Is it possible to design accelerated service life tests for PV modules?

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Durability of Thin Film Solar Cells
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General methodology for service life assessment

Assumptions

1. Only long-term wear out degradation is considered
2. The primary degradation factors are due to weathering
3. The stress-levels depend on local climate and installation
4. The stress-levels depend on the micro-climate at the module
5. The test samples (PV-modules or components) have to be considered as a black-box
6. The modelling is based on investigation of the degradation kinetics of real state-of-the-art modules
7. A service life of 25 years is required
General methodology

Modeling the Accelerated Life Test conditions based on realistic loads

Local climate → PV-modules

Micro-climate → Materials

ALT conditions → Models

Degradation → Performance change

Service life
General methodology Step 1: Outdoor exposure and climate monitoring

City or reference:
Freiburg Germany

Alpes
Zugspitze
Germany

Desert
Sede Boqer
Israel

Tropical
Serpang
Indonesia

Maritime
Pozo Izquierdo
Gran Canaria

Monitoring degradation factors for modelling degradation

Measurement of module performance over time for validation of ALT
Monitoring in Cologne (one year)

Ambient humidity

ambient and module temperatures
Monitoring in the Alpes (one year)

Ambient humidity

ambient and module temperatures
Monitoring in the desert (one year)

Ambient humidity

ambient and module temperatures
Monitoring in tropical Serpong (one year)

Ambient humidity

ambient and module temperatures
General methodology Step 2: **Micro - climate**

Micro-climate := stresses for the material caused by interaction of materials and ambient climate

1. **Module temperature** modeled by solar irradiation, ambient temperature, wind speed

2. **Module surface humidity** modeled by module temperature, ambient temperature and humidity

3. **UV-radiation** modeled from solar irradiation and spectral transmittance of laminated materials

4. **Temperature cycles** of module temperature

5. **Leakage current** as function of voltage, module temperature and surface humidity

6. **Salt concentration** correlated with wetting/drying cycles

7. ......
Micro-climate of modules

Module – Temperature in the desert

![Graph showing temperature variations in the desert, with distinct peaks during the day and troughs at night. The graph illustrates the temperature difference between the module and the ambient air.]
Micro-climate of modules

Outdoor weathering with temperature monitoring

Macro-climate => Micro-climate

Ambient temperature

Average module temperature (c-Si)
Histogram of measured module temperatures in Cadarache, F

What about Thin Film Modules?

- a-Si 1
- CIS 1
- c-Si
- a-Si 3
- CIS 2
- a-Si 4
- CdTe

Module temperature for one year

Special thanks to Antoine Guerin de Montgareuil, CEA-INES, Cadarache, France
Physical modeling of module temperature for each of the different module types using David Faiman’s approach (could be King, Fuentes……as well)

Macro – climate

Irradiation, wind, ambient temperature

\[ T_{\text{mod}} = T_{\text{amb}} + \frac{H}{U_0 + U_1 \cdot v} \]

\( T_{\text{mod}} \) module temperature
\( T_{\text{amb}} \) ambient temperature
\( v \) wind velocity
\( H \) solar radiation

\( U_0, U_1 \) = module dependent parameters

Neglected: IR-radiation exchange and natural convection

The parameters \( U \) are module-specific but location independent

Micro-climate of Modules

Histogram of simulated module temperatures for one year in the Negev

- a-Si 1
- a-Si 2
- a-Si 3
- a-Si 4
- CIS 1
- CIS 2
- CdTe
- c-Si

Temperature in °C

Frequency
Micro-climate of modules

Daily temperature cycling during one year

Type approval testing:
200 cycles from -40 to 85°C
Max. changes 100 K/h
With current injection
Micro-climate of modules

Surface humidity – desert

Night-time = condensation

Day-time = Drying
Micro-climate of modules

Leakage currents as source of Potential Induced Degradation

Leakage currents depend on the module temperature, the voltage and the surface humidity.
Micro-climate of modules

