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Photovoltaic Reliability R&D Toward a Solar-Powered World

Sarah Kurtz and Jennifer Granata
with help from many others

National Renewable Energy Laboratory,
Sandia National Laboratories

SPIE

San Diego, CA

August 2-7, 2009

NREL/PR-520-46412



- 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



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How fast can a world change?





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Solar power is within reach

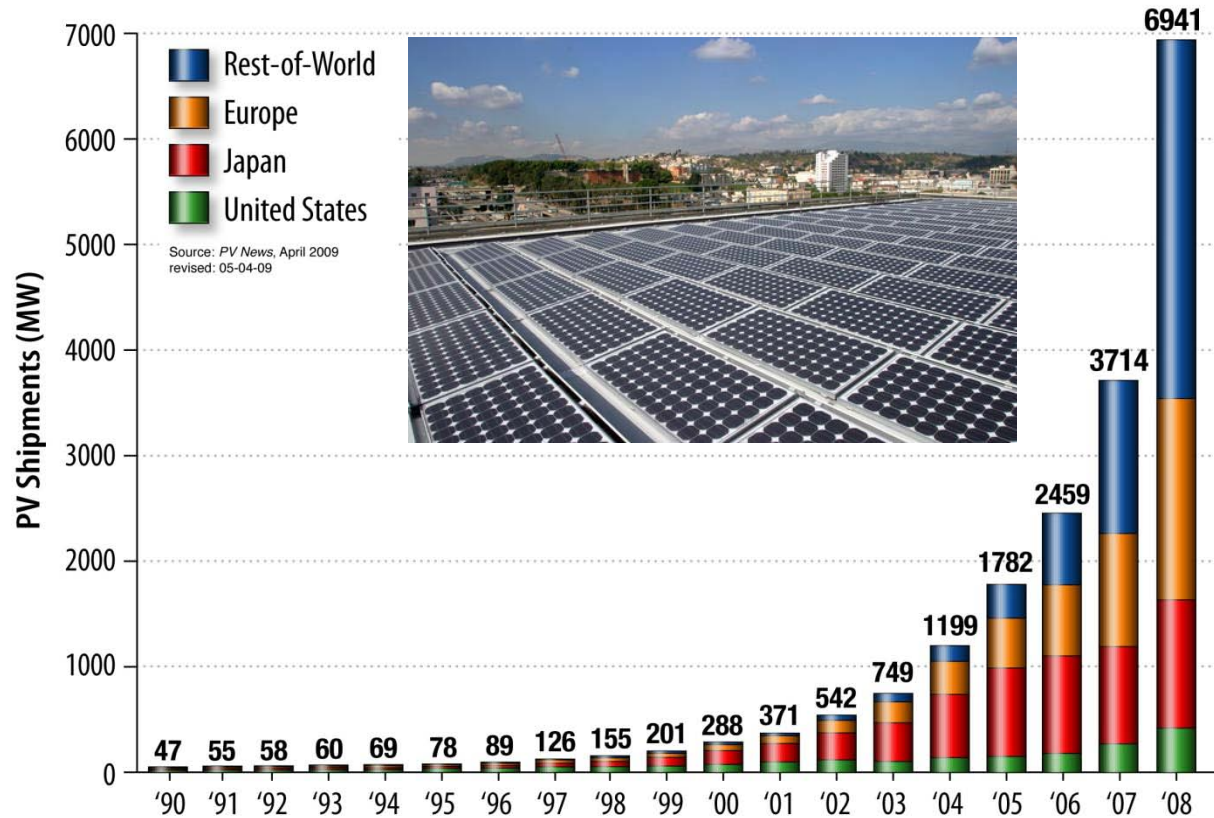


What do we need to do to create a
solar-powered world?





