NREL 2011 International PV Module Quality Assurance Forum
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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

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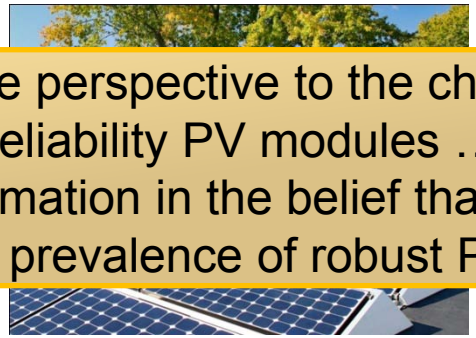
SunPower 2011: 25th Anniversary

- 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

Residential: #1 US



Commercial: #1 US

Power Plant Pioneer

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.

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			

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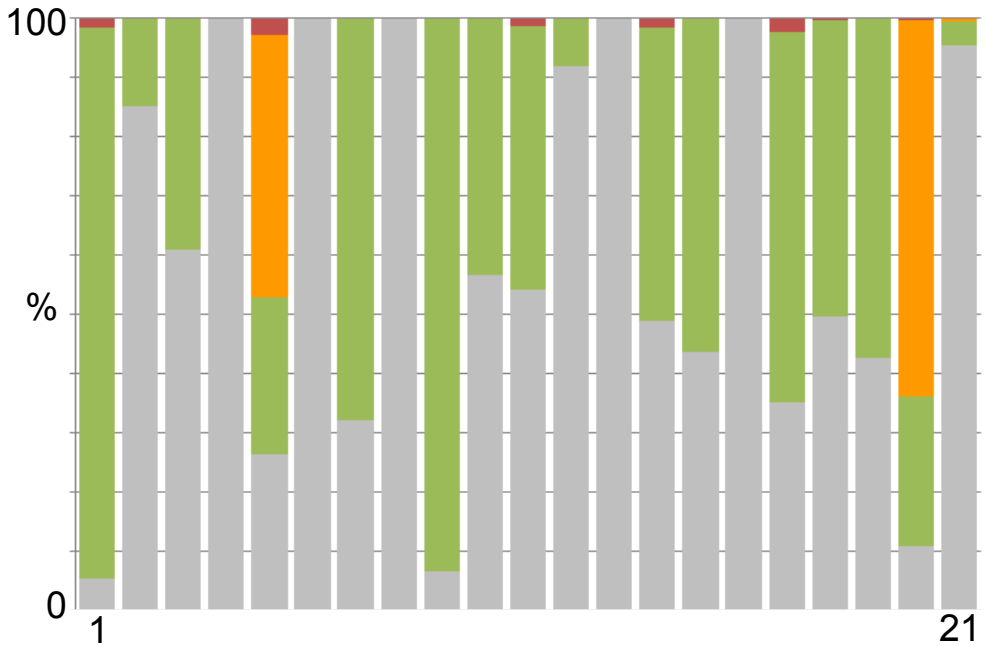
Field data sampling rates by manufacturer



- 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

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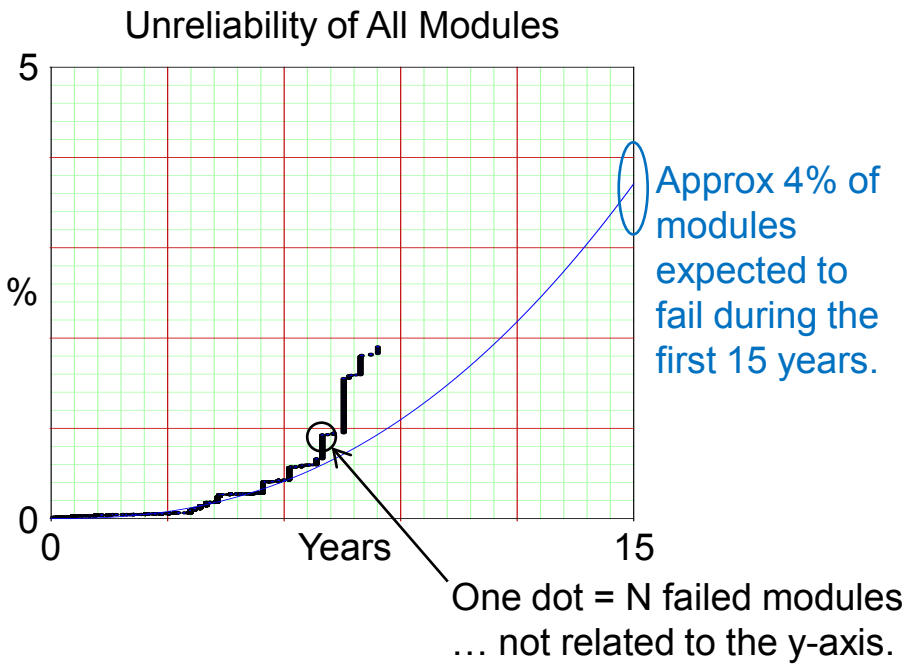
Field statistics: all modules



