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SUNPOWER

How do Qualified Modules Fail – What is the root cause?

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Outline

- Description of datasets: 21 manufacturers
- Summary of failure rates – design problems and mfg quality problems
- Pareto of Causes of Failures
- Analysis of failures according to the causes
- Climate example: damp heat testing vs Florida vs Arizona
- Conclusions

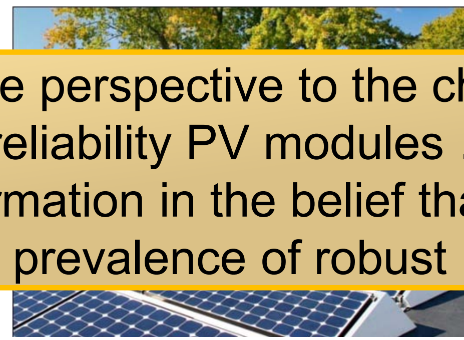
SunPower 2011: 25th Anniversary

- World-leading solar conversion efficiency
- >1.5 GW solar PV deployed
- Diversified portfolio: roofs to power plants
- 5 GW power plant pipeline
- Publicly listed on NASDAQ
- 2010: Revenue Guided >$2 billion
- 5,500+ Employees
- 550 MW+ 2010 production

SunPower brings a unique perspective to the challenge of deploying high-reliability PV modules …

… we are sharing this information in the belief that the entire industry benefits from a high prevalence of robust PV modules.

Residential: #1 US



Commercial: #1 US

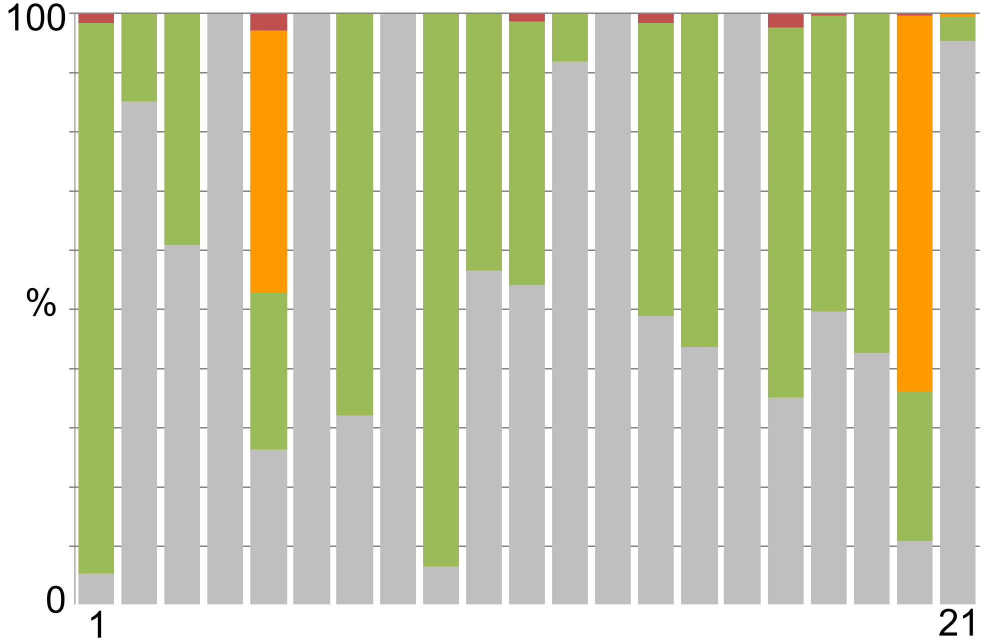
Power Plant Pioneer

Learning from field data

- Data from 21 manufacturers: some extensive, some limited.
- Every effort has been made to convey as much information as possible without indicating the names of any specific manufacturers.
- Mixture of single-crystal and multi-crystal silicon

ASTROPOWER	ISOFOTON	SANYO	SOLAR SEMICON.
ATERSA	KYOCERA	SHARP	SUNPOWER
BP SOLAR	PHOTOWATT	SHELL	SUNTECH
EVERGREEN	POWERLIGHT	SIEMENS	UNISOLAR
FIRST SOLAR	RWE SCHOTT	SOLARFUN	YINGLI
FLUITECNIK			

Field data sampling rates by manufacturer



- Records from all sites with a power production warranty (includes string-level IV-curve tracing each year)
- Operations & Maintenance work orders
- Support incidents
- Corrective and Preventive Action records

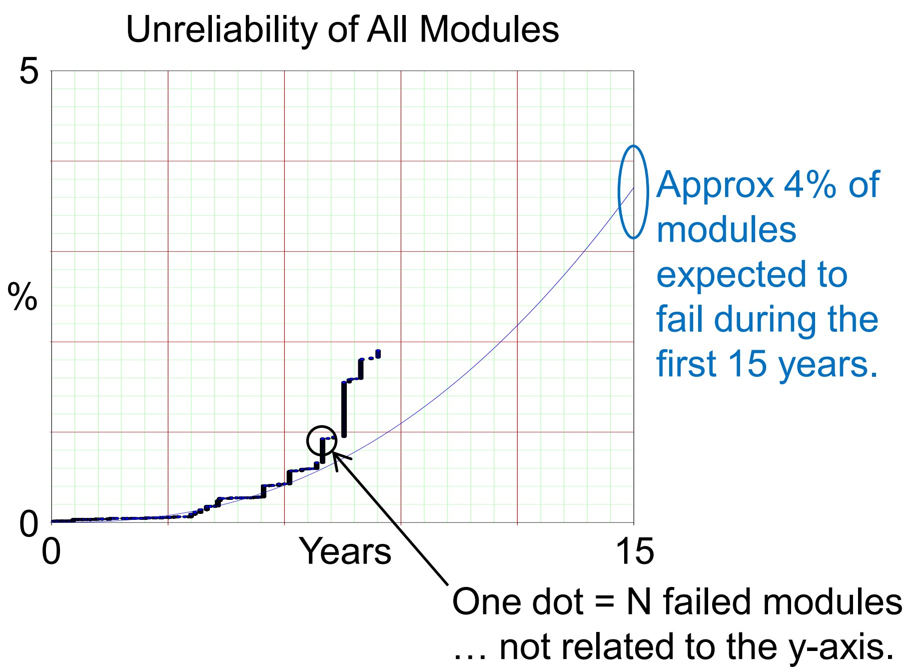
Fail – performance does not meet warranty

