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

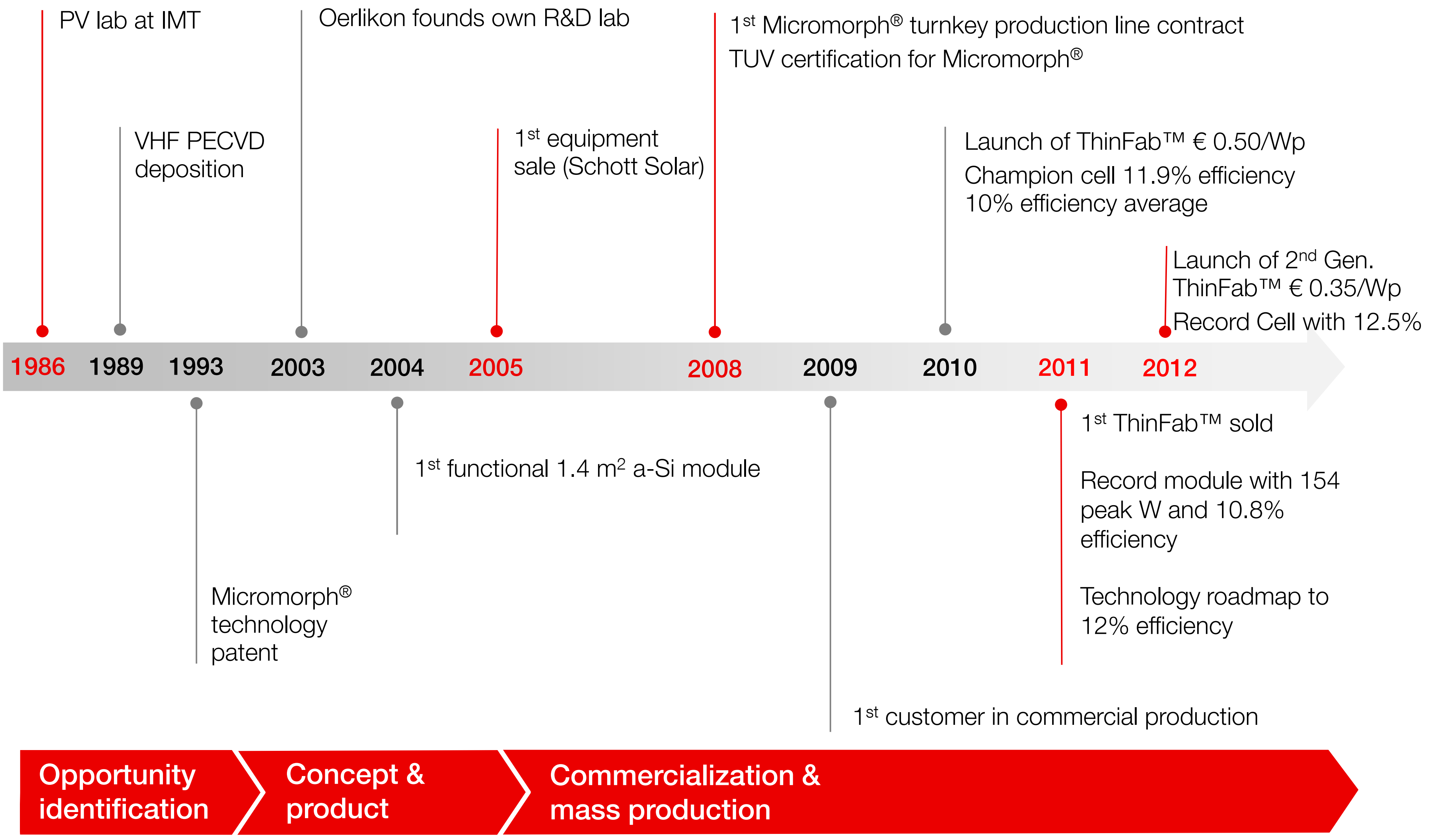
Oerlikon Solar at a glance

Oerlikon Solar strives to make solar power economically viable.

- 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

Oerlikon founds own R&D lab

1st Micromorph® turnkey production line contract
TUV certification for Micromorph®

VHF PECVD
deposition

1st equipment
sale (Schott Solar)

Launch of ThinFab™ € 0.50/Wp
Champion cell 11.9% efficiency
10% efficiency average

Launch of 2nd Gen.
ThinFab™ € 0.35/Wp
Record Cell with 12.5%

1986 1989 1993 2003 2004 2005 2008 2009 2010 2011 2012

1st ThinFab™ sold

1st functional 1.4 m^2 a-Si module

Record module with 154 peak W and 10.8% efficiency

Micromorph® technology patent

Technology roadmap to 12% efficiency

1st customer in commercial production

Opportunity identification

Concept & product

Commercialization & mass production

How a PV module is designed?

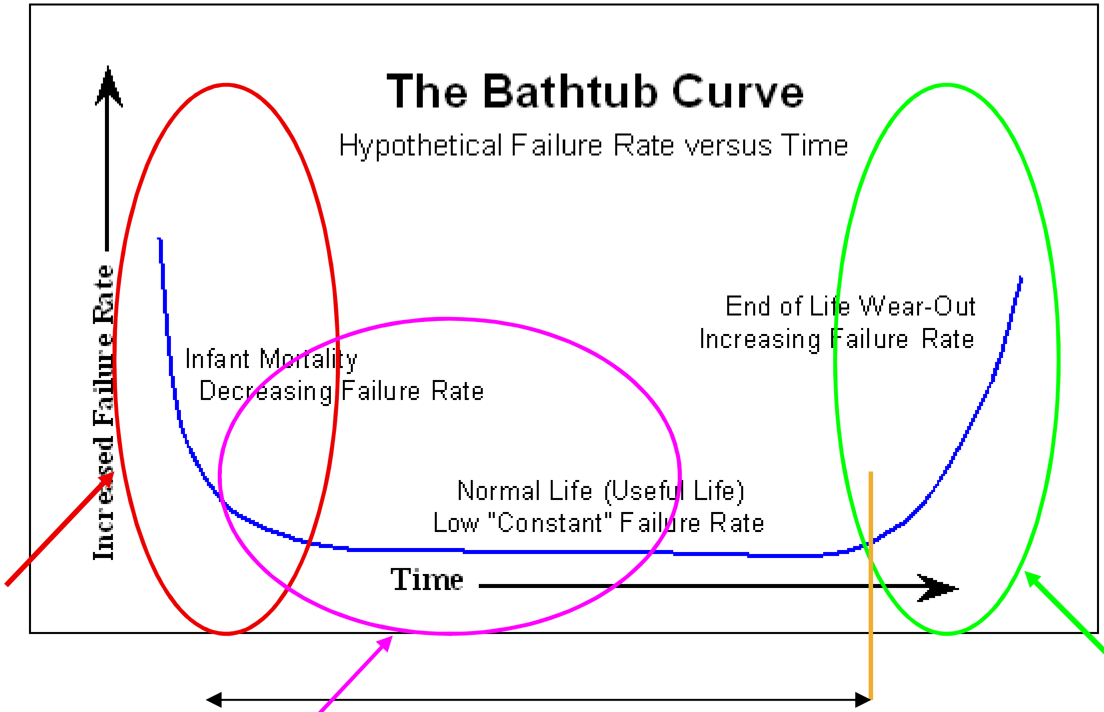
- Design proposal
- DFMEA
- IP
- Sourcing
- Compliance to standards
- Test & qualification procedures
- EHS analysis

- Develop initial prototipe
- 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



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

Off-spec materials
Faulty process control

Durability (t)
(once the «kill ing parameters» are defined)

Module Design only

What should be the PV Module Durability?

The energy produced is not depending ONLY on the efficiency:

$$E \;\alpha\; \eta \text{ x } t$$

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

A bit more realistic is the equation below

$$E(t) \;\alpha\; \eta(t) \text{ x } t$$

and further

$$E(t, \phi, \lambda, \mathit{SV}, \mathit{MS}) \;\alpha\; \eta(t, \phi, \lambda, \mathit{SV}, \mathit{MS}) \text{ x } t$$

What should be the PV Module Durability?

All topics above were still too academical…

At the end, what really matter is price!

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

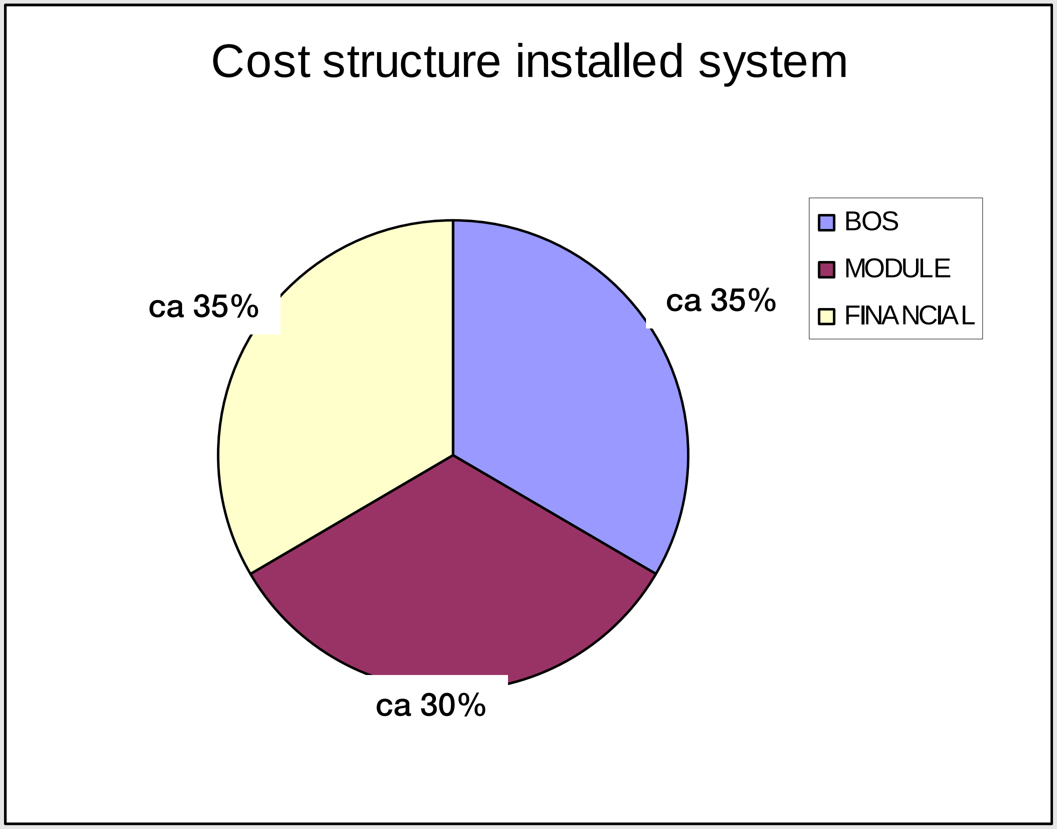
$$= \frac{\text{Initial Investment} - \sum_{n=1}^{N} \frac{\text{Depreciation}^{n}}{(1+\text{Discount Rate})^{n}} \times (\text{Tax Rate}) + \sum_{n=1}^{N} \frac{\text{Annual Costs}^{n}}{(1+\text{Discount Rate})^{n}} \times (1-\text{Tax Rate}) - \frac{\text{Residual Value}}{(1+\text{Discount Rate})^{n}}}{\sum_{n=1}^{N} \frac{\text{Initial kWh/kWp} \times (1 - \text{System Degradation Rate})^{n}}{(1+\text{Discount Rate})^{n}}}$$

Source : The drivers of **L**evelized **C**ost **O**f **E**lectricity 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)



Back to Reality

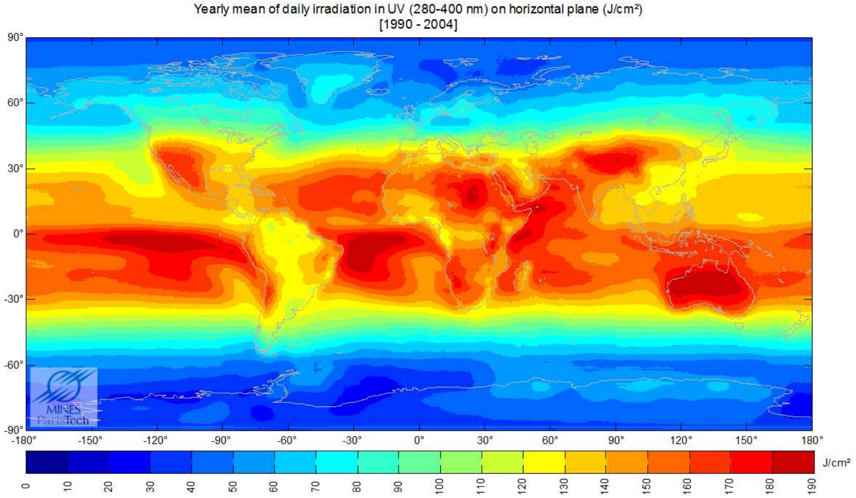
Possible environmental conditions on the Planet Earth

Max. ambient temperature: 58°C
Min. ambient temperature: -67°C
Max. ΔT/24h = 103°C, ΔT/1min = 20°C
Highest average ΔT/24h ca 30°C

Max. yearly average UV (280nm – 400nm) on horizontal surface ca 185KWh/m2

Pressures up to: 10kPa static
: 4kPa dynamic
Hail up to 200gr
rH up to 95% @ 35°C

Basic ambient → PH 11 (near salted roads, farms, sea)
Acid ambient → PH 3 (industry, highway..)
System Voltage: 1000V, 1500V…+
Several possible mounting configurations



