Trends in Field Failure Modes

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Introduction

- Over the years a large number of different module failure modes have been identified.
- Analysis of these are useful:
  - Help us to develop accelerated stress tests.
  - Provide guidance on what changes in module design, materials, processes and handling are necessary to improve long term reliability.
- Will first provide my list of field failures.
- Will then talk about:
  - Past: Some of the things we have learned.
  - Present: What we are seeing today and what still needs to be done to improve reliability.
  - Future: What we can expect to see and how we should be prepared to react.

HISTORY OF FIELD FAILURES for Crystalline Si

- Broken interconnects
- Broken/cracked cells & snail trails
- Corrosion of cells, metals and connectors
- Delamination/loss of adhesion between layers
- Loss of elastomeric properties of encapsulant or backsheet
- Encapsulant discoloration
- Solder bond failures
- Broken glass
- Glass corrosion
- Hot Spots
- Ground faults due to breakdown of insulation package
- Junction box and module connection failures
- Structural failures
- Bypass Diode failures
- Open circuiting leading to arcing
- Potential Induced Degradation

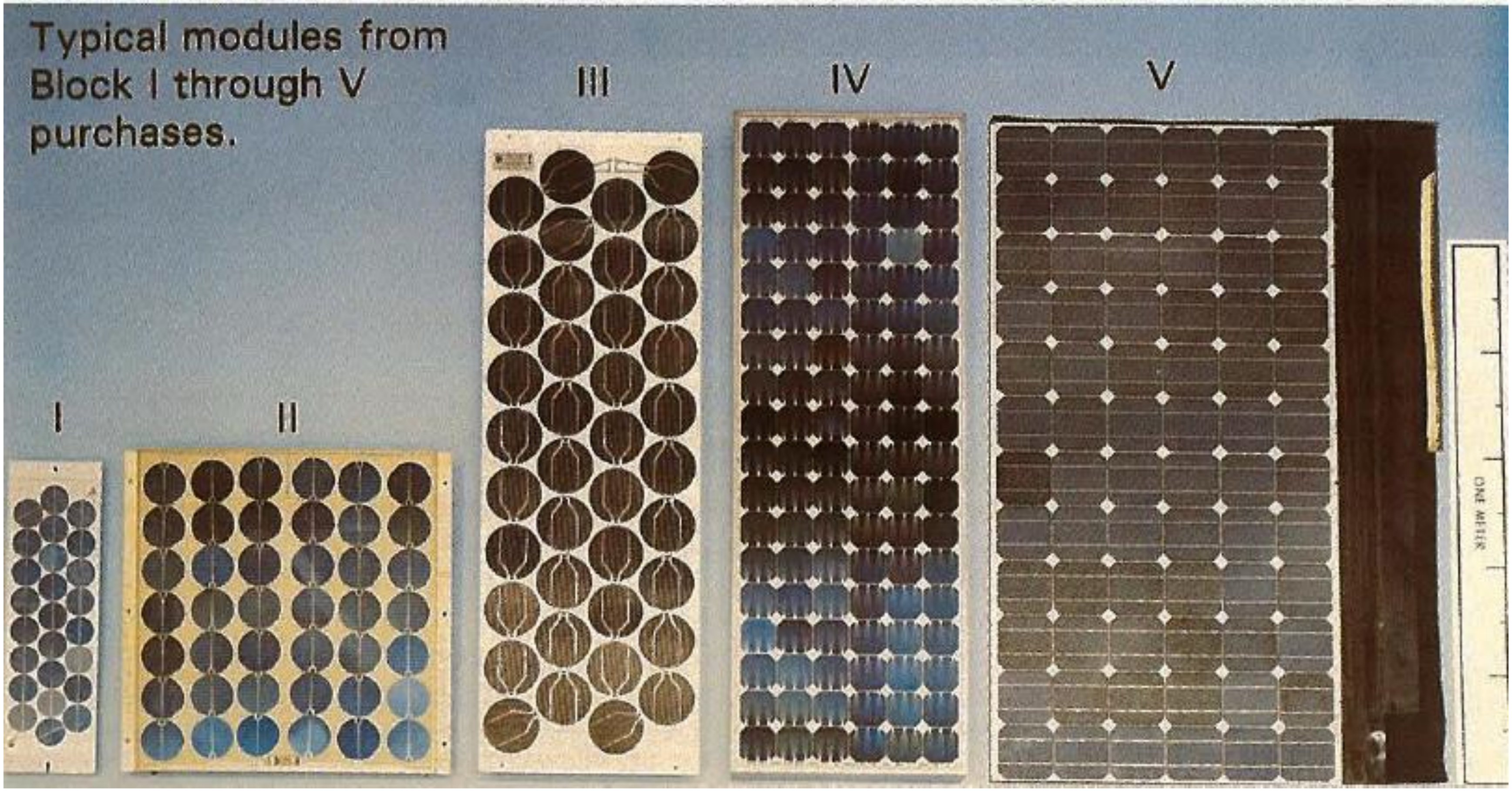
Additional Failure Modes for Thin Film Modules