Humidity and potential-induced degradation (PID) of modules

Leakage current as function of potential, relative humidity and temperature

\[ I = \frac{G}{1 + \exp(-G \times (rh - 0.35) \times 1.75 \times (G/f(0) - 1))} \]

with \( G = 13 \mu A \)

Hoffmann, S., M. Koehl, Effect of Humidity and Temperature on the Potential Induced Degradation, accepted by PIP, 2012
General Methodology Step 3: **Time-transformation functions**

Modelling of the degradation processes as function of the degradation factors

Time-transformation functions

1. Module temperature: Arrhenius, Eyring
2. Module surface humidity impact: power law, TOW
3. UV-radiation: Dose-function, reciprocity?
4. Temperature cycles of module temperature: Coffin-Manson
5. Potential induced degradation
6. Salt concentration correlated with wetting/drying cycles: ?
7. …….
Time-transformation functions

Changes of performance or degradation indicator $\Delta P = \Delta t_i \ast ($

- Temperature $+ A \exp[-E_A/RT_i]$
- Humidity $+ B f(rh)_i \exp[-E_B/RT_i]$
- UV-radiation $+ C l^n_i \exp[-E_C/RT_i]$
- Temperature cycles $+ D f(\Delta T)_i \exp[-E_D/RT_i]$
- Potential-induced Deg. $+ E f(P)_i f_p(rh)_i \exp[-E_E/RT_i]$
- Salt $+ F f(S)_i f_p(rh)_i \exp[-E_f/RT_i]$............)
Simple deterministic model for aging processes:
Time-transformation functions

Changes of property $P$ after the testing time $\Delta t_i$

Degradation factor: $\Delta P = \sum_{i=1}^{m} \{ \Delta t_i (\ldots) \}$

Temperature $+ A \exp[-E_A /RT_i]$

Moisture $+ B f(rh)_i \exp[-E_B /RT_i]$

UV-Radiation $+ C \ln_i \exp[-E_C /RT_i]$

$T$ cycles $+ D f(\Delta T)_i \exp[-E_D /RT_i]$

Potential $I$ $D$ $+ E f(P)_i f_p(rh)_i \exp[-E_E /RT_i]$

Salt $+ F f(S)_i f_p(rh)_i \exp[-E_F /RT_i]$

$\ldots$ $+ \ldots X \ln_i f(X)_i \exp[-E_X /RT_i] \ldots)$
General methodology Step 4: **Accelerated life testing conditions**

ALT – conditions for different locations: temperature impact

**Accelerated life testing**
Equivalent lab tests
(same changes of performance or degradation indicator as after service life)
by integration of the outdoor stresses

Difference in testing time between 8 and 20

![Graph showing testing time at 85°C for 25 years in h vs. Activation energy in kJ/mol](image)

- **South France**: 16000 h
- **Tropic**: 8000 h
- **Arid**: 4200 h
- **Moderate, urban**: 2100 h
- **Alpine**: 2000 h

Temperature stress
Corresponding temperature testing times at 85°C for 25 a exposure in Cadarache, France

based on monitored module temperatures

Different cell-types:
Factor 2 – 4 in testing time (depending on the degradation processes)

In the range of damp/heat
ALT – conditions for different locations: UV-radiation impact

Outdoor testing with radiation monitoring for one year in the desert

Cumulated dose of UV- and solar radiation:

120 kWh/m² (about 8 x IEC)

Reciprocity: \( p = 1 \)

\[
t_{\text{test}} = (I_i / I_{\text{test}})^p \Delta t_i \cdot \exp \left[-\frac{E_a}{R} \left(\frac{1}{T_{\text{test}}} - \frac{1}{T_i}\right)\right]
\]

UV = 5.X % of solar radiation

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Effective surface humidity

\[ \text{rh}_{\text{eff}} = \frac{1}{1 + 1000/\exp(rh \cdot k)} \]

Testing time @85°C/85h for 25 years service life [h]

Humidity

- Tropic
- Arid
- Alpine

Rel. surface humidity

Simulated histograms of the relative humidity

Ambient humidity = partial pressure / saturation pressure ($T_{amb}$)
Surface humidity = partial pressure / saturation pressure ($T_{modul}$)

