Photovoltaic Reliability R&D Toward a Solar-Powered World

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with help from many others
National Renewable Energy Laboratory,
Sandia National Laboratories

SPIE
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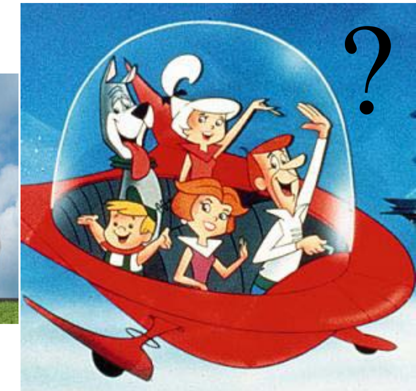
Outline

- A vision of a solar-powered world
- Importance of reliability to success of solar
- Working together to establish reliability
- R&D issues related to:
  - Product Development
  - Quality Assurance during manufacturing
  - Lifetime Predictions
- Current status
- Technology-specific R&D issues
  - Selected highlights from SPIE

How fast can a world change?











Solar power is within reach



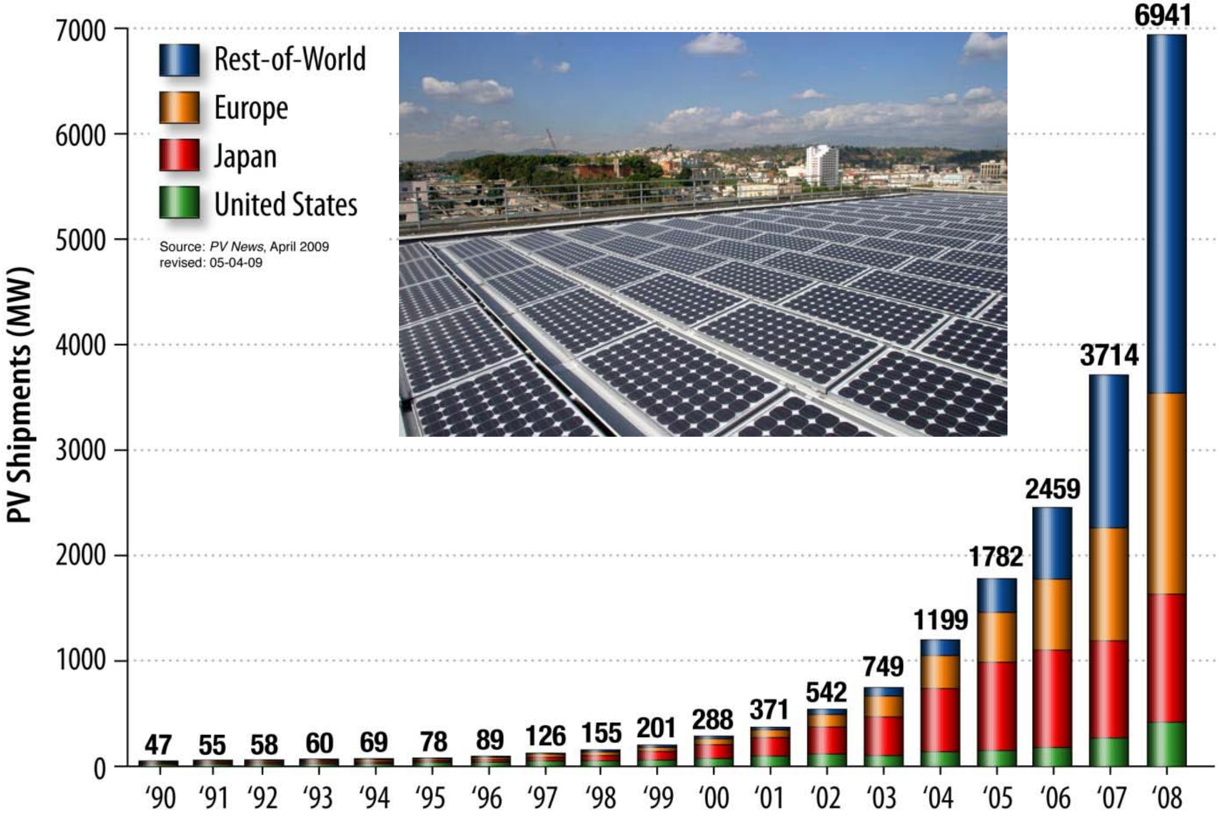





What do we need to do to create a solar-powered world?