Predicted to Fail – well-understood design problem shows these modules will not meet the warranty, but have not failed yet

Pass – performance meets warranty

Not Inspected

Field statistics: all modules



Notes:

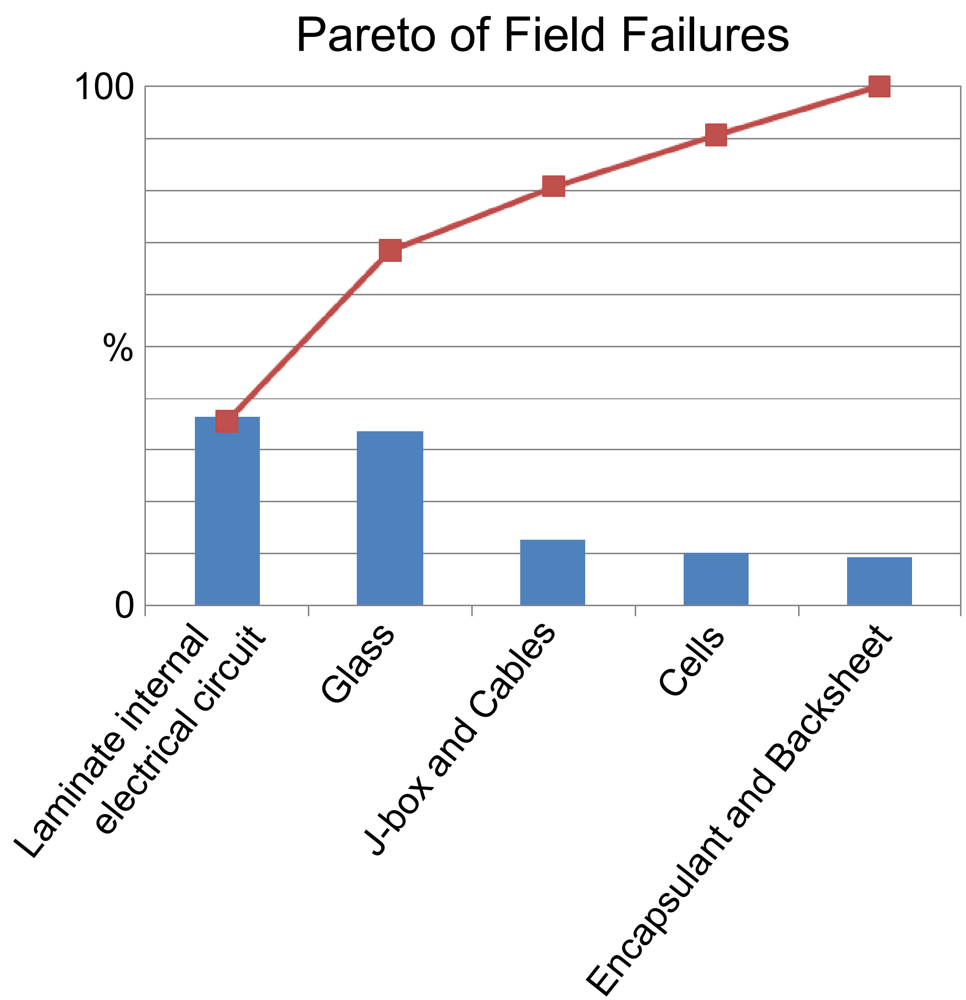
- *Line is a Maximum Likelihood Estimation Weibull fit with a changing number of good modules considered "suspensions."*
  - *Line up every single site with N_{pass} and M_{fail} data at the age of each inspection.*
  - *Find the most likely PDF that will result in that data (fit both the "passes" and the "fails").*
- *Extrapolation error is significant so failure rates should be considered qualitative.*

- A look at the entire fleet of modules suggests the expected reliability will not be met, but this is somewhat misleading due to sampling bias.

The statistics suggests that:

- **Module reliability has a significant impact on Levelized-Cost-Of-Energy**
- **Flawed module designs wear-out quickly**

Specific field failures: their analysis and statistics



The next slides go through examples of these 5 groupings of field failures

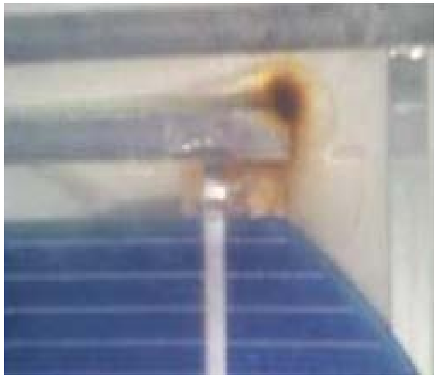
- statistics when available
- suggestions for tests which could eliminate the failures in the design phase
- Includes the “design problems”

Manufacturers are not identified.

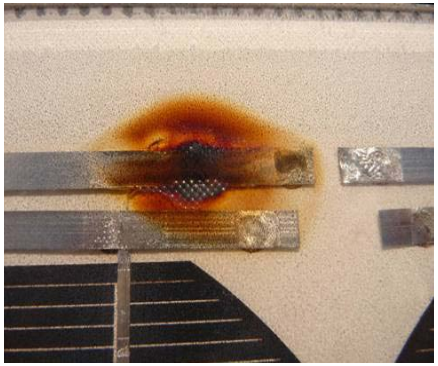
Laminate internal electrical circuit

- Failure mode: Hot solder joints causing EVA browning and backsheet damage
- Possible cause: weak solder joints (likely a process variability issue but could be a design flaw)