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

http://www.ncdc.noaa.gov

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

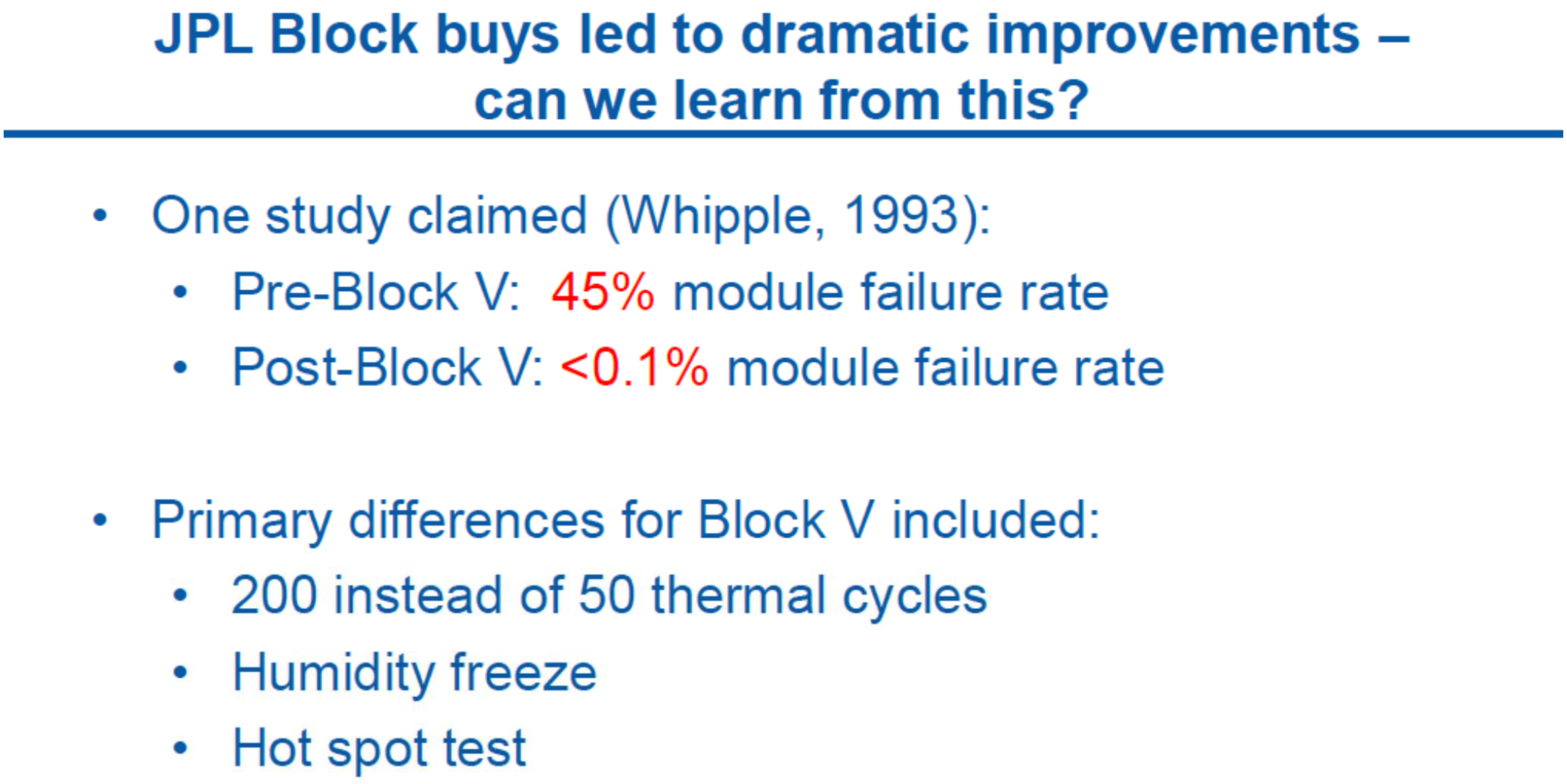
Accelerated Stress Tests

JPL Block buys

Test	I	II	III	IV	V
Thermal Cycles	100 -40 to +90C	50 -40 to +90C	50 -40 to +90C	50 -40 to +90C	200 -40 to + 90C
Humidity	70C,90% 68 hrs	5 cycles 40 to 23C 90%	5 cycles 40 to 23C 90%	5 cycles 54 to 23C 90%	10 cycles 85 to -40C 85%
Hot Spot (intrusive)					3 cells 100 hrs
Mechanical Load		100 cycles ± 2400 Pa	100 cycles ± 2400 Pa	10000 ± 2400 Pa	10000 ± 2400 Pa
Hail				9 impacts ¾" –45 mph	10 impacts 1" – 52 mph
High Pot		<15 µA 1500 V	< 50 µA 1500 V	< 50 µA 1500 V	< 50 µA 2*Vs+1000

From: History of Qualification Standards; J. Wolgemuth

Accelerated Stress Tests



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

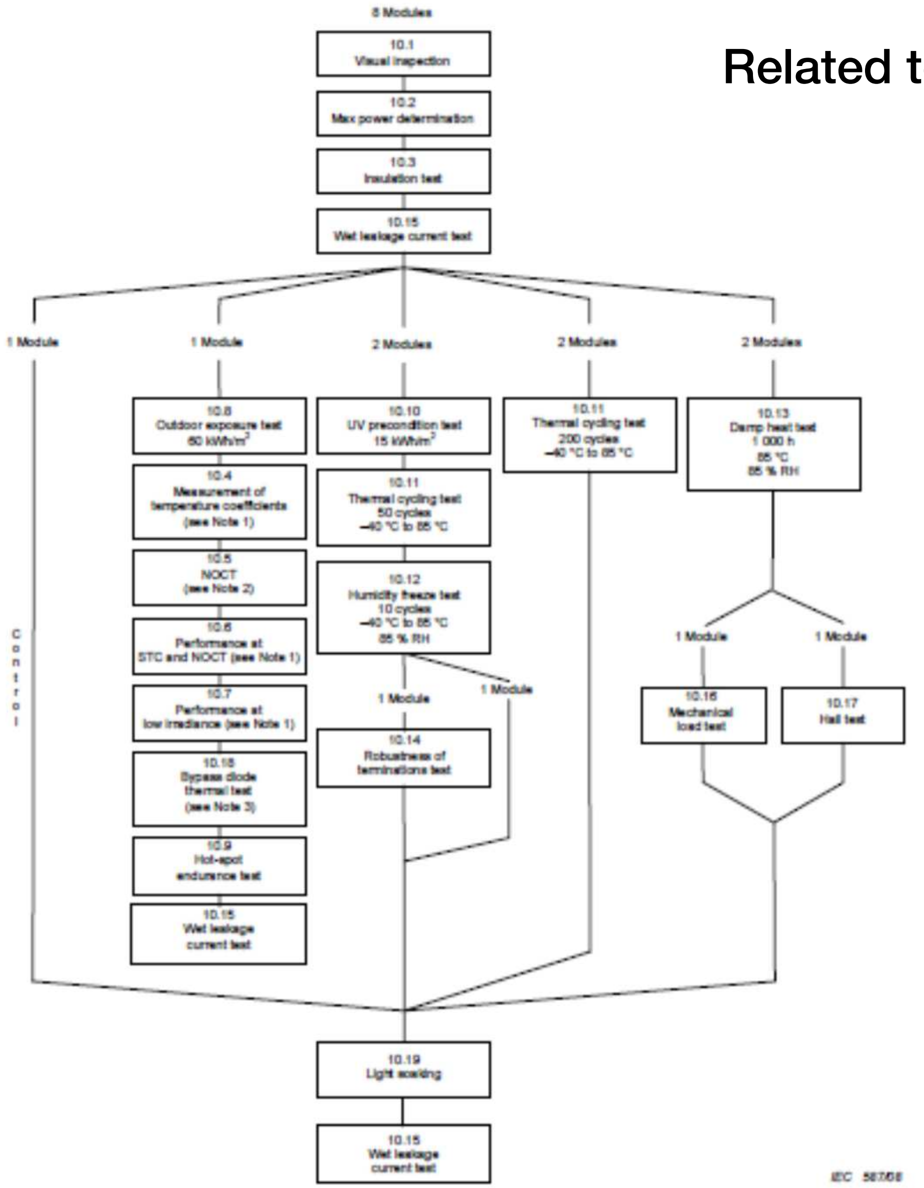
- One study claimed (Whipple, 1993):
  - Pre-Block V: 45% module failure rate
  - Post-Block V: <0.1% module failure rate

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

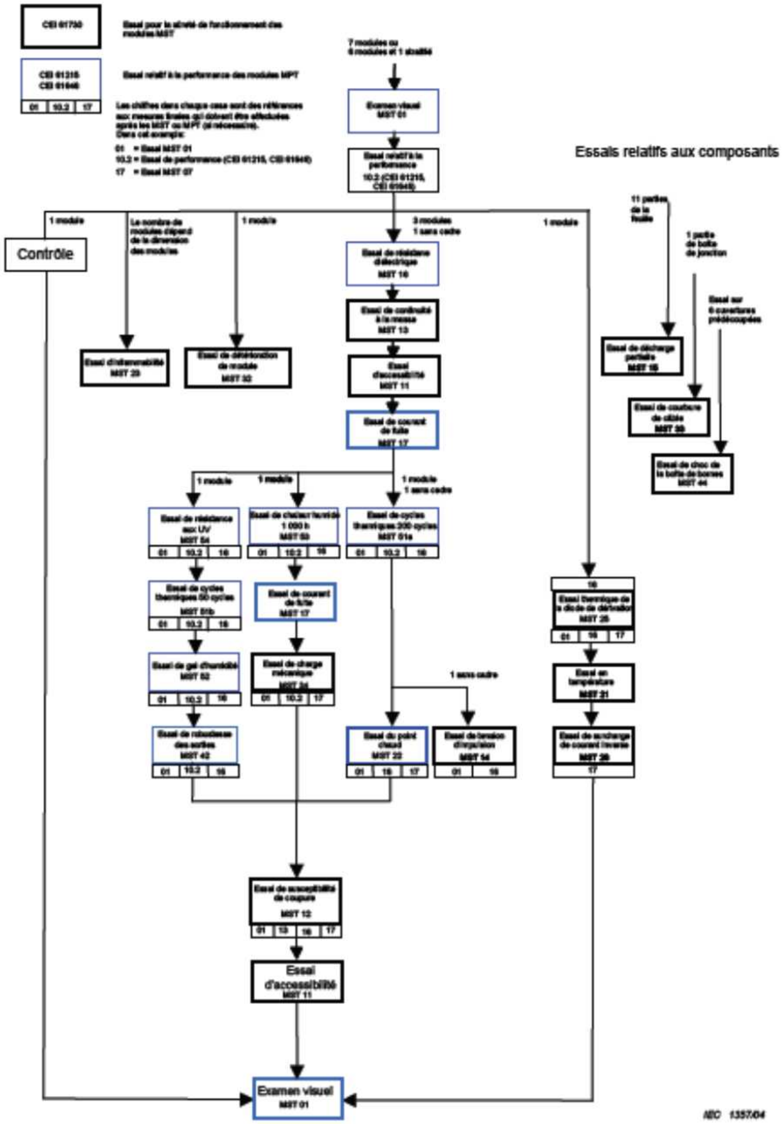
From: History of Qualification Standards; J. Wolgemuth

Test Sequences for IEC 61646 Qualification

Related to Performance



Test Sequences for IEC 61730 Qualification



Related to Safety

Failure Modes and IEC Stress Tests

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

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:

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

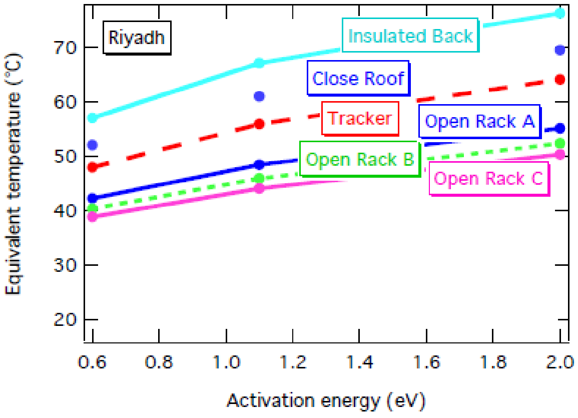
With this model is possible to model degradation rates by using characteristic temperature T_{eq} associated with a time averaged degradation rate

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

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).

