NREL 2011 Photovoltaic Module Reliability Workshop
Golden, Colorado

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Degradation Mechanisms in Si Module Technologies Observed in the Field; Their Analysis and Statistics

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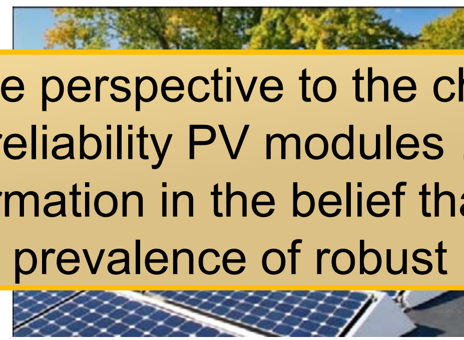
SunPower 2011: 25th Anniversary

- 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

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.

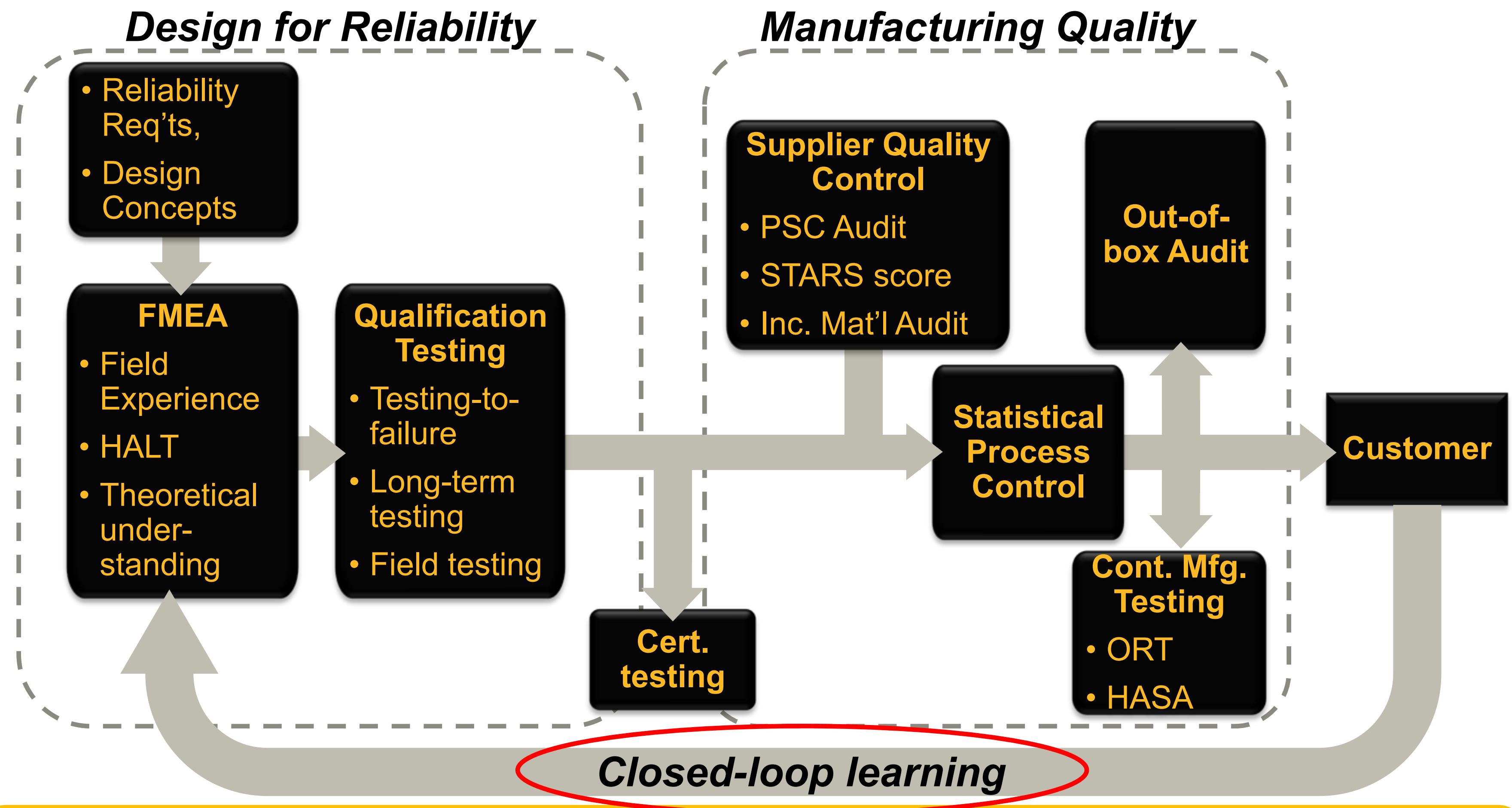
Residential: #1 US



Commercial: #1 US

Power Plant Pioneer

Deploying high-reliability PV Modules: Overall Process



The overall process was articulated in D. DeGraaff, et. al., “*Qualification, Manufacturing, and Reliability Testing Methodologies for Deploying High-Reliability Solar Modules*,” EUPVSEC Valencia Spain, Sept. 2010

