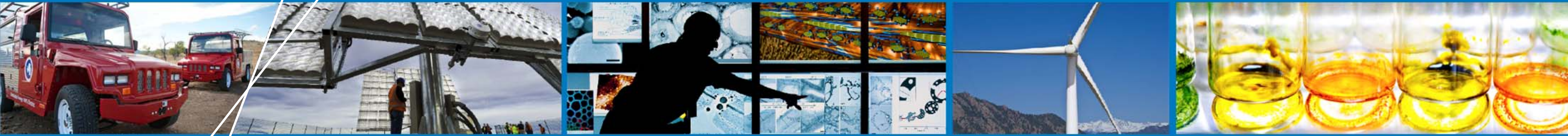
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Considerations for a Standardized Test for Potential-Induced Degradation of Crystalline Silicon PV Modules



2012 PVMRW

Peter Hacke

February 29, 2012

NREL/PR-5200-54581

Major contributions from:

Steve Glick
Ryan Smith
Mike Kempe
Steve Johnston
Joel Pankow
Sarah Kurtz
Kent Terwilliger
Dirk Jordan
Steve Rummel
Alan Anderberg
Bill Sekulic

Motivation

"Oh no! our modules are down 40%,
we think it is potential–induced degradation"

-anonymous module manufacturer, 2010

- **Over the past decade, there have been observations of module degradation and power loss because of the stress that system voltage bias exerts.**
  - More sensitive modules
  - Higher system voltage
- **This results in part from qualification tests and standards not adequately evaluating for the durability of modules to the long-term effects of high voltage bias that they experience in fielded arrays.**
- **This talk deals with factors for consideration, progress, and information still needed for a standardized test for degradation due to system voltage stress.**

Timeline for system voltage durability

- Need for a better standard for system voltage durability brought up several times in the last decades, but did not get traction. Lack of field data, proposed tests overly harsh.

- I brought this up again in the Fall 2010 Working Group 2 (WG 2) meeting (Köln) and got a small working together, but most people were in the process of getting experience about system voltage effects.

- Spring 2011 WG 2 meeting (Shanghai), indications of increased urgency for a standard, assembled more people for this task team.

- Fall 2011 WG 2 meeting (Montreal), presented an initial draft for comments.

- Present day…

Goals for a standard – two steps

1. **Stand-alone test (new standard):**

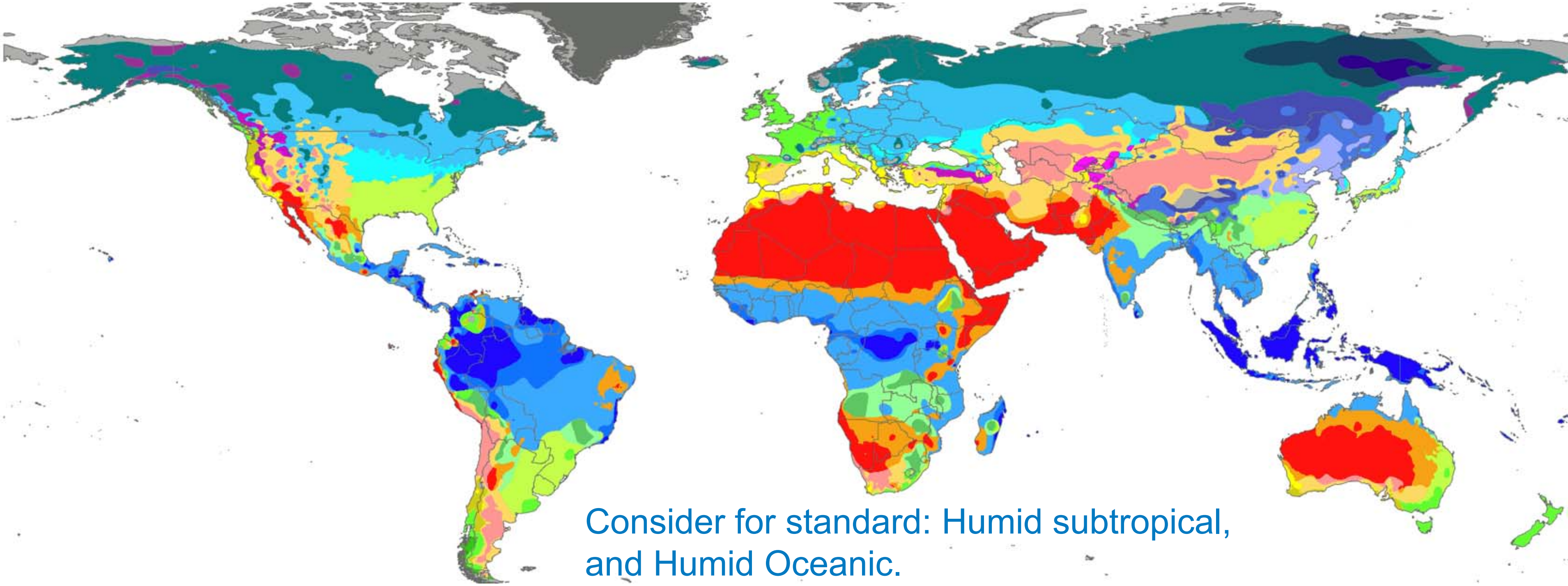
   System voltage durability test for crystalline silicon modules – design qualification and type approval, submitted as a New Work Item Proposal to IEC, Dec. 2011.

2. **Incorporate test into IEC 61215**

   Seek to incorporate above stand-alone test with any necessary supplements within IEC 61215

   – add test after clause 10.13, Damp Heat Test 1000 h under consideration.

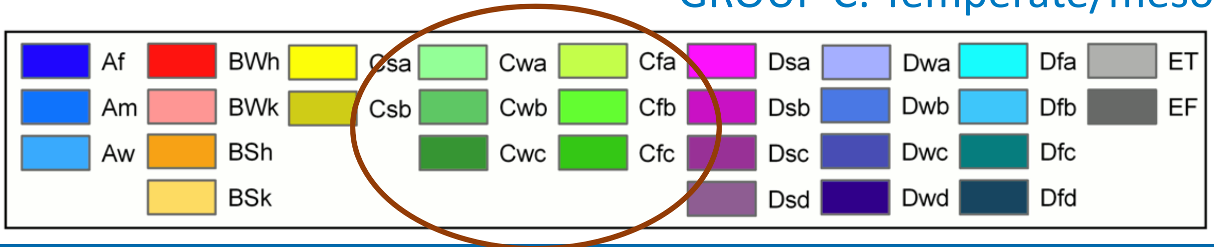
Design standard for a climate: Köppen climate classification



Consider for standard: Humid subtropical, and Humid Oceanic.

Need to design for the market. More stressful environments exist, and that should be noted in the eventual standard.