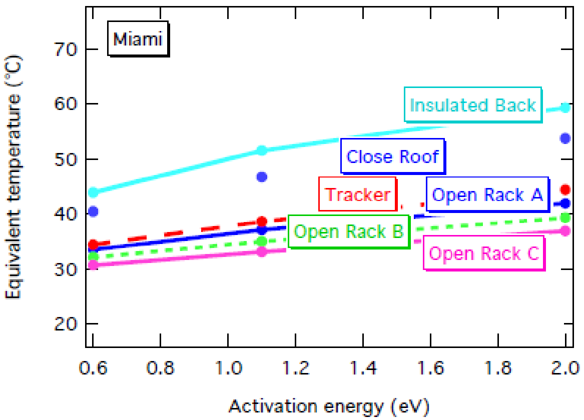
$$\text{Rate} \propto [rH]^n \times e^{[-E_a/kT]}$$

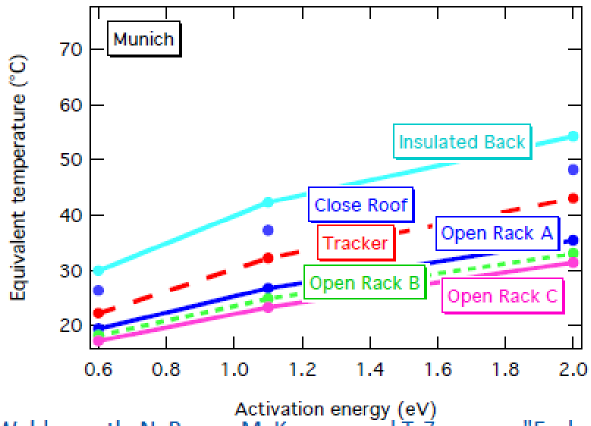
T_{eq} Varies by Location and Mounting Configuration



Mounting Configuration: ±10°C
Location: ±15°C
Activation Energy: ±10°C

Total Range: ±30°C

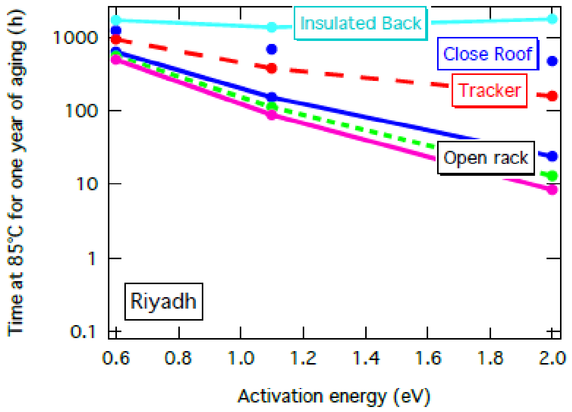




S. Kurtz, K. Whitfield, G. TamizhMani, M. Koehl, D. Miller, J. Joyce, J. Wohlgemuth, N. Bosco, M. Kempe, and T. Zgonena, "Evaluation of high-temperature exposure of photovoltaic modules," *Progress in Photovoltaics: Research and Applications,* DOI: 10.1002.

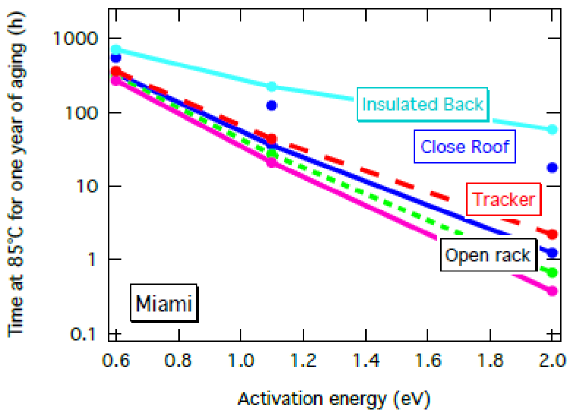
Accelerated Stress Tests

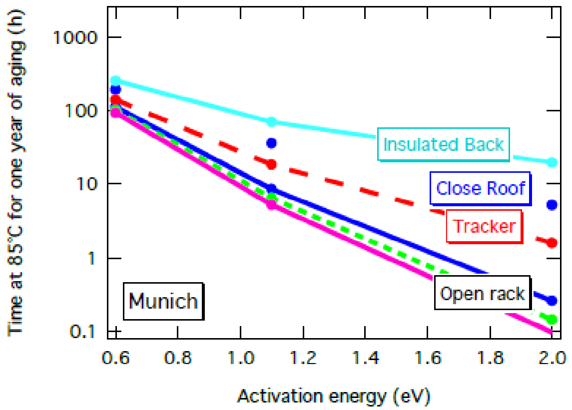
Thermal Acceleration Depends on Mounting and Environment



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

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





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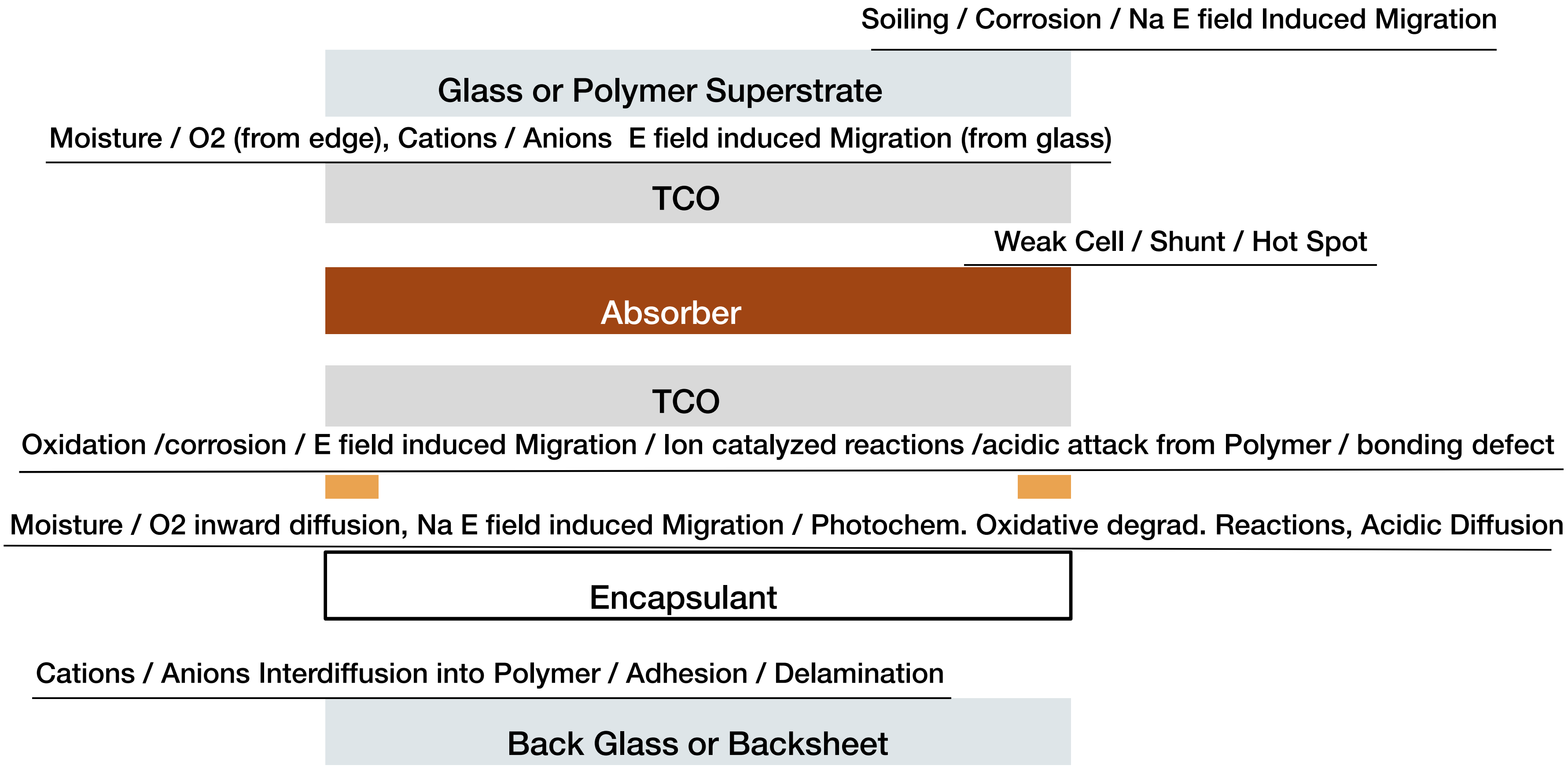
IEC Qualification Tests into Reliability Tests?

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



Soiling / Corrosion / Na E field Induced Migration

Glass or Polymer Superstrate

Moisture / O2 (from edge), Cations / Anions E field induced Migration (from glass)

TCO

Weak Cell / Shunt / Hot Spot

Absorber

TCO

Oxidation /corrosion / E field induced Migration / Ion catalyzed reactions /acidic attack from Polymer / bonding defect

Moisture / O2 inward diffusion, Na E field induced Migration / Photochem. Oxidative degrad. Reactions, Acidic Diffusion

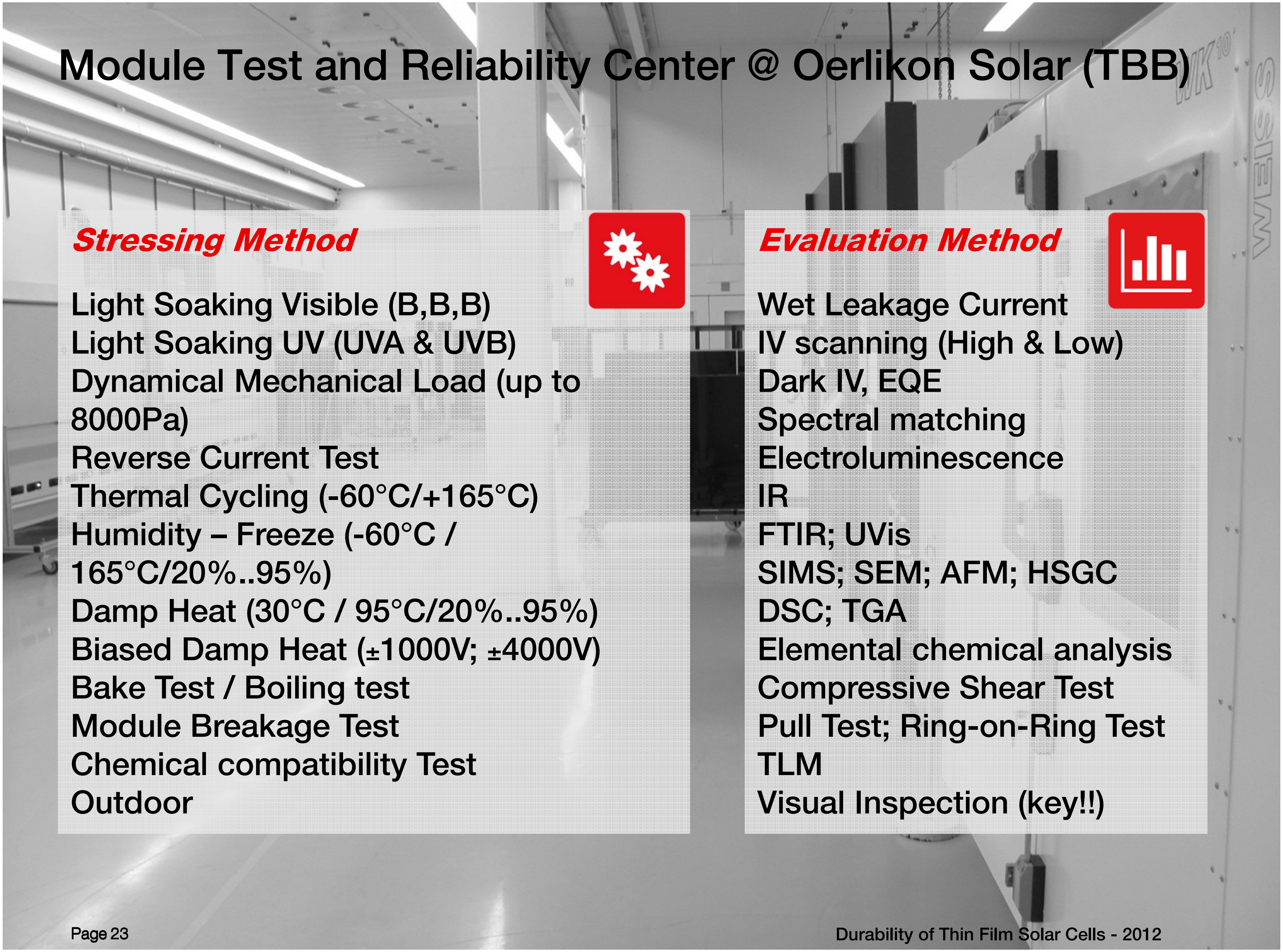
Encapsulant

Cations / Anions Interdiffusion into Polymer / Adhesion / Delamination

Back Glass or Backsheet

Main drivers: T, rH, V, PH, UV, O_2, H_2O (vapor or liquid)

Module Test and Reliability Center @ Oerlikon Solar (TBB)