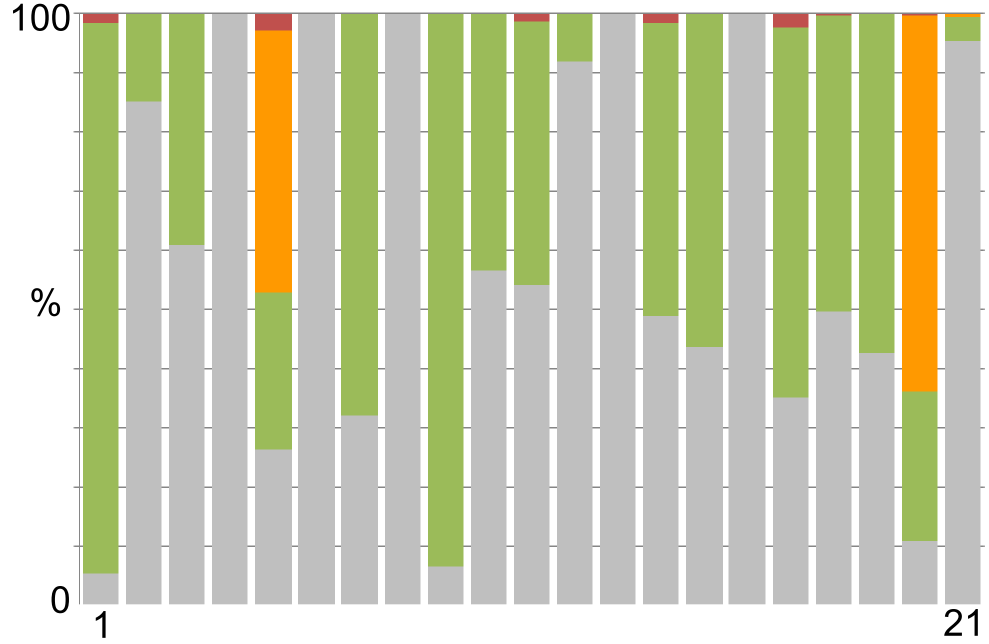
The focus of today is Closed-loop learning from module field failures.

Closed-loop learning from field data

- While some data is significant, some does not have enough samples and is only qualitative.
- Every effort has been made to convey as much information as possible without indicating the names of any specific manufacturers.

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

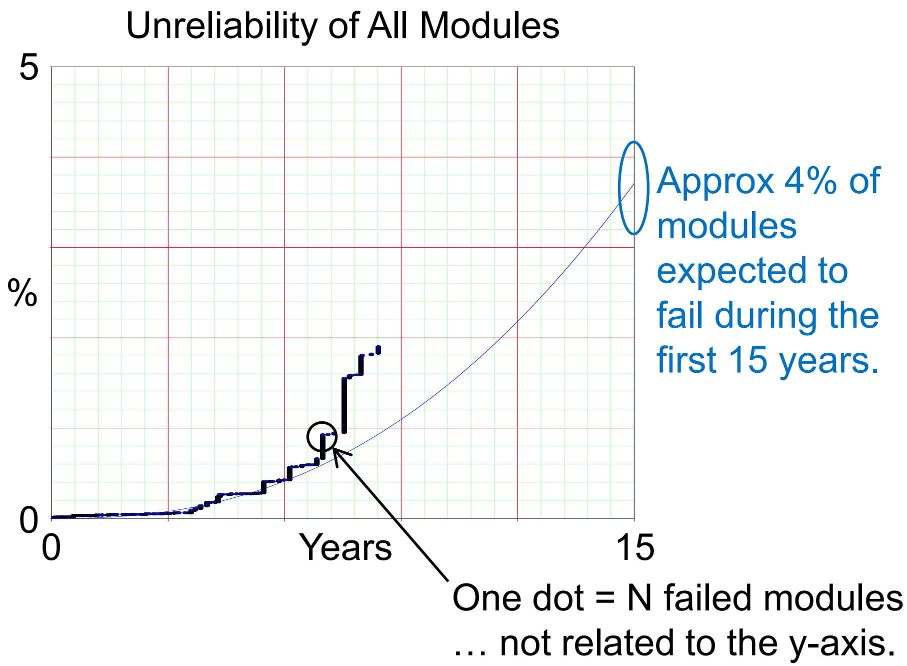
Fail – performance does not meet warranty

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



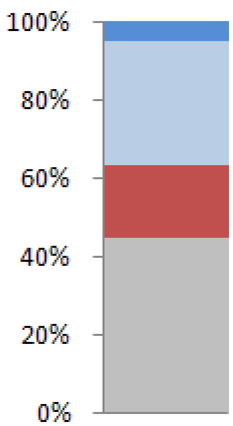
Notes:

- *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 misleading:
  - Sampling is biased toward sites where customers have reported problems.
  - A high rate of failure for a few module designs is skewing the statistics of the entire fleet (although plot only shows actual failures and not predicted failures).

Field statistics: predicting reliability for a good design

Entire fleet



← Biased – site was surveyed due to a reported problem

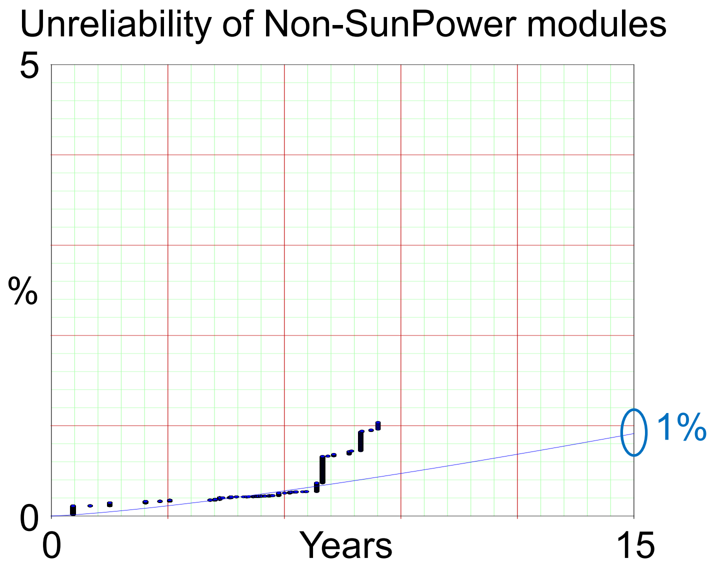
← Unbiased – site was surveyed as part of routine maintenance