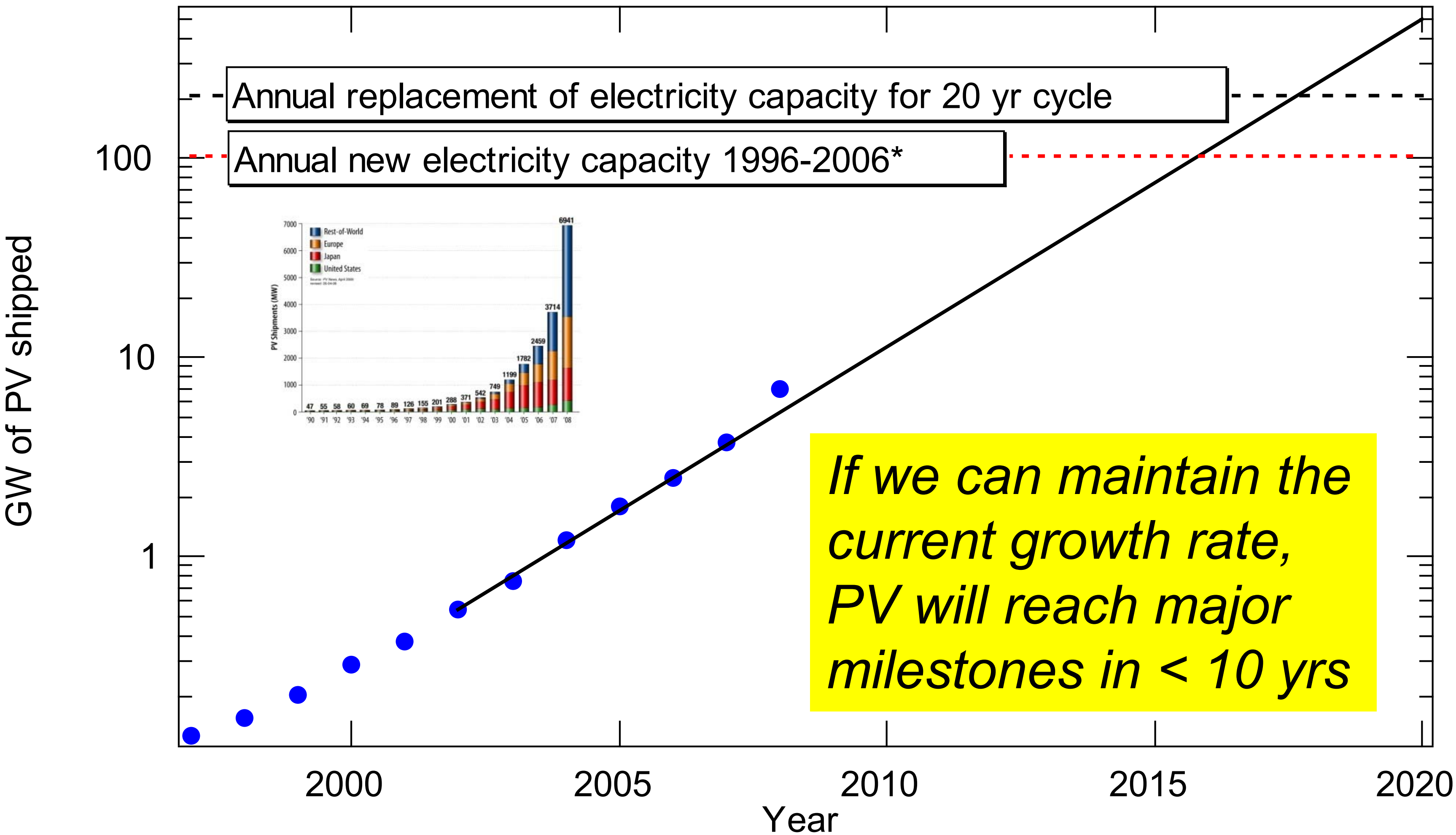



Growth of PV industry



PV shipments have been doubling every two years

Growth of PV industry

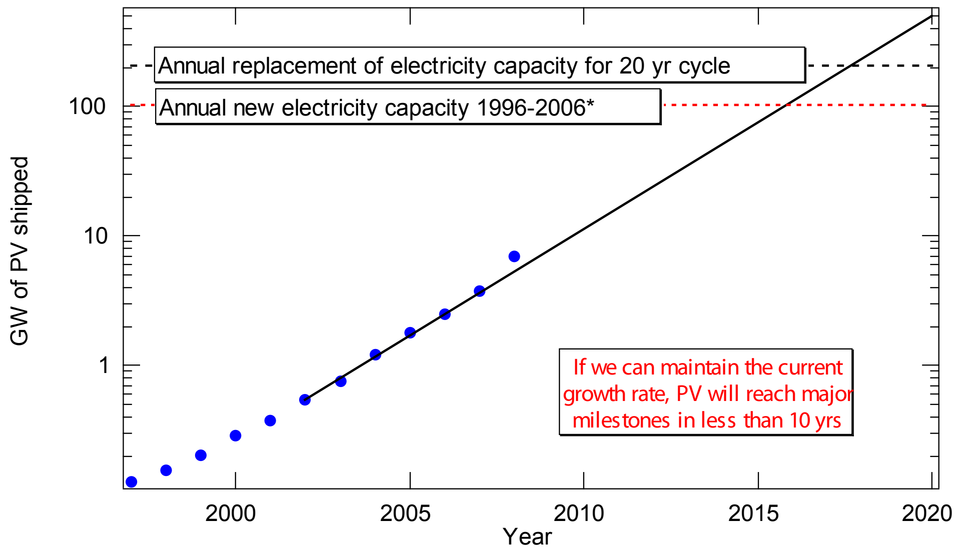


*www.eia.doe.gov/emeu/international/electricitycapacity.html (4012-2981 GW)/10 yr

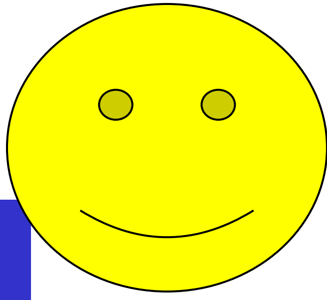
Why is reliability important?

Improved reliability helps to reduce life-cycle cost:
- Longer lifetime
- Slower degradation
- Lower O&M costs

Improved reliability improves customer satisfaction
- Good performance builds customer confidence
- Better confidence inspires investors



With reliability, this graph leads to a solar-powered world



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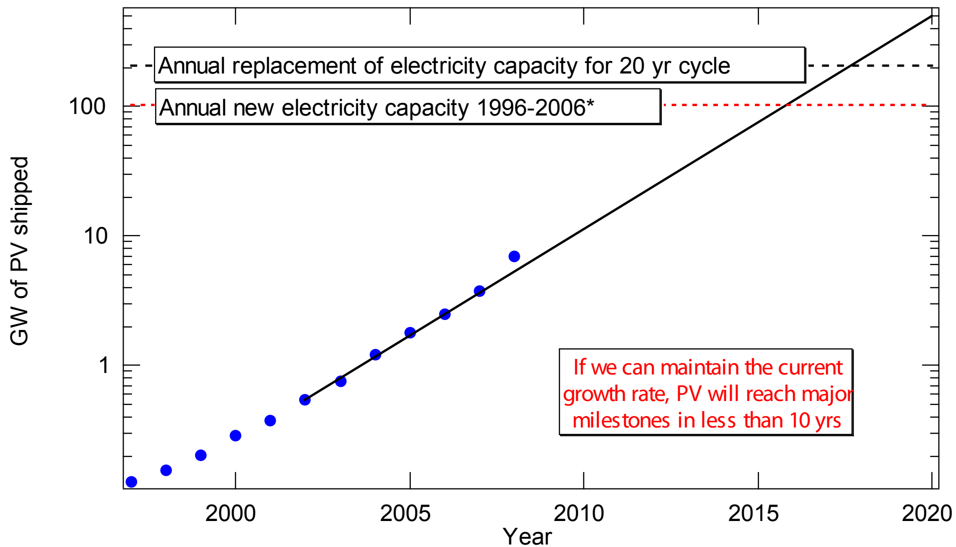
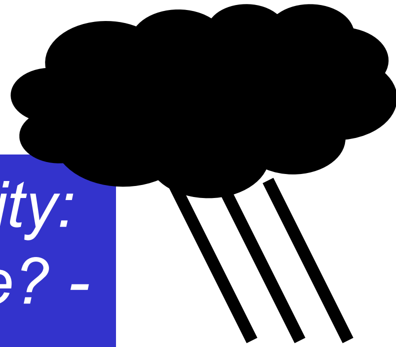


Without reliability: a Ponzi scheme? - Bill Marion



Reliability should be considered by venture capitalists

Venture capitalists funding dot.com look for
- Novel (secret) idea
- Return on investment in a couple of years

Venture capitalists funding PV need to look for
- Good approach (not necessarily novel)
- Excellent implementation
- Plan for enough time to check reliability

Developing a PV product is difficult!!!
The investors must recognize that the potential return on investment is huge, but will take time.
Community should demand public demonstration of reliability before IPO.

Years of standards development/field experience

Building a solar-powered world

Universities
- -Educate work force
- -Original research to extend useful PV-reliability knowledge

National labs
- -Build foundation of PV-reliability knowledge through R&D
- -Long-term or larger projects

Years of standards development/field experience

Complementary roles

Companies (& investors)
- Develop reliable products
- Manufacture quality products
- Customer satisfaction

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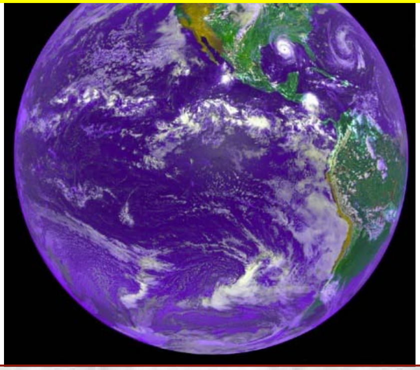
Building a solar-powered world

Solar-powered world



Defining complementary roles allows more efficient use of resources

Social acceptance and utility acceptance of PV

Companies (& investors)
-Development of reliable product
-Manufacturing of quality product
-Customer satisfaction

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What do we mean by reliability?

For a solar-powered world,
Reliability means:
the lights go on when the switch is flipped

For today's talk,
Reliability means a PV system working as expected when the sun is shining (with low O&M costs and long life)

Developmental stages

Achieving excellent reliability is a step-by-step process; you can't skip the early steps and expect to be successful with the final steps

Product development
-Identify failure modes
-Understand failure mechanisms
-Test for failures
-Mitigate

→

Quality assurance
-Test raw and refined materials
-Control process
-Test final products

→

Predict reliability
-Identify useful tests
-Understand all components
-Make predictions

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Product development

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Reliability should be considered from day 1 forward