GROUP C: Temperate/mesothermal climates



Maritime/oceanic climates: (Cfb, Cwb, Cfc)

Humid subtropical climates (Cfa, Cwa)

Experimental Overview

1) HV Test bed in Florida USA

- **2 module types fielded in February 2011**

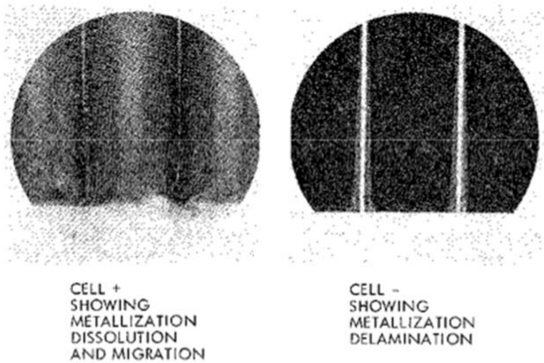
2) Chamber testing of the same 2 module designs tested in Florida

- **85% RH; 85°C, 60°C, 50°C**

  P_{max} vs *t*

3) Comparison of failure rates for determination of acceleration factors and failure mechanisms for input into standardized test

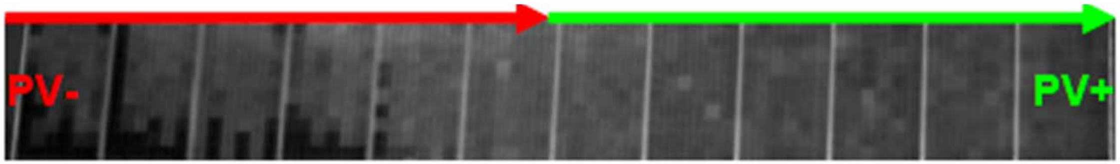
Definitions



← Electrochemical corrosion
c-Si
Mon & Ross
JPL, 1985

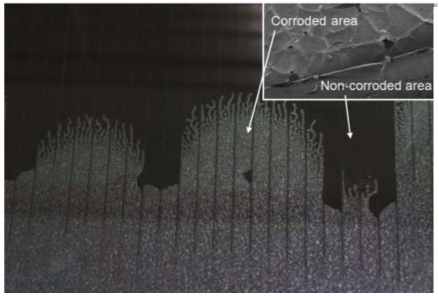
Polarization →
c-Si
Swanson
SunPower, 2005

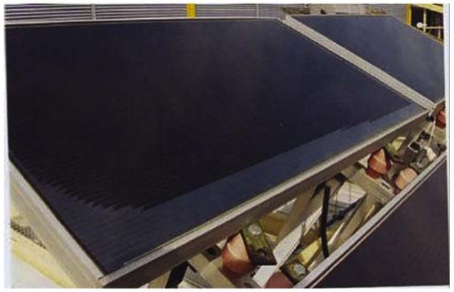
Potential-Induced Degradation



Electroluminescence of mc-Si module strings indicating shunting in the negative portion of a center mounted or floating string

S. Pingel et al., "**Potential Induced Degradation of Solar Cells and Panels**," 35th IEEE PVSC, Honolulu, 2010, pp. 2817–2822.





J. H. Wohlgemuth et al. "LONG TERM RELIABILITY OF PHOTOVOLTAIC MODULES", WPSEC-4 (2006) p. 2050

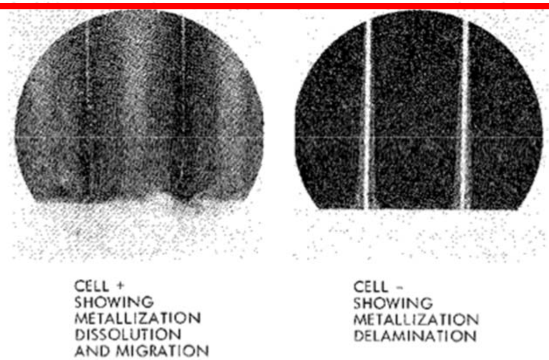
← Delamination, corrosion
a-Si
Wohlgemuth
BP Solar, 2000

Other power loss →
thin-films
unpublished

?

Definitions

Potential-Induced Degradation



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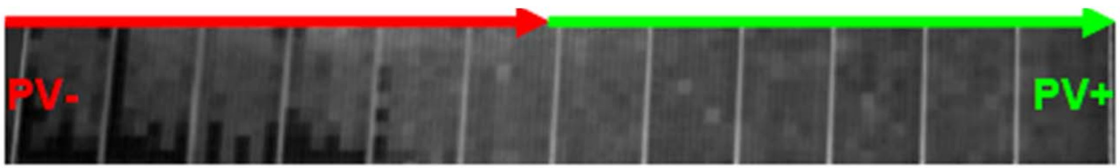
Needs an unambiguous name →



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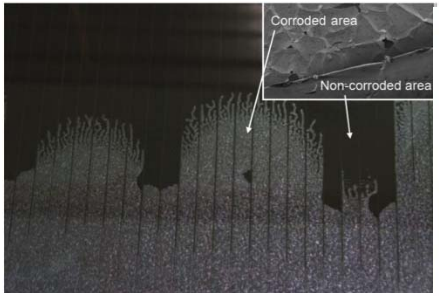

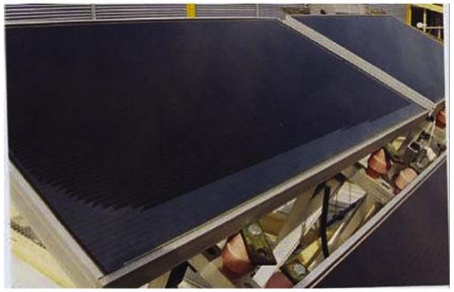

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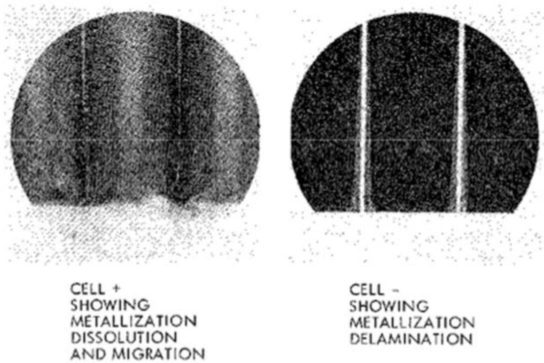
Definitions – this standard will cover



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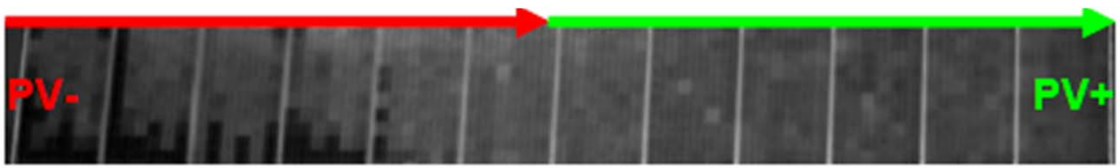