- Electro-chemical corrosion of TCO.
- Light Induced Degradation
- Inadequate Edge Deletion
- Shunts at laser scribes
- Shunts at impurities in films
- Failure of Edge Seals
- Broken Glass (Non tempered)
- Diffusion of metals from contacts through the junction

Past Experiences

- **Good to remind ourselves how we got to our present situation:**
  - **Most modules sold with at least 25 year warranty**
  - **Modules usually considered most reliable part of PV system.**
  - **Multi-gigawatt business based on use of these modules.**
- **A number of early programs, particularly the JPL Block buy helped establish the need for reliable products through qualification testing and use of Quality Management Systems in module production.**
- **The next page summarizes the gains made between Block I and Block V.**
- **A vast majority of the major changes implemented during the JPL Block Buy are still found in modules today.**

JPL Block Procurement Modules



Modules from JPL Block Program

Property	Block I	Block V
Power Range	5 to 13 W	70 to 185 W
Module Efficiency	5.8 %	10.6%
Wafer/Cells	2.25 to 3" CZ	3- 4" CZ, 10 by 10 Multi & EFG
Construction	1 glass superstrate 3 substrates with silicone front	All glass superstrates
Encapsulant	Cast Silicone Rubber	Laminated EVA
Interconnect Redundancy	None	Multiple
By-pass Diodes	No	Yes

Qualification tests from Block Program

Test	Thermal Cycle	Humidity	Hot Spot	Hail Test	High Pot
Block I	100	70C/90% 72 hours	None	None	None
Block V	200	85 to -40C 85% 10 cycles	Yes	Yes	< 50 µA 2*Vs+1000

- One study (Whipple, 1993) claimed:
    - Modules not qualified to Block V had 45% module failure rate in first 10 years of operation
    - Modules qualified to Block V had <0.1% module failure rate in first 10 years of operation.

Some Examples from the Past

- Review data on observed field failures.
- Look at a few examples from past.
- Tried to select examples that had an impact on module design, materials selection and testing protocols.
- Hopefully these examples can help us now and in the future.

Solarex Field Returns (1994-2005)

Type of Defect	% of Returns
Corrosion	45
Cell or Interconnect Breakage	41
Output Lead Problems	4
Junction Box Problems	4
Delamination	3
Overheating of wire, diode or terminal strip	2
Mechanical Damage	1

From Wohlgemuth, 20th EUPVSEC, 2005
Represents only returns of Solarex Cry-Si modules

Powerlite Fleet Field Returns

Type of Defect	Description of Defect	% of Defects
Internal Circuitry	Hot spots due to bond failure	35
Glass	AR Coating Degradation	32
Junction Box and Cables	Mostly overheating	12
Cells	Hot Spots in IR	10
Encapsulant & Backsheet	Backsheets coming off	10

Degraff, 2011 NREL PVMRW
Represents data on modules from 20 different module manufacturers
Most were a result of inadequate qualification of a change in material or process.