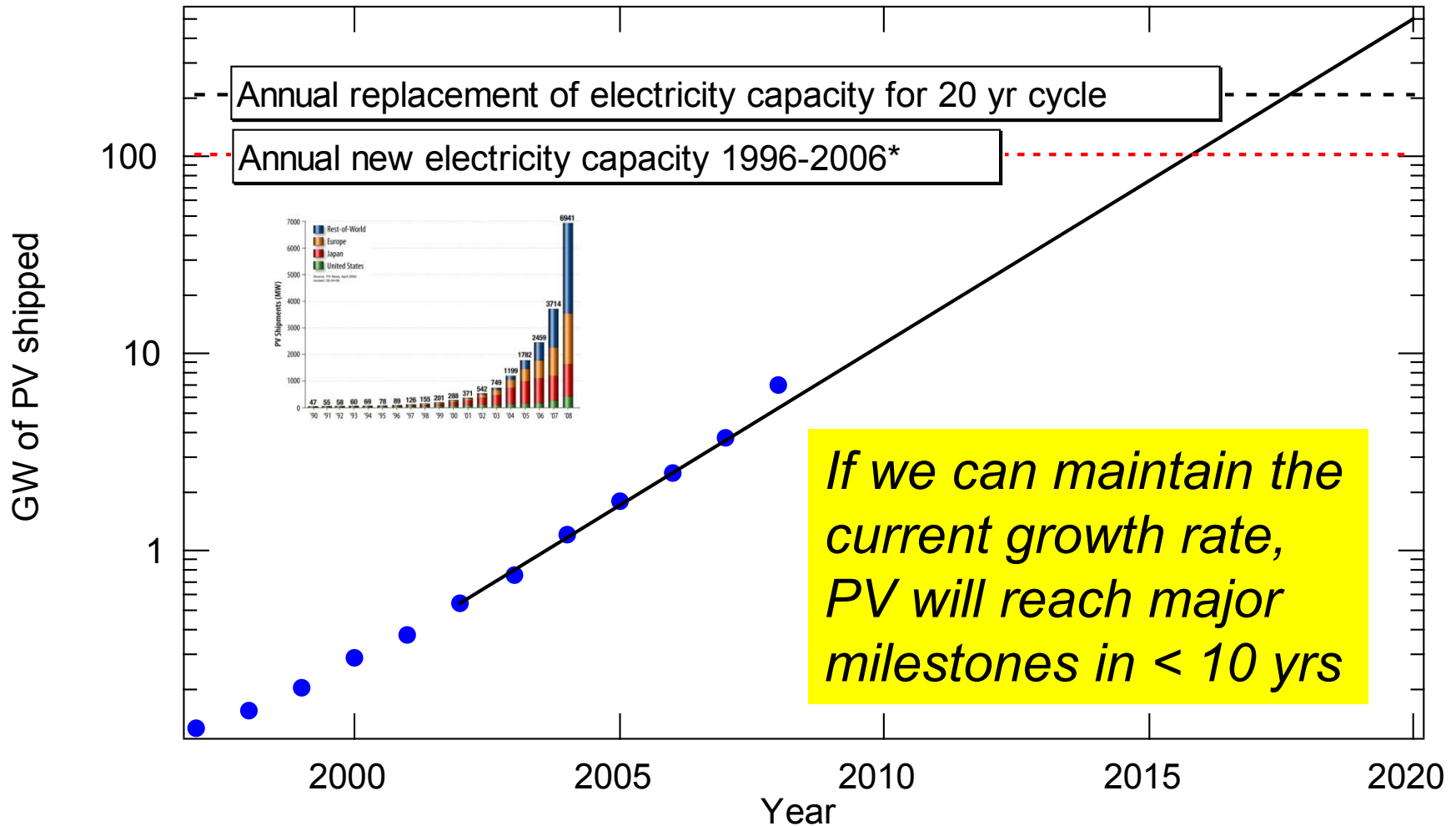
Growth of PV industry



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

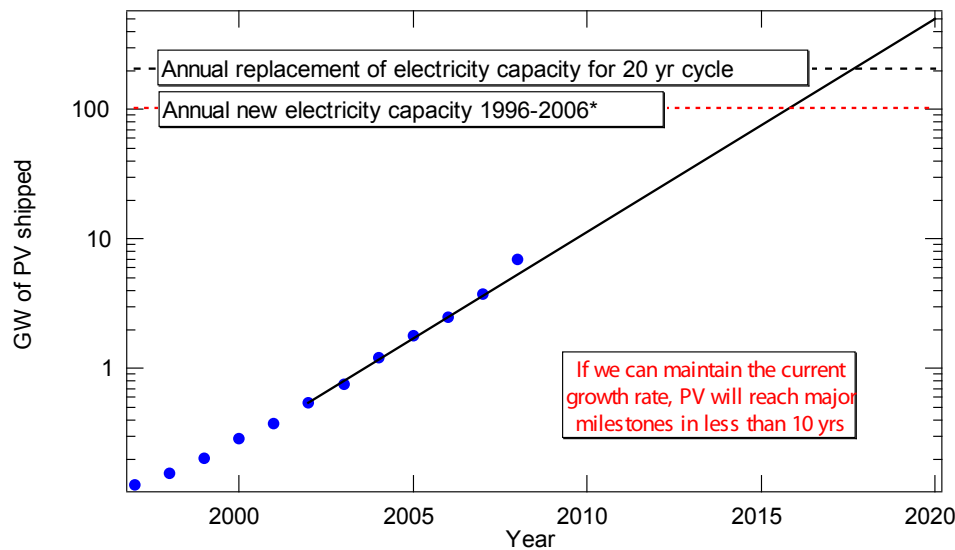


Improved reliability helps to **reduce life-cycle cost**:

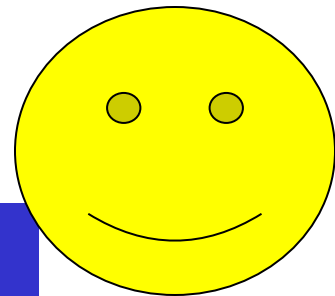
- Longer lifetime
- Slower degradation
- Lower O&M costs

Improved reliability **improves customer satisfaction**

- Good performance builds customer confidence