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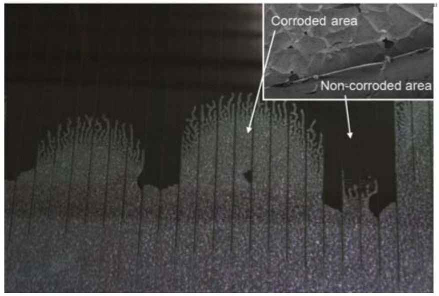

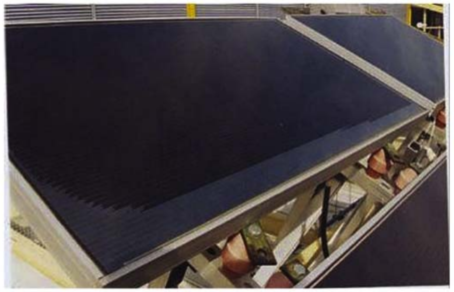

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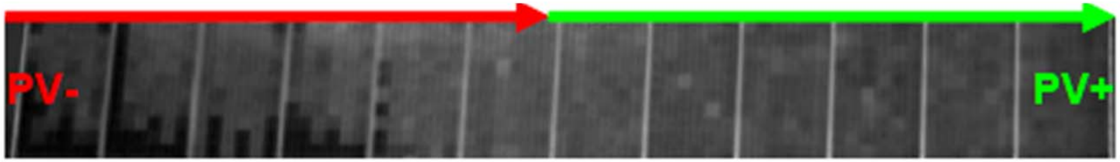

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System voltage durability

- Designed to cover c-Si

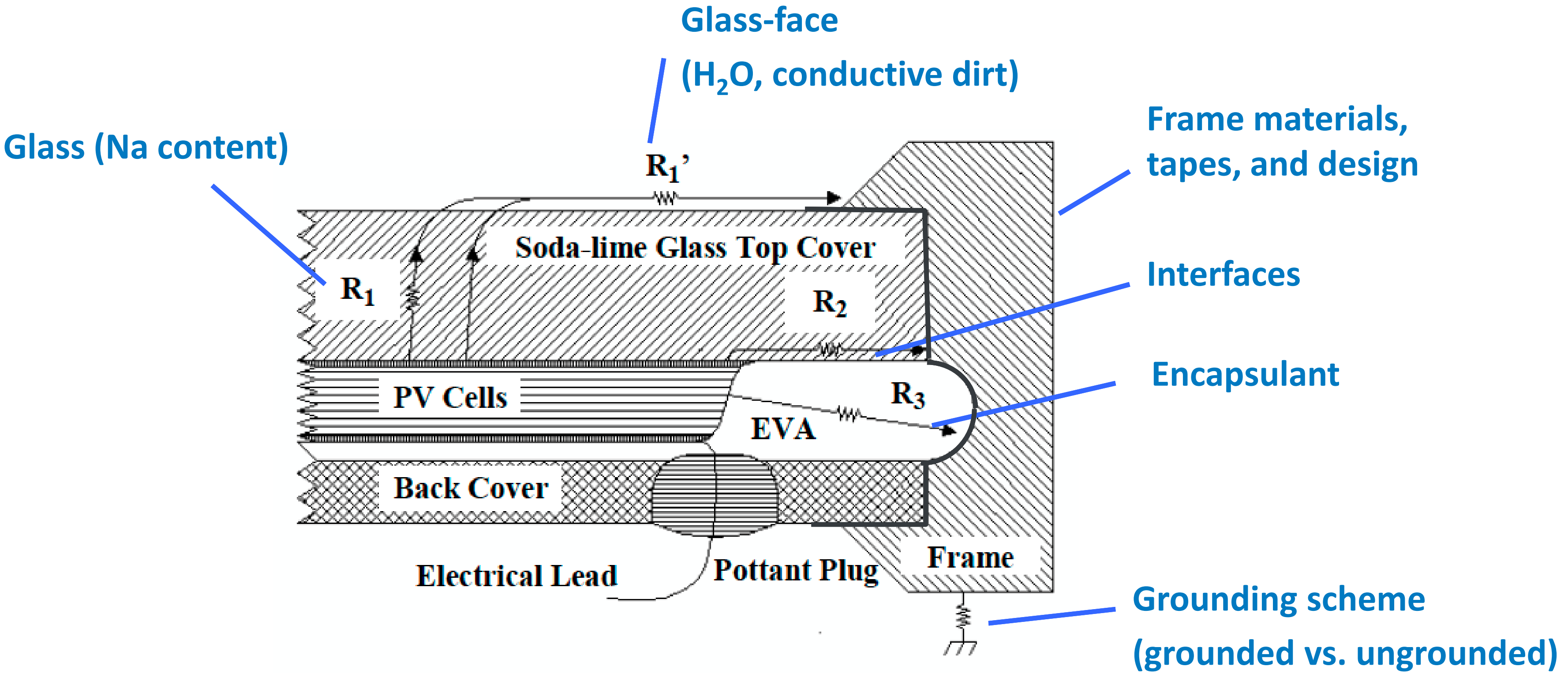
- More than just PID of conventional cells/modules
- Polarization (like SunPower)
- Non-reversible elements of PID
- Rear junction bifacial cells. ECN bifacial/Yingli 'Panda'
- HIT cells
- Framed/unframed modules of various types

- Long term view for harmonization with thin film system voltage durability

Factors for test – leakage current

Voltage potential of active layer, and leakage from that voltage to ground govern degradation in susceptible modules

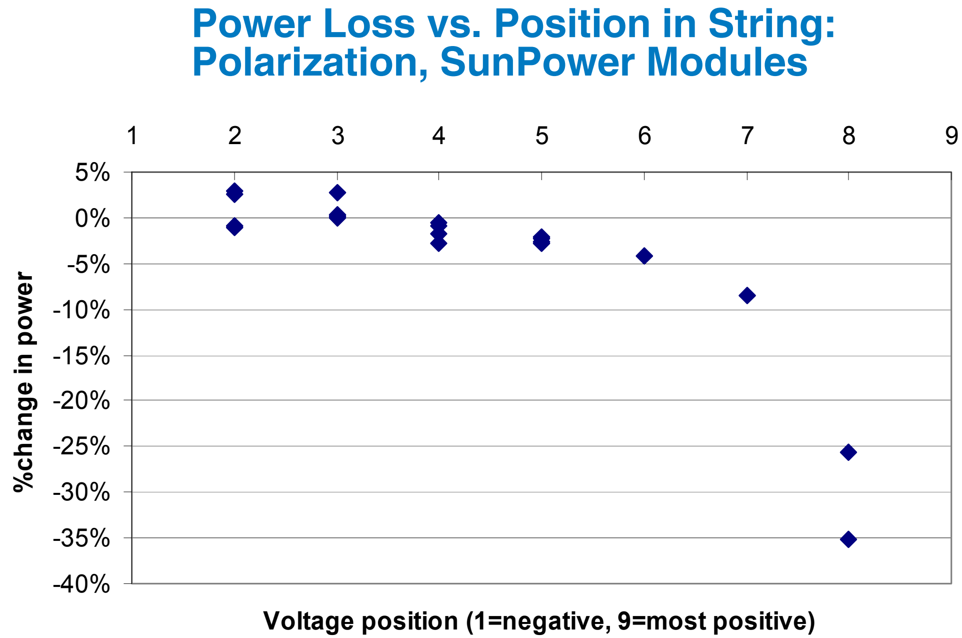
Circuit resistance factors – cutting relevant series R cuts degradation