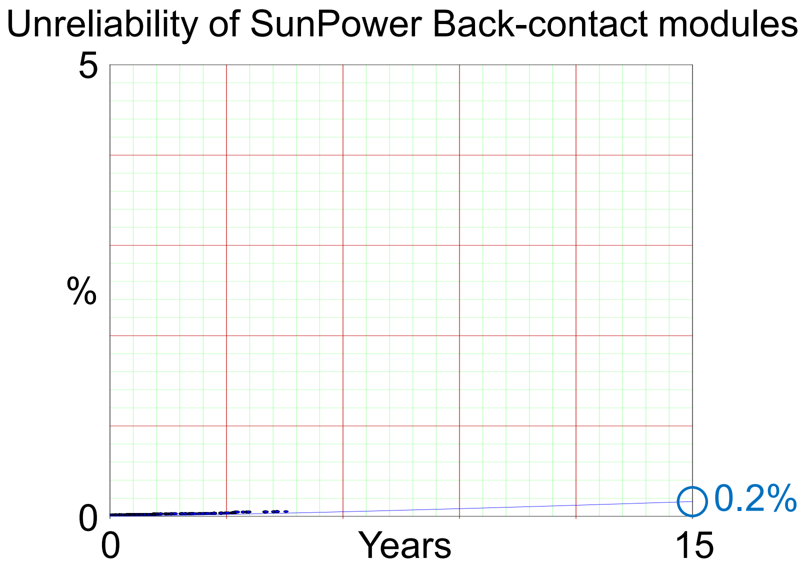
← Design problem – an identified sub-population suffers a specific and non-general failure mode

← Not inspected

Apply the “unbiased” failure rates to the “not inspected” modules, and remove the “design problem” modules, to arrive at a **baseline fleet reliability** estimate …

Field statistics: predicting reliability for a good design



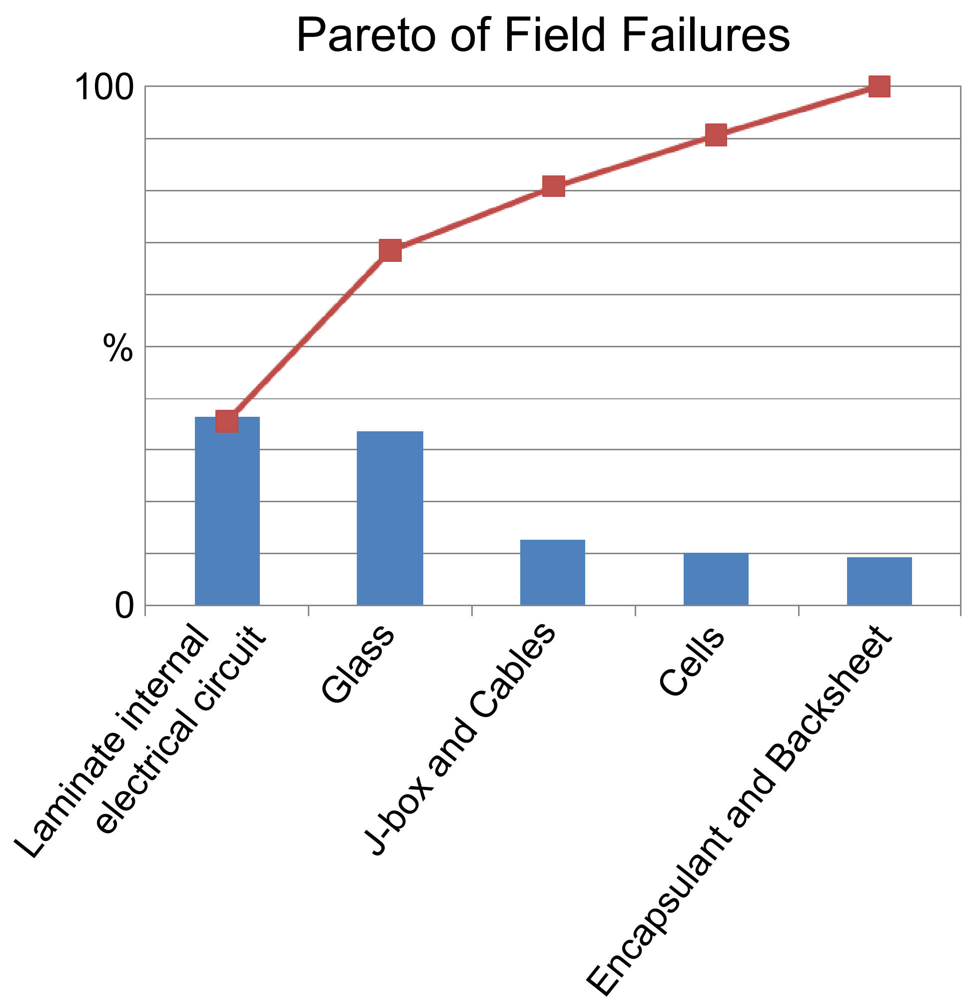


- A look at the fleet of modules *without identified design problems* gives a rough idea of the reliability of the fleet.
- This is only qualitative since the time period is not long enough, and bucketing a bunch of different failure modes into a single predictive Weibull fit is dubious.