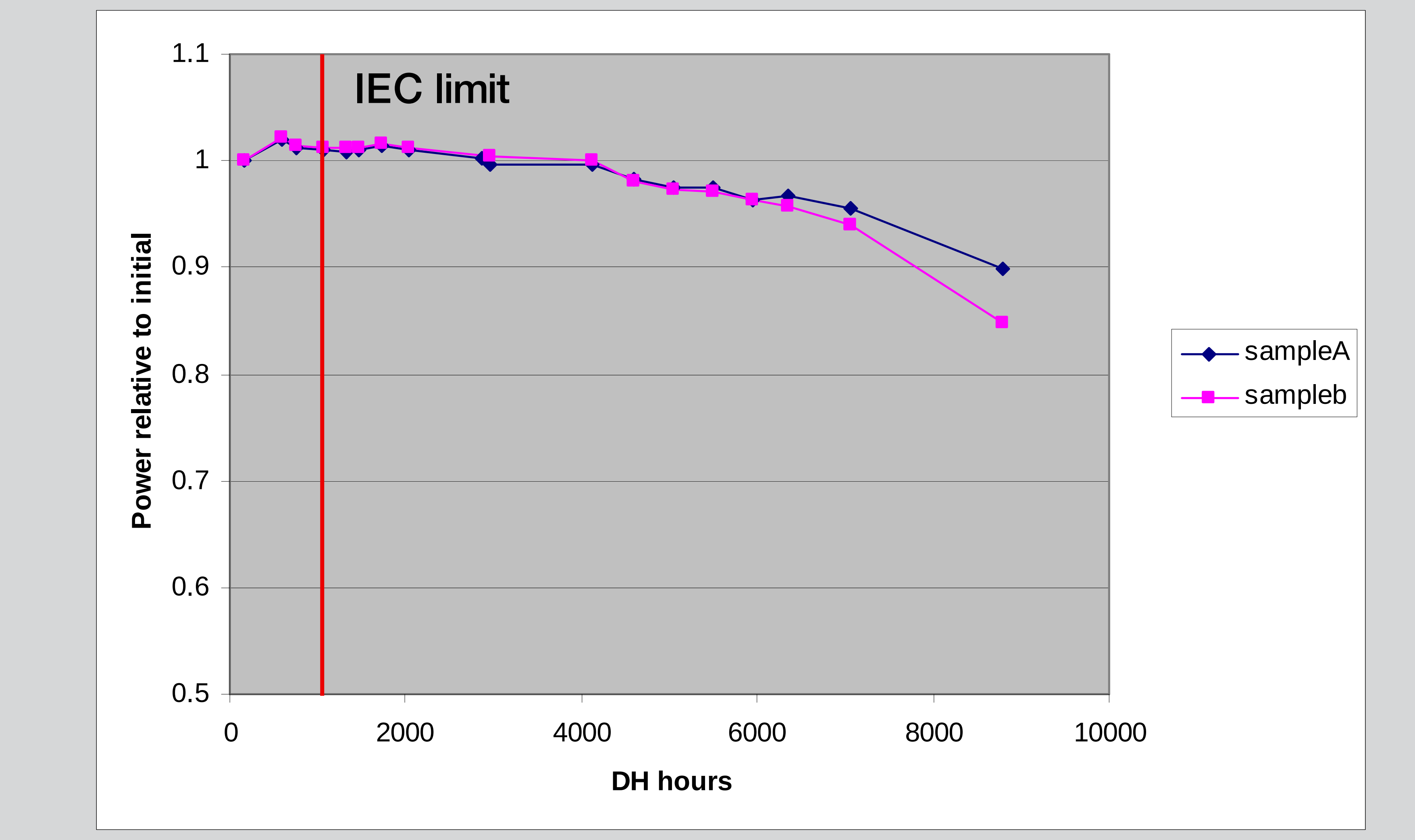
Stressing Method

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)



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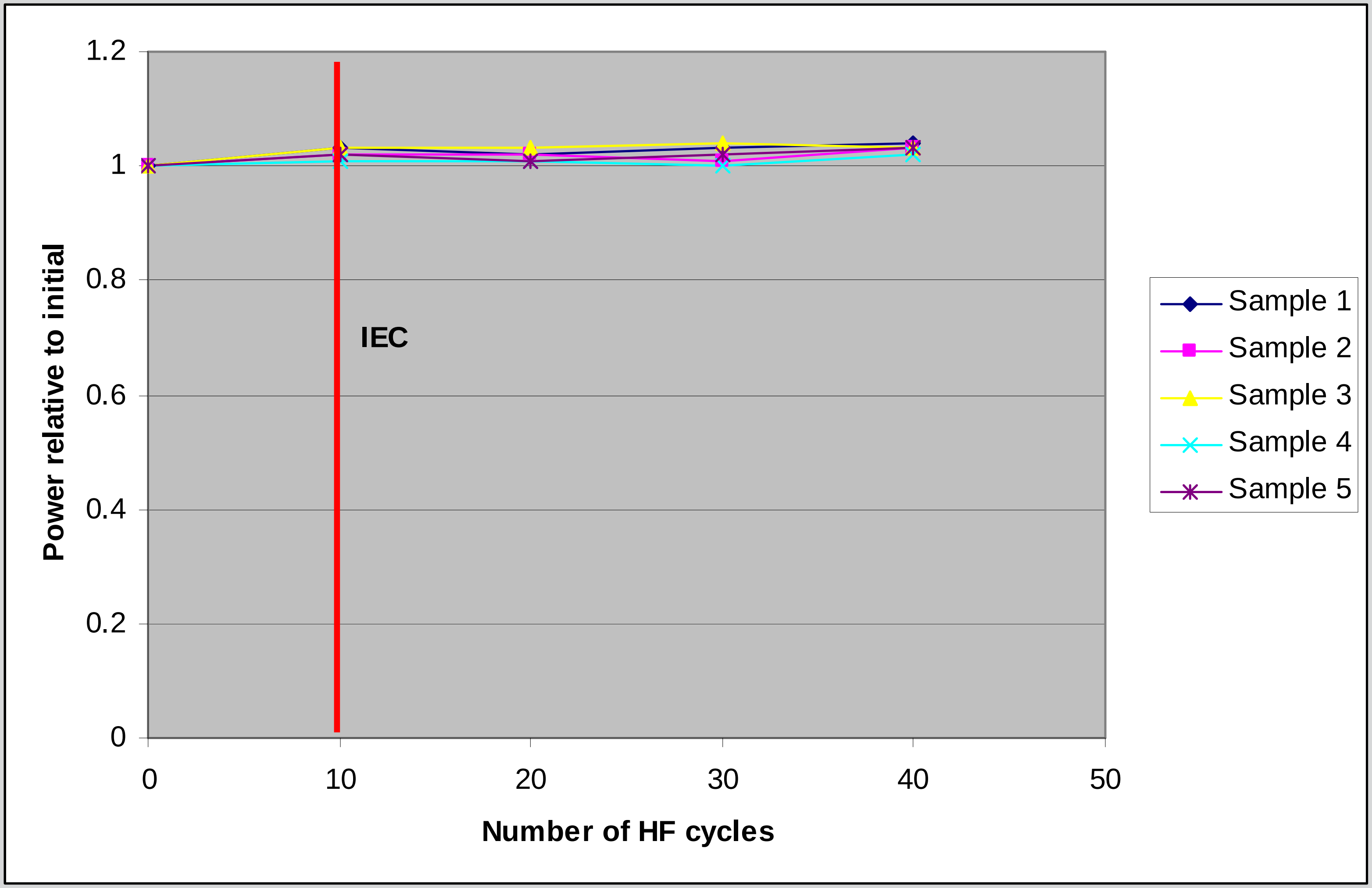

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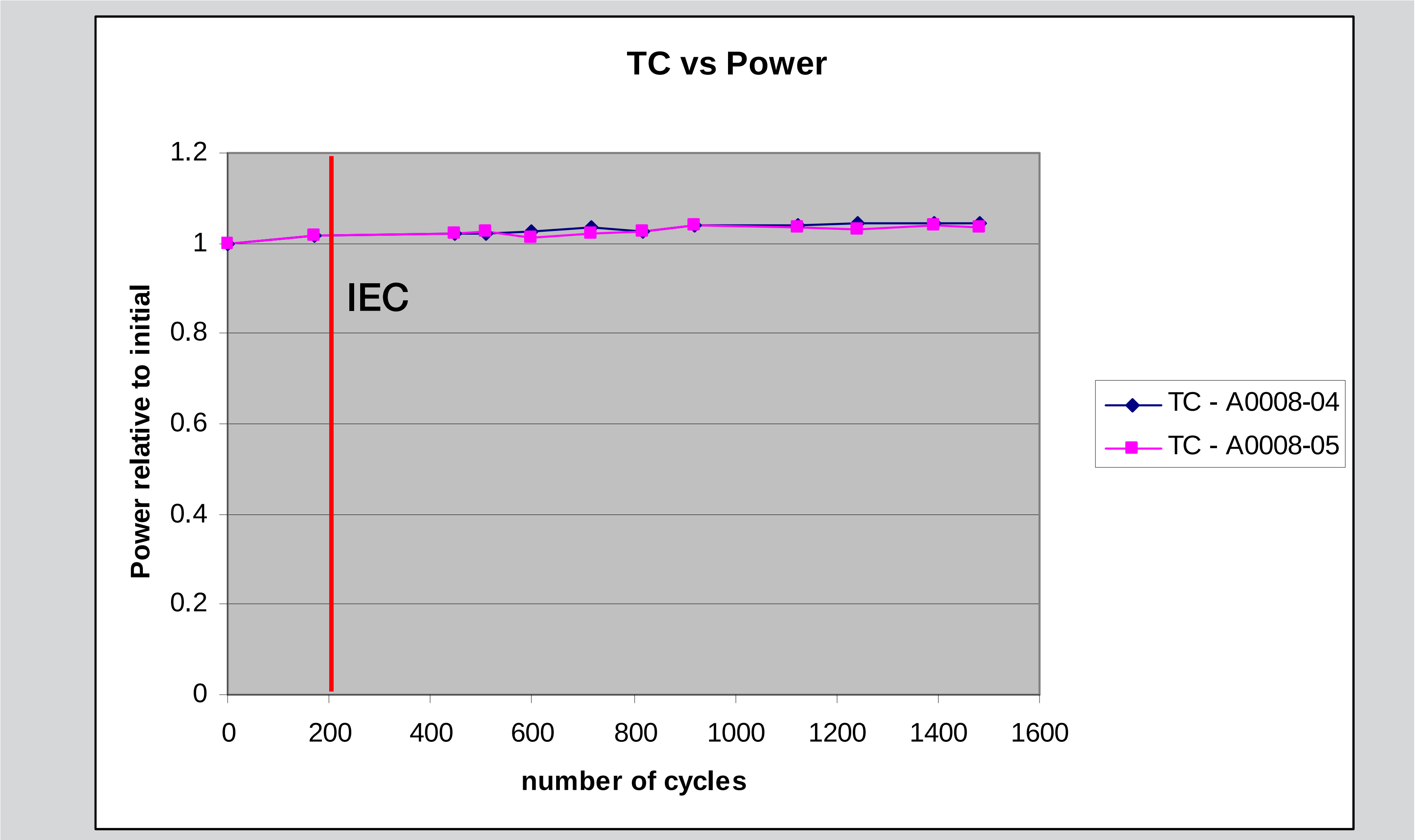

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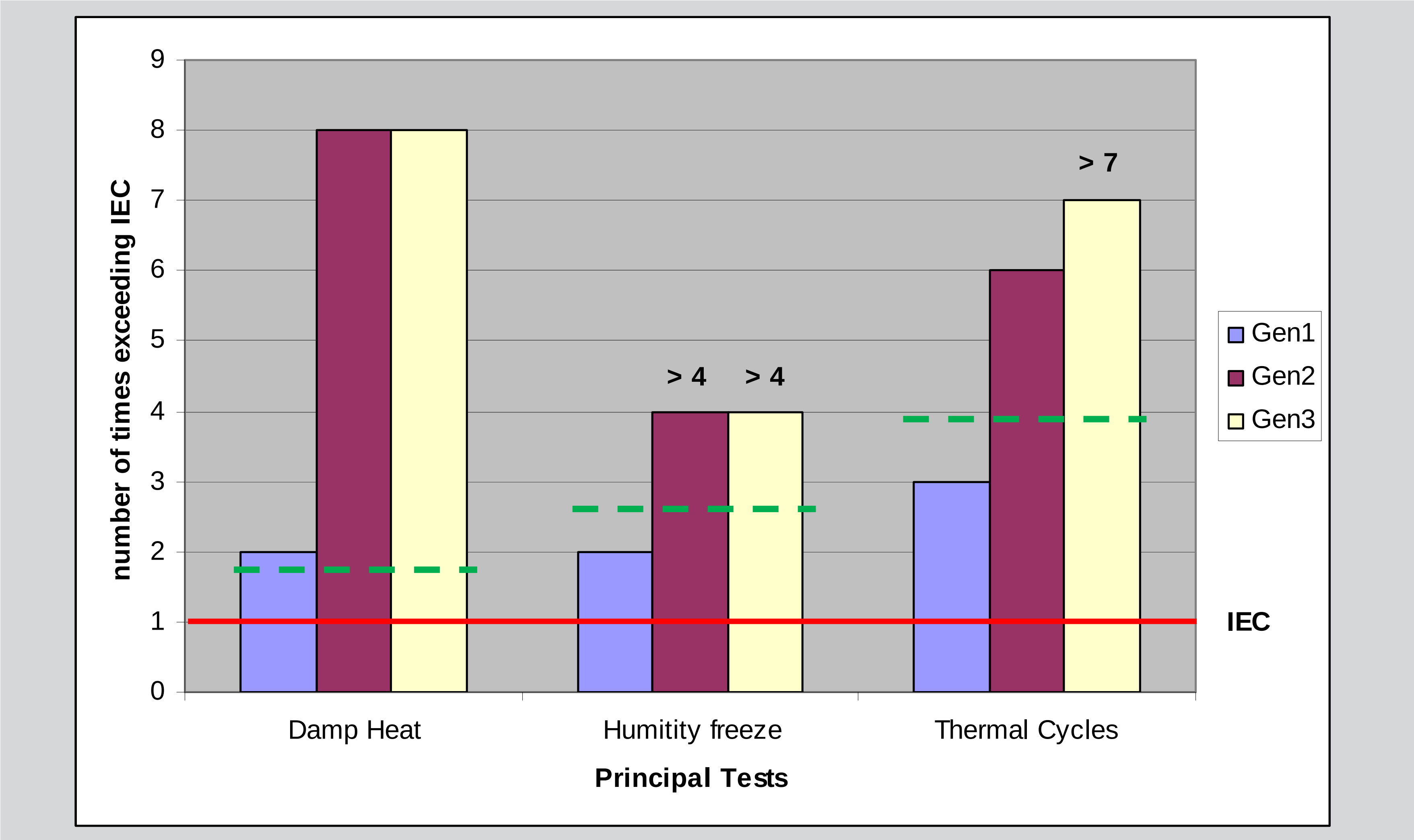
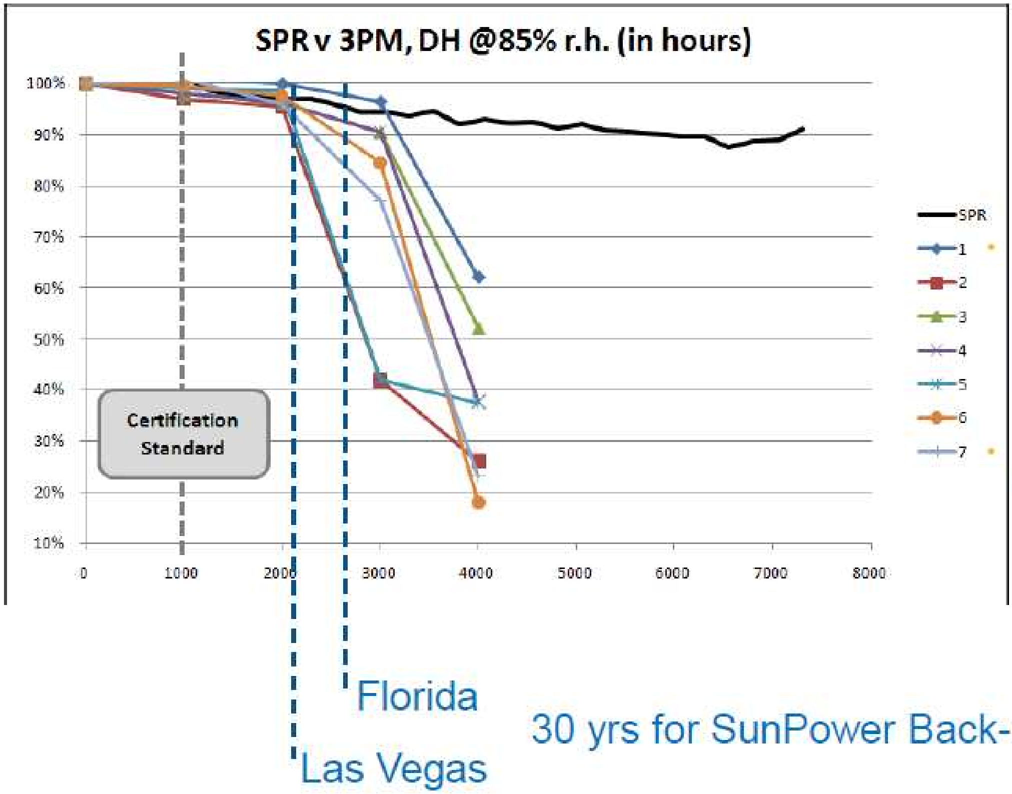
Beyond IEC (Example of OS modules design evolution)