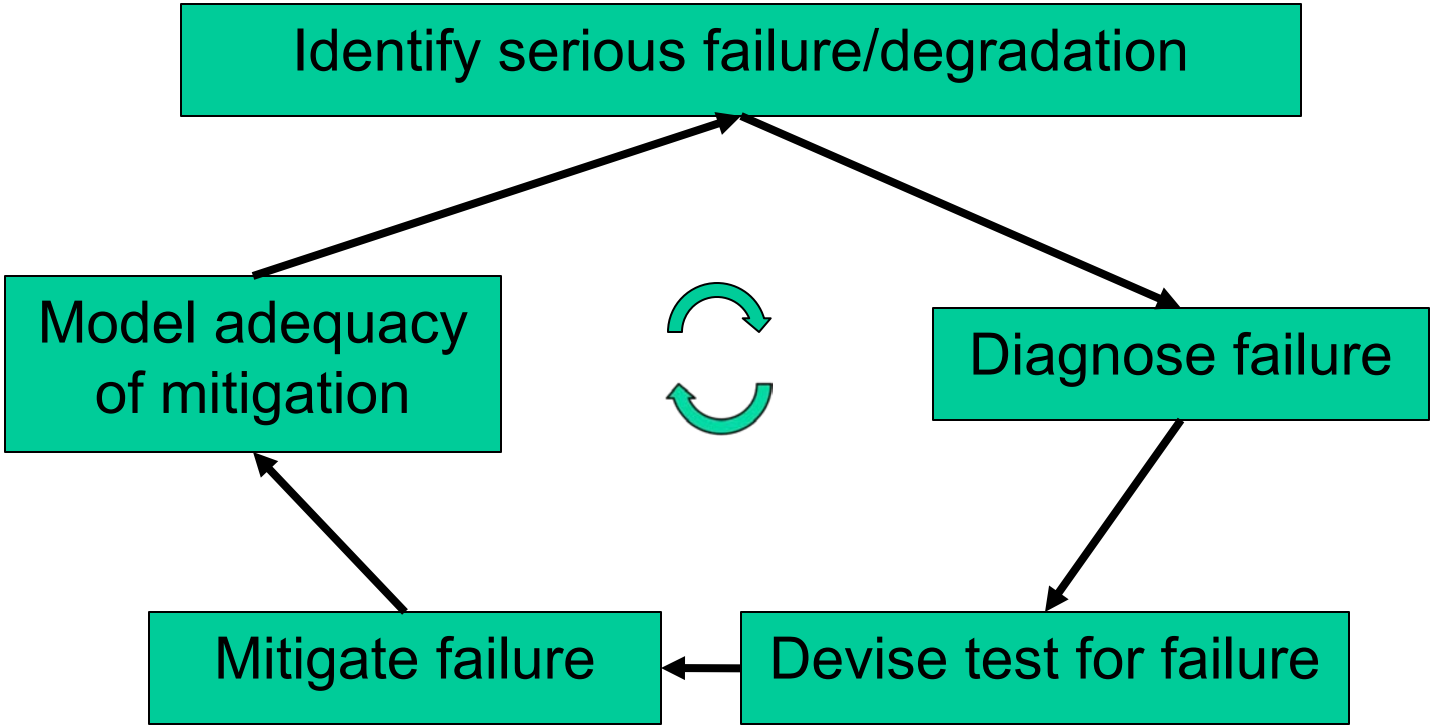
Lots of tools:
-Advanced Product Quality Planning
-Design Failure Modes Effects and Analysis
-Fault Tree Analysis
-Design for Manufacturability
-Design Review Based on Failure Mode (Toyota)

Prototype testing

Product development

-Identify failure modes
-Understand failure mechanisms
-Test for failures
-Mitigate

This cycle has been effective at improving PV module reliability and in developing standard for qualification test; not done yet!



History of Si module qual. test: JPL (Jet Propulsion Lab) Block buys

Test	**I**	**II**	**III**	**IV**	**V**
Year	1975	1976	1977	1978	1981
Thermal Cycle (°C)	100 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	200 cycles -40 to +90
Humidity	70 C, 90%RH, 68 hr	5 cycles 40 C, 90%RH to 23 C	5 cycles 40 C, 90%RH to 23 C	5 cycles 54 C, 90%RH to 23 C	10 cycles 85 C, 85%RH to -40 C
Hot spots	-	-	-	-	3 cells, 100 hrs
Mechanical load	-	100 cycles ± 2400 Pa	100 cycles ± 2400 Pa	10000 cyc. ± 2400 P	10000 cyc. ± 2400 Pa
Hail	-	-	-	9 impacts 3/4” - 45 mph	10 impacts 1” - 52 mph
NOCT	-	-	-	Yes	Yes
High pot	-	< 15 µA 1500 V	< 50 µA 1500 V	< 50 µA 1500 V	< 50 µA 2*Vs+1000

JPL Block buys led to dramatic improvements

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

Today's qualification test retains similarities to JPL tests

- IEC 61215 - Crystalline silicon design qualification includes 18 test procedures
  - Thermal cycling - 200 cycles -40°C to +85°C
  - Humidity freeze - 10 cycles +85°C, 85% RH to -40°C
  - Damp heat - 1000 hrs at +85°C, 85% RH
  - Wet leakage current - Wet insulation resistance X area > 40 $M\Omega m^2$ at 500 V or system voltage
  - Requirement is typically to retain 95% of original power production
- IEC 61646 (thin film) and IEC62108 (CPV) are similar

www.iec.ch

Developmental stages

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Predict reliability
- -Identify useful tests
- -Understand all components
- -Understand field failures
- -Make predictions

Silicon modules – R&D needs for QA

Quality assurance
-Test raw and refined materials
-Control process
-Test final products

SunTech raised question of purity of silicon in 2008

Quality assurance – R&D opportunities

- IEC standards do not address periodic retesting (when?)
- What QA tests/controls are needed? (e.g. Si purity, EVA cure)
- How can we keep the cost of the QA low, while keeping confidence high and learning as much as possible?