T. J. McMahone, Prog. Photovolt: Res. Appl. 2004; 12:235–248

Test factors

- **Voltage**
- Mounting/grounding
- Humidity, surface conductivity
- Temperature



R . M. Swanson, The surface polarization effect in high-efficiency solar cells, PVSEC-15, Shanghai

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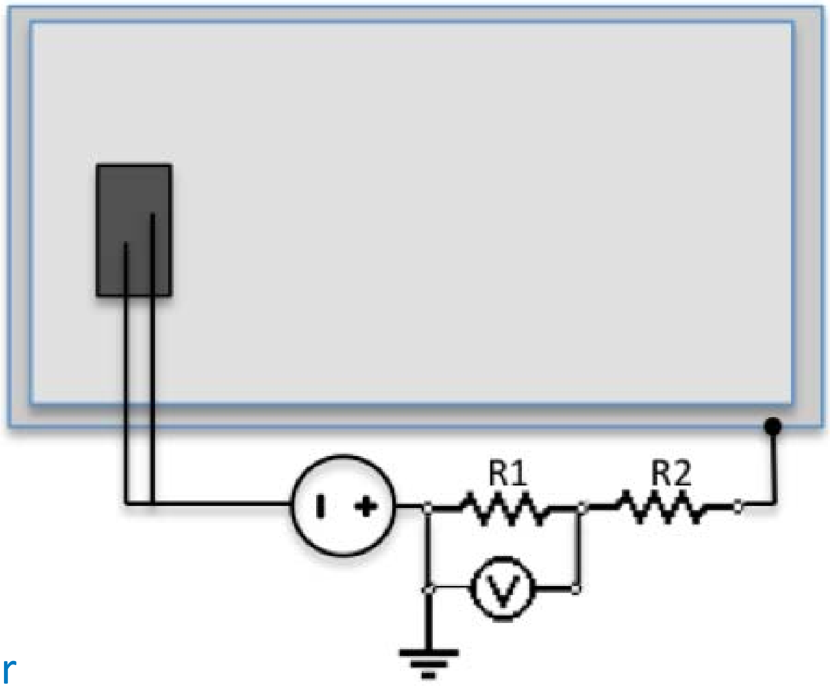


Completing the circuit to ground in a manner representative of mfg. module mounting scheme

Leakage current may be measured as in indicator of module package resistance

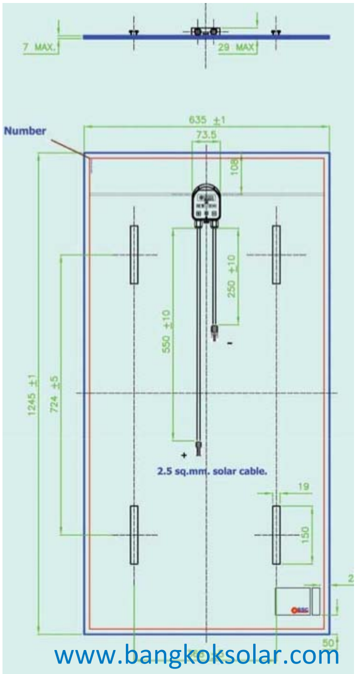
Test factors

- Voltage
- Mounting/grounding
- **Humidity, surface conductivity**
- Temperature

Photo: Erik Eikelboom 2011:10:17

Al foil, carbon film, etc, for surface conductivity

+ Quick/cheap
+ Good screening test
– Won't differentiate humidity effects
(water leaches Na-lime glass)
– unclear how it connects to textured glass
– bypasses frame or laminate mount's ability to reduce degradation, limiting fixes to PID



From: C. R. Osterwald, Solar Energy Materials & Solar Cells 79 (2003) 21–33

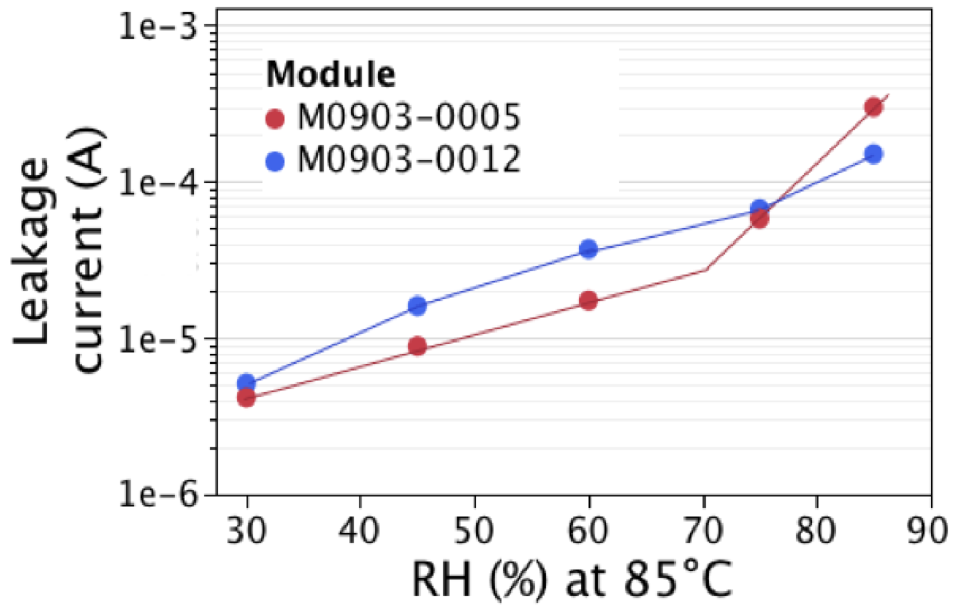
*** Modules that lack a frame and use mounting points bonded to the backsheet glass show no damage [to the extent tested].**

*** Damage rates can be slowed if leakage currents that are caused by voltage potentials between the frame and the internal circuitry are reduced.**