Average survival (all technologies) according to IEC criteria

Damp Heat Acceleration Factors by Climate

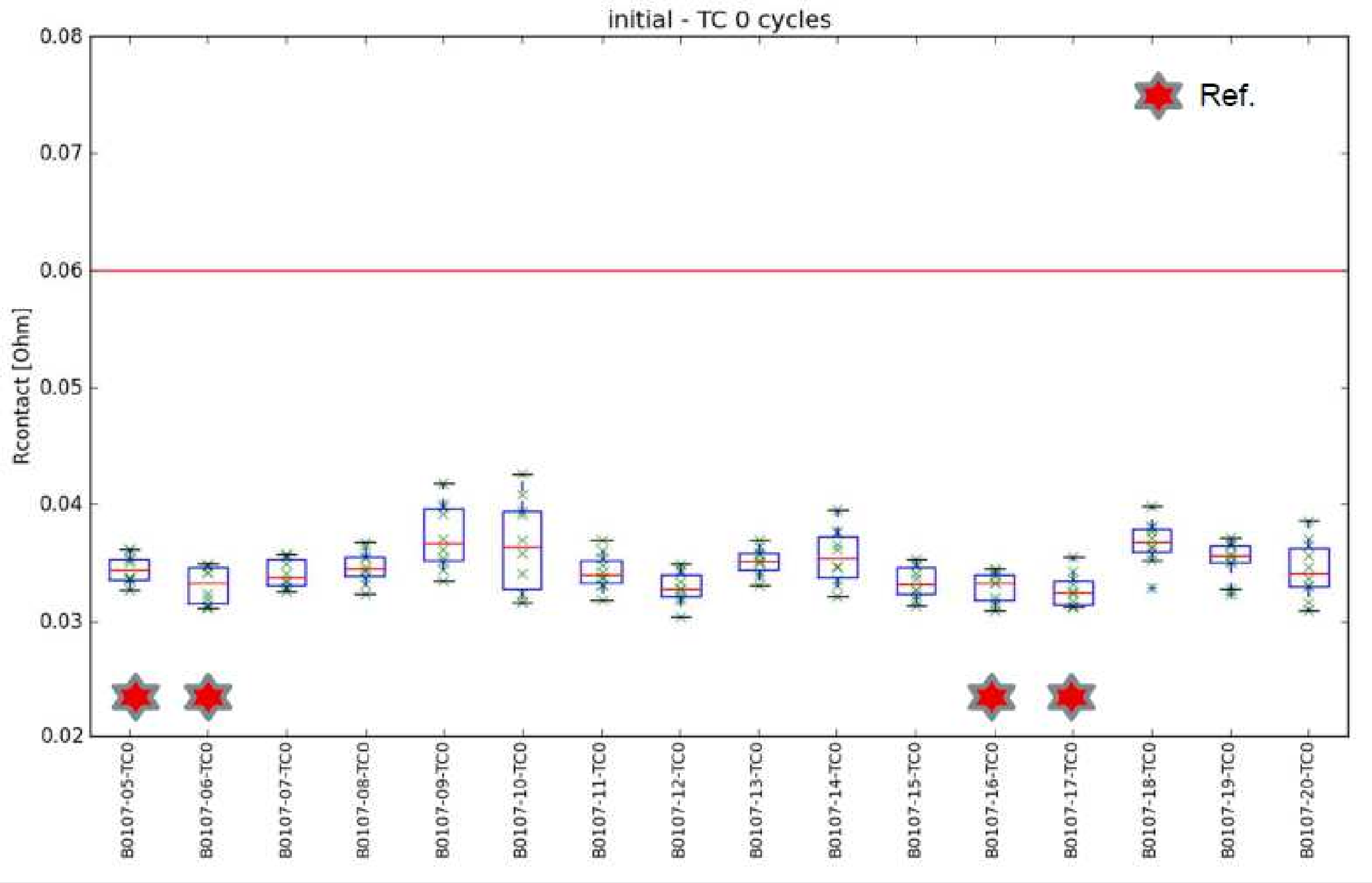


1-7 are silicon-cell module measurements from Koehl, Michael, et. al. "PV Reliability: Accelerated Aging Tests and Modeling of Degradation." Fraunhofer ISE and TUV Rheinland. Presented at EUPVSEC, Valencia Spain, Sept 2010.

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

30 yrs for SunPower Back-contact cells.

TLM Method - contacting resistance loss (initial)



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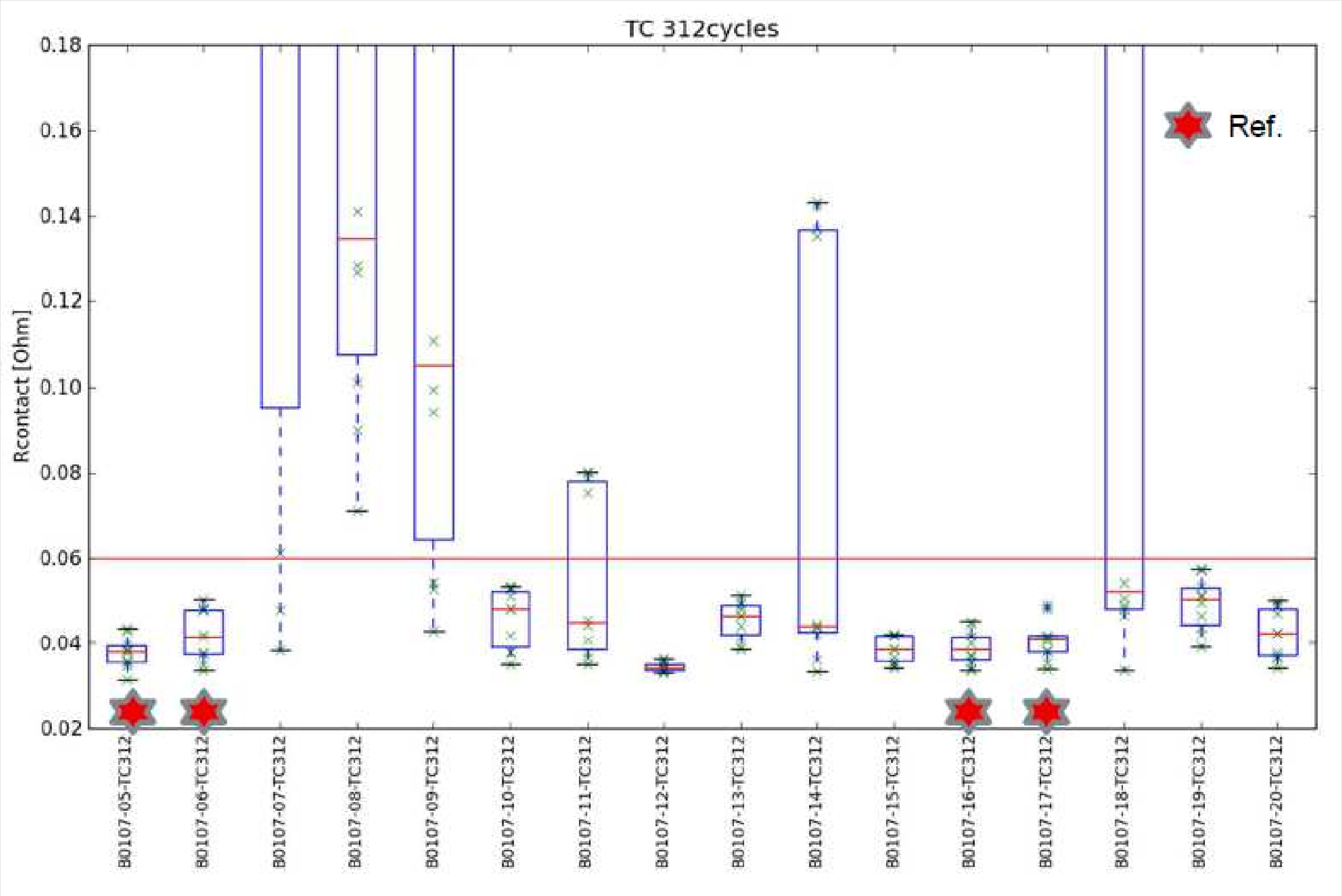
TLM Method - contacting resistance loss (after 320 TC)



Beyond IEC (Biased Damp Heat)

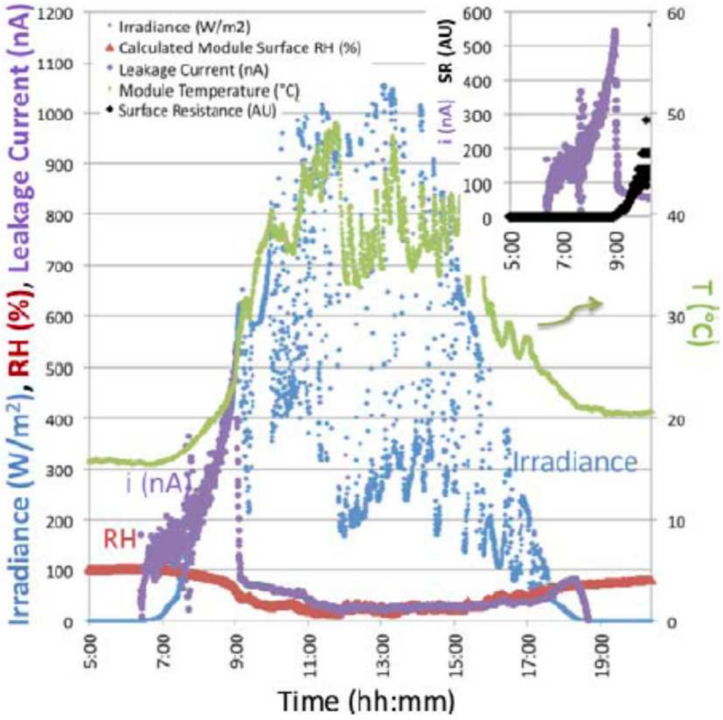


Figure 1. Leakage current to ground, irradiance, calculated module surface relative humidity (RH), and module temperature over a one-day period in Florida. The module is horizontally mounted, the active layer is biased to scale logarithmically with irradiance to a maximum voltage of –600 V with the module leads connected to a load resistor to maintain approximately P_{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.