- Better confidence inspires investors



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



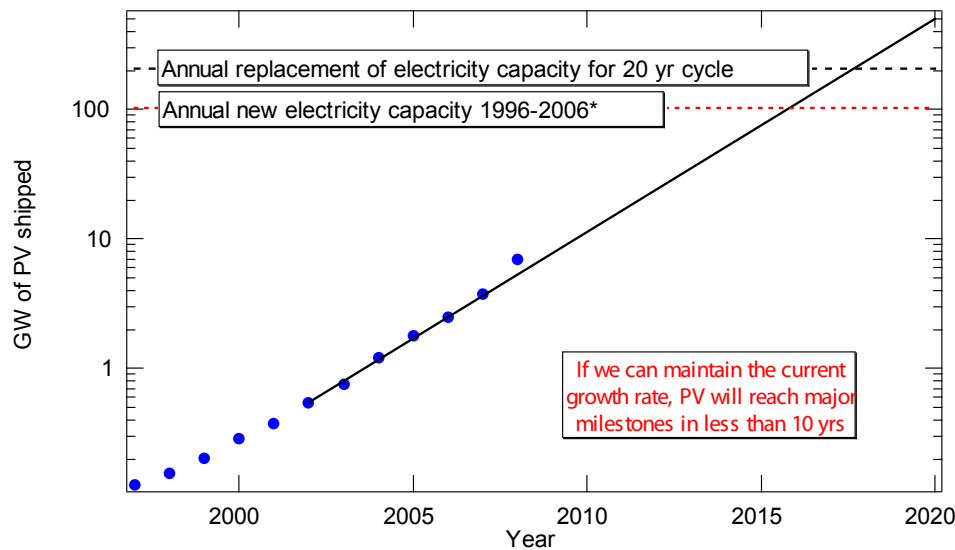


Improved reliability helps to **reduce life-cycle cost**:

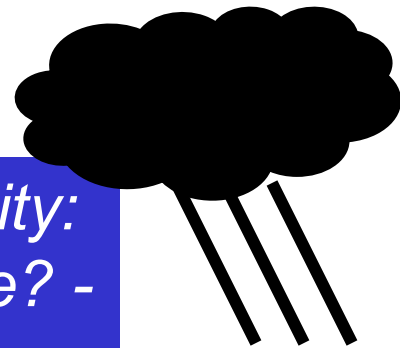
- Longer lifetime
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*Without reliability:
a Ponzi scheme? -
Bill Marion*





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.