Test factors

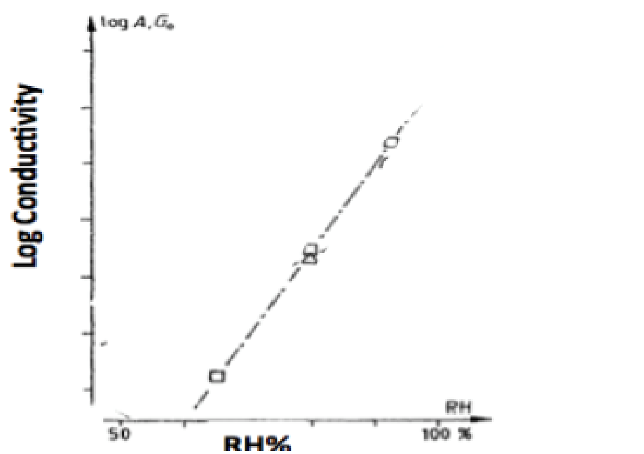
- Voltage
- Mounting/grounding
- **Humidity, surface conductivity**
- Temperature

Module leakage vs. humidity



P. Hacke *et. al.*, *25th EPVSEC*, 6-10 September 2010, Valencia, Spain

Surface conductivity of soda-lime glass vs. humidity

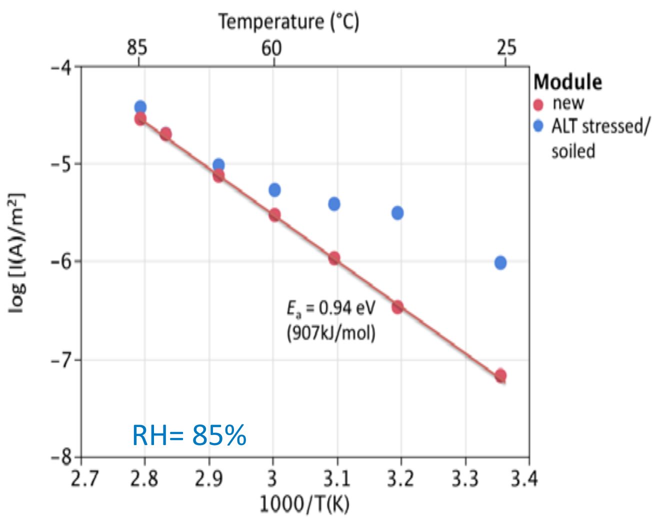


IEEE Transactions on Electrical Insulation Vol. 23 No. 3, June 1988

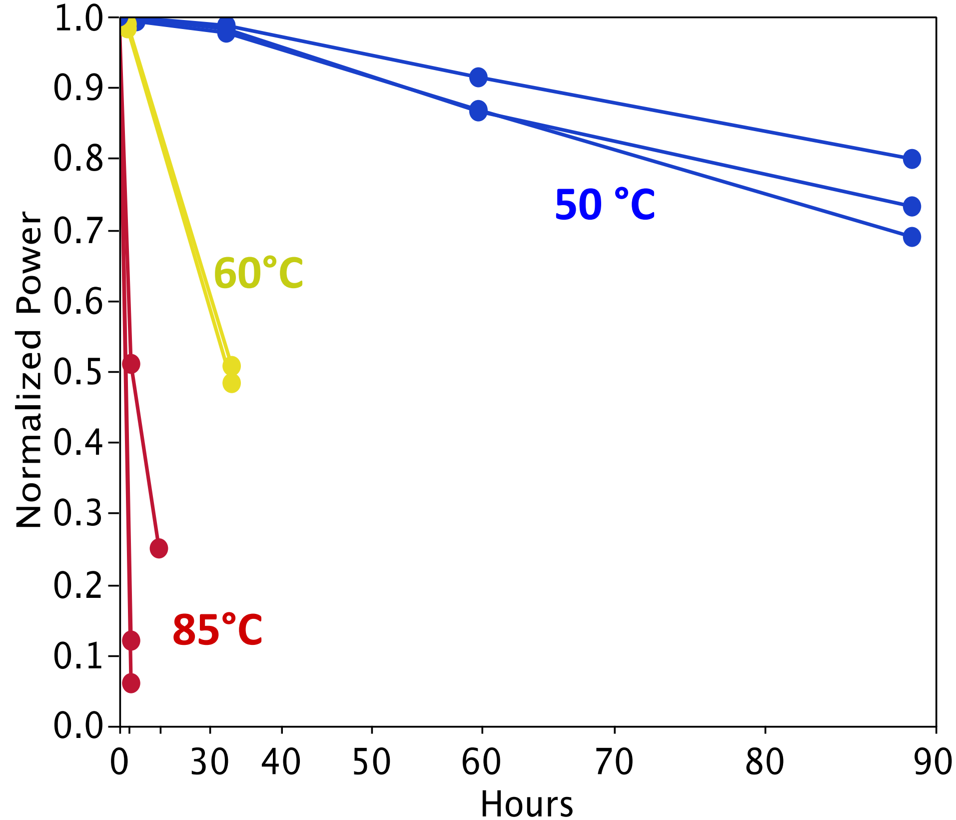
Because we need to measure the performance of not only the module laminate, but the frame or mounts, the standard as written uses humidity for the circuit to ground.

Test factors

- Voltage
- Mounting/grounding
- Humidity, surface conductivity
- **Temperature**



Degradation vs. time of mc-Si modules, -600 V, 85% RH



P. Hacke *et al.*, Testing and Analysis for Lifetime Prediction of Crystalline Silicon PV Modules Undergoing Degradation by System Voltage Stress, 38th IEEE PVSC, Austin, 2012

- **Temperature dependence, repeatable**
- **Arrhenius behavior over temperature range, unless alternate conduction paths exist**

Test levels

- **Voltage**
- Mounting/grounding
- Humidity, surface conductivity
- Temperature
- System voltage, now effectively governed by IEC 61730-2's partial discharge test, not PID, generally
- Test at rated system voltage
  - Maximum nameplate value (behind-the-fence/utilities don't run to UL code)
  - Both polarities (if not polarity is specified)
  - Slight acceleration since actual operating V lower

D. Buemi, *Thin-Film PV Powers the Number 1 Global Solar Integrator,* davebuemi.com, accessed Feb 22, 2012

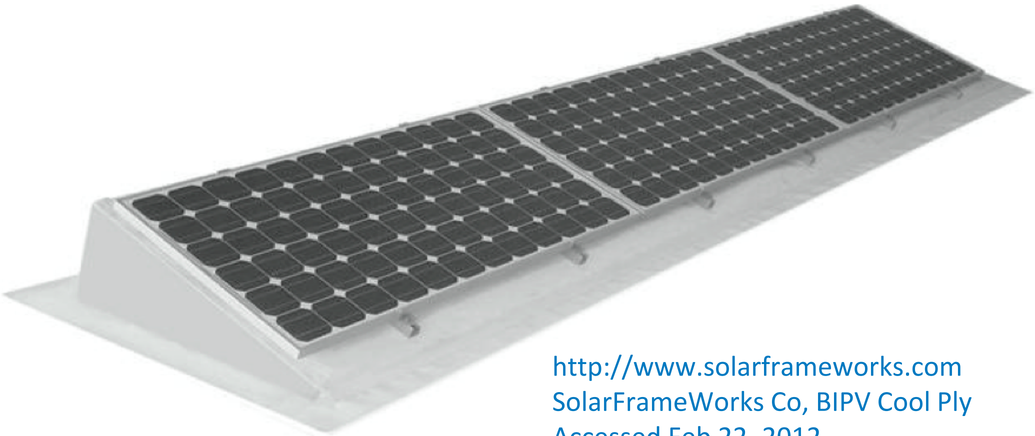
Test levels

- Voltage
- **Mounting/grounding**
- Humidity, surface conductivity
- Temperature