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**

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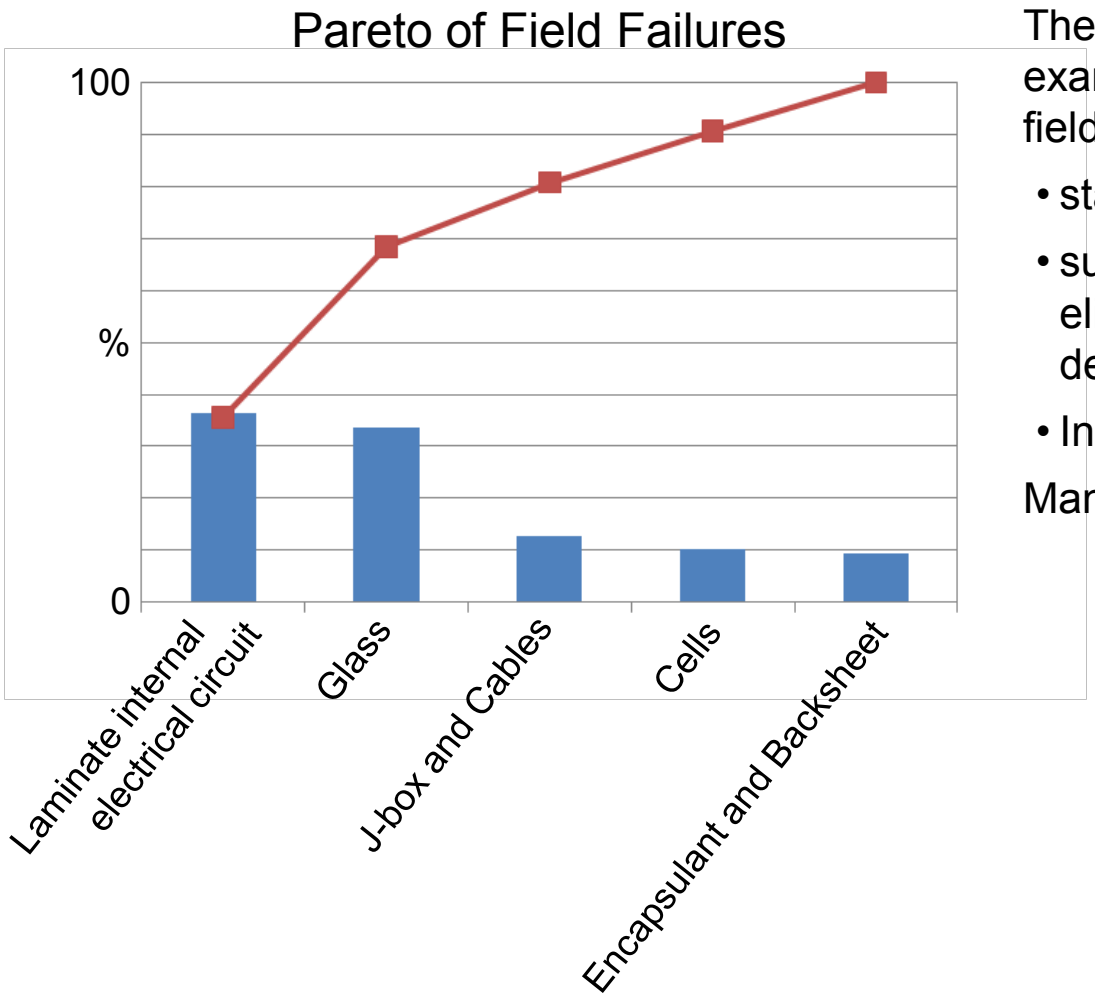
Specific field failures: their analysis and statistics



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.

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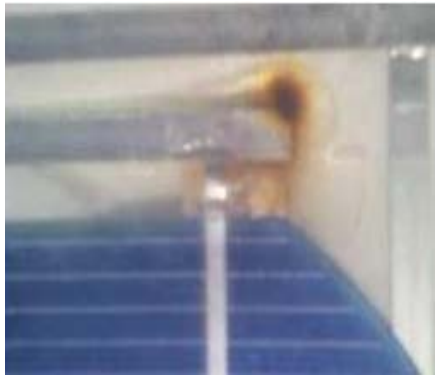
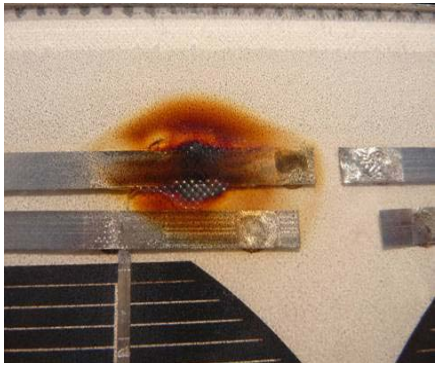
Laminate internal electrical circuit

- 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)