QA must be in place before confident predictions can be made

Developmental stages

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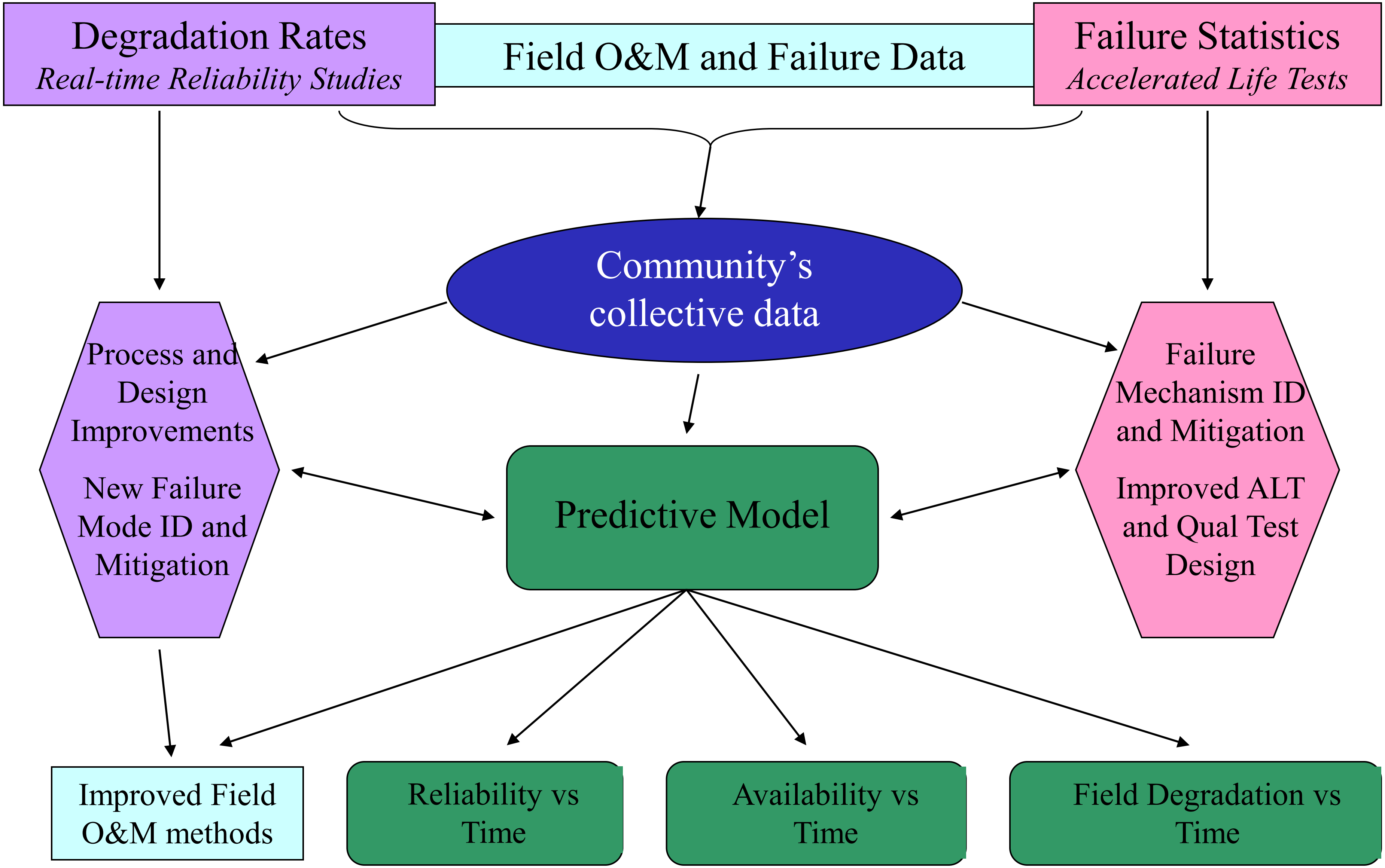
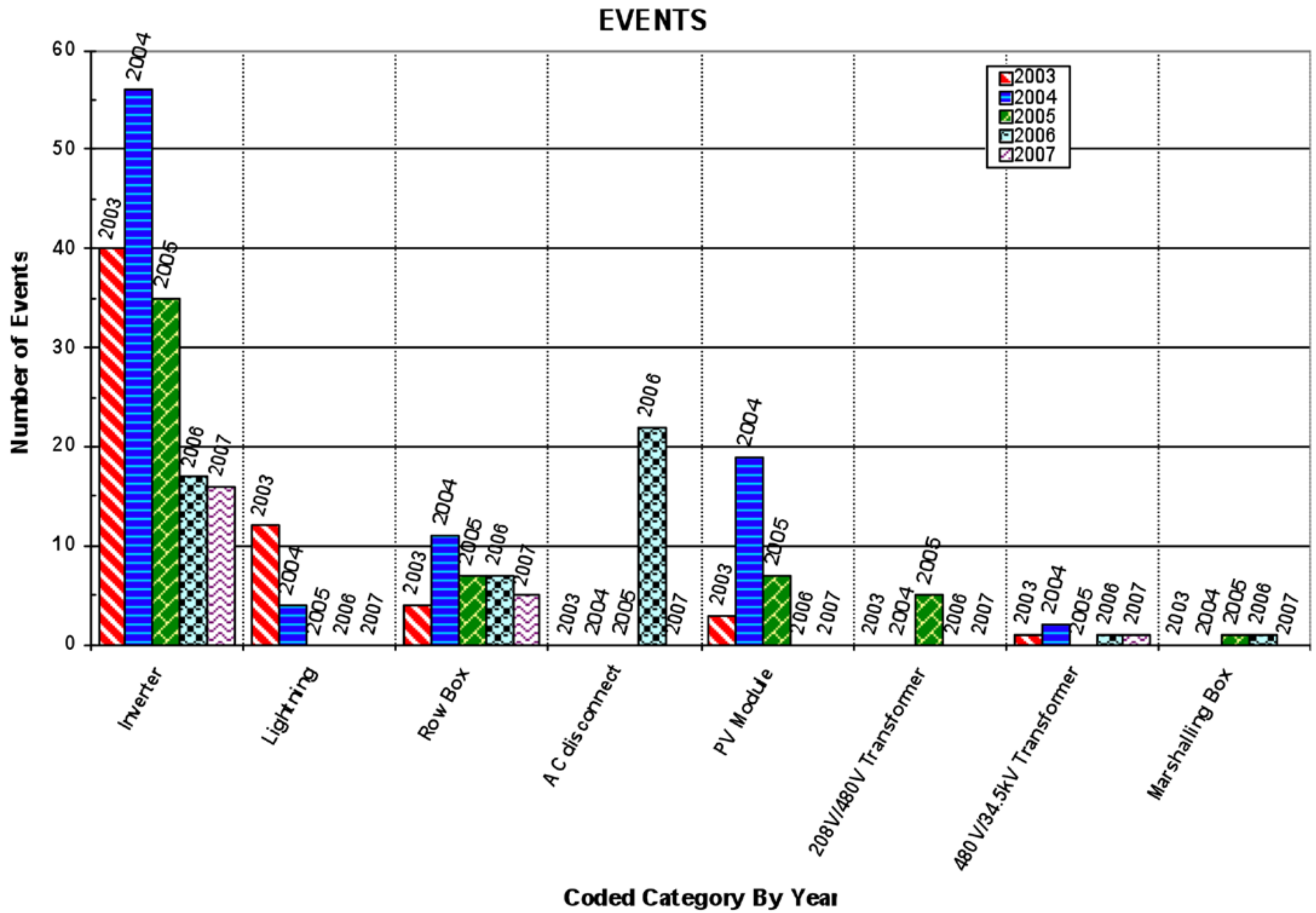
Predictive Model Development



Predictive Model Development



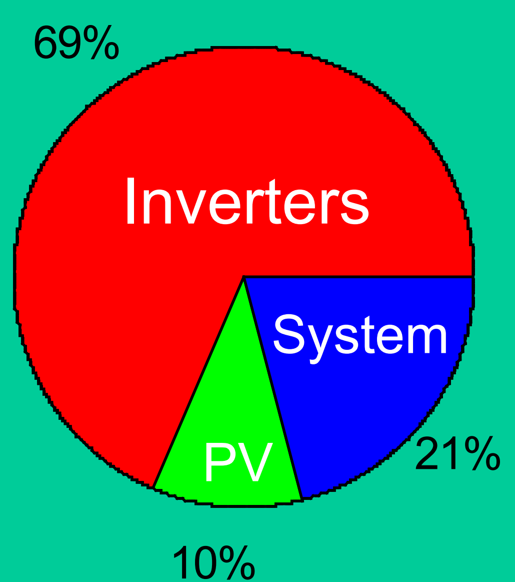
Reliability and availability analysis of a fielded PV system
34th PVSC Elmer Collins

Status – System level

Systems Approach:

- Understand how each component fits into the system
- The overall reliability of the system is dominated by the least reliable component(s)

Unscheduled maintenance costs



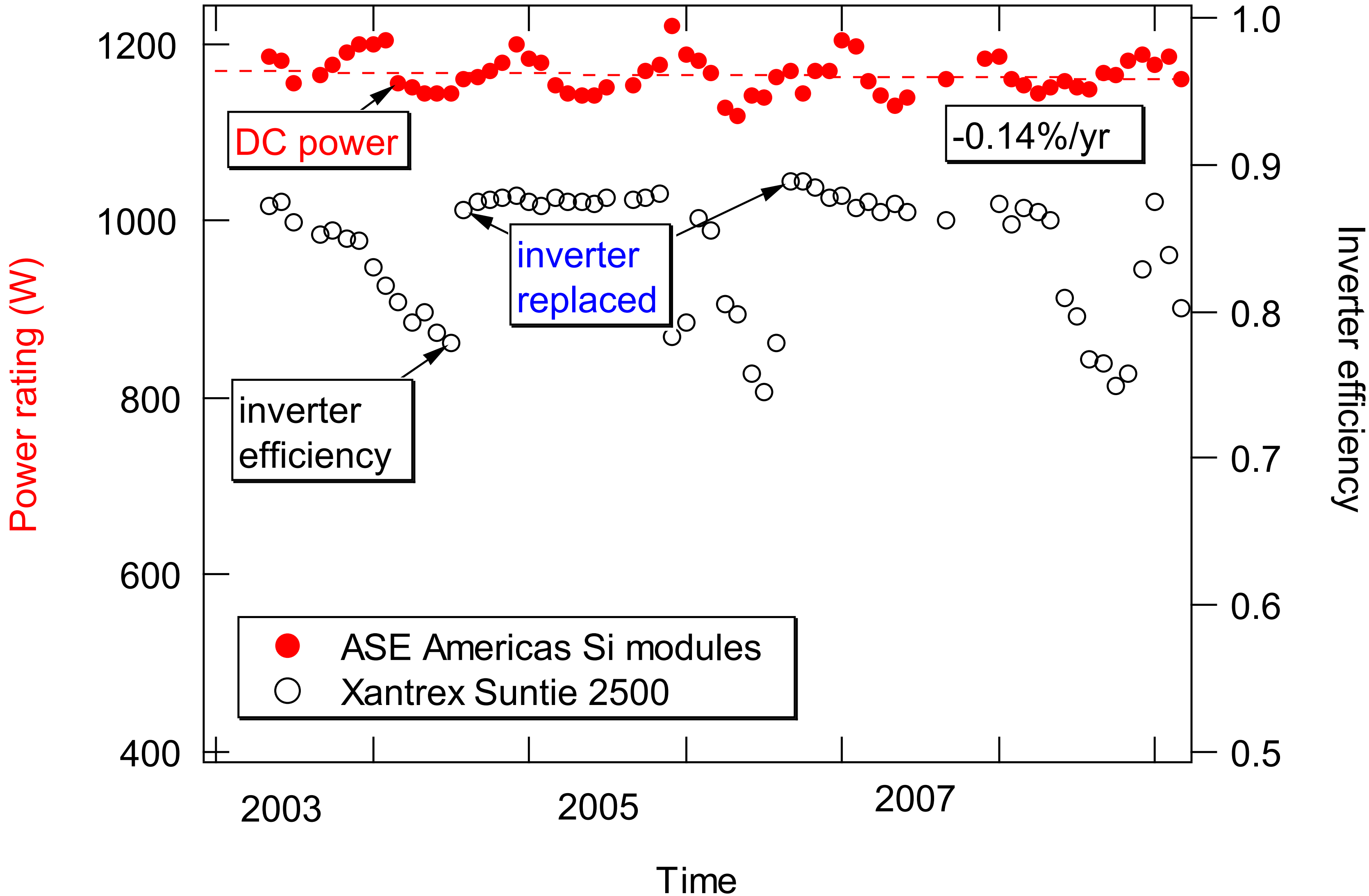
(Prog. PV 2008; **16**:249)