Draft standard:

“For continuous metallic frames encasing the perimeter of the module, the ground terminal of the high voltage power supply shall be connected … to a module grounding point of the module. “

“If (1) the PV module is provided or is specified for use with means for mounting and (2) the module is designed and specified not to be connected to ground, then such method of mounting the module shall be implemented to the extent possible.”



http://www.solarframeworks.com
SolarFrameWorks Co, BIPV Cool Ply
Accessed Feb 22, 2012

Test levels

- Voltage
- Mounting/grounding
- **Humidity, surface conductivity**
- Temperature

  - **85% RH damp heat chamber, a level that chambers are capable of holding, uniformly**

Test levels

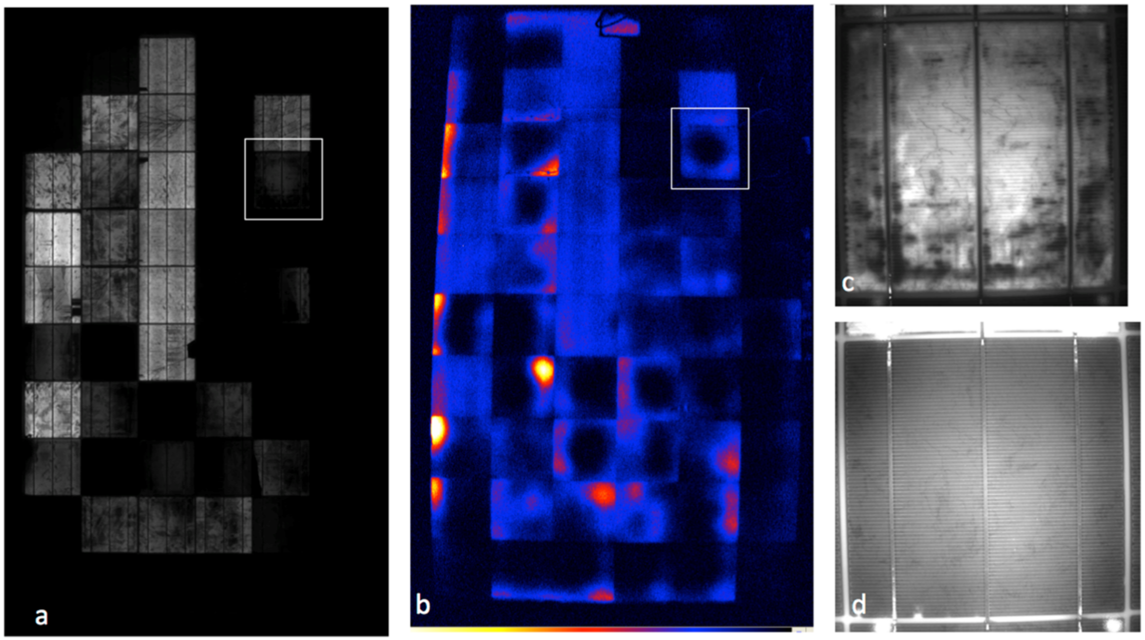
- Voltage
- Mounting/grounding
- Humidity, surface conductivity
- **Temperature**

What level of stress in an accelerated tests reproduces well the failure modes we seek to test for ?

How long should it be stressed at that temperature?
What is the acceleration factor?

Failure mode in fielded module

Module mounted in Florida, USA after ten months with the active layer biased at -1500 V during the day degraded to 0.35 P_{max_0}