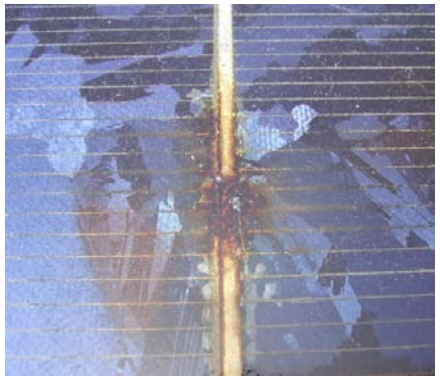
Mfg A: 0.3% failure rate



Mfg B: 1.5% failure rate



Mfg C: 2.9% failure rate



← Front

Back →

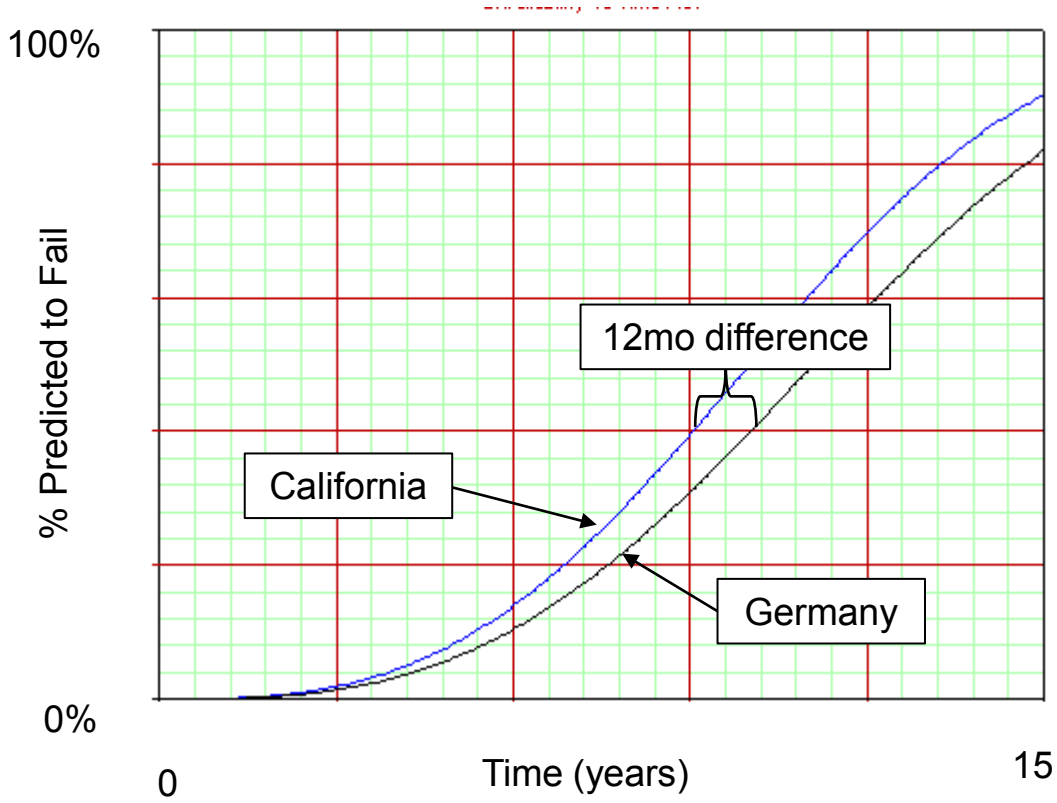
Mfg E: 0.1% failure rate

← 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.



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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)

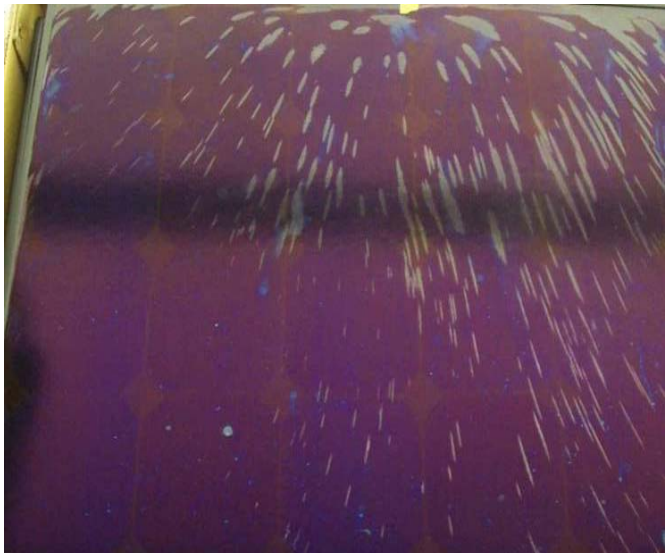
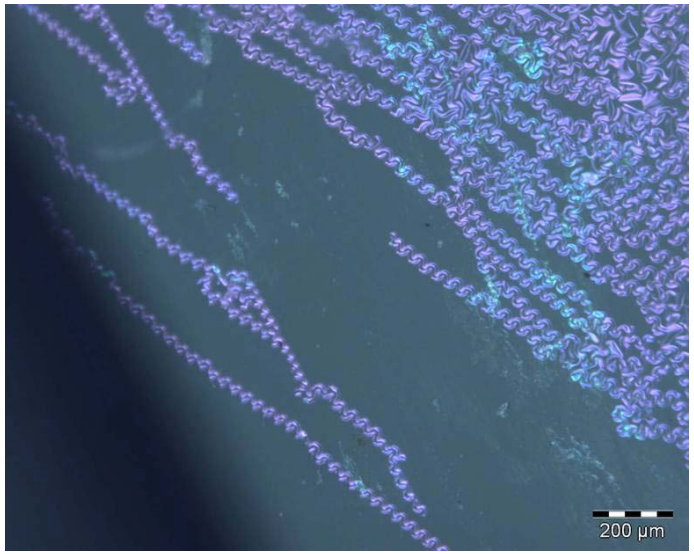


Photo of module with delaminating AR coating



Microscope image of delamination

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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.

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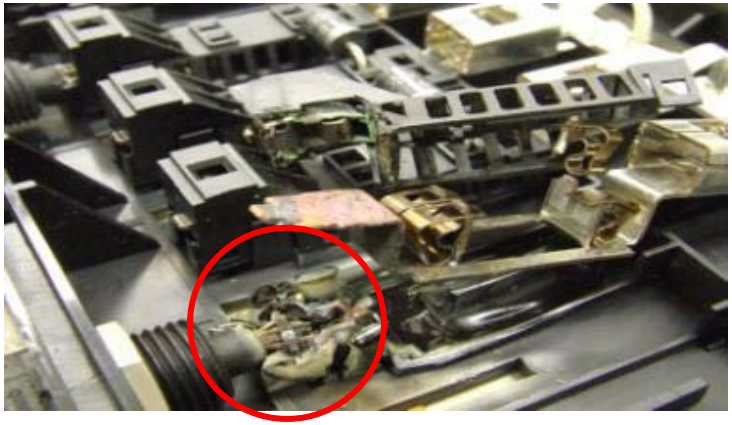
J-box and cables