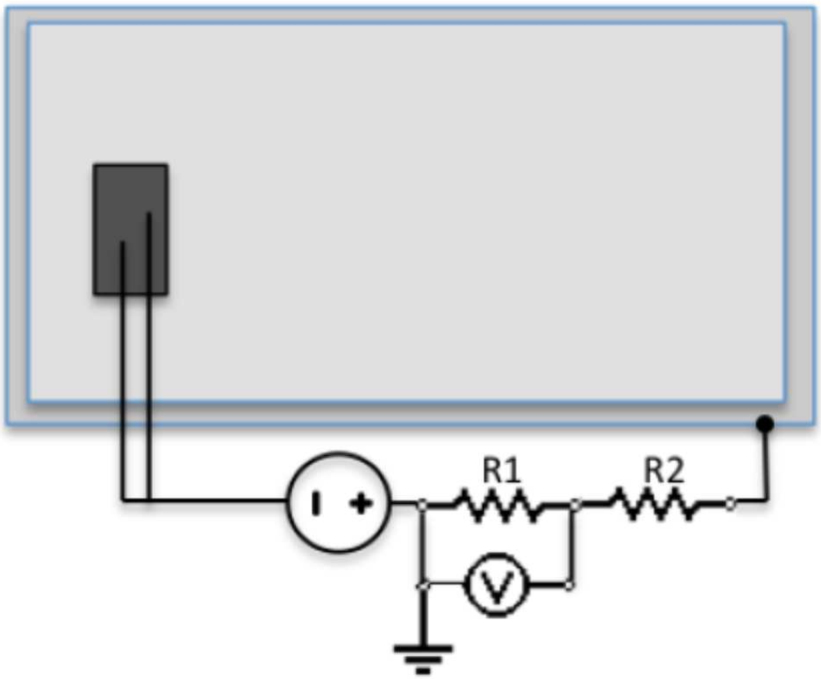


Figure 2. Application of voltage to the active layer of a PV module via the shorted leads. The leakage current is monitored by a voltmeter across a resistor R1 connected to ground. The voltmeter may be protected from overvoltage by a second resistor R2.

Beyond IEC (Biased Damp Heat)

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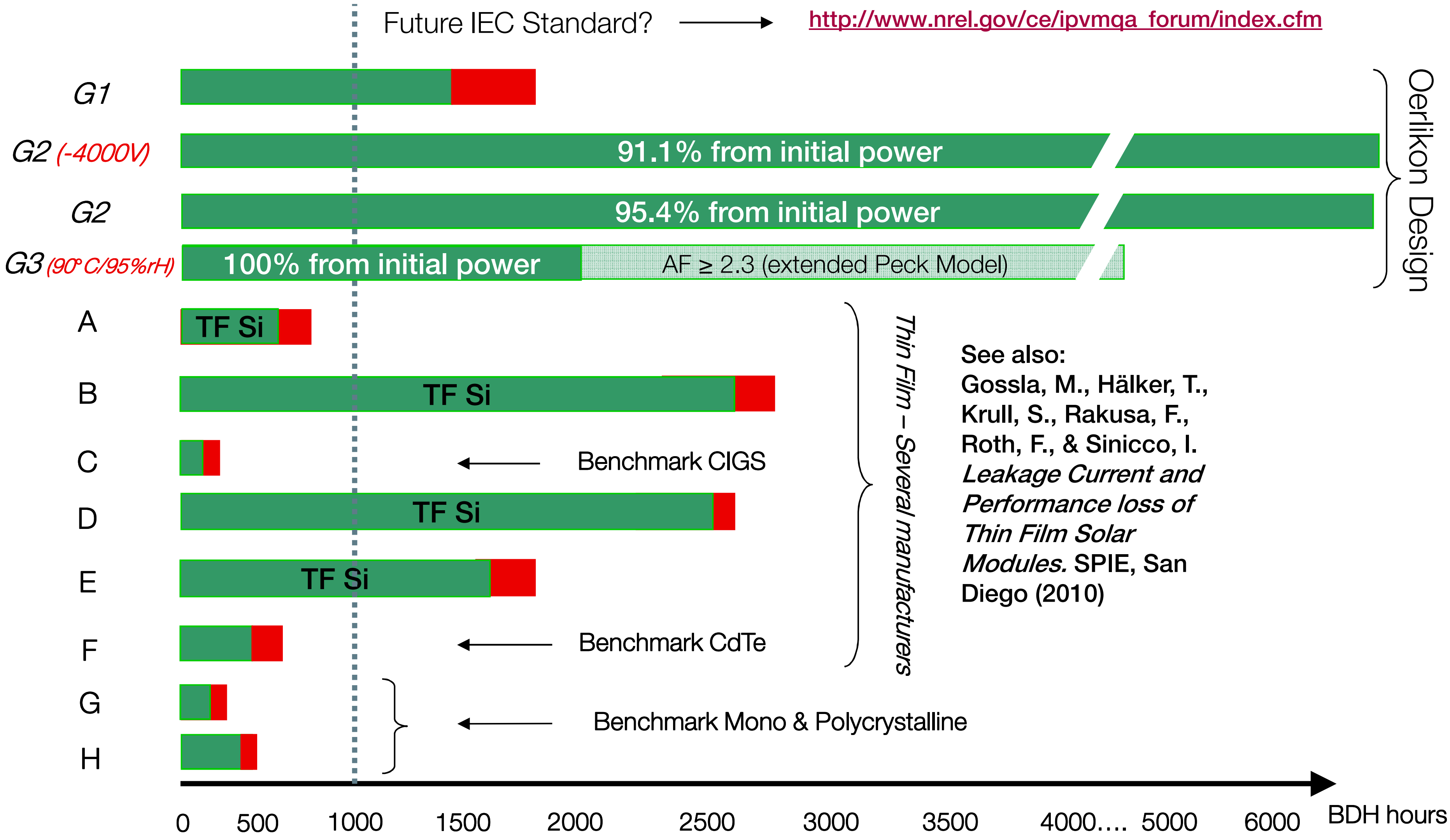
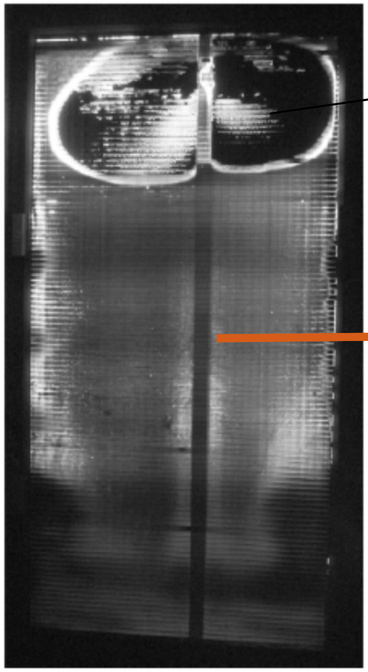


**See also:
Gossla, M., Hälker, T., Krull, S., Rakusa, F., Roth, F., & Sinicco, I. *Leakage Current and Performance loss of Thin Film Solar Modules.* SPIE, San Diego (2010)**

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.

Beyond IEC (Biased Damp Heat)

EL example: Module F

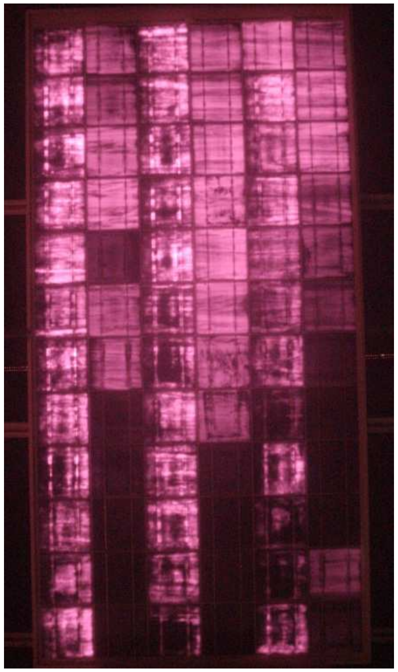


Moisture Diffusion
& TCO Corrosion

E Field Induced
migration

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

EL example: Module H



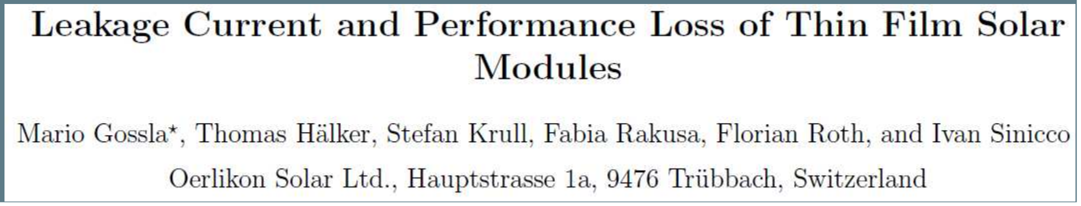
800hrs BDH -1000V (60% P_{ini})

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:

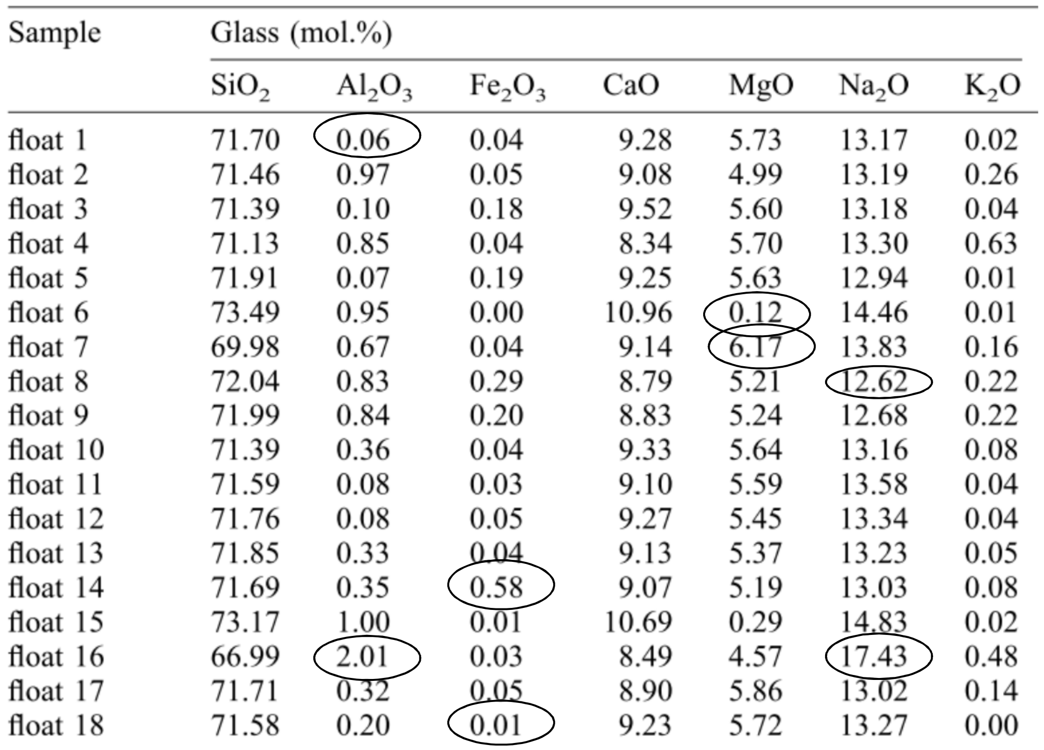


Leakage Current and Performance Loss of Thin Film Solar Modules

Mario Gossla*, Thomas Hälker, Stefan Krull, Fabia Rakusa, Florian Roth, and Ivan Sinicco
Oerlikon Solar Ltd., Hauptstrasse 1a, 9476 Trübbach, Switzerland

Glass Chemistry

Chemical composition variation from float line to float line



Sample	Glass (mol.%)						
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
float 1	71.70	0.06	0.04	9.28	5.73	13.17	0.02
float 2	71.46	0.97	0.05	9.08	4.99	13.19	0.26
float 3	71.39	0.10	0.18	9.52	5.60	13.18	0.04
float 4	71.13	0.85	0.04	8.34	5.70	13.30	0.63
float 5	71.91	0.07	0.19	9.25	5.63	12.94	0.01
float 6	73.49	0.95	0.00	10.96	0.12	14.46	0.01
float 7	69.98	0.67	0.04	9.14	6.17	13.83	0.16
float 8	72.04	0.83	0.29	8.79	5.21	12.62	0.22
float 9	71.99	0.84	0.20	8.83	5.24	12.68	0.22
float 10	71.39	0.36	0.04	9.33	5.64	13.16	0.08
float 11	71.59	0.08	0.03	9.10	5.59	13.58	0.04
float 12	71.76	0.08	0.05	9.27	5.45	13.34	0.04
float 13	71.85	0.33	0.04	9.13	5.37	13.23	0.05
float 14	71.69	0.35	0.58	9.07	5.19	13.03	0.08
float 15	73.17	1.00	0.01	10.69	0.29	14.83	0.02
float 16	66.99	2.01	0.03	8.49	4.57	17.43	0.48
float 17	71.71	0.32	0.05	8.90	5.86	13.02	0.14
float 18	71.58	0.20	0.01	9.23	5.72	13.27	0.00

Glass / Foil interface after 1000 h DH 85/85 for a glass with low magnesia content