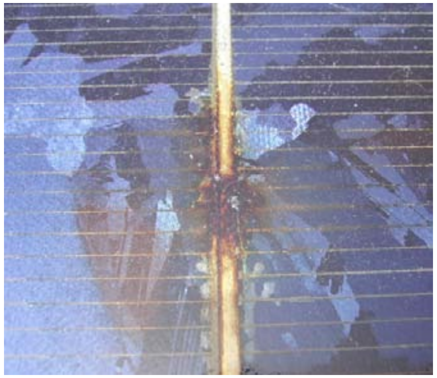
Mfg A: 0.3% failure rate



Mfg B: 1.5% failure rate



Mfg C: 2.9% failure rate



← Front

Back →

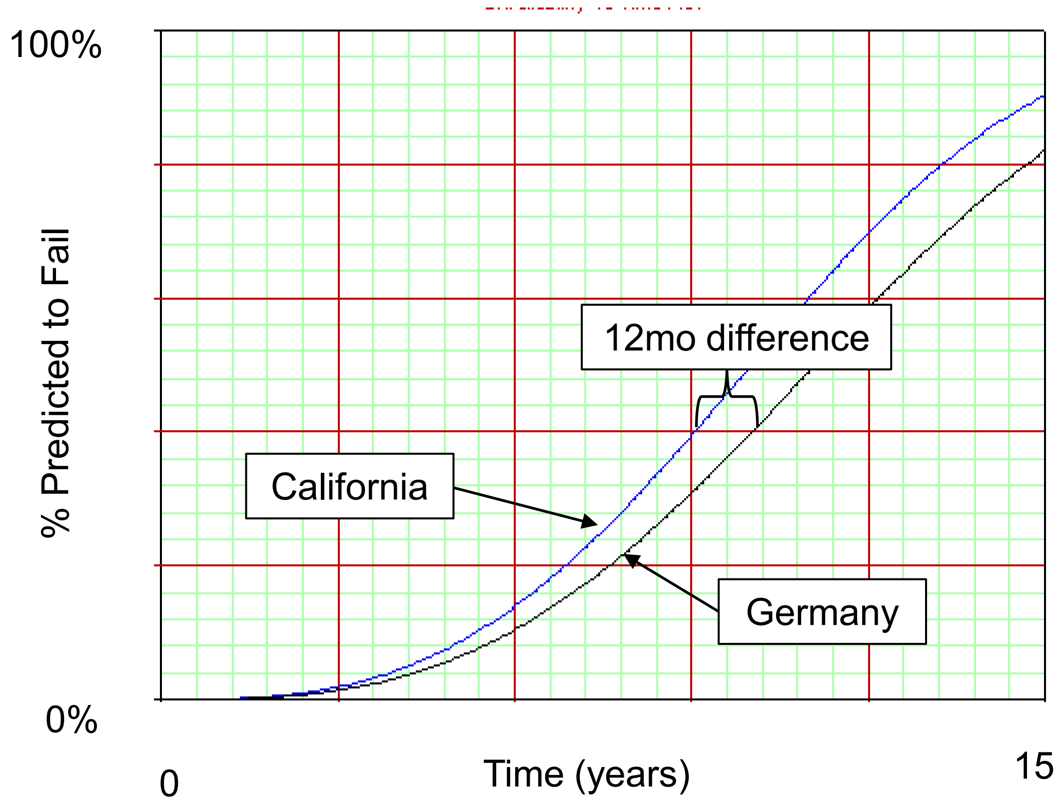
Mfg E: 0.1% failure rate

← Front

Back →

Laminate internal electrical circuit

- Solder joint failures presumably from a process or design defect.
- Some variation by climate indicates different stress levels on the solder joints.



Glass

- Failure mode: anti-reflective coating delamination
- Cause: tempering processes caused high stress and weakened adhesion.
- Happened during ramp to full scale manufacturing and not on prototype manufacturing process.

SunPower: 0.03% failure rate (limited launch)

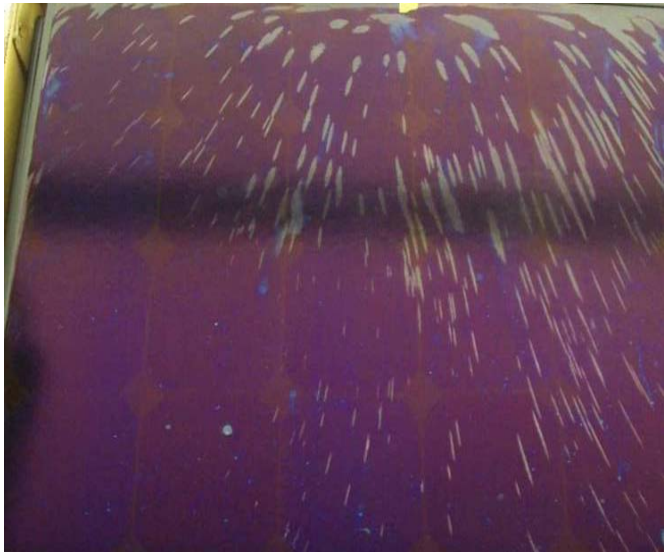
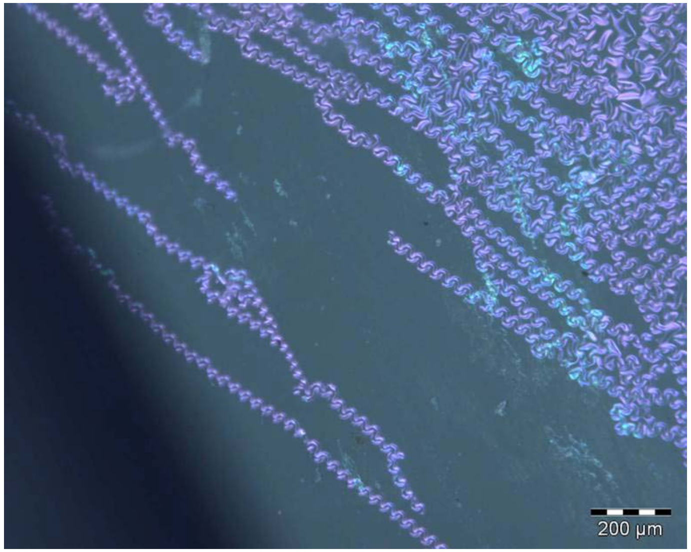