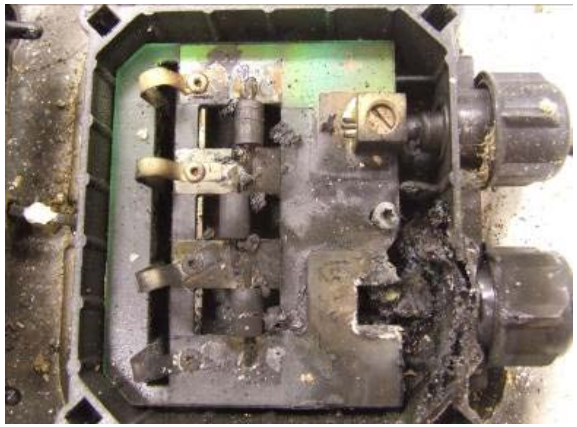
- Failure mode: connectors disconnecting causing arcing
- Poor designs that made product susceptible to workmanship issues - not “error proof”
- Most such problems can be seen with longer term testing performed periodically on production products

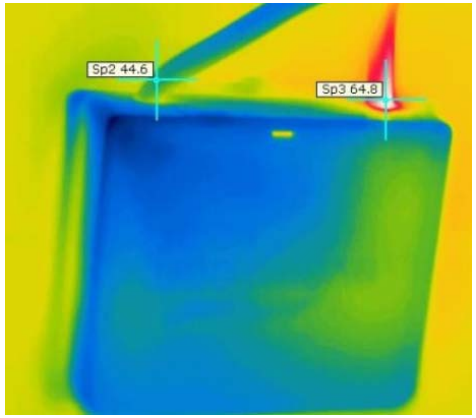
Mfg E: 0.4% failure rate



Mfg F

Mfg G





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

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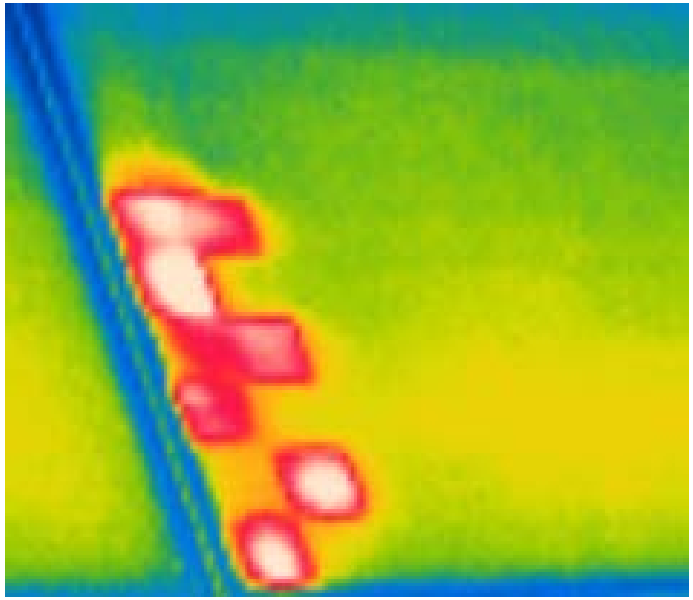
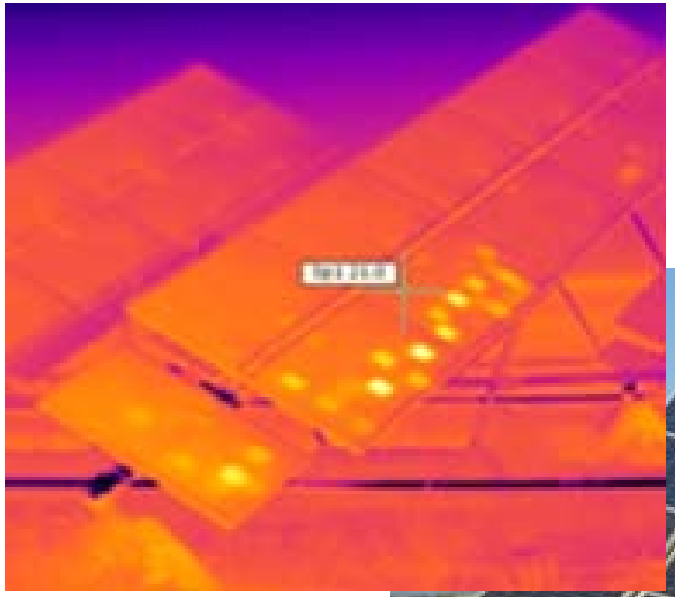
Cells

- 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

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Encapsulant and backsheet

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

Mfg J: 100% affected for this model

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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