Studies of c-Si systems typically show few module failures;

Inverters typically dominate O&M cost

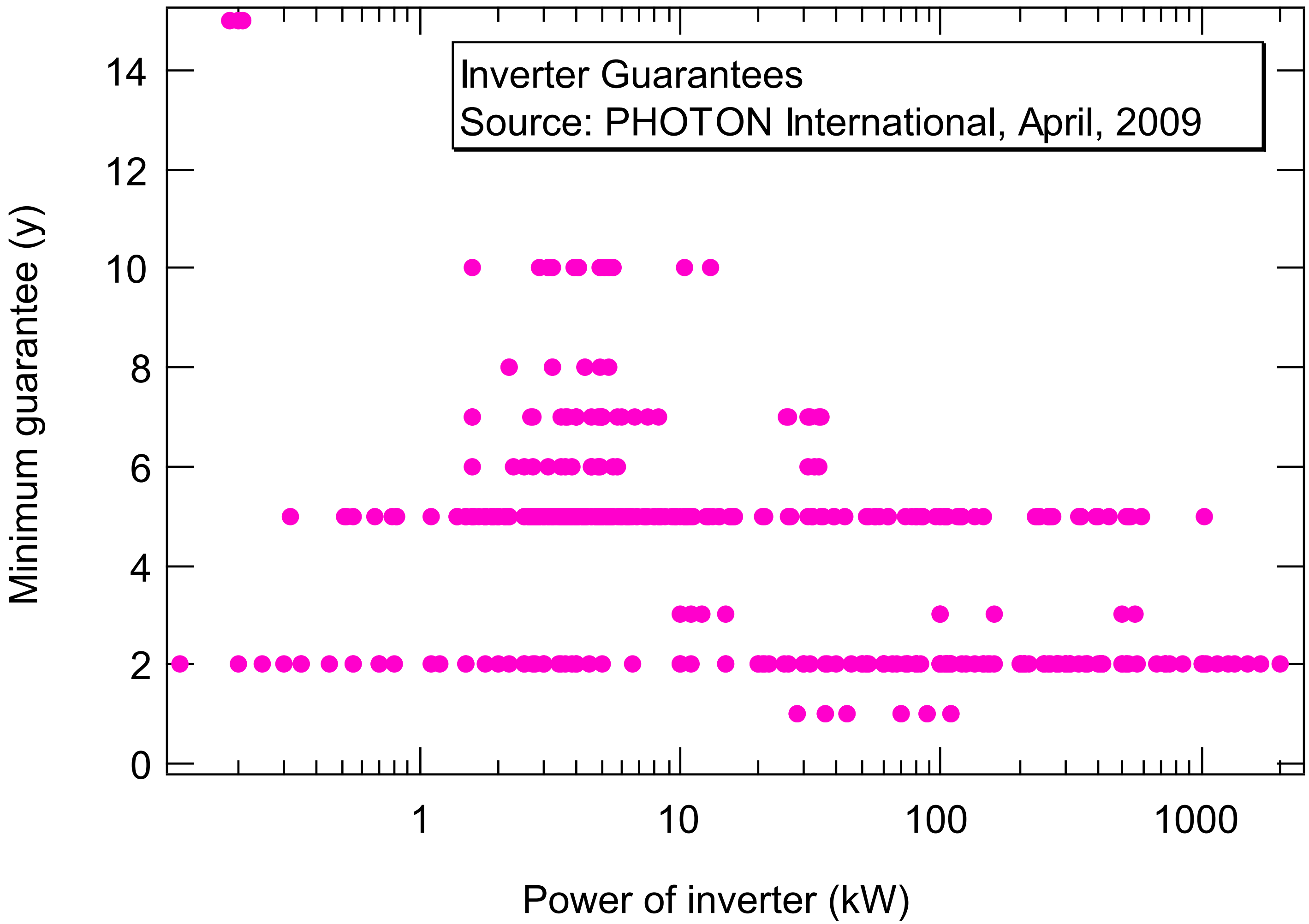
Reliable Si modules are demonstrated, but not guaranteed

Systems model helps to evaluate status



Module performance can be good; Some inverters have short lifetimes

Inverters are improving, but still need more



Limited warranties may be longer

Qualification/performance standards for inverters and BOS are not well defined

Inverters suffer from early failures in the field, temperature-related failures, & mismatch between PV voltage & inverter window.

Documented degradation rates

Manufacturer	Module Type	Exposure (years)	Degradation Rate (% per year)	Measured at System Level?	Ref.
ARCO Solar	ASI 16-2300 (x-Si)	23	-0.4	N	2
ARCO Solar	M-75 (x-Si)	11	-0.4	N	3
[not given]	[not given] (a-Si)	4	-1.5	Y	4
Eurosolare	M-SI 36 MS (poly-Si)	11	-0.4	Y	5
AEG	PQ40 (poly-Si)	12	-5.0	N	6
BP Solar	BP555 (x-Si)	1	+0.2	N	7
Siemens Solar	SM50H (x-Si)	1	+0.2	N	7
Atersa	A60 (x-Si)	1	-0.8	N	7
Isofoton	I110 (x-Si)	1	-0.8	N	7
Kyocera	KC70 (poly-Si)	1	-0.2	N	7
Atersa	APX90 (poly-Si)	1	-0.3	N	7
Photowatt	PW750 (poly-Si)	1	-1.1	N	7
BP Solar	MSX64 (poly-Si)	1	0.0	N	7
Shell Solar	RSM70 (poly-Si)	1	-0.3	N	7
Würth Solar	WS11007 (CIS)	1	-2.9	N	7
USSC	SHR-17 (a-Si)	6	-1.0	Y	8
Siemens Solar	M55 (x-Si)	10	-1.2	Y	9
[not given]	[not given] (CdTe)	8	-1.3	Y	9
Siemens Solar	M10 (x-Si)	5	-0.9	N	10
Siemens Solar	Pro 1 JF (x-Si)	5	-0.8	N	10
Solarex	MSX10 (poly-Si)	5	-0.7	N	10
Solarex	MSX20 (poly-Si)	5	-0.5	N	10

Table 1. PV module degradation rates published within the past five years.