Photo of module with delaminating AR coating



Microscope image of delamination

Glass

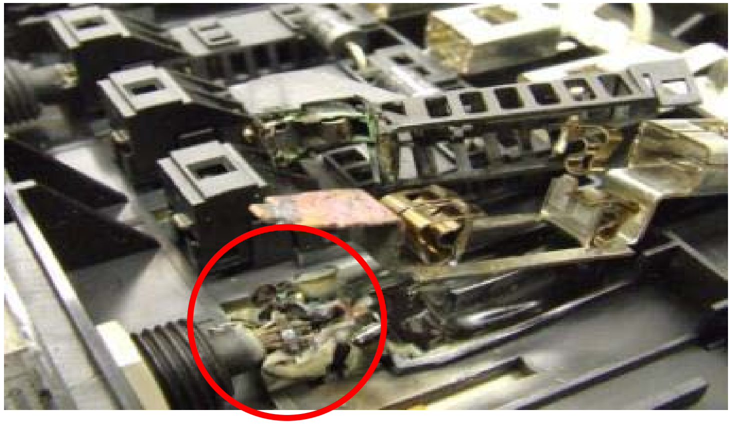
- Failure mode: silicone residue from manufacturing caused increased soiling.
- Cause: greasy, hard-to-remove residue on modules due to cloth on laminate racks changing from teflon to silicone oil based coating.
- Failure to test change in materials, process or design (no matter how small).

Did not impact performance, but brought them all back for cleaning.

J-box and cables

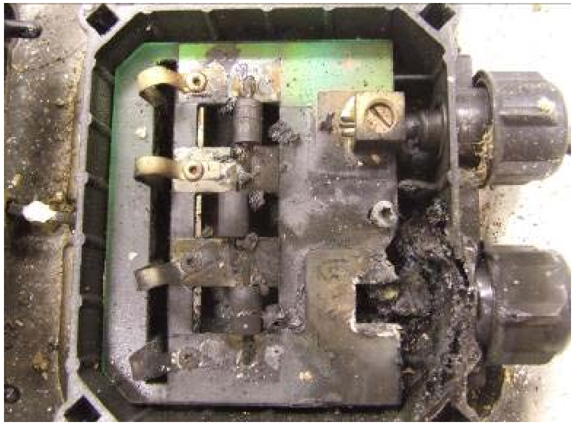
- Failure mode: connectors disconnecting causing arcing
- Poor designs that made product susceptible to workmanship issues - not “error proof”
- Most such problems can be seen with longer term testing performed periodically on production products

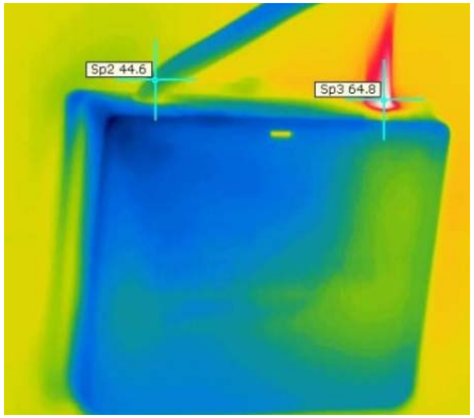
Mfg E: 0.4% failure rate



Mfg F

Mfg G



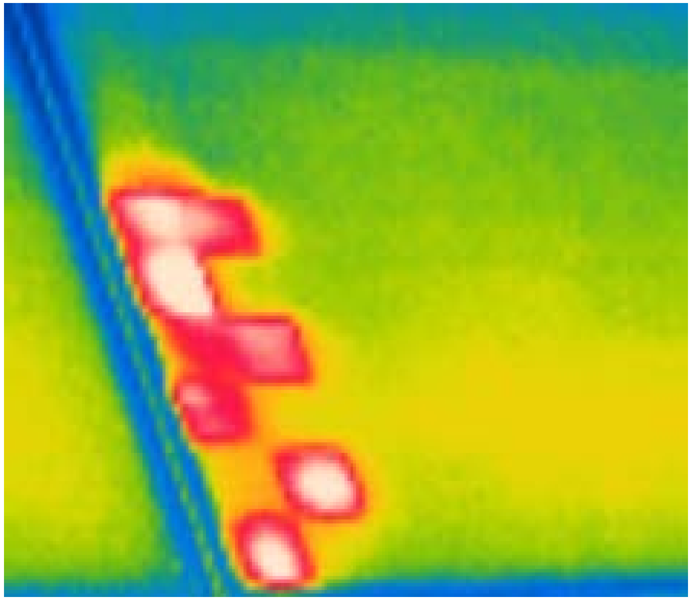


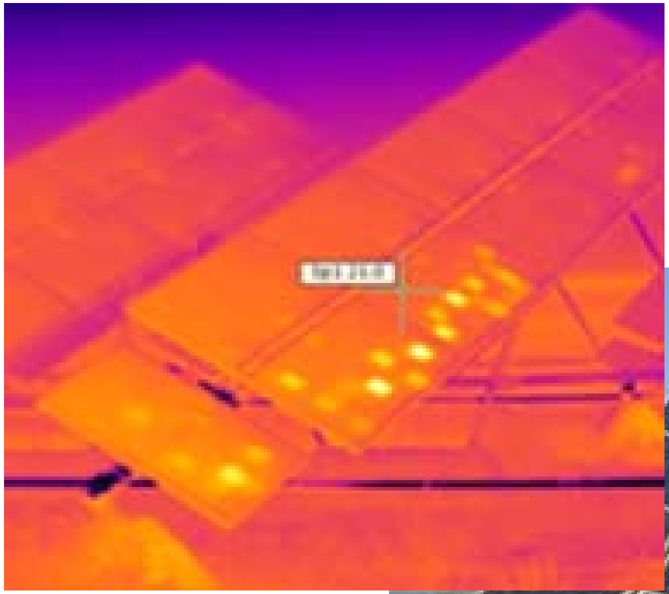
Mfg H: 50% j-boxes show defect (20C hotter)

Cells

- Failure mode: Hot cells causing burned backsheets, delamination and sometimes cracked glass
- Possible cause: Unknown cell defect(s)

Mfg J: 1.2% failure rate





Mfg K

- Tests that may cover these types of failures:
  - Full screening for shunted cells at manufacturing

Encapsulant and backsheet

- Failure mode: Backsheet delamination
- Possible cause: unknown (Quality control? Design problem with materials mismatch?)