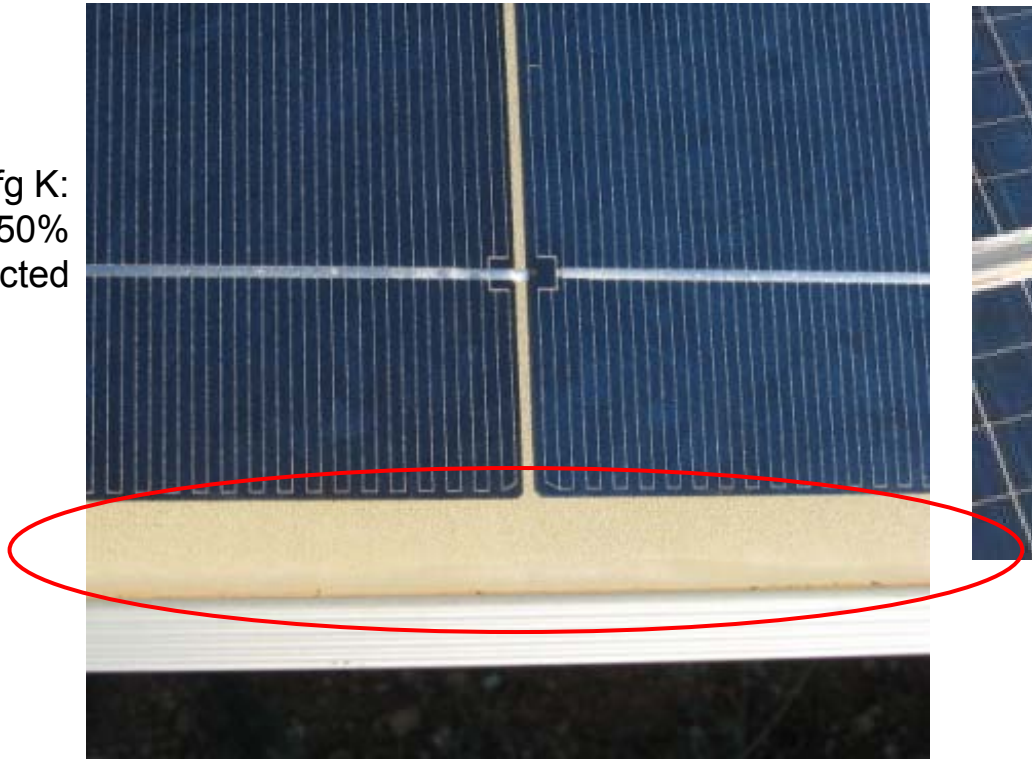

Image of browned EVA after one year in the field

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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

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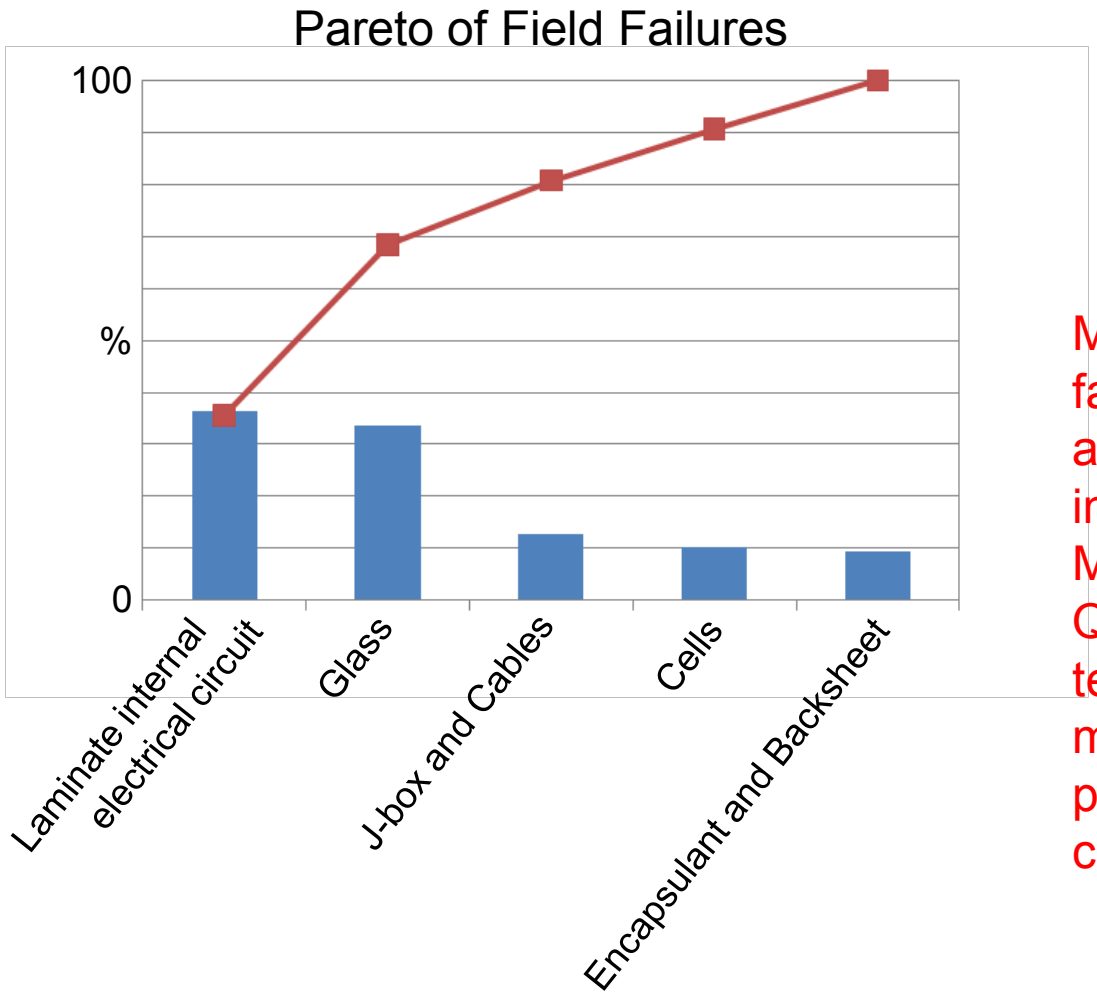
Specific field failures: their analysis and statistics