Eff. Humidity: $r_{heff} = 1/(1 + \exp(-rh*k) \times (1/f(0)-1))$

Humidity dose: $\Delta t_{eff} = \Delta t \times r_{heff} / 0.85$
General methodology Step 5: **Accelerated life testing**

Seven different commercial c-Si modules

Damp-Heat at 85°C and 85% rel. humidity

Damp-Heat at 90°C and 85% rel. humidity

M. Koehl et. al., PV reliability (Cluster II): Results of a German four-year joint project - Part I, results accelerated ageing tests and modelling of degradation, 25th EU-PVSEC (2010)
Damp-heat testing at 85%rh and 85°C, module 1

- Induction phase
- Degradation phase
- Degradation function
Damp-heat testing at 85%rh and 85°C, module 1 and module 2

Service lifetime @ 0.8 $P_{mpp}$

- 2300 h
- 3200 h
Damp-heat tests at 85%rh@85°C and 85%rh@90°C (large dots), Module 1 and module 2
Damp-heat tests at 85\% rh@85\°C and 85\% rh@90\°C (large dots), Module 1 and module 2

\[ a = \exp \left[ -(E_a / R) \cdot (1/T_1 - 1/T_2) \right] \]

- Module 1 (65 kJ/mol)
- Module 2 (33 kJ/mol)
Equivalent testing times (25 years at 85%rh @ 85°C

Module 1 would be suitable for all climates.

Module 2 would survive in the mountains.

Service lifetime
General methodology Step 6: **Analysis of materials degradation**

Polymer Analysis with Raman-Spectroscopy and cell analysis by electroluminescence

**Comparison of Vinyl-Band (red) and fluorescence back-ground (black)**

initial data and after 4000h damp-heat testing

Elektroluminescence-image of degraded cells


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General methodology Step 7: **Simulation of materials degradation**

Numerical simulation of energy and mass transport

Water vapour permeation and -diffusion in the back-sheet and the Encapsulant during damp-heat testing (85%rh @85°C)
Numerical simulation of energy and mass transport

Water vapour permeation and diffusion in the Back-sheet and in the Encapsulant during damp-heat testing (85%rh @85°C)

Simulation with real climate data

Alps (cold and dry)

Tropic (hot and humid)

Between cell and glass

Behind the cell
What happens with PV – modules in operation?

Degradation processes are induced or caused by transport phenomena.

<table>
<thead>
<tr>
<th>Time constant</th>
<th>energy</th>
<th>mech. tension</th>
<th>charge</th>
<th>mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>about zero</td>
<td>light</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>seconds</td>
<td>vibrations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>minutes</td>
<td>heat</td>
<td>thermo-mech</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hours to years</td>
<td></td>
<td></td>
<td>ions</td>
<td>oxygen, water vapor</td>
</tr>
<tr>
<td>years</td>
<td></td>
<td></td>
<td></td>
<td>pollutants (salt, etc.)</td>
</tr>
</tbody>
</table>
General methodology Step 8: Service life testing

**Multiple stress testing**

<table>
<thead>
<tr>
<th>Power Density</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>200-250 W/m²</td>
<td>0 – 100°C</td>
</tr>
<tr>
<td>2<em>3</em>1.6m²</td>
<td>0 – 85%rF</td>
</tr>
</tbody>
</table>

UV-source for combined UV and humidity tests

**Physical limits of combined testing**

- Testing with radiation requires large areas (expensive)
- Concentration is needed for acceleration (4-5 X)
- Highly efficient irradiation sources require lamp cooling
- Water cooling limits the freezing at temperature cycling
- Solar simulator (incl. VIS and NIR) causes heating of the samples
- Cooling of the samples spoils high humidity by condensation at the heat exchanger
- How to integrate mechanical loads
Summary

Modelling the micro-climatic stress conditions

Time-series of climatic data
ambient temperature and humidity, solar irradiation, wind speed