Mfg J: 100% affected for this model

Encapsulant and backsheet

- Failure mode: EVA browning/yellowing
- Possible cause: EVA material variation
- Current qualification tests don’t combine UV and heat and wont catch this problem

Mfg K:
50%
affected

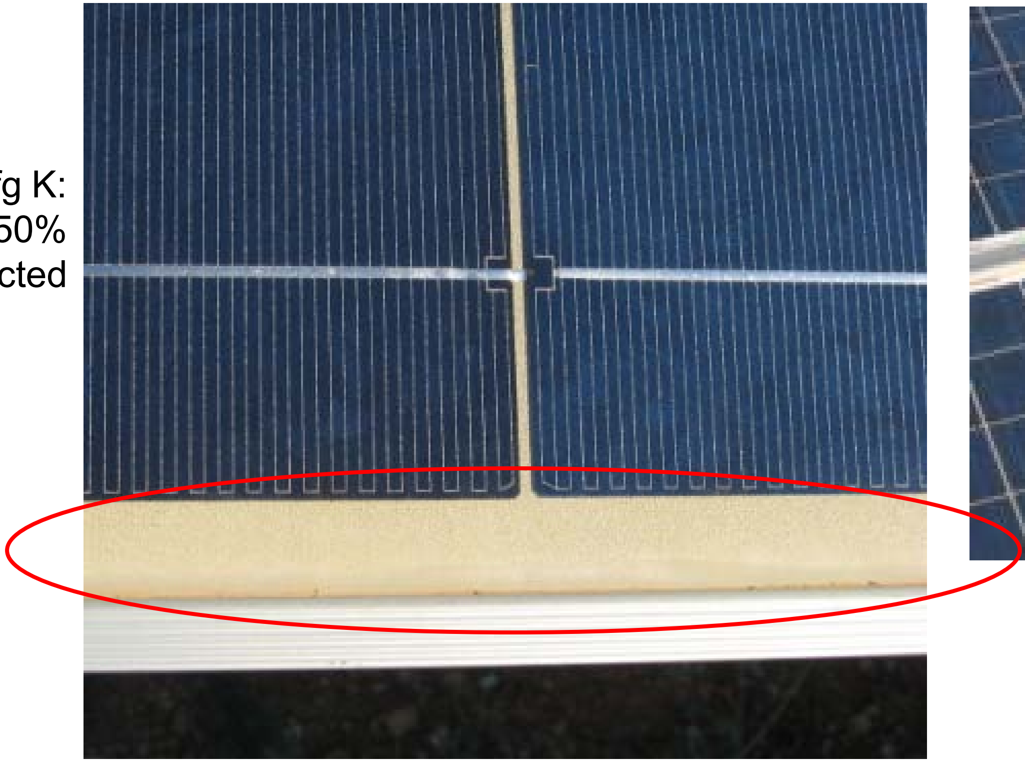


Image of browned EVA after one year in the field

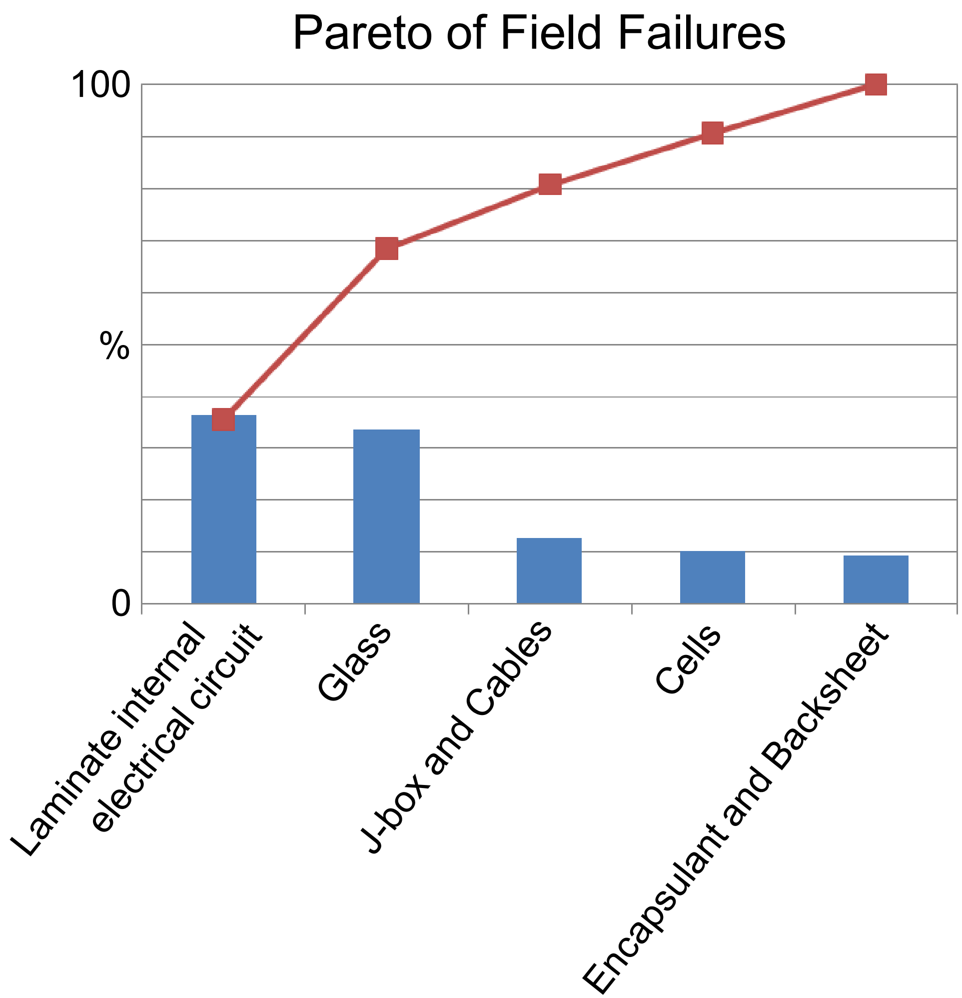
Encapsulant and backsheet

- Failure mode: backsheet peeling off exposing backside of cell
- Possible cause: Unknown (Process control? Incoming materials? Design?)