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

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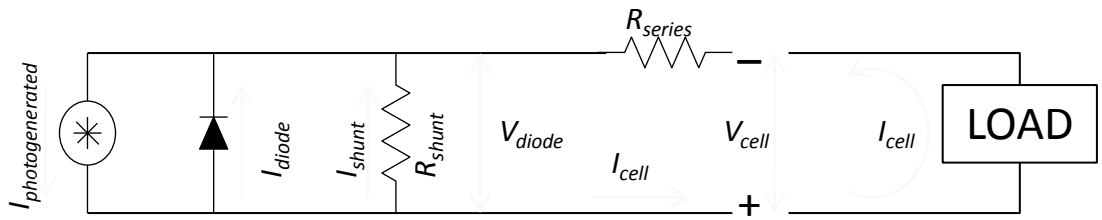
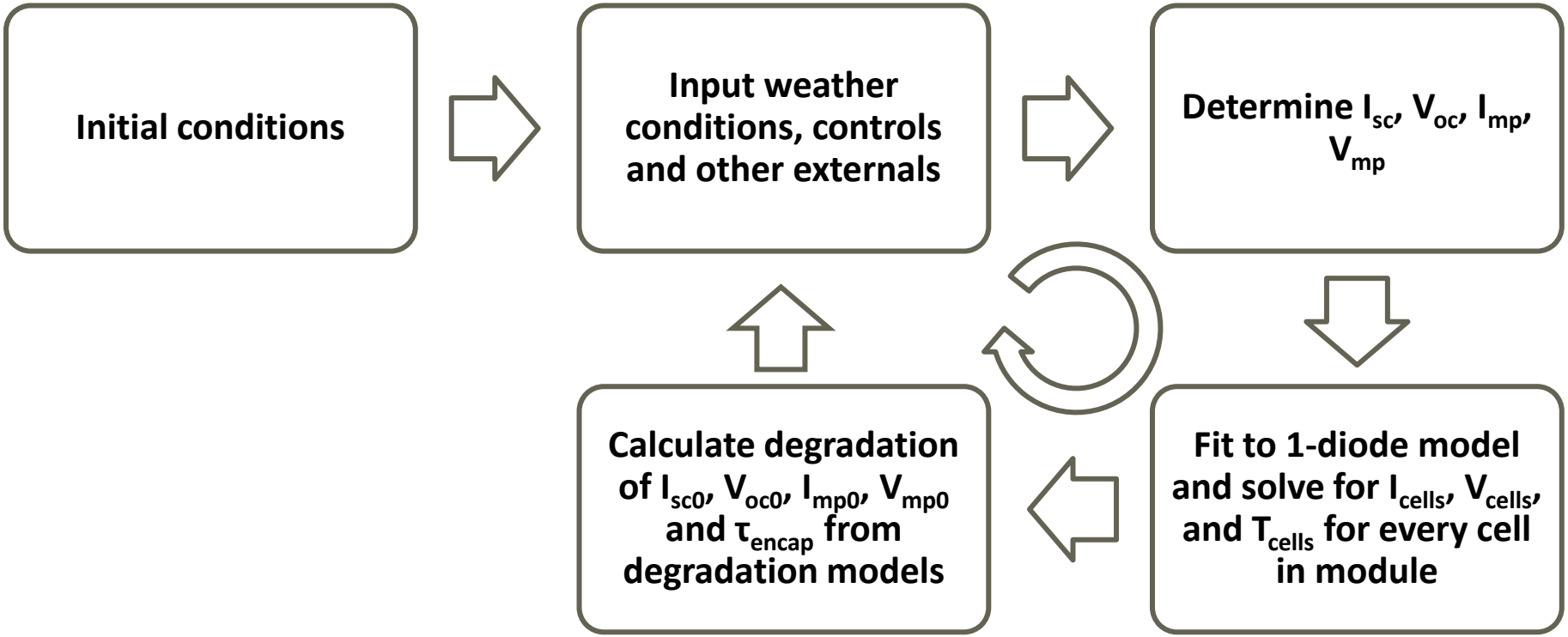
Climate impact from physical modeling





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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.

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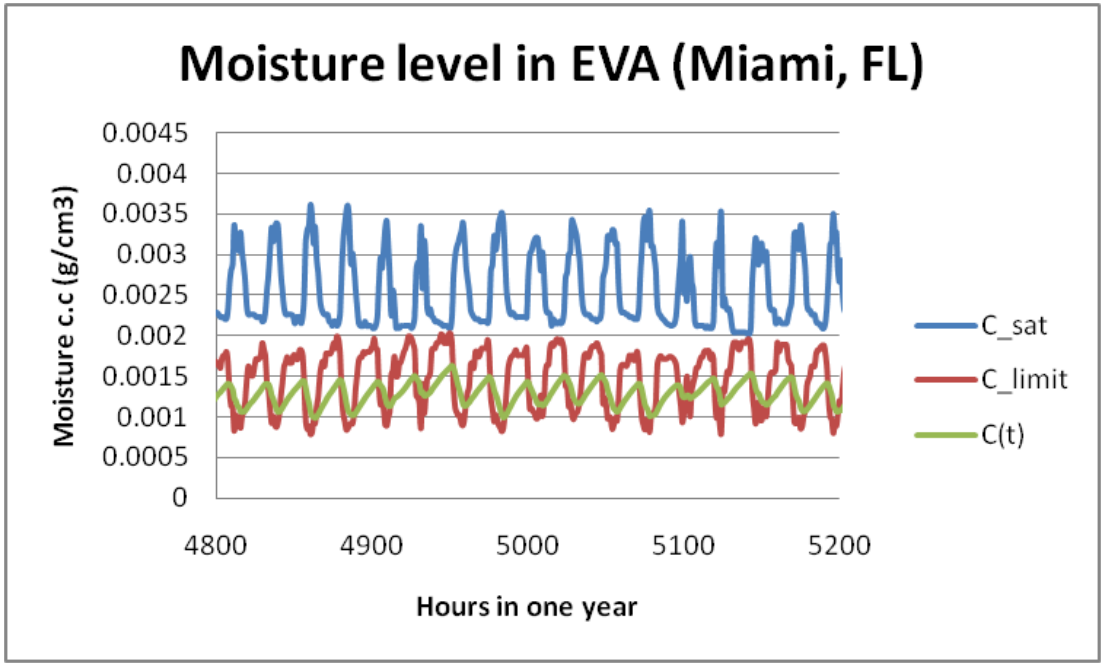
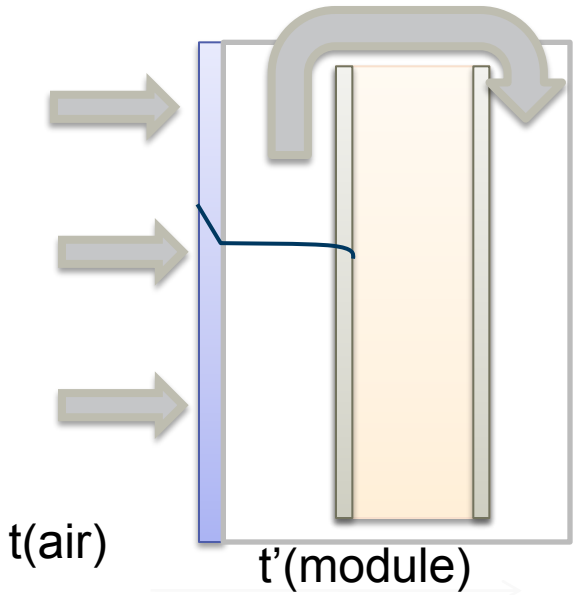
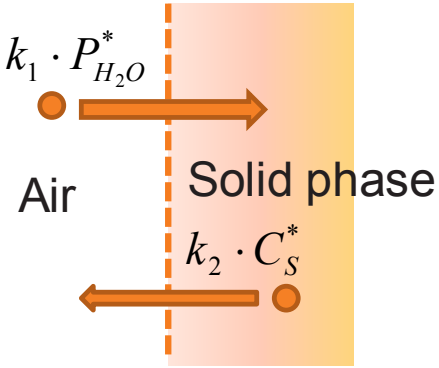
How to determine the moisture level in EVA