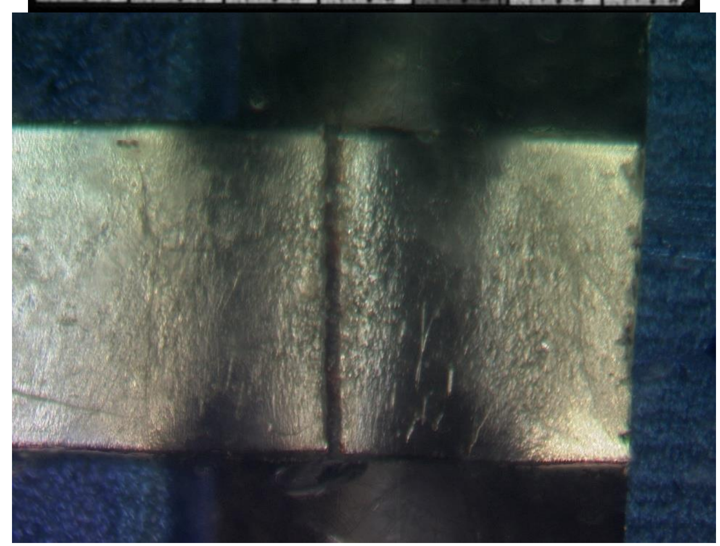
Defects in Southwest US Array

Type of Defect	% of Defect	Found in how many types
Discoloration	62	3 out of 6
Backsheet	29	2 out of 6
Delamination	4	Only glass/glass
Cracked Cells	2	Only glass/glass
Hotspots (IR)	2	all
Edge Adhesive Deterioration	2	2 out of 6

Tamizhmani, 2013 NREL PVMRW
Modules inspected in array exposed for 13 years in US Southwest
All modules cry-Si

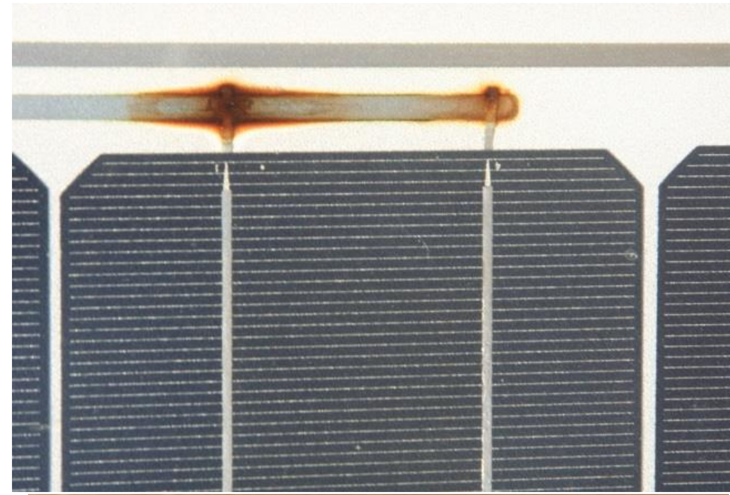
Broken Interconnects

- Interconnects break due to stress caused by thermal expansion and contraction or due to repeated mechanical stress.
- Early modules suffered open circuits due to broken interconnects so redundancy helps.
- Observed in EL as dark areas where that interconnect should be collecting.
- What makes it worse
  - Substrates with high thermal expansion coefficients
  - Larger cells
  - Thicker ribbon
  - Stiffer ribbon
  - Kinks in ribbon
  - Not enough free ribbon between solder bonds on adjacent cells.
- Problem mostly eliminated with
  - Extremely soft flexible ribbon
  - Tab across designs
  - Multiple ribbons per cell
  - Use of glass superstrates



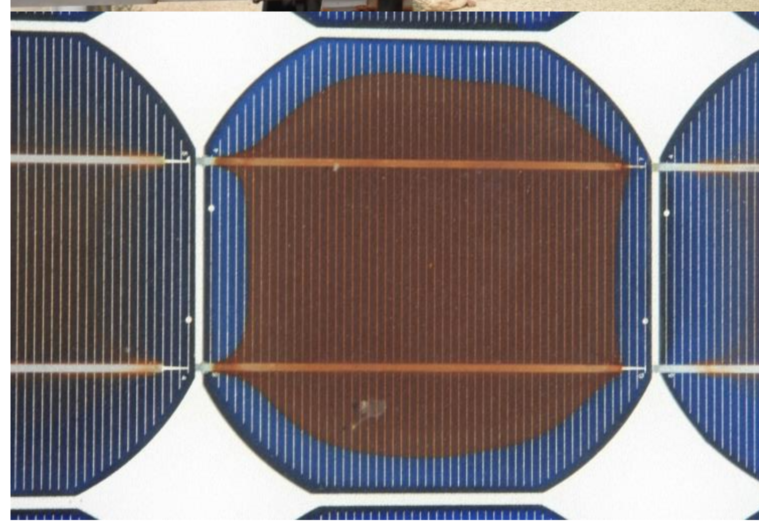
Solder Bond Failures

- Solder bonds fail due to fatigue caused by cyclic loading, e.g. repetitive thermal, mechanical or electrical stresses.
- Early modules typically only had 1 solder bond at each end of the interconnect ribbon and only one ribbon per cell so failure of one solder bond resulted in an open circuit failure of the whole module.
- Even today non-cell solder bonds often have little or no redundancy so failure of one of these bonds can lead to drop out of a cell string, a whole module or even a whole string of modules.
- Single point failures like the top picture are usually workmanship related.
- Multiple failures like the bottom picture are usually design related (solder bonds too small) or a process issue (production equipment not in control).