Mfg M: 0.1% failure rate

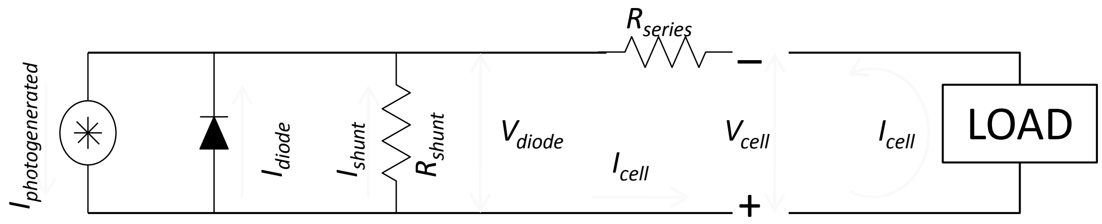
Image of a severely peeled backsheet from the field

Specific field failures: their analysis and statistics



Majority of failures can be attributed to inadequate Manufacturing QA and/or not testing when materials or processes are changed.

Climate impact from physical modeling



Initial conditions

Input weather conditions, controls and other externals

Determine I_{sc}, V_{oc}, I_{mp}, V_{mp}

Fit to 1-diode model and solve for I_{cells}, V_{cells}, and T_{cells} for every cell in module

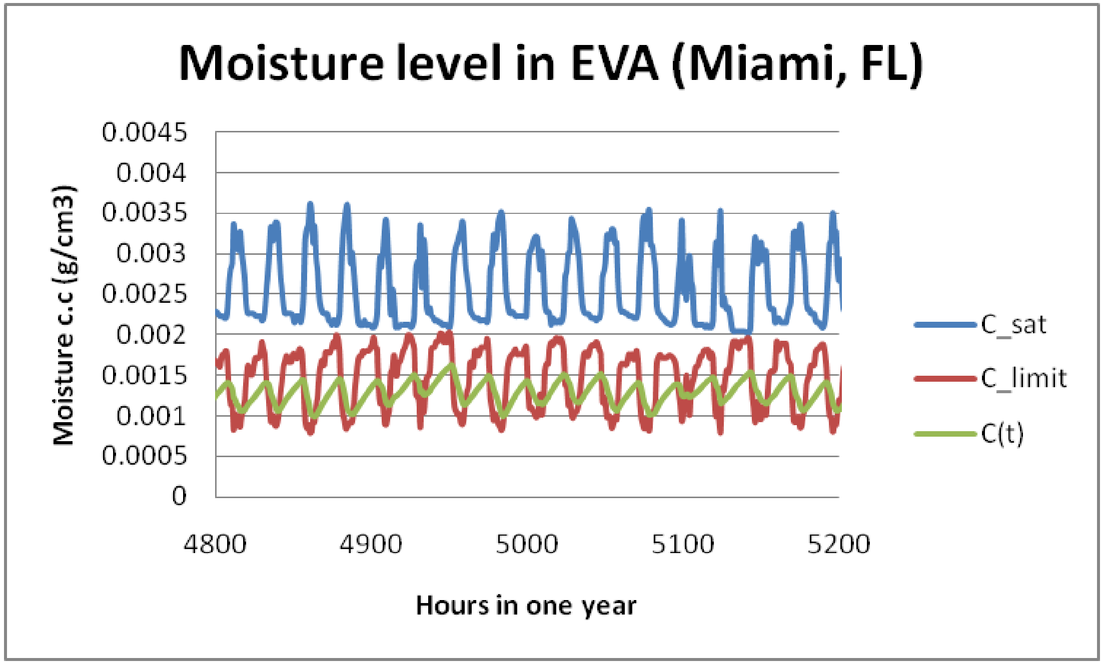
Calculate degradation of I_{sc0}, V_{oc0}, I_{mp0}, V_{mp0} and τ_{encap} from degradation models

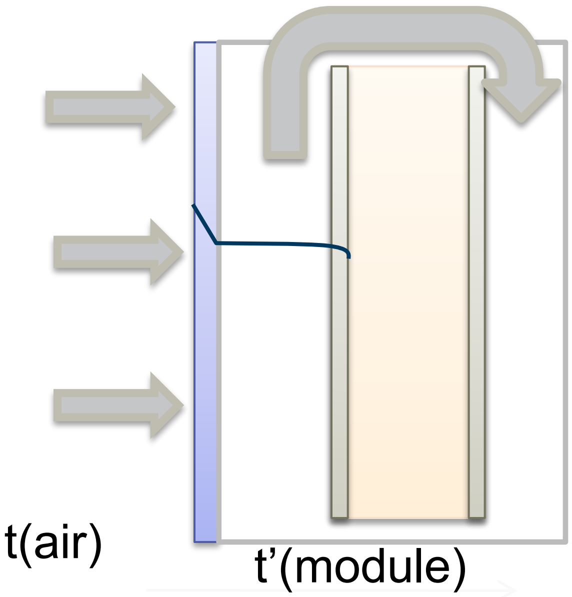
Degradation modes in the Module Degradation Model

Degradation Mode
Cell degradation from UV
Encapsulant degradation from UV
Polarization and High-Voltage degradation
Bypass diode failure
Solder joint failure
Encapsulant adhesion failure
Soiling
Reverse Bias Degradation
Cell Cracks
Back-sheet Delamination
Damp Heat Degradation
Metal corrosion
Ion migration (solder flux, sodium)

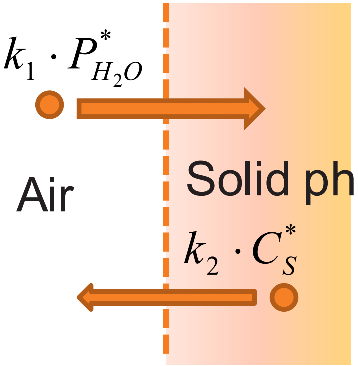
Detailed discussion and model output will be presented at EUPVSEC in Sept.