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



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

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

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

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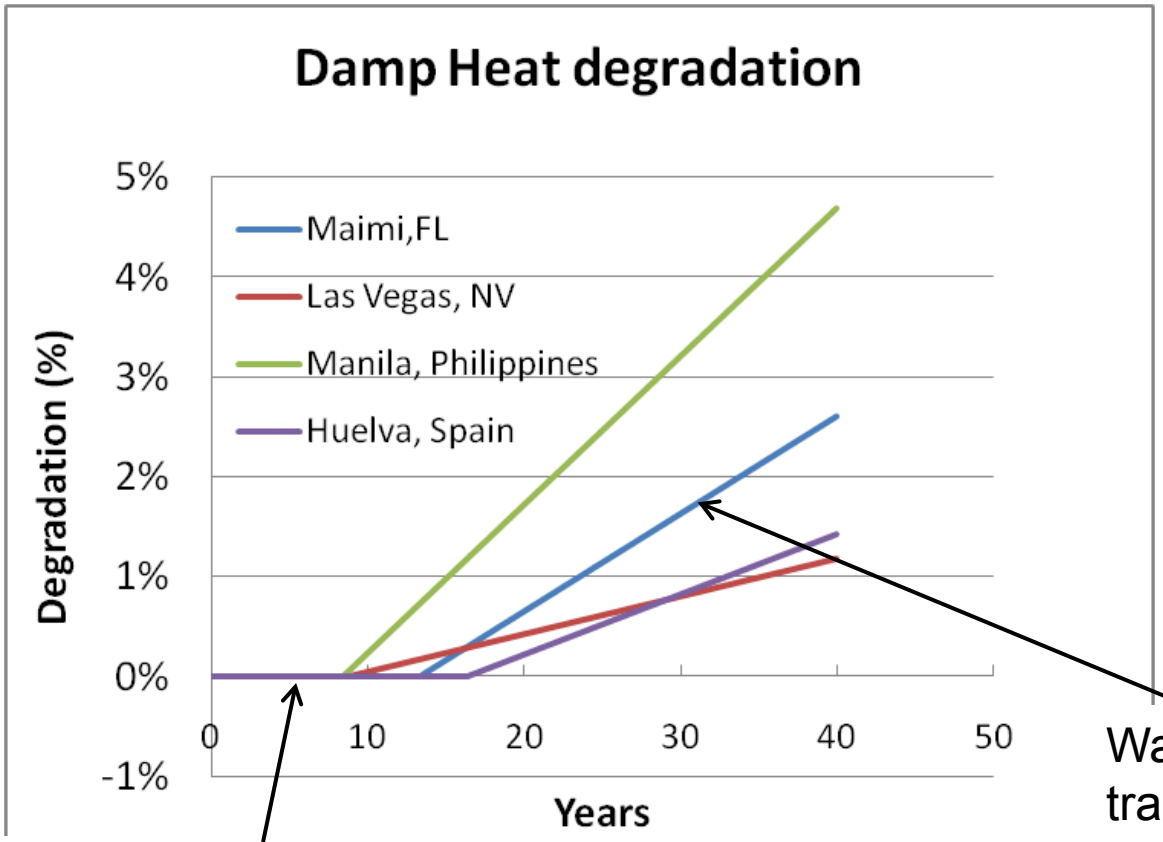
Damp heat degradation for a SunPower module