31st IEEE PVSC p.2085 (2006)

Manufacturer	Module Type	Exposure (years)	Degradation Rate (% per year)	No. of Modules
BP Solar	BP 585F (x-Si)	7	-0.30	2
BP Solar	BP 270F (x-Si)	8	-0.32	2
Kyocera	KC40 (poly-Si)	4.5	-0.91	2
Solarex	SX40U (poly-Si)	5.6	-0.01	2
Siemens	PC-4-JF (x-Si)	9.5	-0.51	1
Photowatt	PWX500 (poly-Si)	6	-0.13	1
Sanyo	H124 (a-Si/x-Si HIT)	2.6	-1.59	1
ECD Sovonix	[none] (a-Si) †	12	-1.17	1
Solarex	SA5 (a-Si)	12	-0.69	1
Uni-Solar	UPM-880 (a-Si)	12	-0.62	2
APS	EP55 (a-Si)	9.5	-1.62	2
Solarex	MST-22ES (a-Si)	6	-0.86	1
Uni-Solar	US-32 (a-Si)	8.5	-0.39	1
EPV	EPV40 (a-Si) †	6.5	-1.40	2
BP Solarex	MST-50 MV (a-Si)	4	-2.47	2
Siemens	ST40 (CIS) †	7	-1.63	1
Solar Cells Inc.	[none] (CdTe) †	10	-1.84	1

Table 2. PV module degradation rates obtained from monthly PTC regressions of PERT I-V data. Module types marked with a '†' indicate non-production prototypes that are not indicative of current products.

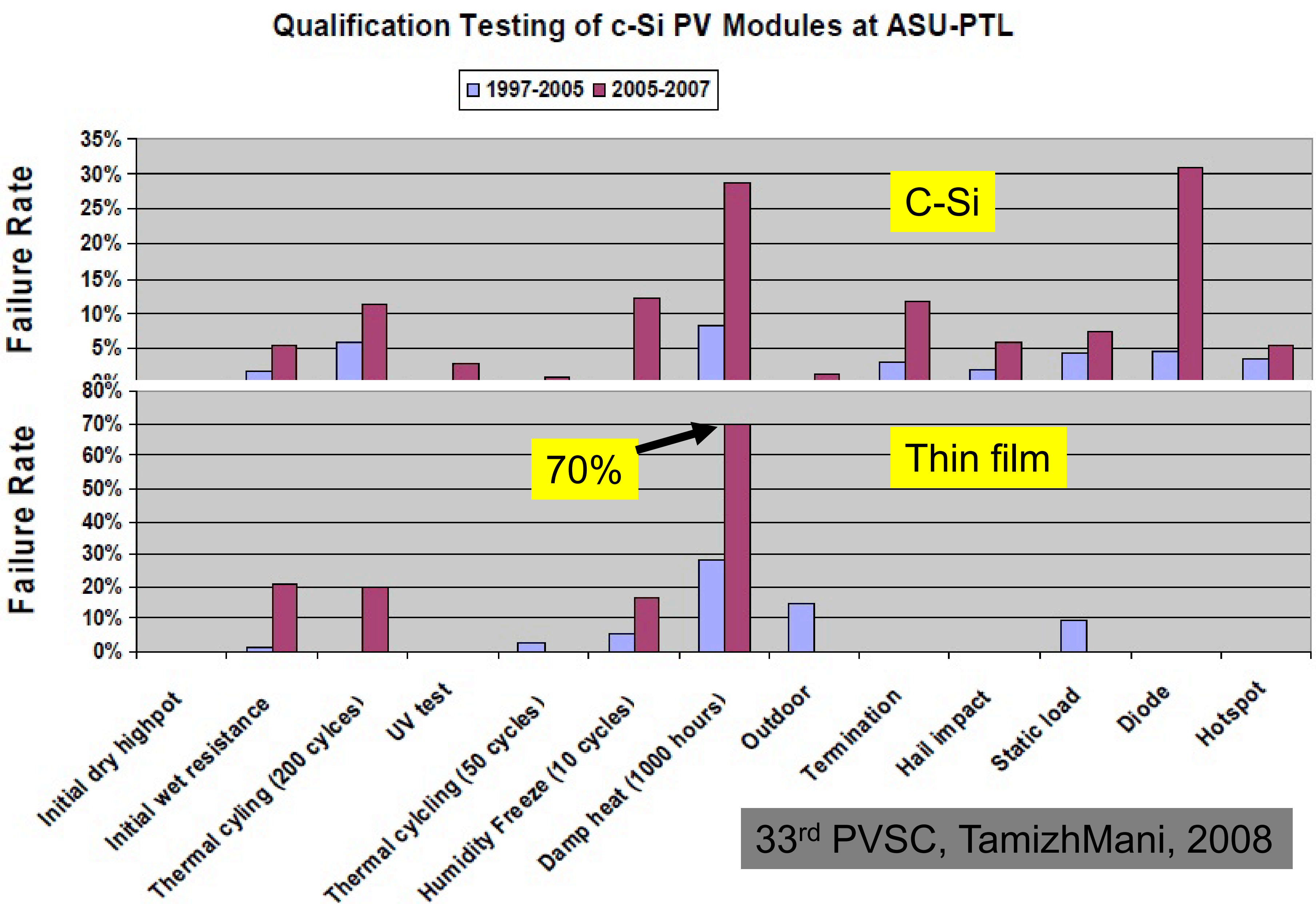
Summary of some studies on PV module field degradation around the w

Vazquez, Prog. in PV (2008)

Location	Test duration	Module Tech.	Degradation rate (%/year)
Perth (Australia) *Temperate climate*	16–19 months	c-Si	0·5–2·7
		p-Si	1·0–2·9
		a-Si	18·8
		CIS	12·6
Mesa, Arizona (USA) *Desert climate*	2·4–4 years	c-Si	0·4
	2·4–2·7 years	p-Si	0·53
	2·7–6·7 years	a-Si	1·16 (6·7year) to 3·52 (2·7year)
Trinidad, California (USA) *Cool coastal climate*	11 years	c-Si	0·4
Hamamatsu (Japan) *Temperate climate*	10 years	c-Si	0·62
Golden, Colorado (USA) *Mountain continental climate*	8 years	c-Si	0·75
Ispra (Italy) *Temperate climate*	22 years	p-Si	0·3 (Silicone)
		c-Si	0·67 (EVA)
Lugano (Switzeland) *Temperate climate*	20 years	c-Si	0·53
Negev desert (Israel) *Desert climate*	3·4 years	p-Si	1·3

About two-thirds of degradation rates are measured as < 1%/yr

Past success does not guarantee future success



33rd PVSC, TamizhMani, 2008

Current/recent studies

With highlights of presentations at SPIE this week

Improved stress testing

Stress tests need to be
- More complete (all stresses)
- More thorough
- More quantitative
- Faster
- Less expensive

Development and application of a UV light source for PV-module testing
Wed. 8:30 am Michael Kohl (7412-2)