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

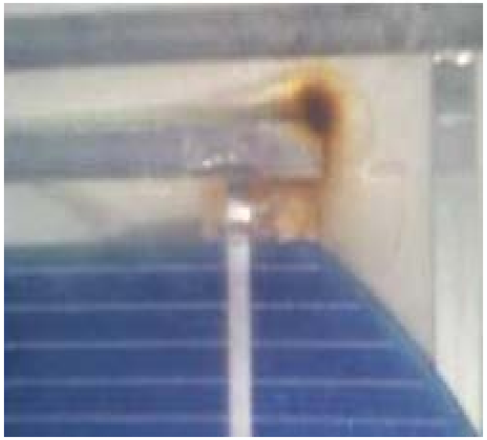
- statistics when available
- suggestions for tests which could eliminate the failures in the design phase
- Includes the “design problems”

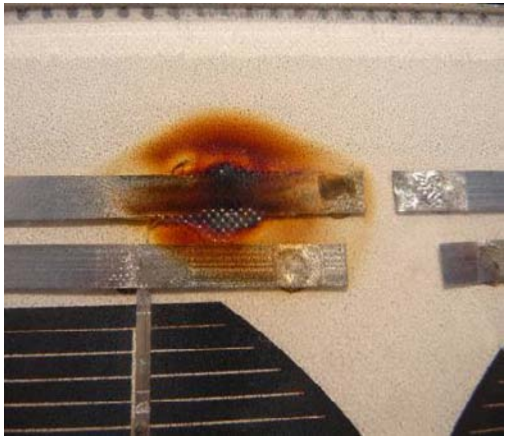
Manufacturers are not identified.

Laminate internal electrical circuit

- Failure mode: Hot solder joints causing EVA browning and backsheet damage
- Possible cause: weak solder joints

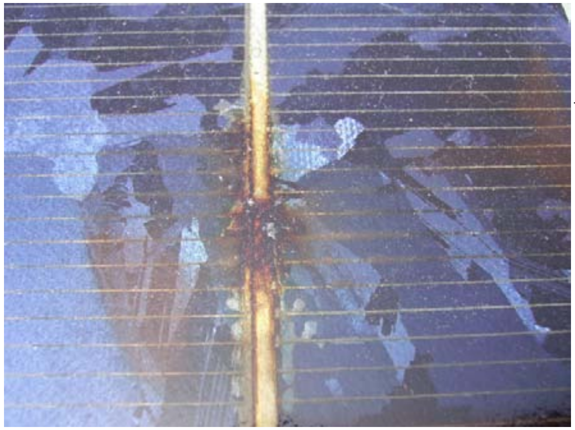
Mfg A:
0.3%
failure
rate





Mfg B:
1.5%
failure
rate

Mfg C:
2.9%
failure
rate

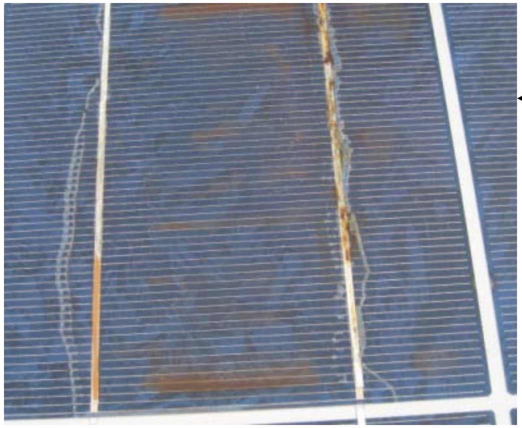


Front

Back

Laminate internal electrical circuit

Mfg E: 0.1% failure rate



Front

Back

Brown EVA over the cell

Hot cell causes brown backsheet and cracking

- Tests that may cover these types of failures (after enough cycles):
  - DH with bias
    - Accelerates front metal corrosion.
  - TC with current
    - Reveals bad solder joints faster than TC alone because the current heats up the bad solder joints causing bubbled and burned backsheets.

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Glass

- Failure mode: anti-reflective coating delamination
- Cause: tempering processes caused high stress and weakened adhesion.

SunPower: 0.03% failure rate (limited launch)

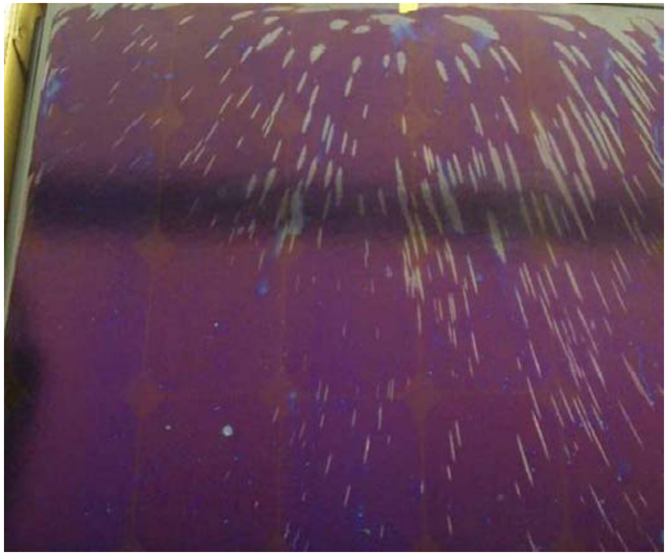
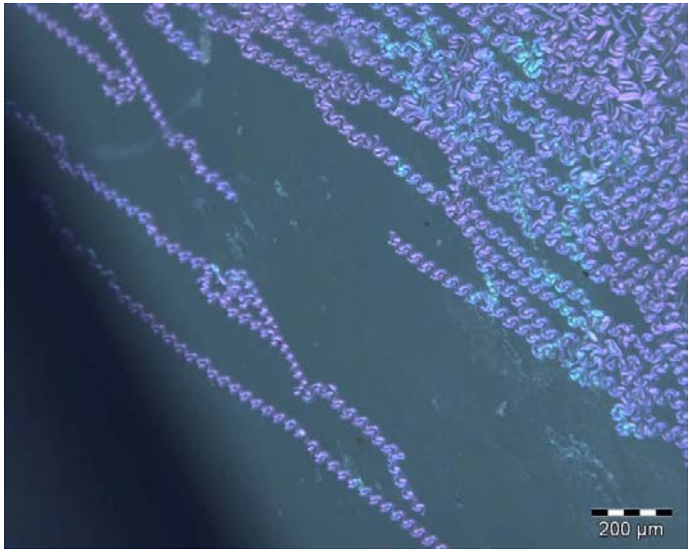


Photo of module with delaminating AR coating



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.

