ Accelerating >10x, expect errors; may see failures that don’t occur in real world
Summary: 6 Basic Principles of Weathering Tests

1. Simultaneous application of primary weather stress factors
2. Change test parameters cyclically as in nature
3. Do not exceed maximum stress levels.
4. Laboratory light must match global solar radiation in UV and VIS and usually NIR.
5. Acceleration of a laboratory test is limited.
6. Use "Black box" agnostic approach to avoid altering mechanisms or skewing tests to what you think you know.

See ISO 4892-1 / ASTM G151 for a good explanation of factors that decrease laboratory test correlation to outdoor weathering for polymers.
# Part 2: Environmental Stresses on Backsheets

<table>
<thead>
<tr>
<th>Weather exposed side of Backsheet</th>
<th>Encapsulated side of Backsheet</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Global Solar Radiation</strong></td>
<td><strong>Global Solar Radiation</strong></td>
</tr>
<tr>
<td>• E reflected from Ground - Albedo</td>
<td>• Transmitted through glass and encapsulant</td>
</tr>
<tr>
<td>• E reflected from next PV modules</td>
<td>• Irradiance, radiant exposure?</td>
</tr>
<tr>
<td>• Irradiance, radiant exposure?</td>
<td>• Spectral Power Distribution (SPD)?</td>
</tr>
<tr>
<td>• Spectral Power Distribution (SPD)?</td>
<td></td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td><strong>Temperature</strong></td>
</tr>
<tr>
<td>• Dark: Ambient temperature</td>
<td>• Dark: Ambient temperature</td>
</tr>
<tr>
<td>• Light: between module operating T and ambient T</td>
<td>• Light: module operating temperature</td>
</tr>
<tr>
<td>• Day-night cycles</td>
<td>• Day-night cycles</td>
</tr>
<tr>
<td>• Diurnal variations (rain, etc.)</td>
<td>• Diurnal variations (rain, etc.)</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td><strong>Water</strong></td>
</tr>
<tr>
<td>• Condensation</td>
<td>• Relatively negligible</td>
</tr>
<tr>
<td>• Heavy rain / spray</td>
<td></td>
</tr>
<tr>
<td>• Atmospheric humidity</td>
<td></td>
</tr>
<tr>
<td><strong>Secondary factors</strong></td>
<td></td>
</tr>
<tr>
<td>• Sand abrasion in deserts</td>
<td></td>
</tr>
<tr>
<td>• Salt in marine environments</td>
<td></td>
</tr>
<tr>
<td>• Ammonia in agricultural installations</td>
<td></td>
</tr>
<tr>
<td>• Air pollutants in industrial areas</td>
<td></td>
</tr>
<tr>
<td>• Biological agents, e.g. mildew, algae, fungi etc.</td>
<td></td>
</tr>
<tr>
<td>• ...others</td>
<td></td>
</tr>
</tbody>
</table>
Mounting Geometry - Three Cases

On-rack – Ground or flat roof
Utility Scale

On-roof
Residential, Commercial

BIPV
Residential, Commercial
Typical Geometry - On-Rack Installation

Example for Germany:
Beta = 30°,
Module area / ground area = ca. 1/3

Bild 2.9: Verschattung bei aufgeständerten Photovoltaikanlagen; Quelle: Eigene Darstellung


Pictures: Solar Park Lieberose
Solar Radiation on Front and Back of Backsheet

Note: Diffuse reflection of direct solar radiation from next panel not considered.
Solar Radiation on Front and Back of Backsheet

On Back of BS
• Direct solar radiation through glass and encapsulant
• + Diffuse solar radiation through glass and encapsulant
• = Global solar radiation through glass and encapsulant

On Front of BS
• Diffuse ground albedo
• + Direct reflected radiation of diffuse global solar radiation by next panel row
### Terrestrial Albedo of Ground Surfaces in VIS, IR

<table>
<thead>
<tr>
<th>Surface</th>
<th>Typical albedo</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh asphalt</td>
<td>0.04</td>
<td>(1)</td>
</tr>
<tr>
<td>Worn asphalt</td>
<td>0.12</td>
<td>(1)</td>
</tr>
<tr>
<td>Bare soil</td>
<td>0.17</td>
<td>(2)</td>
</tr>
<tr>
<td>Green grass</td>
<td>0.25</td>
<td>(2)</td>
</tr>
<tr>
<td>Desert sand</td>
<td>0.40</td>
<td>(3)</td>
</tr>
<tr>
<td>New concrete</td>
<td>0.55</td>
<td>(2)</td>
</tr>
<tr>
<td>Fresh snow</td>
<td>0.80 – 0.90</td>
<td>(2)</td>
</tr>
</tbody>
</table>


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![Graph showing albedo comparison across different surfaces](image-url)
Terrestrial Albedo of Ground Surfaces in UV, VIS, IR

![Graph showing spectral reflectance of different ground surfaces](image-url)
Reflected Solar Radiation on Front of BS Includes Considerable UV

Shown sun to the north of a south-facing module for worst-case sun shining on back of module.