Encapsulant Discoloration

- Worst reported case was in slow cure EVA in a low concentration system at Carissa Plains, CA.
- Standard cure EVA formulation A9918 does discolor.
  - Caused by heat and UV.
  - Bleached by oxygen
  - So with breathable backsheet center of cells discolor while outside ring remains clear.
- Evaluation of modules after 27 years of exposure at SMUD – measured current loss of 10 to 12%.
- It was not EVA itself that discolored, but additives in the formulation.
- Changing additives dramatically reduced or eliminated the problem.
- Formulations that do not discolor are now available.



Inadequate Edge Deletion

- **If thin film layers are not adequately removed from the edge of the glass plate, the remaining material can cause high leakage currents and provide pathways for moisture ingress.**
- **High leakage currents are a safety issue (exposure to systems voltage) and a reliability issue (electro-corrosion of contacts and thin film PV layers).**
- **This was the reason for the addition of the wet leakage current test into the Qualification Standards.**
- **This problem has mostly been eliminated through improved process control and the use of the wet leakage current test.**

Lessons learned from Field Experience

Building better modules

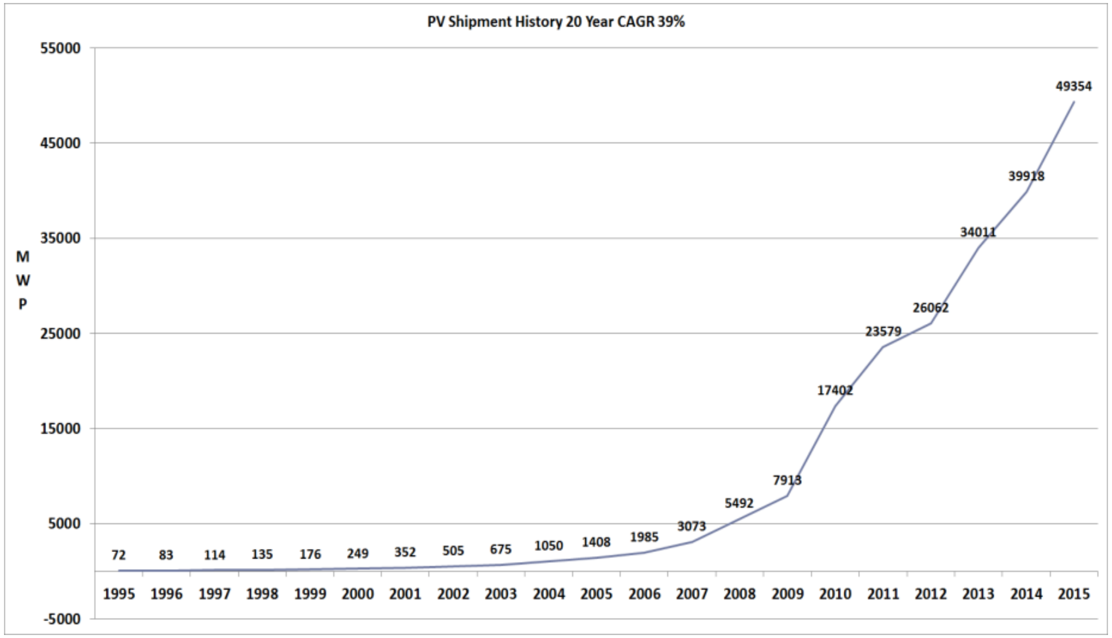
- Tempered glass superstrates
- Multiple tab across ribbons
- Process control in soldering
- Incorporate by-pass diodes
- Make sure encapsulant formulation is UV stable

Testing modules for reliability

- Thermal cycling
- Humidity exposure
- Hail test
- Hot spot test
- Mechanical load test
- Wet high pot test

Present

- Remember that many of the module types from the past are still functioning so we should expect to continue to see many of the same defects described already.
- However, the dramatic increase in PV volume means that the vast majority of deployed modules have been fabricated in the last few years.
- So the main question for us is what do we expect to see in the way of defects in those newer modules?