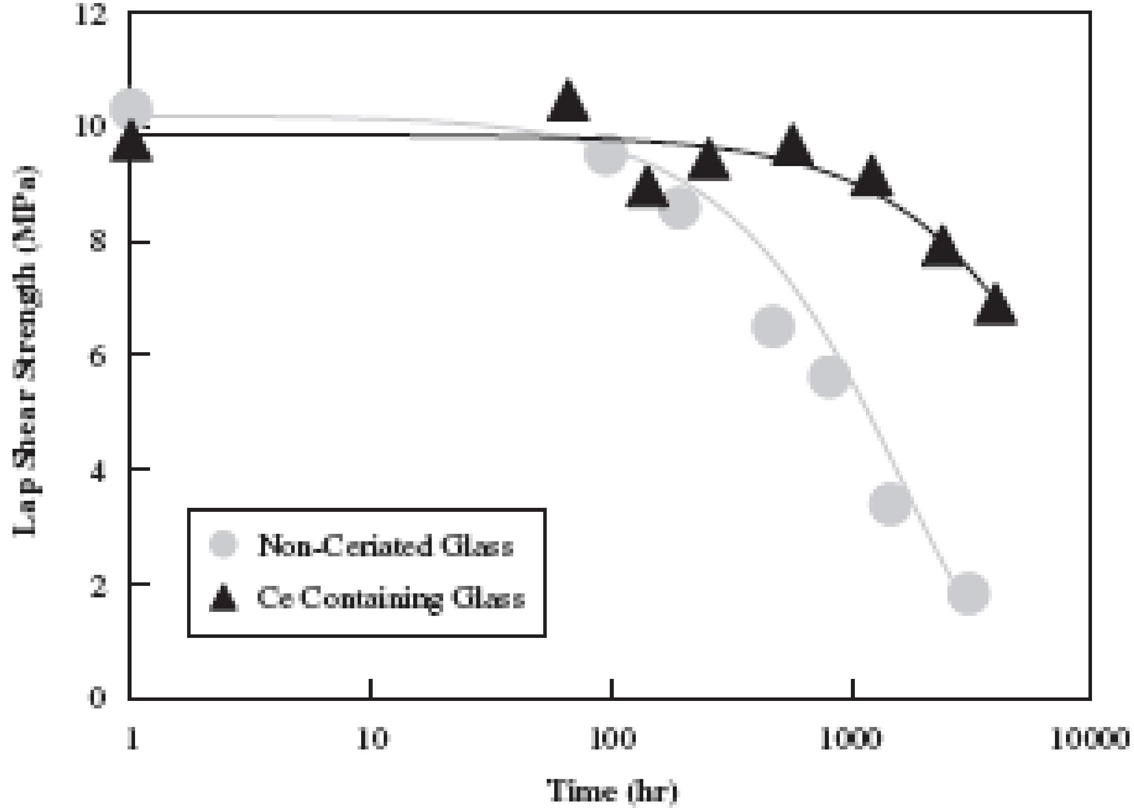
Outdoor monitoring and high voltage bias testing of PV modules as necessary test for assuring long-term reliability
Thurs. 3:50 pm Neelkanth Dhere (7412-28)

Accelerated stress testing of hydrocarbon-based encapsulants for medium-concentration CPV applications 34th PVSC Michael Kempe

Application of the NREL test-to-failure protocol for PV modules
Silicon Workshop (Aug 2009) Peter Hacke

Improved performance requires vigilance for reliability

Removing Ce from glass may improve performance and decrease cost, but will it affect reliability?

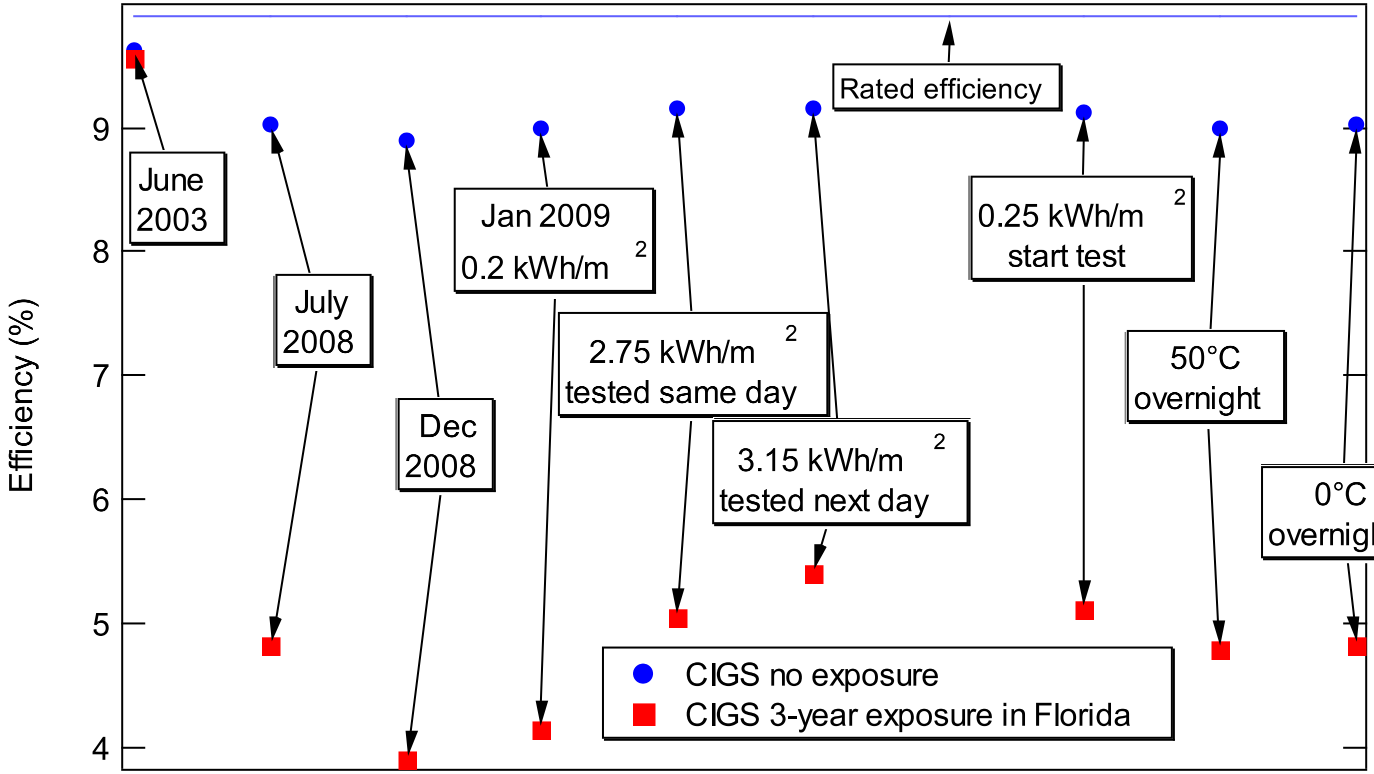


60°C/60% humidity; 2.5 suns UV

Effects of cerium removal from glass on photovoltaic module performance and stability
Thurs. 3:05 pm Michael Kempe (7412-26)

Separate reversible from irreversible changes

After exposure, thin-film modules show reversible and irreversible changes



One module showed 30% increase

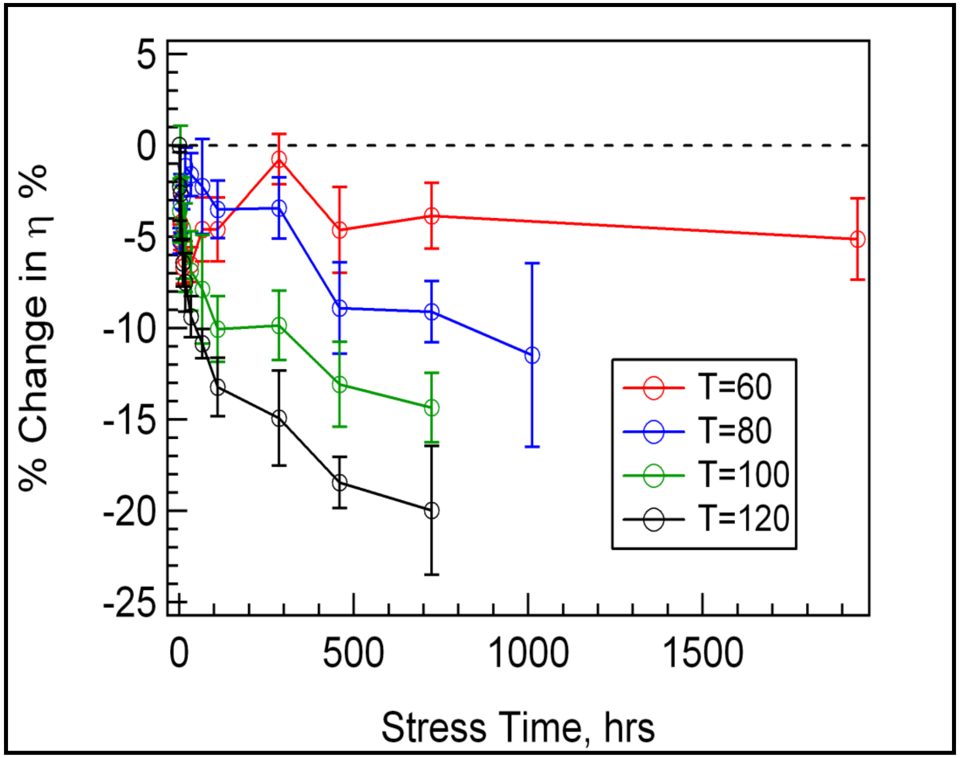
Striving for a standard protocol for preconditioning or stabilization of polycrystalline thin-film PV modules