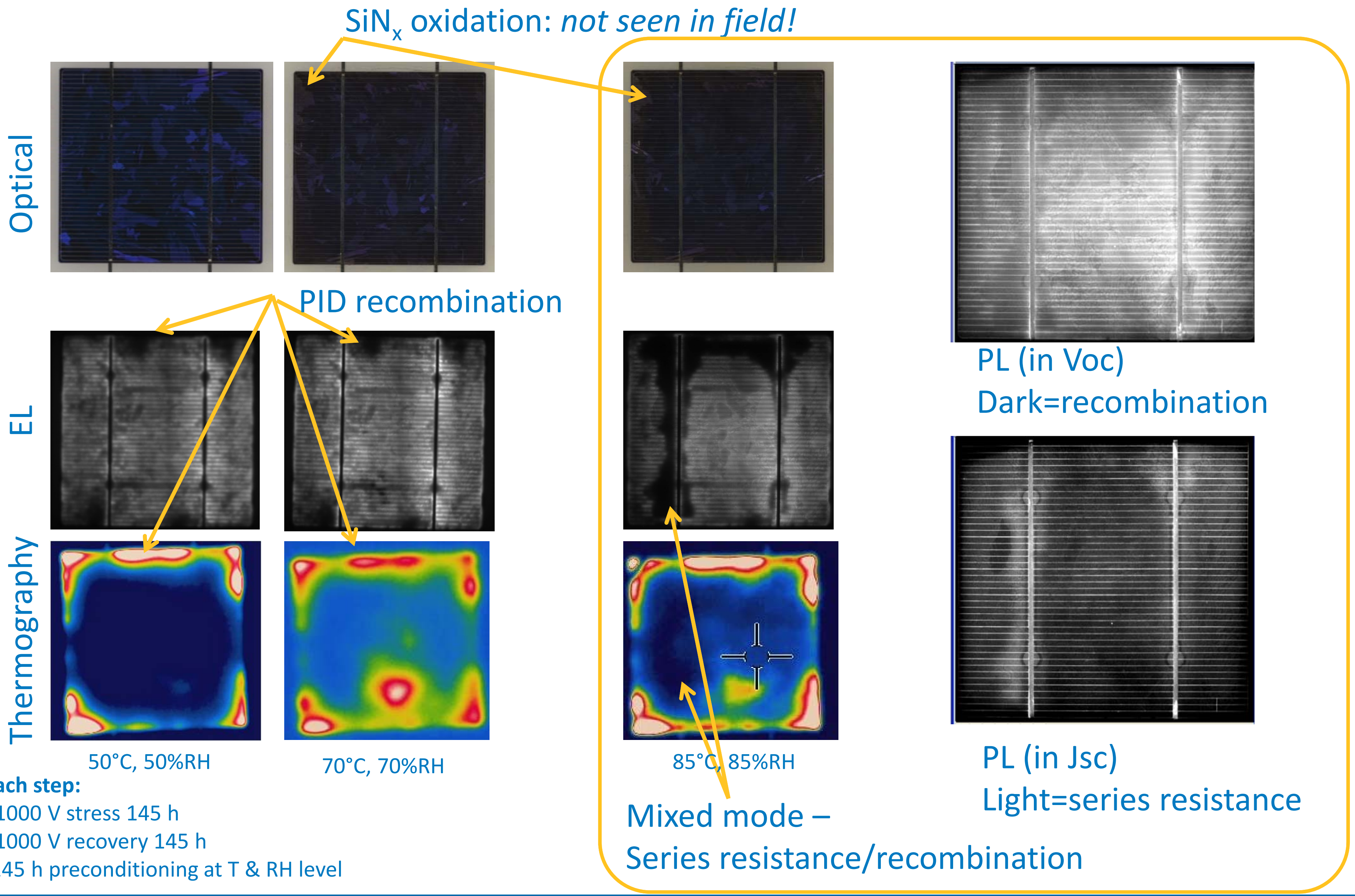
PL (in Voc)
Dark=recombination

PL (in Jsc)
Light=series resistance

EL Thermography

Series resistance losses, as seen in chamber tests, are not yet observed in the field

Step-stress for determination of failure mode



Each step:

–1000 V stress 145 h

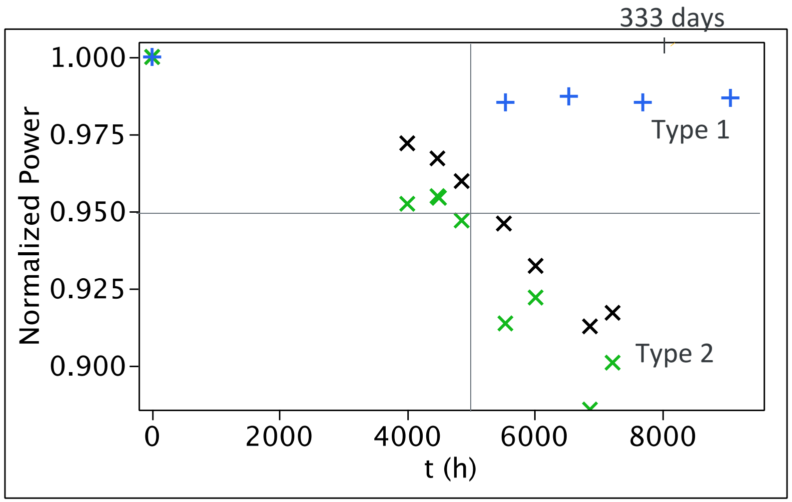
+1000 V recovery 145 h

(145 h preconditioning at T & RH level

Performance of two module types

In Florida, USA

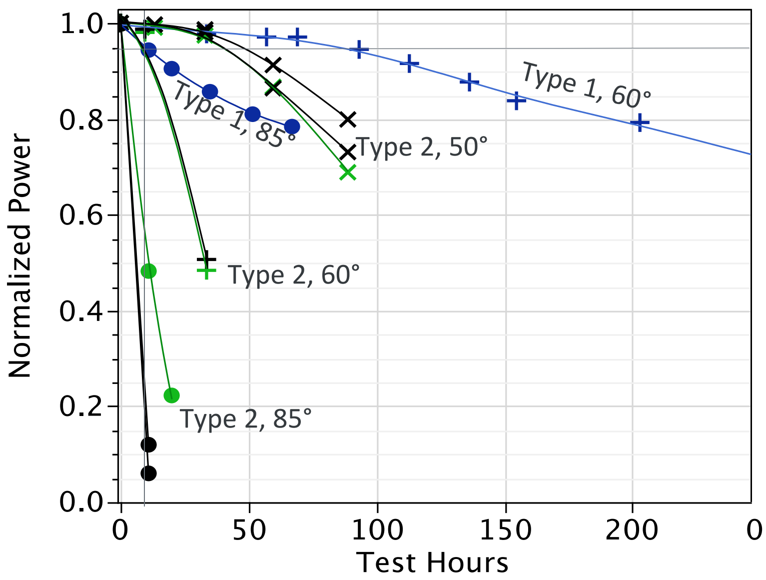
–600 V applied logarithmically with irradiance



In chamber

85% RH

–600 V

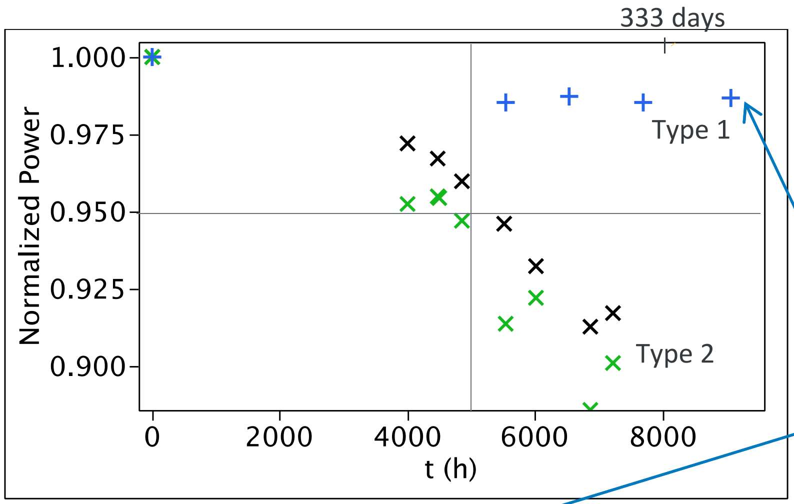


More details at 2012 IEEE PVSC

Performance of two module types

In Florida, USA

–600 V applied logarithmically with irradiance

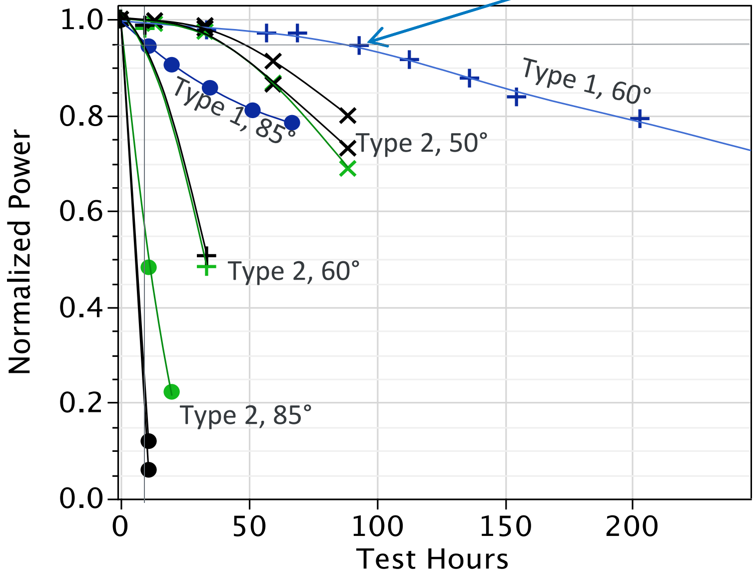


Module Type 1: Acceptable performance in the field survives with less than 5% power drop in chamber with 85% RH, 60°C, rated system voltage, for 96 h