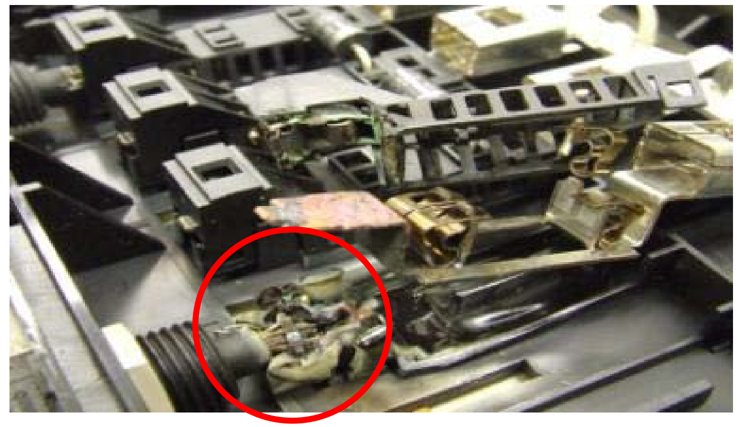
Did not impact performance, but brought them all back for cleaning.

- Tests that may cover these types of failures after enough cycles:
  - Damp heat, Thermal cycling or humidity-freeze cycling
  - Water spray and outdoor exposure

J-box and cables

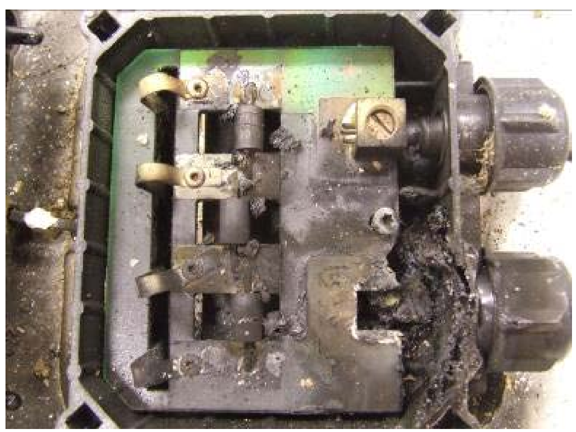
- Failure mode: connectors disconnecting causing arcing
- Possible causes: connector designs susceptible to soiling, incorrect torquing or sizing of wire and grommet, embrittlement or creep of plastic over time, crimping problem

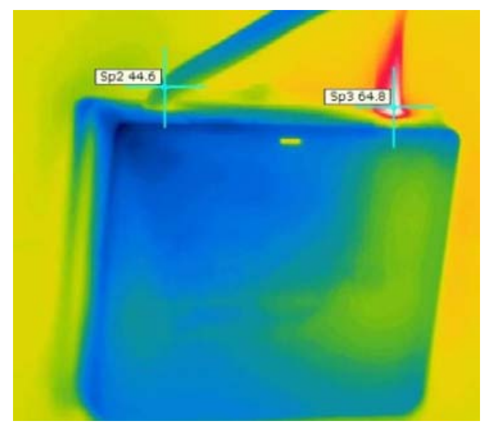
Mfg E: 0.4% failure rate



Mfg F

Mfg G

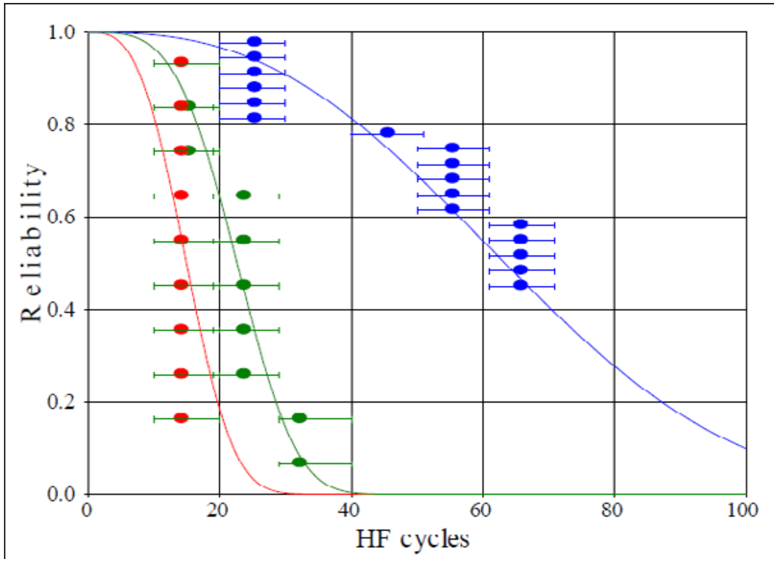




Mfg H: 50% j-boxes show defect (20C hotter)

J-box and cables

- Tests that may cover these types of failures:
  - HF50 on connector assemblies followed by dipping connectors in water bath to look for leakage.
    - Proved very good at comparing connector designs.