Wed. 9:15 am Joseph del Cueto (7412-3)

Light-soaking and power measurements of thin-film modules

Mon. 9:35 am Karl-Anders Weiss (7409-24)

Thin-film layers can change

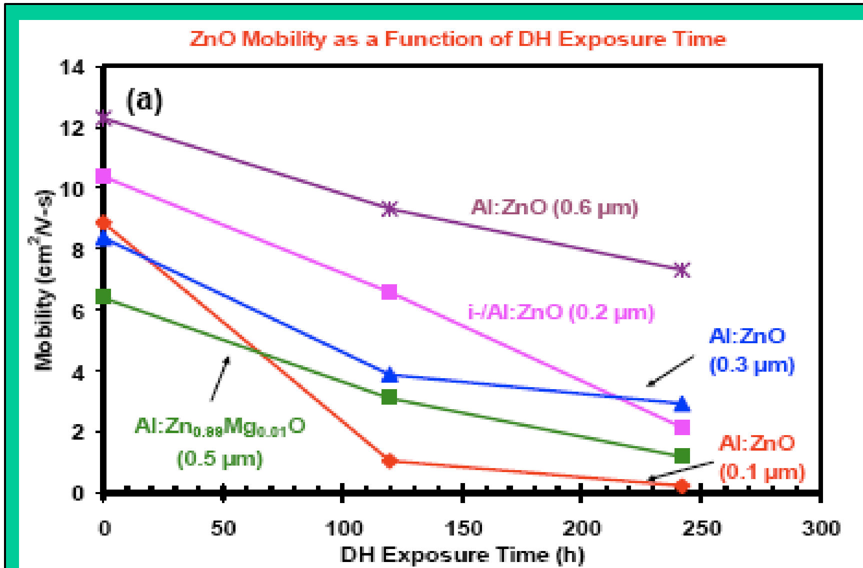


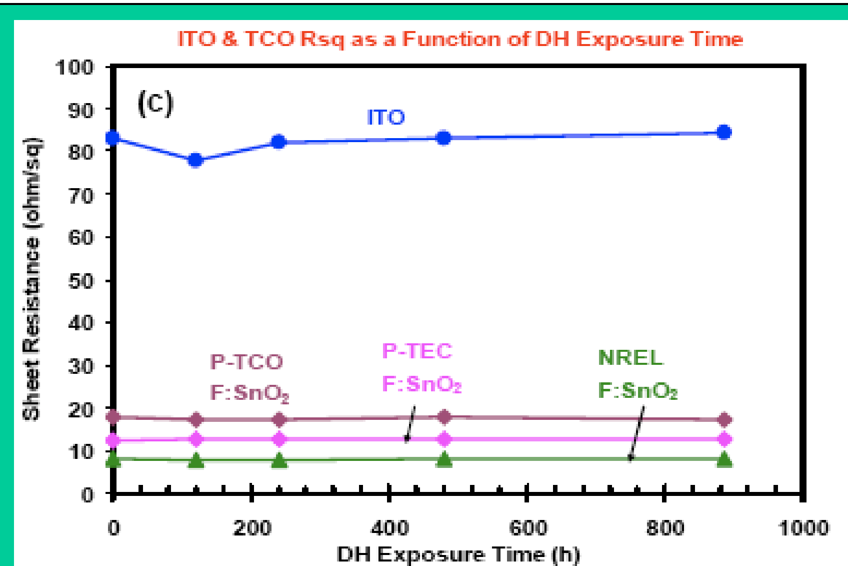
Change in CdTe cells after annealing (Albin)

Degradation and capacitance voltage hysteresis in CdTe devices
Thurs. 10:30 am David Albin (7412-18)
Understanding and mitigating effects of nonuniformities on reliability of thin-film PV
Thurs. 11:40 am Victor Karpov (7412-21)
The effect of metal foil tape degradation on the long-term reliability of PV modules
Thurs. 3:30 pm Rob Sorensen (7412-27)

Moisture can degrade TCO

Flexible configuration is especially difficult: harden the cell or the package?





ITO and SnO_2 are stable in 85% humidity, 85°C

Pern, 2008

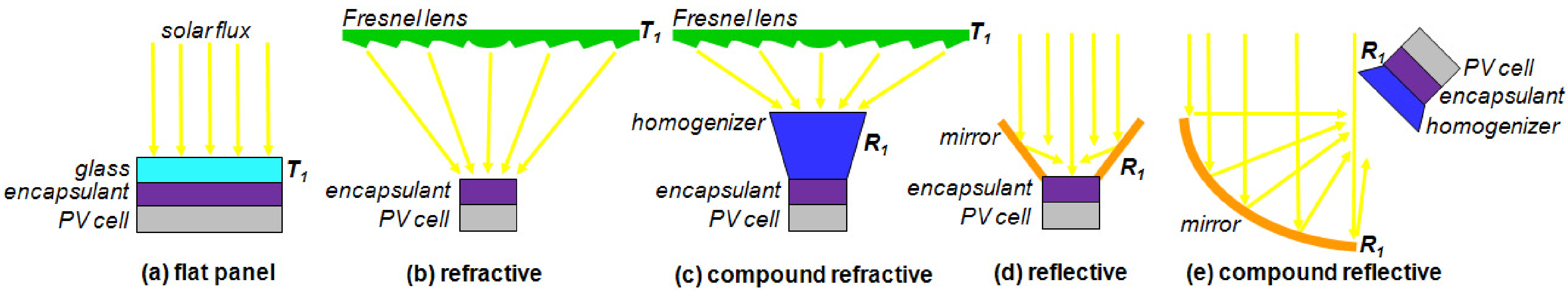
Stability of TCO window layers for thin-film CIGS solar cells upon damp heat exposures

Thurs. 10:55 am Rajalakshmi Sundaramoorthy (7412-19)

Thurs. 11:15 am John Pern (7412-20)

When is concentrated UV a problem for CPV?

Does concentrated sunlight at cell contain damaging UV dose?

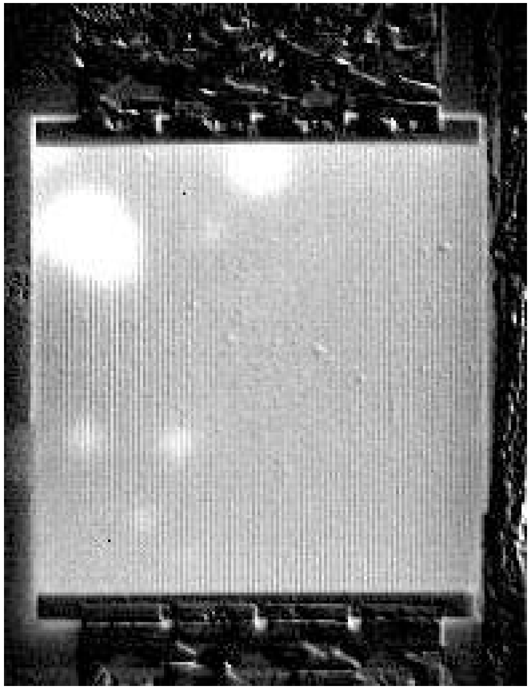


Analysis of transmitted optical spectrum enabling accelerated testing of CPV designs
Wed. 11:35 am David Miller (7407-16)

Are optics durable?

Stress in large-area optics for solar concentrators
Wed. 10:25 am Ralf Leutz (7412-5)

Bond to heat sink is R&D topic for CPV



IR image of void in die attach

Reliability testing the die attach of CPV cell assemblies
34th PVSC Nick Bosco

Summary

- Solar is growing rapidly; could become a significant source of electricity within 10 yrs
- Excellent performance of silicon modules has been demonstrated in the field; but new products may repeat old mistakes
- Inverters currently dominate system failures
- Many R&D needs are best met by community working together
- *Need to ensure reliability to build foundation for a solar-powered world*

Planet powered by renewable energy By year 2100 or before?

Thank you to :
Dave Albin
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Tom Moricone
Bill Marion
David Miller
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John Pern
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Kent Terwilliger
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