In chamber

85% RH

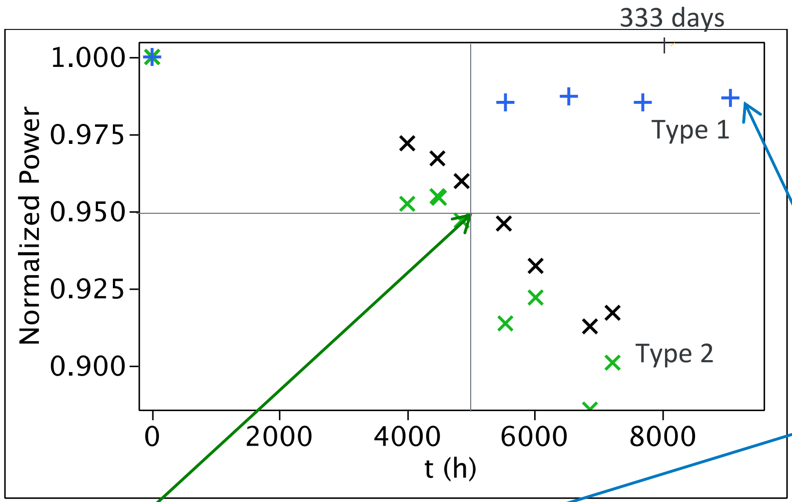
–600 V



Performance of two module types

In Florida, USA

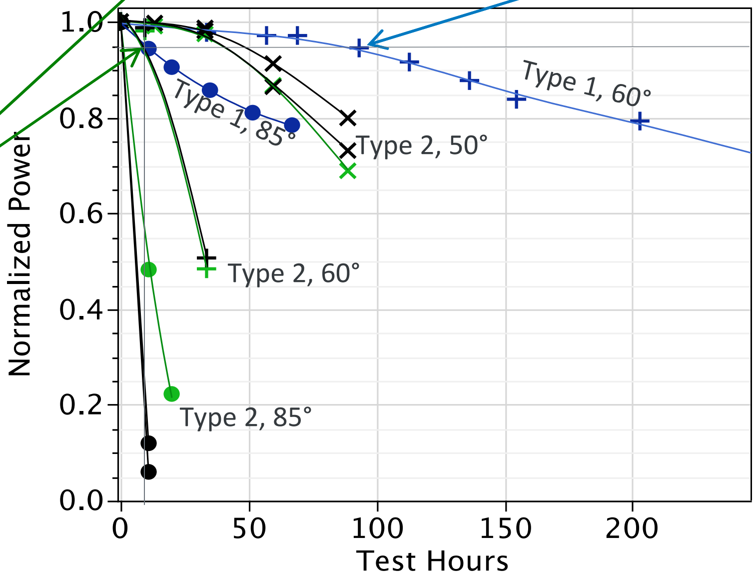
–600 V applied logarithmically with irradiance



In chamber

85% RH

–600 V



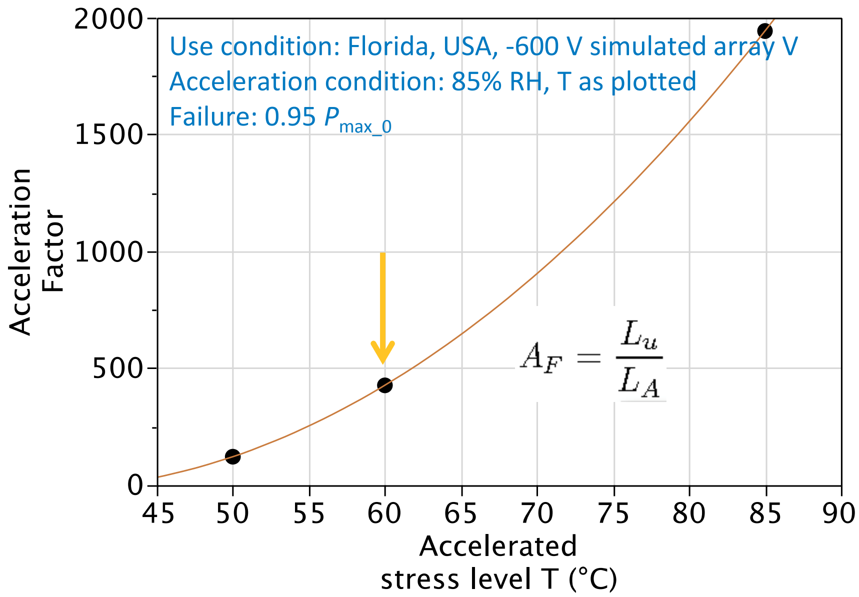
Module Type 1: Acceptable performance in the field survives with less than 5% power drop in chamber with 85% RH, 60°C, rated system voltage, for 96 h

Module Type 2: 5% power drop in 4934 h in Florida and 12 h in chamber at 60° C, (considered a failing module)

More details at 2012 IEEE PVSC

Test levels

- Voltage
- Mounting/grounding
- Humidity, surface conductivity
- **Temperature**



Draft standard:

"The following conditions shall be applied:

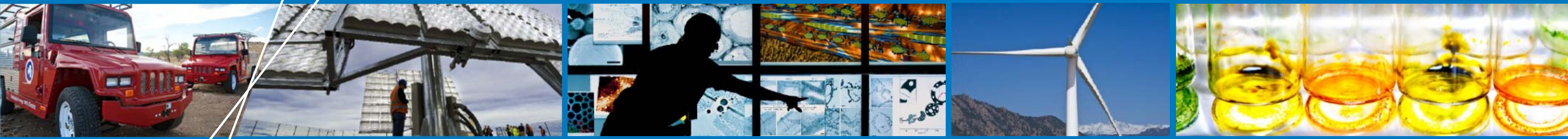
- Chamber air temperature 60 °C ± 2°C
- Chamber relative humidity 85 % ± 5 % RH
- Test duration 96 h
- Voltage: module rated system voltage and polarities" (one module per polarity)"

AF = 427 at 60°C, 85% RH
Test duration, 96 h
Field equivalent: 4.7 y

Next steps: Testing at multiple labs

Determine reproducibility

- **2-3 samples per condition**
  - Presumably 85% RH-60°C, but consider alternates for post IEC-61215 tests
- **5 labs**
  - NREL
  - ASU
  - …let us know if you are interested!
- **Samples from 3 manufacturers**



Thank you