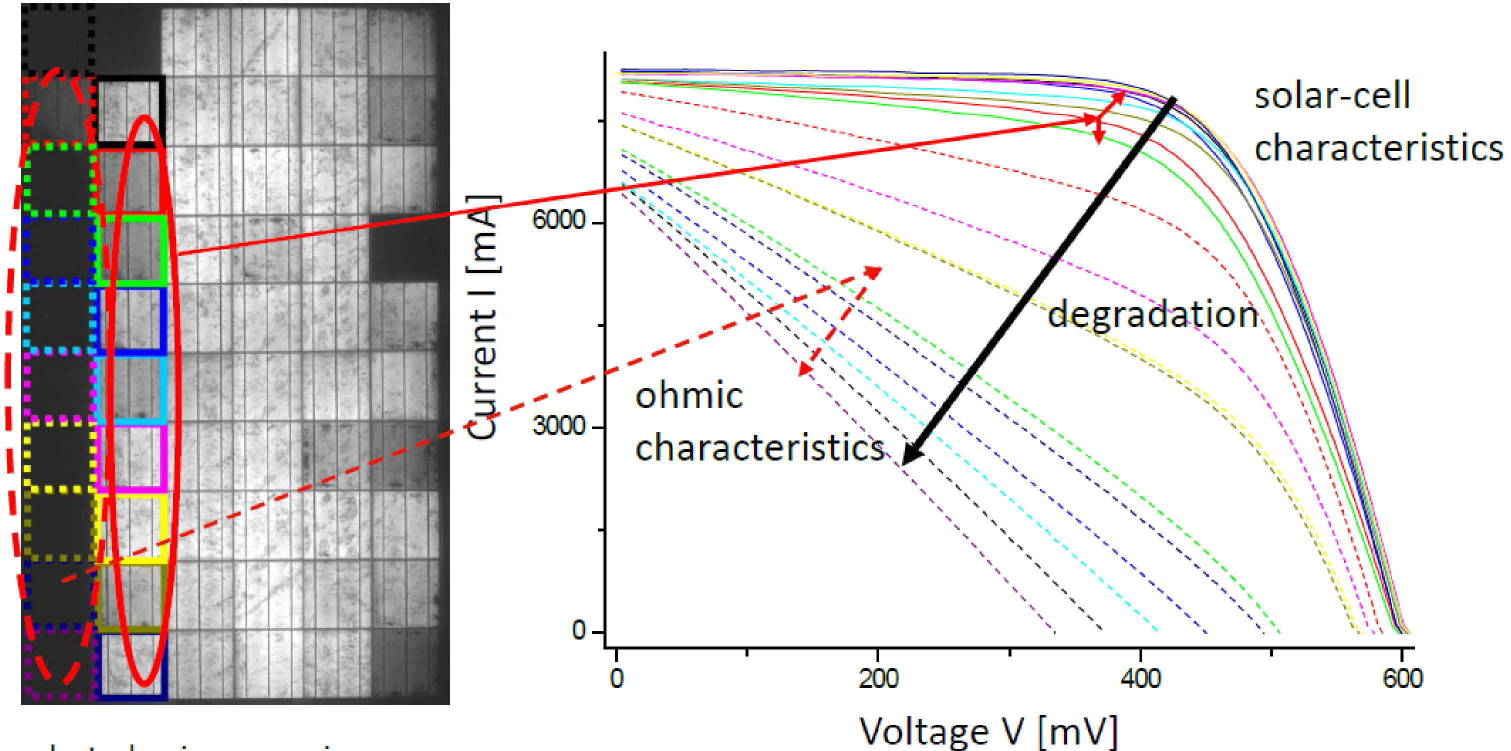


From Paula Mints

Prevalent Defects in today's Modules

- Potential induced degradation (PID)
- Glass breakage for modules with annealed glass, usually thin films.
- Broken cells
- Issues related to specific module design.
  - Junction box lids popping off
  - Junction boxes falling off
- Workmanship issues, especially where single point failures can occur.
- Shipping, handling and installation issues