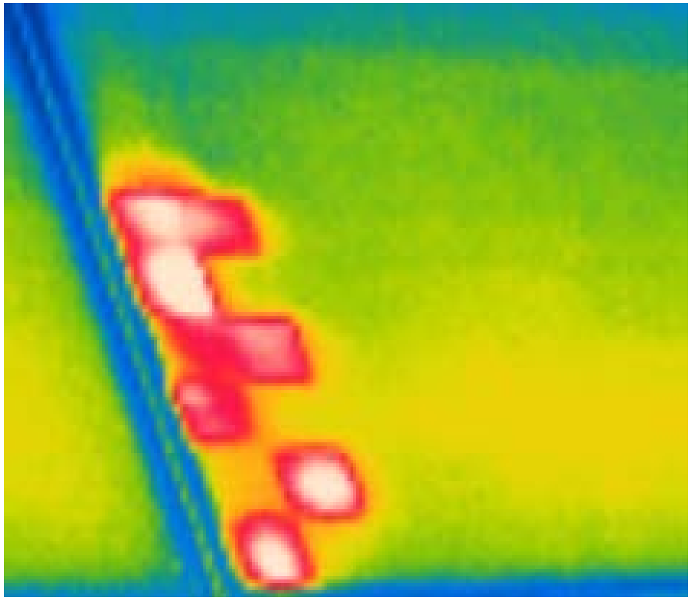
HF then leakage current testing on 3 cable/connector pairs

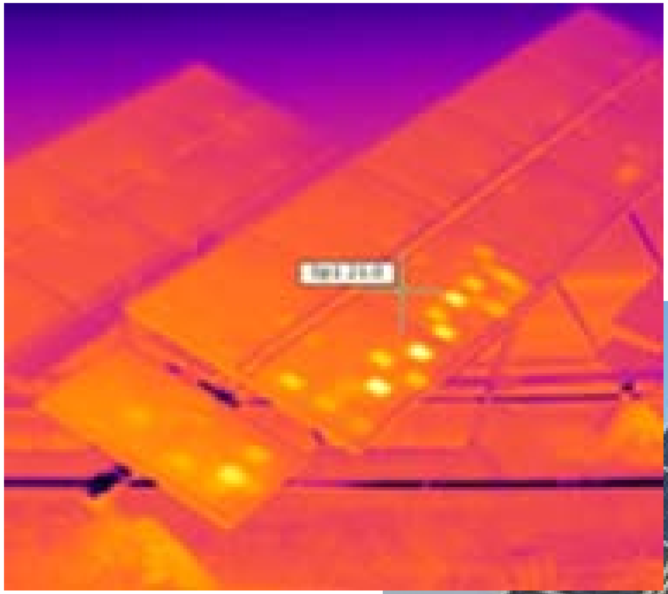
  - Temperature and Vibration
    - Reveals marginal connections, threads that will come loose and J-box adhesion

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
  – Dynamic load testing (1000 cycles at 2400 Pa) to quantify cell breakage

Encapsulant and backsheet

- Failure mode: Backsheet delamination
- Possible cause: unknown

Mfg J: 100% affected for this model

Encapsulant and backsheet

- Failure mode: EVA browning/yellowing
- Possible cause: EVA material variation

Mfg K:
50%
affected

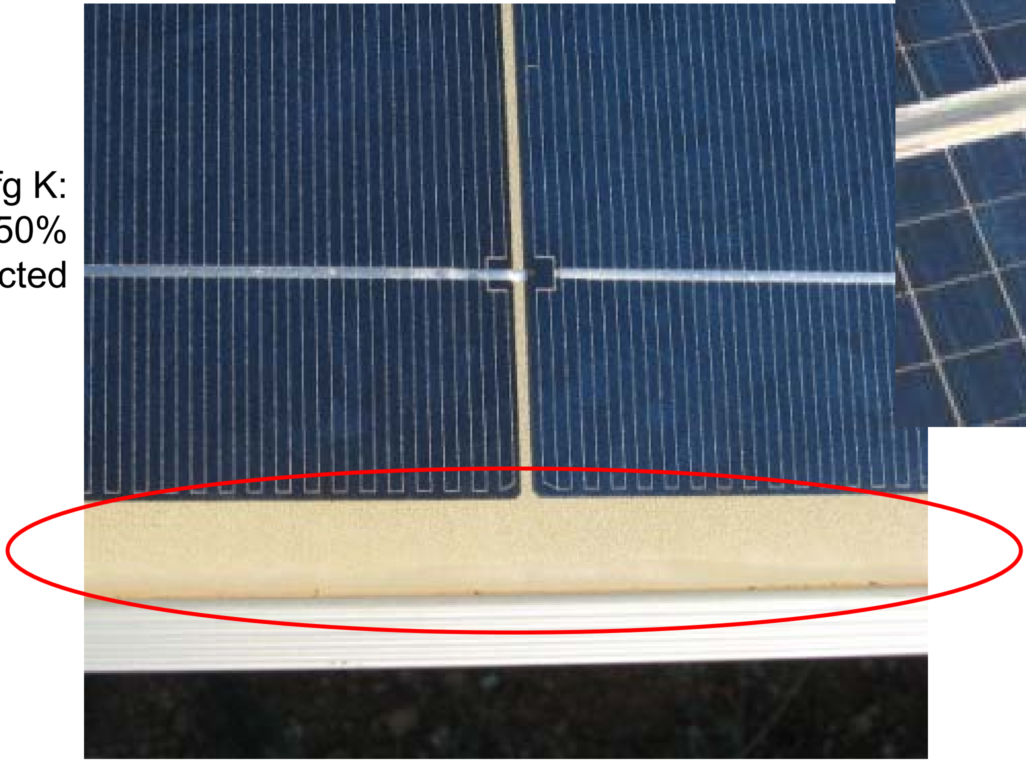


Image of browned EVA after one year in the field

Encapsulant and backsheet

- Failure mode: backsheet peeling off exposing backside of cell
- Possible cause: Unknown