How to determine the moisture level in EVA





$$\frac{dC_E(t)}{dt} = \frac{WVTR_{B,sat}}{C_{E,sat} \cdot l_E}[C_{E,sat} - C_E(t)]$$

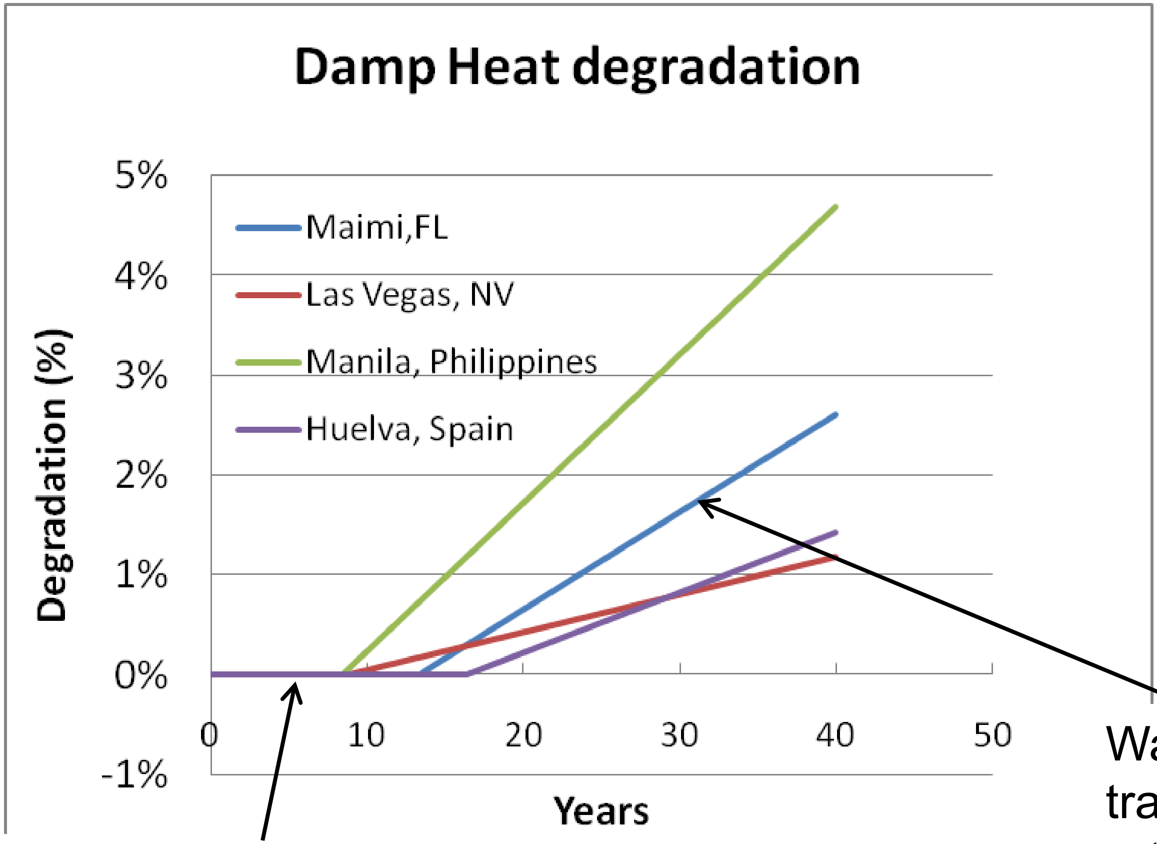


$WVTR_{B,sat}$: WVTR for back sheet

$C_{E,sat}$: moisture solubility of encapsulant, function of module temperature

$C_E(t)$: moisture level at any given time

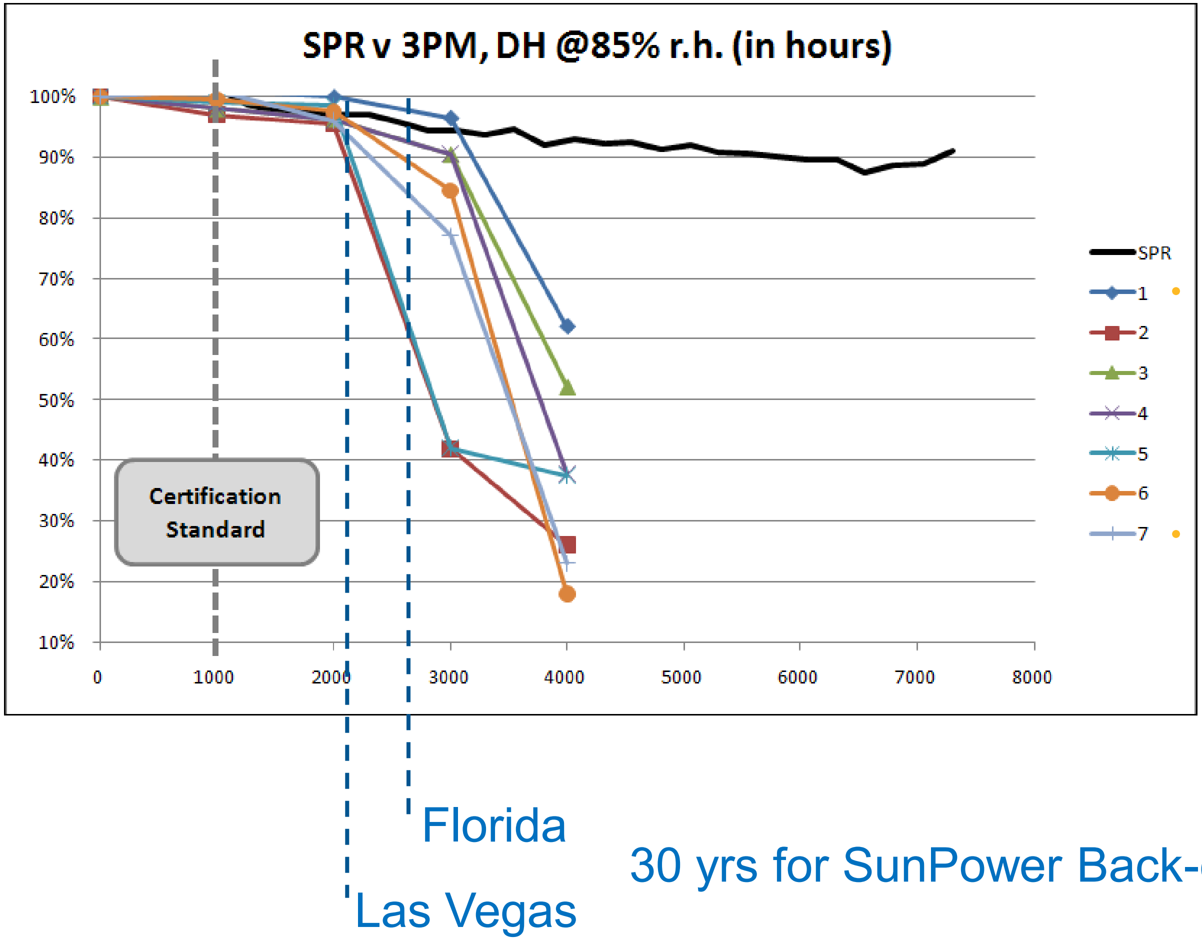
Damp heat degradation for a SunPower module