Time for moisture to penetrate through the nitride layer

Water vapor transmission rate limited reaction in the oxide layer

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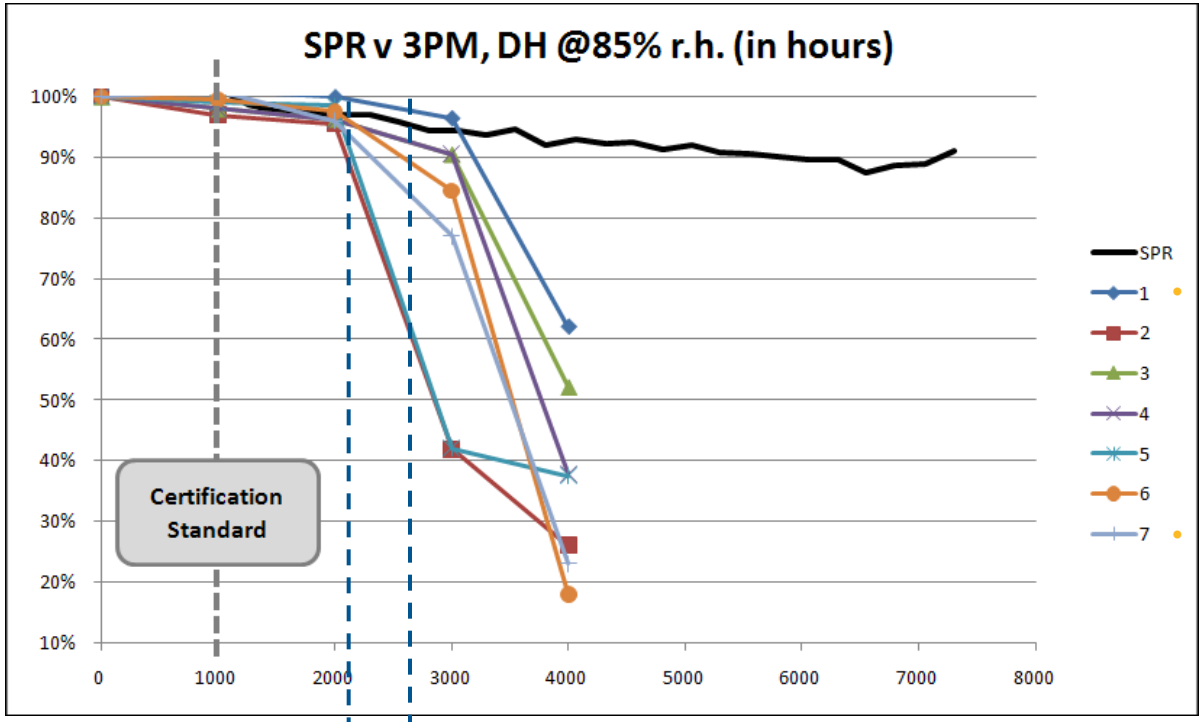
Damp Heat Acceleration Factors by Climate



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

Florida

Las Vegas

30 yrs for SunPower Back-contact cells.

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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

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Appendix

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Critters, Guns, and the Wrath of God

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

- Rats!

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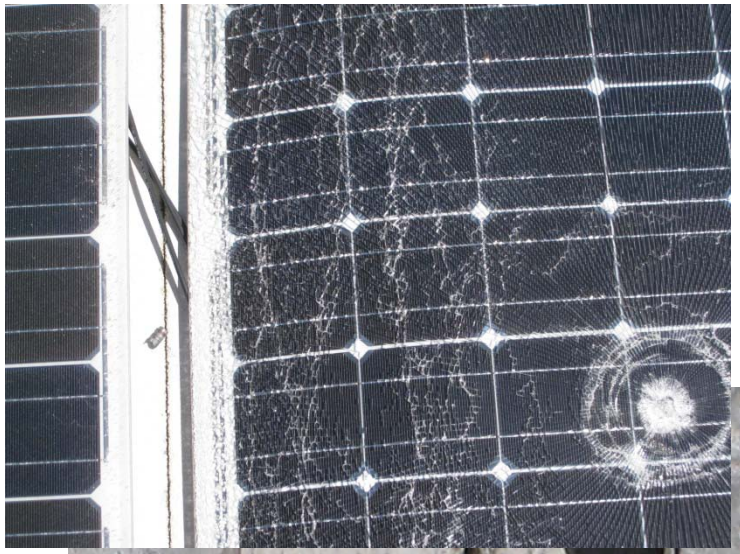
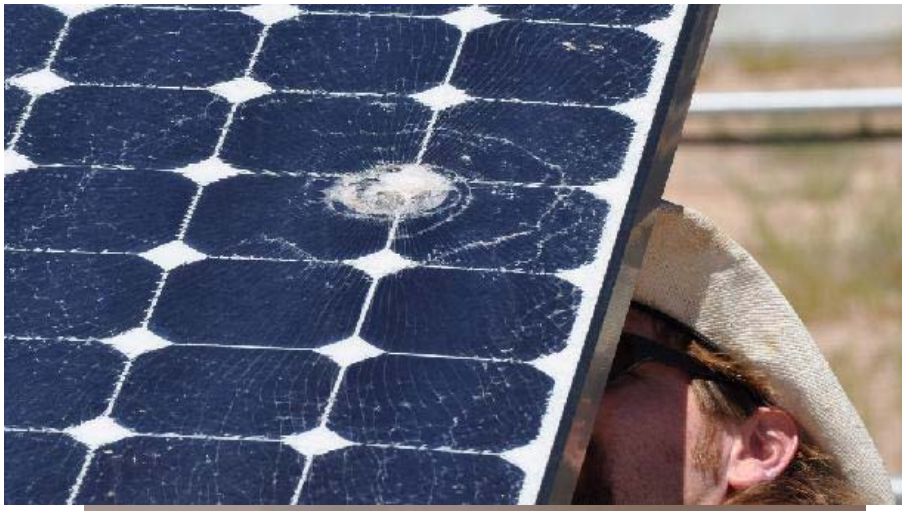
Critters, Guns, and the Wrath of God



- Bullet holes!



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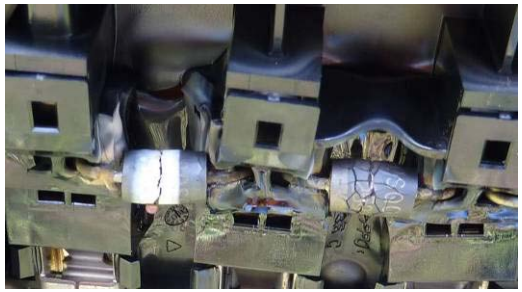
Critters, Guns, and the Wrath of God

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

Point of contact on the glass



Backsheet damage

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