Calculation on the right →:
• Spectral irradiance on Front of BS
• Low morning sun
• Ground cover: dry grass
→ Very low direct E
→ Considerable diffuse and reflected E

Calculation on the left:
• Spectral irradiance on Front of BS
• High sun at local solar noon
• Ground cover: dry grass
→ No direct E (sun to the north)
→ Considerable diffuse and reflected E
→ UV 6 x higher than at morning

Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS), developed by Dr. Christian Gueymard,
PV Modules Reflect Considerable Amounts of Solar UV Radiation

Total (brown) and diffuse (blue) reflection of a CIGS solar reference cell with Schott BK7 glass.

Measured to ASTM E903. Reflected UV > Vis off glass.
Solar Radiant Exposure on Front of BS v. Module Surface

Arizona
Radiant Exposure
Model Year 2006
Albedo: bare soil

Front side of BS
- 53 MJ/m² (UV)

Incident Module Surface
- 457 MJ/m² (UV)

Relation: 11.6 %
→ The Front of BS receives only 11.6 % of Incident radiant Exposure (factor of 8.6)

Dry grass albedo = 22%, ~2X bare soil.
Summary for Solar Radiation on Front of BS

- Reflected and diffuse solar irradiance on the Front of BS contains considerable UV, as well as VIS and IR.

- "Xenon-arc with daylight filters" per ISO and ASTM standards should be an appropriate laboratory light source for testing the total effects of sunlight (UV, Visible, and NIR for heating)*

- Yearly radiant exposure on the Front of BS can be assumed as 10 – 20 % of solar radiation incident on front of PV module (in AZ for different ground covers; excluding effect of module row spacing).

* Note that all standards compliant implementations of spectral power distributions are equivalent; consult manufacturer for specifications.
Solar Radiation on Back of BS
“Light Window Pane Effects“

Poly-crystalline
Mono-crystalline
Thin-film
An accurate optical assessment of a PV module is not trivial.

Glass Shifts Cut-on $\lambda$ of Transmitted Solar from $300 \rightarrow 320$ nm

Spectral irradiance through 3 mm window glass; individual glasses vary.

High sun at noon

Perpendicular incident light (DNI)

$\rightarrow$ direct E dominates
Solar Through Glass and Encapsulant Still Contains UV

Transmission curves of glass / EVA laminates allow considerable amounts of UV to reach the BS.

Source: Zhao Ruo Fei, DuPont China R&D Center. Photovoltaic Encapsulant Optical Property Study. 9 May 2009.  
Summary for Solar Radiation on Back of BS

- For crystalline Si modules, there is light passing through glass and encapsulant onto the back of BS.

- Solar radiation through glass and encapsulant still contains UV; the effect adds up over time.

- For realistic testing, it is recommended to use either test coupons made from glass / encapsulant / backsheet or representative mini modules.
## Recommendations for Laboratory Testing Methods

<table>
<thead>
<tr>
<th></th>
<th>Front of BS</th>
<th>Back of BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen</td>
<td>Backsheet only or Coupon</td>
<td>Coupon or (oper.) mini-module</td>
</tr>
<tr>
<td>Geometry</td>
<td>Light on BS</td>
<td>Light through glass/encapsulant</td>
</tr>
<tr>
<td>Light Source</td>
<td>Daylight spectrum (UV + VIS)</td>
<td>Daylight spectrum (UV + VIS)</td>
</tr>
<tr>
<td>Irradiance</td>
<td>1 sun (60 W/m² in UV)</td>
<td>1 sun (60 W/m² in UV)</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Per ISO, ASTM: e.g. 50 % or as appro.</td>
<td>Per ISO, ASTM or as appropriate</td>
</tr>
<tr>
<td>Rain / Water</td>
<td>Per ISO, ASTM standards: e.g. 102 min Light / 18 min Light + H₂O Spray</td>
<td>none</td>
</tr>
<tr>
<td>Spray</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Accel. over</td>
<td>Lab: ~5X – 10X faster than real time exposure</td>
<td>~4 - 5 times faster than real time</td>
</tr>
<tr>
<td>AZ real time</td>
<td>(@ 10-20% of incident E)</td>
<td></td>
</tr>
</tbody>
</table>
Summary and Conclusions

• Stress by solar radiation on Front of BS:
  – Reflected and diffuse solar irradiance on the Front of BS contains considerable UV, as well as VIS and IR.
  – "Xenon-arc with daylight filters“ acc. to ISO and ASTM standards should be an appropriate laboratory light source for testing.
  – Yearly radiant exposure on the Front of BS can be assumed as 10 – 20 % of solar radiation incident on front of PV module (in AZ for different ground covers).

• Stress by solar radiation on Back of BS:
  – For crystalline Si modules, there is light Passing through glass and encapsulant on the back of BS.
  – Solar radiation through glass and encapsulant still contains UV.
  – For realistic testing, it is recommended to use either test coupons made from glass / encapsulant / backsheet or representative mini modules.

• Weathering Test on the Front of BS may be up to 10-50 times faster than in real life (with regard to E only)

• Recommendation for weathering tests parameters are made for testing both sides of BS.
Thank you very much! Your questions?

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