PID



electroluminescence image

PID-s → Potential induced degradation by shunting of solar cell

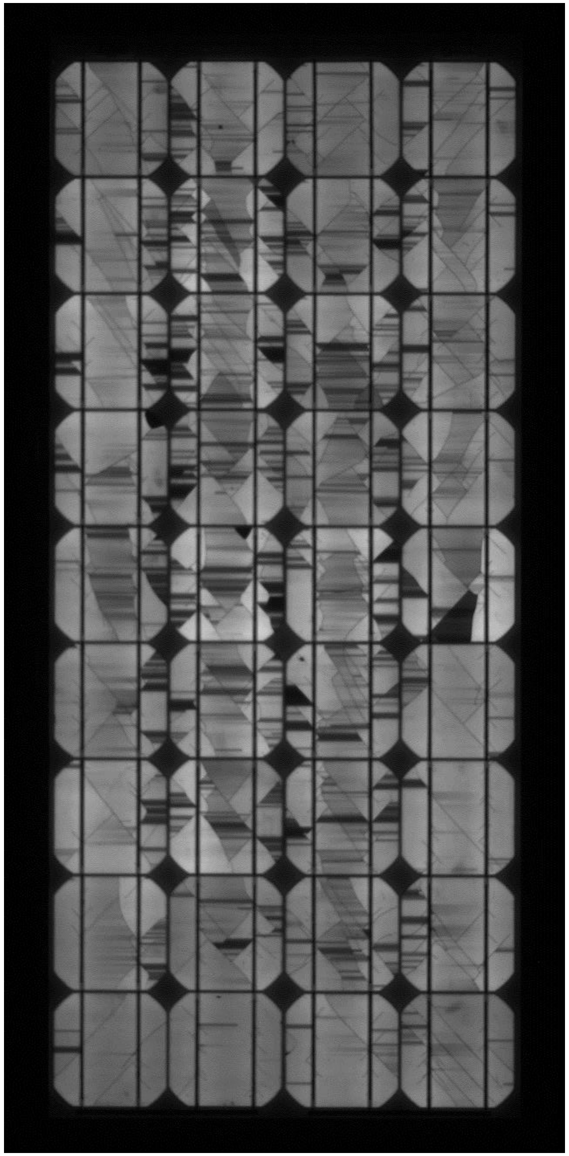
Koentopp, NREL PVMRW 2016

PID

- This is a more recent defect with reports of PV systems suffering power loss due to System Voltage Stress or PID.
- It only occurs when modules are operated at high negative bias and seems to require high humid or frequent rain, that is the module front glass gets wet.
- Appears to be related to Na ion migration from the glass through the encapsulant to the cells. Effected cells are shunted. See EL picture
- Only cells with SiN AR coating appear to be susceptible. Tuning the index of the SiN can change the degree of degradation significantly. This may mean it is susceptible to process variability, so some so called PID resistant cells end up having PID field problems.
- Process is at least partially reversible by switching the direction of the bias voltage or removing bias.
- More permanent solution appears to be use of lower conductivity encapsulants.

Broken or Cracked Cells

- Crystalline Si cells can (and will) break due to mechanical and thermal stresses.
- EL is an excellent tool for seeing cell breakage.
- Small amount of cell breakage often doesn't lead to power loss, but large amount of breakage will. Look for areas in EL that are completely black, they are no longer electrically connected to the circuit.
- The module in the picture was down 9% in power.
- Use of thinner cells, larger cells and larger modules increase the likelihood and impact of cell breakage .
- Use of more bus bars reduces the impact of cell breakage.
- It is likely that in the future more cells will break, but that this breakage will have less impact on power loss.
- Some of the current/power loss reported for fielded modules is likely to be due to broken cells.



Future

- Most modules will be deployed in large arrays.
- Unlikely to be able to detect most defects.
- Those defects that are observed and reported are likely to be because of:
  - Safety issues: fires and high leakage currents
  - Significant changes in performance so they either affect a large number of modules or single point failures take out whole modules or strings of modules
- In either case the solutions are pretty much the same as for today in terms of design, workmanship, handling and installation.

PV Design, Workmanship, Handling & Installation

- **IEC TS 62491: Terrestrial photovoltaic (PV) modules – Guidelines for increased confidence in PV module design qualification and type approval**
- **Should use IEC TS 62491 as guidance for design, manufacturing quality management system and to establish a continuing accelerated stress testing program.**
- **IEC TS 63049: Terrestrial photovoltaic (PV) systems - Guidelines for effective quality assurance in PV systems installation, operation and maintenance**
- **Should use IEC TS 63049 as guidance for module handling and installation practices.**

Summary

- History has shown how important observation of module defects and failures are to developing the best designs with the optimum materials and defining what accelerated stress tests are most useful.
- As the size of the PV market expands it becomes more difficult to undertake the levels of inspection used in the past.
- However, it is critical that module inspections continue. The question is who is best suited to perform these inspections and provide the necessary feedback to module manufacturers to improve the products and reliability researchers to improve the accelerated stress tests?
- Ultimately we hope that the research community can provide the manufacturers with a methodology for assessing specific module lifetimes in different climates and mounting configurations.

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Thank You for Your Attention

The End