Modeling the module temperatures
ambient temperature, solar irradiation, wind speed, module-specific coefficients (mounting situation might be considered)

Modeling the UV-radiation
5.5% of the solar radiation, module temperature

Modeling the effective surface humidity
ambient temperature and humidity, module temperature
Modelling the ALT conditions

Use a simple time-transformation function (Arrhenius based, eg)
Time, module temperature and other degradation factors, but separately first

Modeling the module temperature stress
as function of the material-specific activation energy,
(could be eventually included in damp-heat testing)

Modeling the UV-radiation impact
as function of the material-specific activation energy (which is low, UV-dose more important)

Modeling the moisture test
Higher test temperatures needed, as function of the material-specific activation energy,
Conclusions

Single constant stress testing

**One test:**

Infant mortality, quality tests
type approval testing acc. to IEC or UL

**Enhanced stress testing:**

Infant mortality, higher quality requirements
offered by a number of test labs

**Degradation over time:**

Performance, materials or degradation indicator over time
=> Changes of micro-climate (stress) because of material changes
stability beyond infant mortality, induction periods,
stress factor sensitivity

**Needed for service life testing:**

Performance or degradation indicator over time until failure
Conclusions

Single cyclic stress testing

Temperature cycling:
Thermo-mechanical stress
No scientific base for type approval testing acc. to IEC or UL
Which relaxation time at which temperature?

Temperature cycling with humidity:
Closer to reality, takes into account temperature dependence of water vapour permeation

Voltage cycling or UV-radiation cycling:
Dark periods allow recovery or diffusion of reactants

Needed for service life testing:
Investigation of relaxation times and diffusion processes
Frequency and amplitudes of dynamic mechanical testing
Conclusions

Multiple stress testing

Reasons:

Material changes caused by a degradation process due to stress factor 1 might change the micro-climate from stress factor 2

A combination of stress factors might cause new degradation processes (Photodegradation and hydrolysis, hydrolysis and corrosion)

Problems:

How to design life-tests for cdegradation changed micro-climatic stress?

How to define accelerated life tests with similar acceleration factors for all stress factors taking into account different time constants?

Needed for service life testing:

A big number of unknown factors have to be determined:

\[
\Delta P = A \Delta t_i \exp\left[-\frac{E_A}{RT_i}\right] + B \Delta t_i f(\text{rh})_i \exp\left[-\frac{E_B}{RT_i}\right] + C \Delta t_i \ln_i \exp\left[-\frac{E_C}{RT_i}\right] + \\
D \Delta t_i f(\Delta T)_i \exp\left[-\frac{E_D}{RT_i}\right] + E \Delta t_i f(P)_i f_p(\text{rh})_i \exp\left[-\frac{E_E}{RT_i}\right] + F_{pq} \Delta t_i f(S_p)_i f(S_q)_i \exp\left[-\frac{E_{pq}}{RT_i}\right]
\]

Experimental design for a respective number of tests at different stress levels
Thanks for your attention

To my colleagues

Daniel Philipp
Franz Brucker
Stefan Hoffmann
Philipp Huelsmann
Markus Heck
Stefan Brachmann
Karl-Anders Weiss
Stefan Wiesmeier

To our partners

TÜV Rheinland
Schott Solar
Solarfabrik
Solarwatt
Solarworld
Solon
Workshop on Reliability of PV-Modules

Testing
Analysing
Simulating  module - reliability

Organised by Fraunhofer ISE and SUPSI

www.supsi.ch/go/pv-module-reliabilty

Lugano
Switzerland
Mai 3 – 4 2012

Meeting of the IEC TC82 WG2
After the Workshop in Stresa
Structure of the workshop

The topics will be presented by experts and further developed in small discussion groups.

Block I: Mechanics

Block II: PID -Humidity (Potential induced degradation)

Block III: UV –Humidity

Block IV: Failure modes and effects

Block V: Materials

Plenary discussion with presentation of discussion results

Optional: Visit of the outdoor exposure test site of ISAAC Supsi