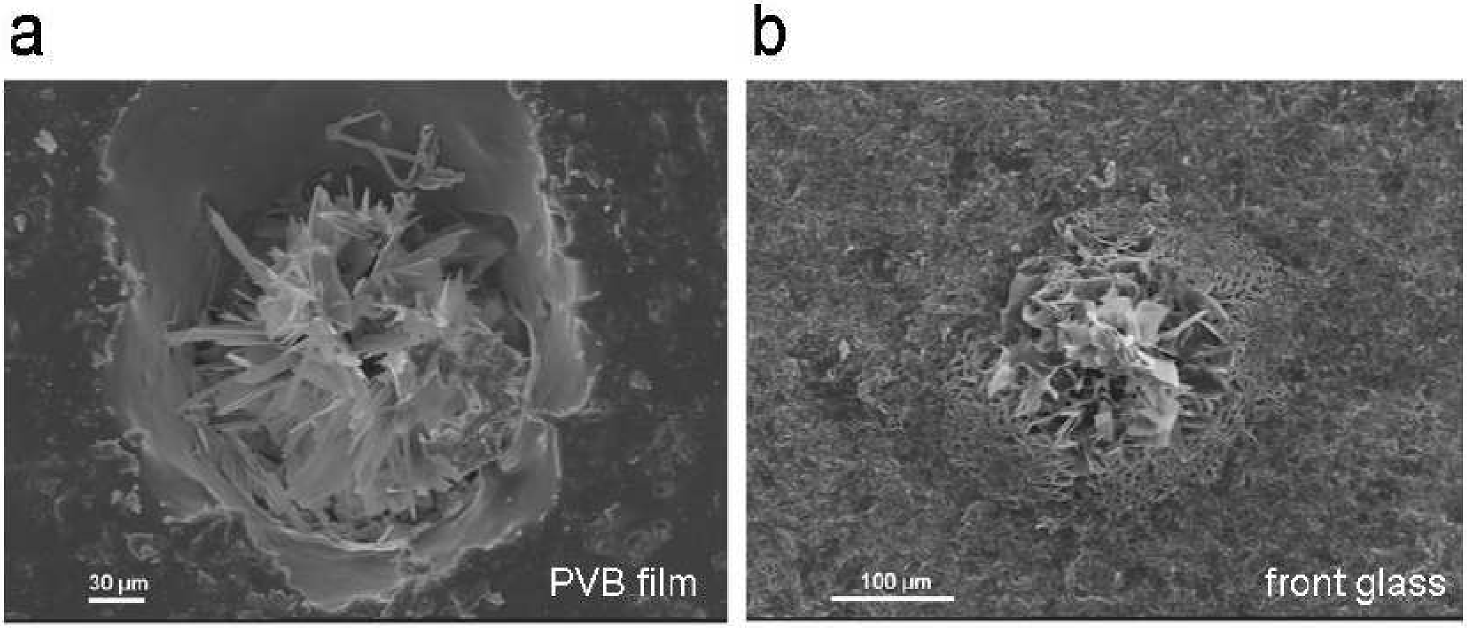
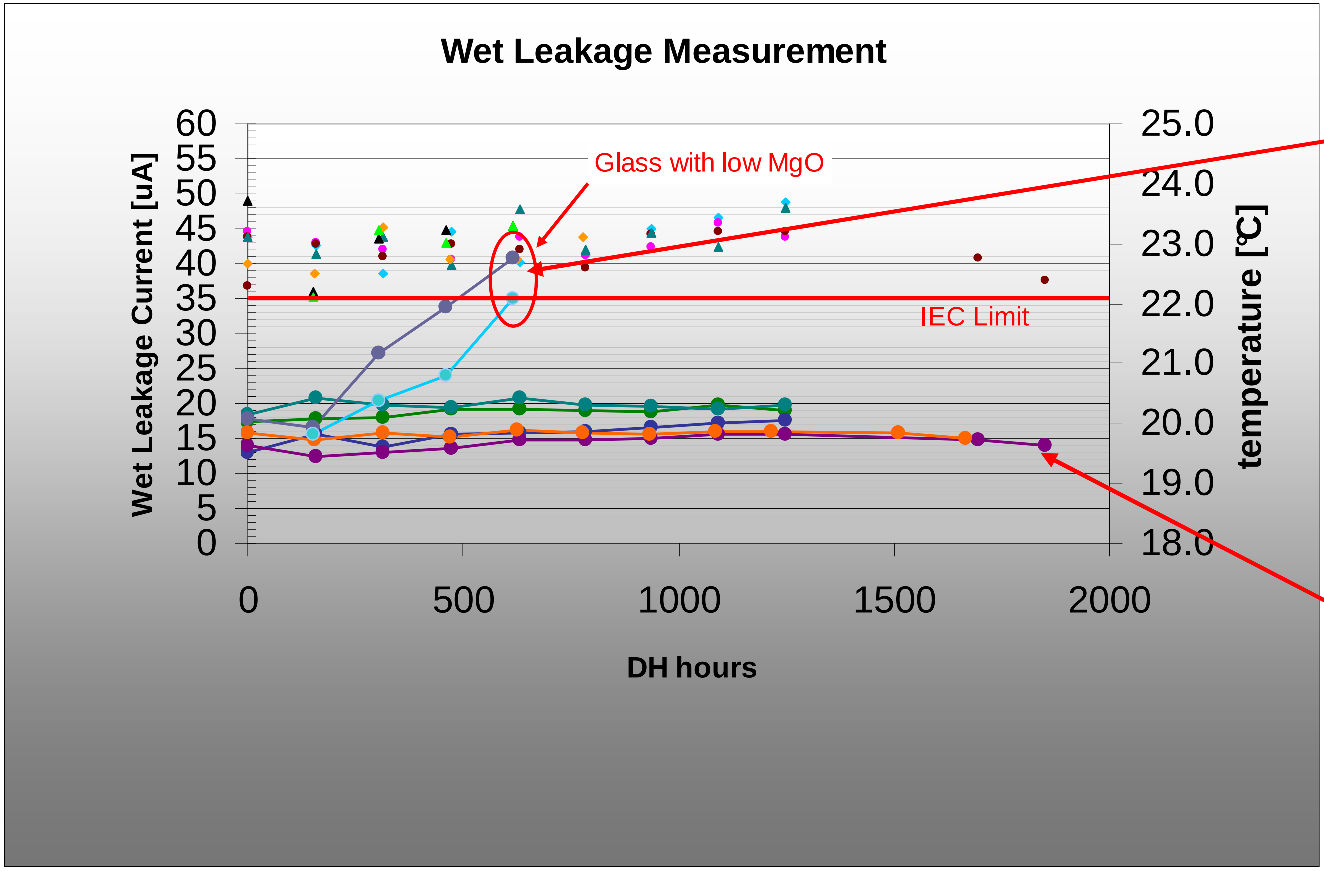


Figure 6: SEM micrographs taken from the glass- clear PVB interface of sample b (Glass type A) in figure 3 after delamination,. (a) Crystallites formed by Ca/Na segregation from the glass bulk, penetrating into the clear PVB film. (b) Origin of the Ca/Na rich crystallites seen at the same position of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

From: Analysis of the Glass- Clear PVB Lamination foil interface of Thin Film Laminates

Jens Günster[a,b], Stefan Krull, Fabia Rakusa[a], Florian Roth and Ivan Sinicco[a]

Safety Integrity: Wet Leakage Currents



Glass A

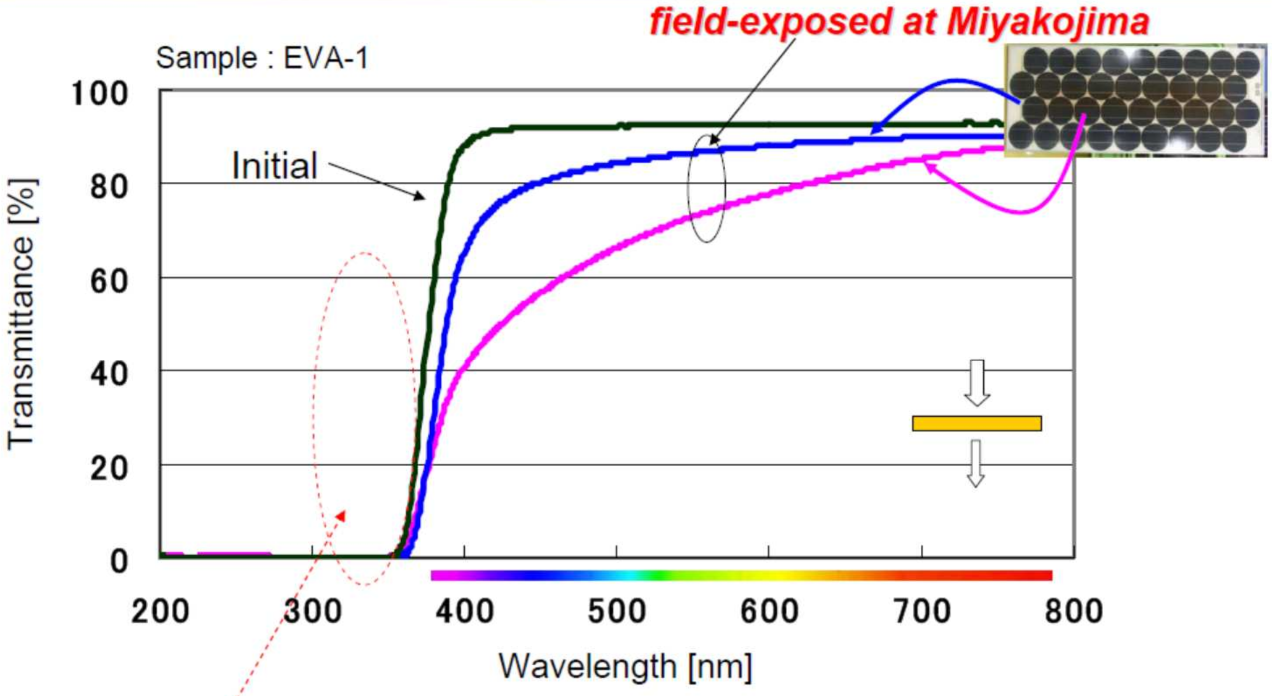
Glass C

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

Roth, F., Krull, S., Günster, J. and Sinicco, I., “Is The IEC 61646 – 10.15 Test Reliable?“, 24th EUPVSEC, 2009, pp. 3553-3556

Care must be taken when using accelerated stress tests

Transmittance spectra of EVA field-exposed at Miyakojima



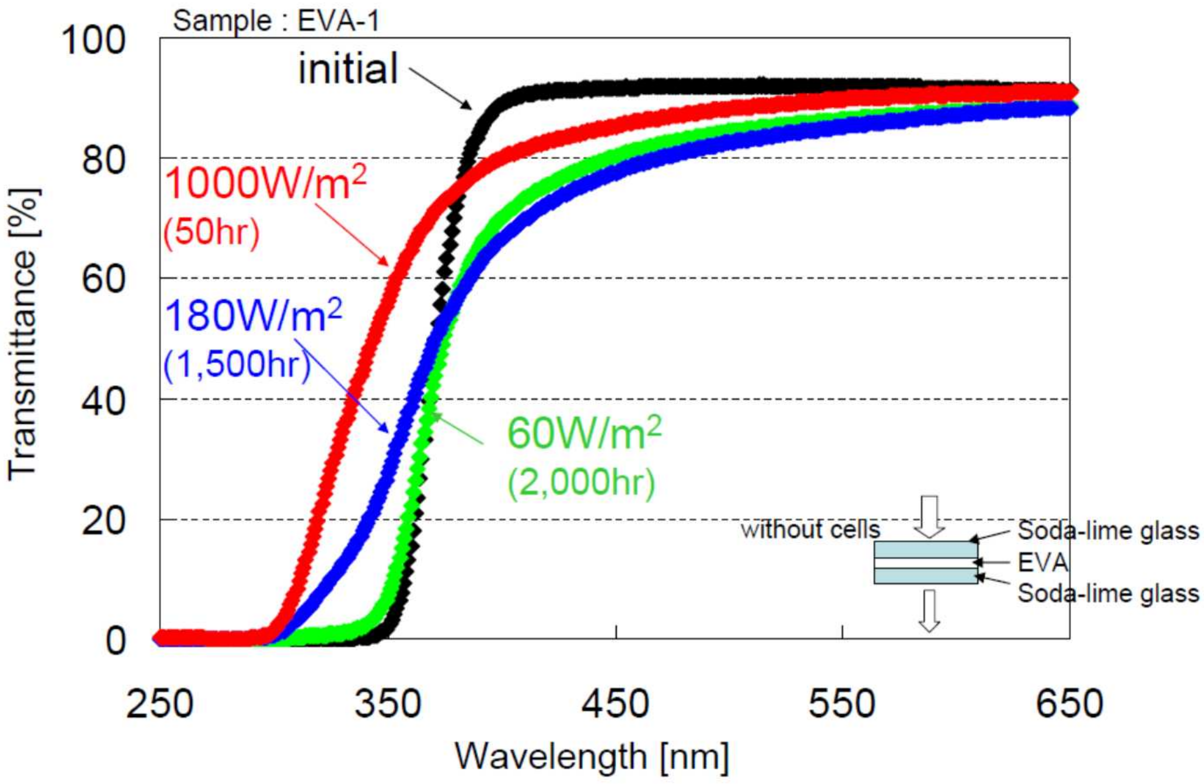
Active UV absorber formulated in EVA encapsulant is still remained even 17 years field exposed at Miyakojima.

From: Tsuyoshi Shioda

Mitsui Chemicals, Inc.
Mitsui Chemicals Tohcello Inc.