Mfg M: 0.1% failure rate

Image of a severely peeled backsheet from the field

- Tests that may cover these types of failures:
  - DH followed by wet leakage test
    - DH degrades the backsheet and the wet leakage test determines if the insulation integrity has been compromised. Partial Discharge testing is the most sensitive.
    - Also reveals both browning and backsheet peeling (requires more than 2000 cycles)
  - Accelerated UV testing (3x UV at 60C ambient for 5 days)
    - Browns EVA because it combines UV and temperature stress.
  - High temperature soak
    - Very effective in inducing bubbled backsheets.

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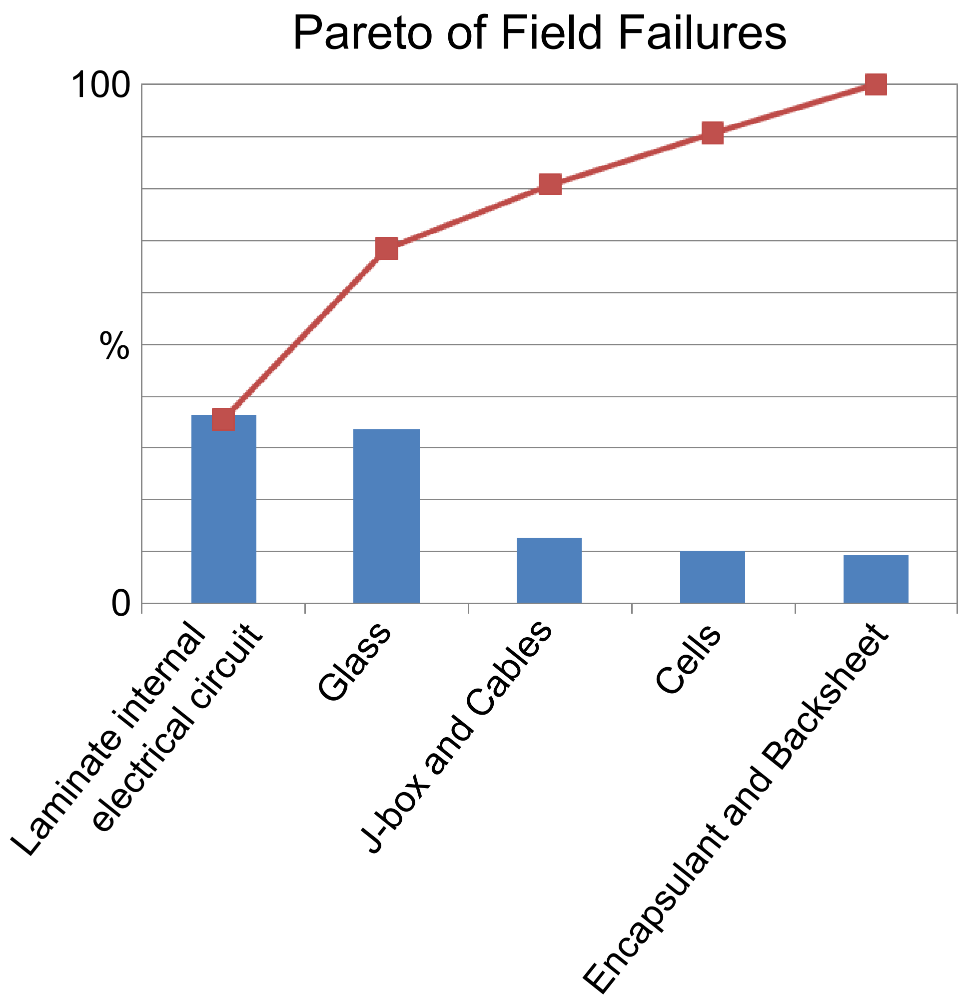
Specific field failures: their analysis and statistics