Time for moisture to penetrate through the nitride layer

Water vapor transmission rate limited reaction in the oxide layer

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.

Conclusions

- Passing Certification testing does not ensure reliability.
- Modules failed because
  - Hard-to-manufacture designs
  - Changes made in processes or materials without adequate testing
  - Supplier and/or Production QA procedures were not adequate
  - Periodic qualification tests were not conducted to verify production processes
  - Longer term testing and modeling was not performed to evaluate wear-out mechanisms beyond the qualification stress levels.
  - Real-world combined stresses were not tested
- Modeling the physics can help quantify acceleration factors and long-term reliability

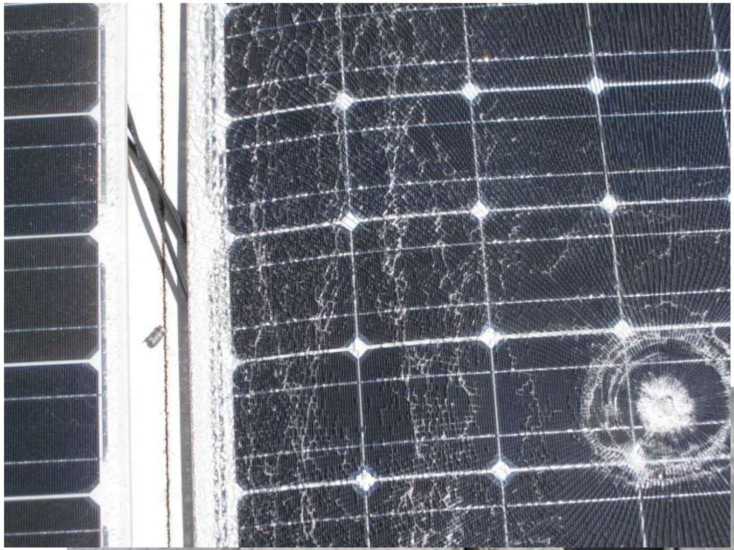
Appendix

Critters, Guns, and the Wrath of God

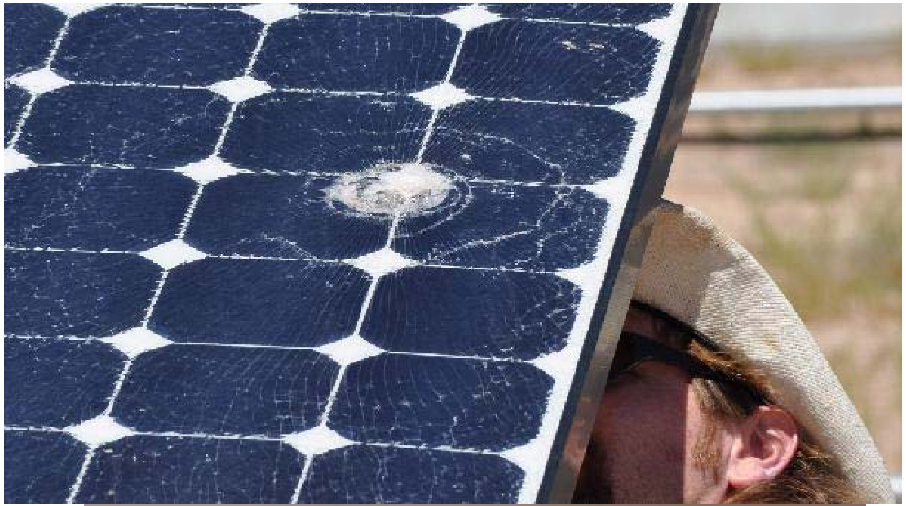
- Ants attracted to combiner boxes (warmth? electricity? safety?)
- Dead ants' bodies are acidic and corrosive

- Rats!

Critters, Guns, and the Wrath of God



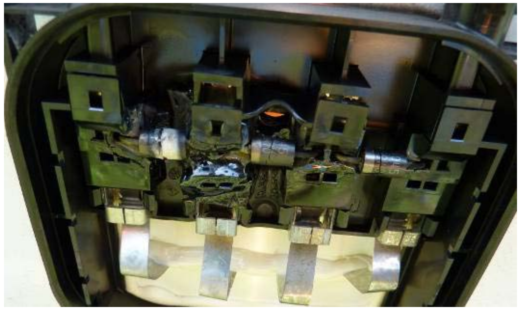
- Bullet holes!

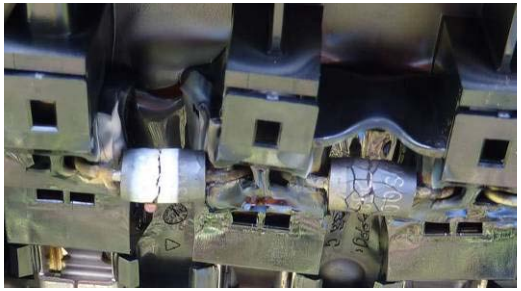


Critters, Guns, and the Wrath of God

- Direct-hit lightening strike: module works fine (!), but diodes were badly damaged

Point of contact on the glass





Backsheet damage