Care must be taken when using accelerated stress tests

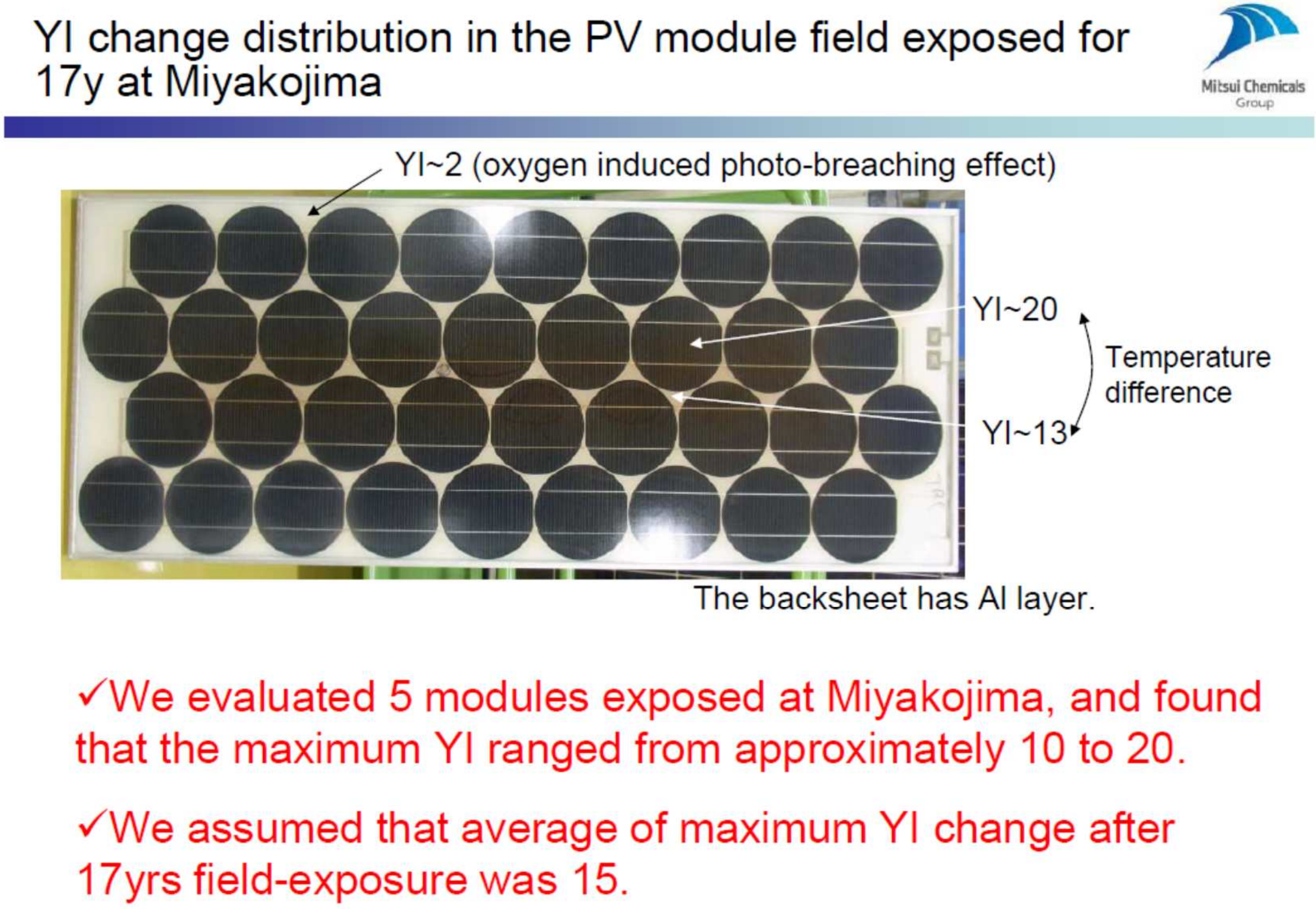
Transmittance spectra of EVA aged by UV accelerated tests



From: Tsuyoshi Shioda

Mitsui Chemicals, Inc.
Mitsui Chemicals Tohcello Inc.

Care must be taken when using accelerated stress tests



YI change distribution in the PV module field exposed for 17y at Miyakojima

The backsheet has Al layer.

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

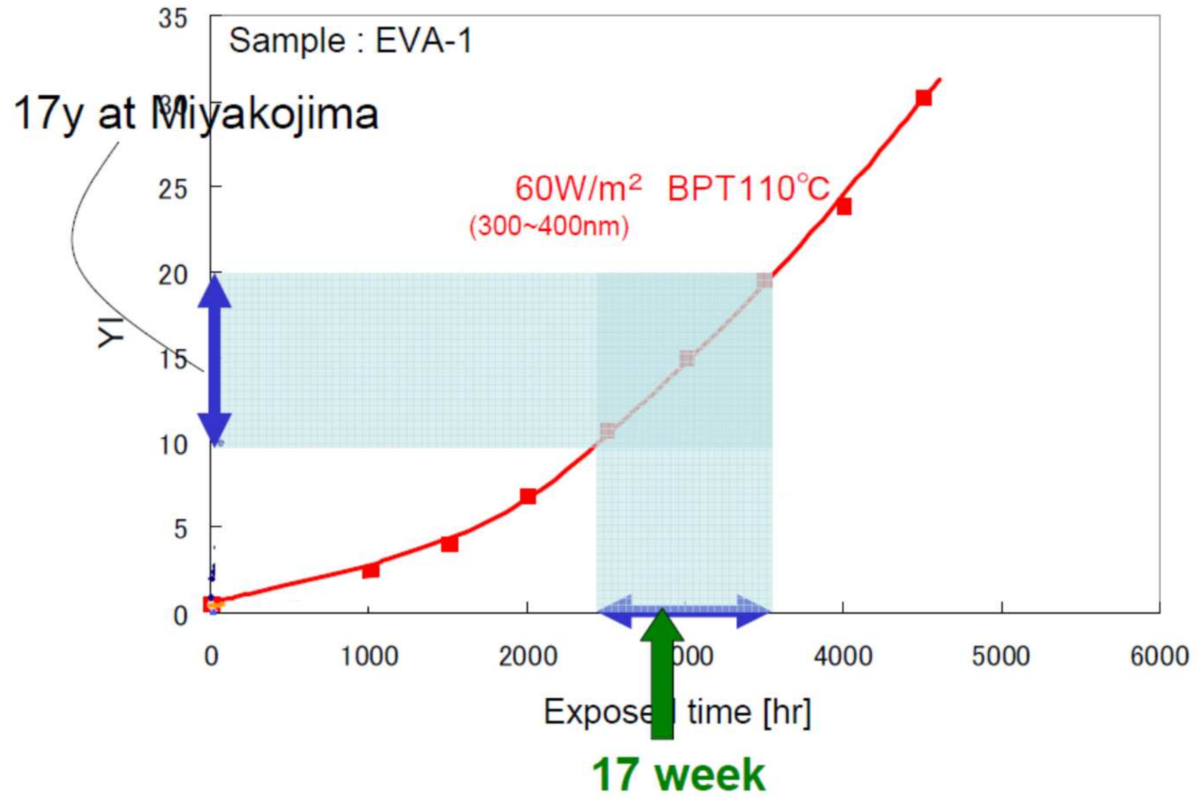
✓We assumed that average of maximum YI change after 17yrs field-exposure was 15.

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



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 warrantees and reduce insurance costs (bankability)*

How the designed module is produced?

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

Material control

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

Process control

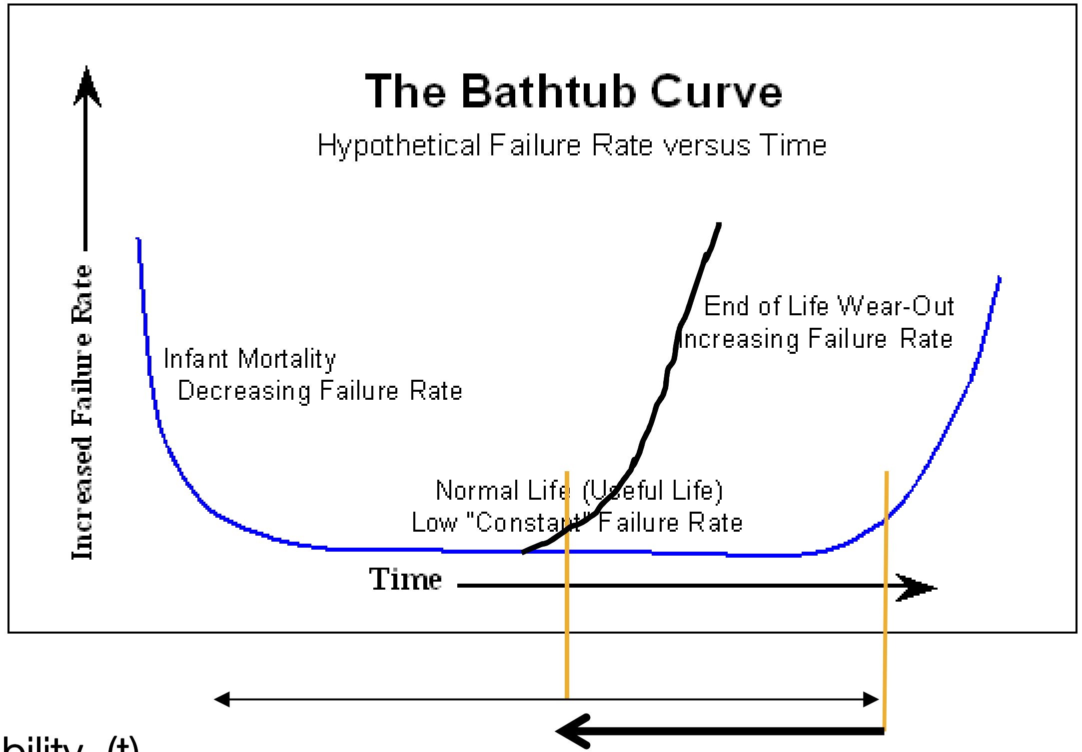
- WPI are updated?
- Are operators well trained?
- Are machine settings well adjusted?
- Engineeering lot successful?
- Run process

Operation control

- 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?

Product control

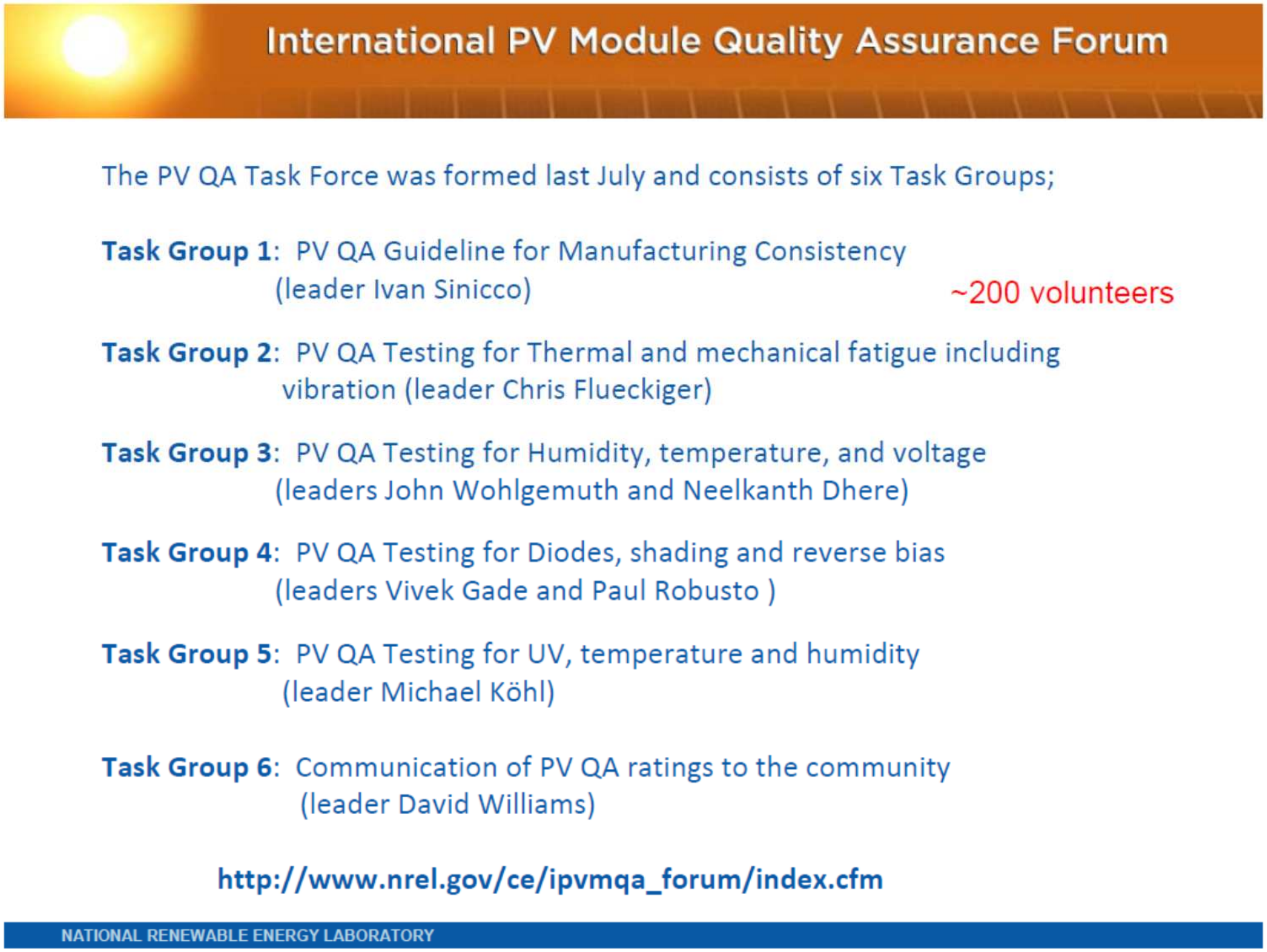
Implications on Module Reliability and Durability of non consistent manufacturing processses



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

Due to off-spec materials
Faulty process control

How to insure manufacturing consistency? (or is the module produced identical to the approved one?)



International PV Module Quality Assurance Forum

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)

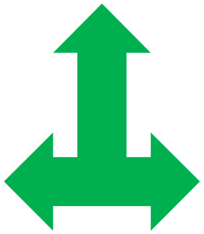
Task Group 6: Communication of PV QA ratings to the community (leader David Williams)

http://www.nrel.gov/ce/ipvmqa_forum/index.cfm

NATIONAL RENEWABLE ENERGY LABORATORY

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™

oerlikon
solar

Competitive

Clean

Sustainable

Thank you for your attention !