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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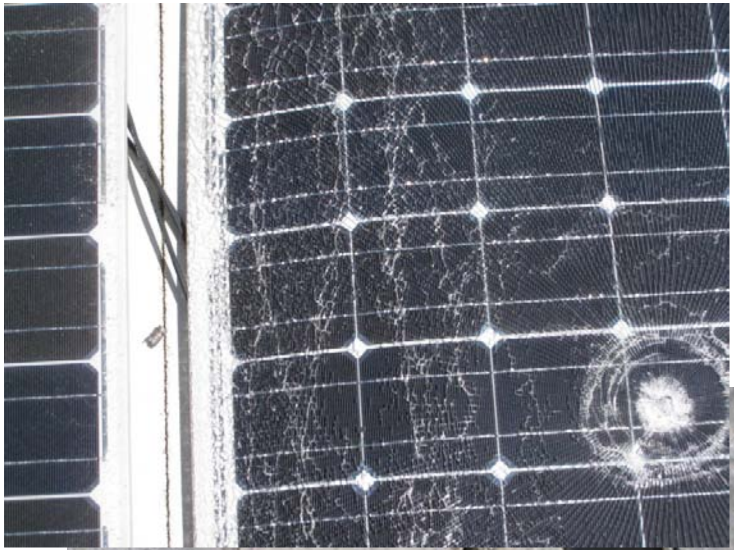
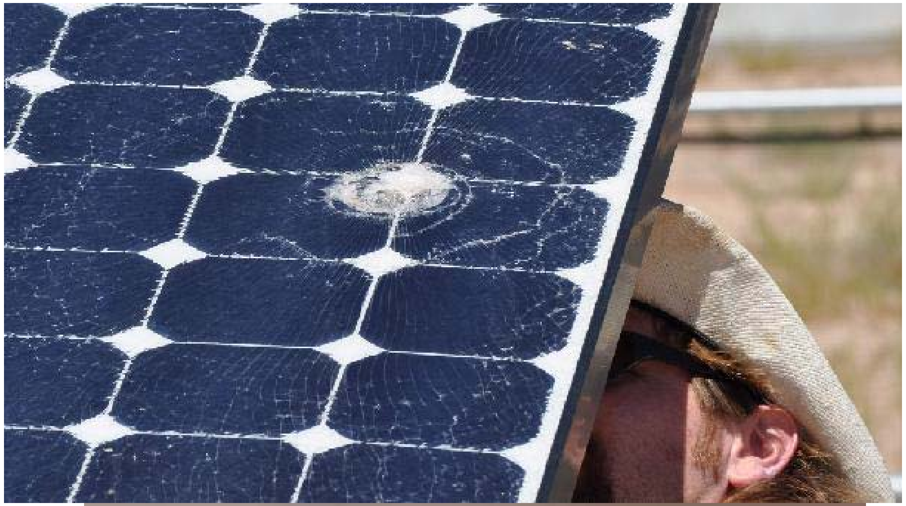
Critters, Guns, and the Wrath of God

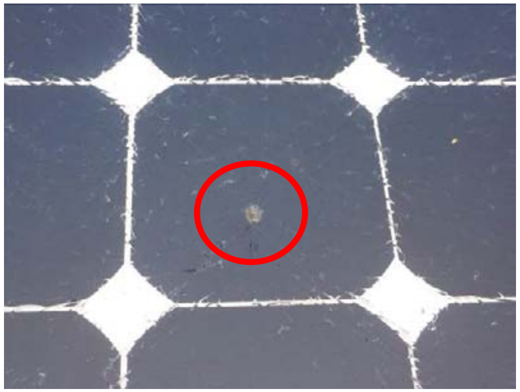


- Bullet holes!

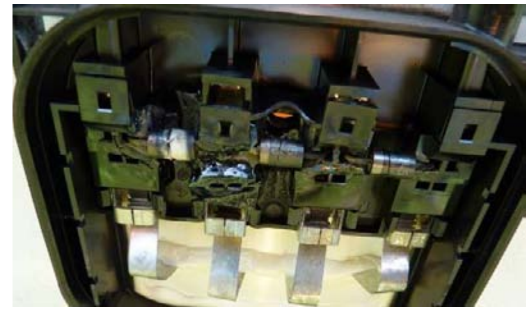


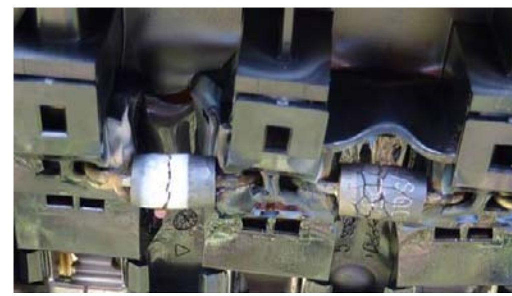
Critters, Guns, and the Wrath of God

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



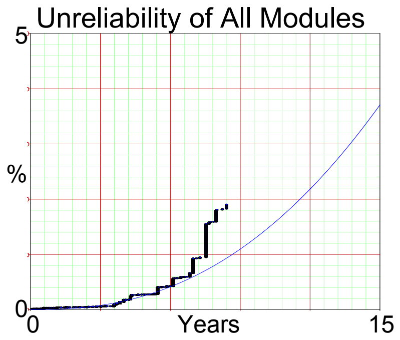
Point of contact on the glass



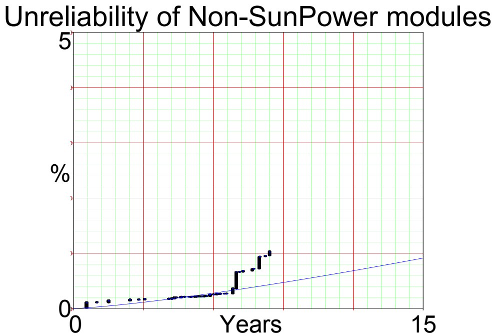


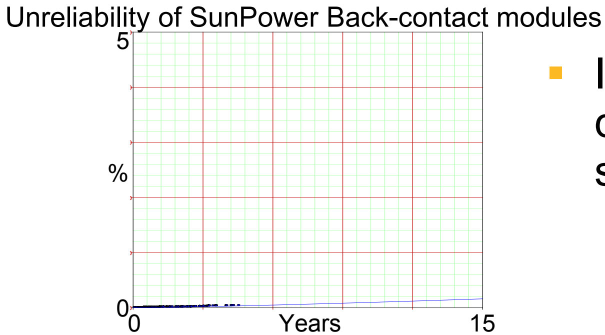
Backsheet damage

Conclusions



- Statistics on the entire fleet qualitatively suggest a reliability problem for a 25 year warranty, but are skewed:
  - Sample bias.
  - A few module types with a specific and non-general design problem.





- If the bias is corrected, and key design problems tested out, the statistics qualitatively suggest:
  - High reliability is not a given, but is attainable.
  - Reliability and Quality play an important role in LCOE.

High reliability can be attained with careful testing that targets possible design problems, based on the physics of the failure modes, HALT testing, and field data.

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