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Building a solar-powered world

Years of standards development/field experience



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

Universities

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

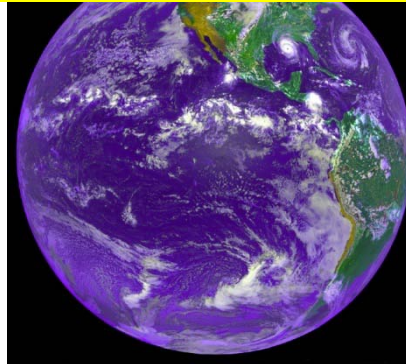
National labs

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

Years of standards development/field experience



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

Universities

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- Original research to extend useful PV-reliability knowledge

National labs

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Years of standards development/field experience



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)*



*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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Reliability should be considered from day 1 forward

Lots of tools:

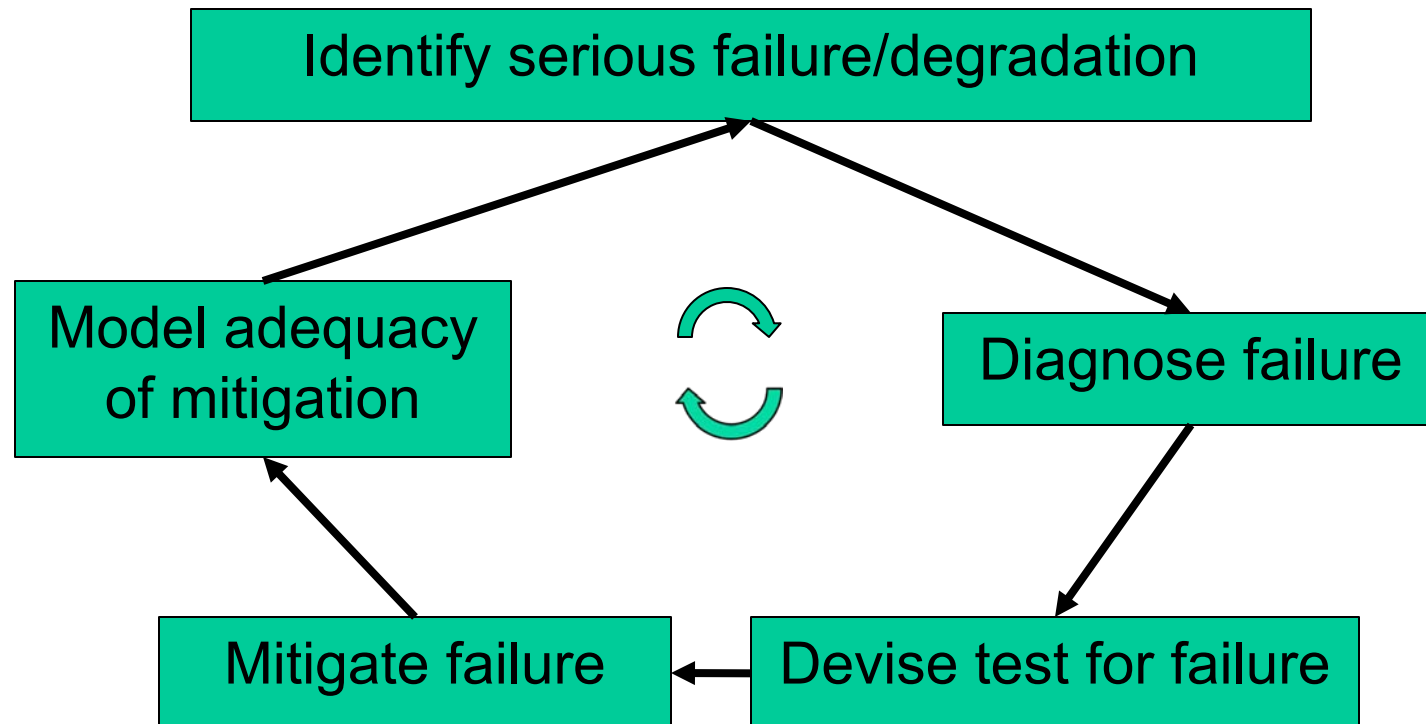
- Advanced Product Quality Planning
- Design Failure Modes Effects and Analysis
- Fault Tree Analysis
- Design for Manufacturability
- Design Review Based on Failure Mode (Toyota)



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!





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



- 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 MΩm² 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



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Quality assurance

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Predict reliability

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



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



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- Test for failures
- Mitigate



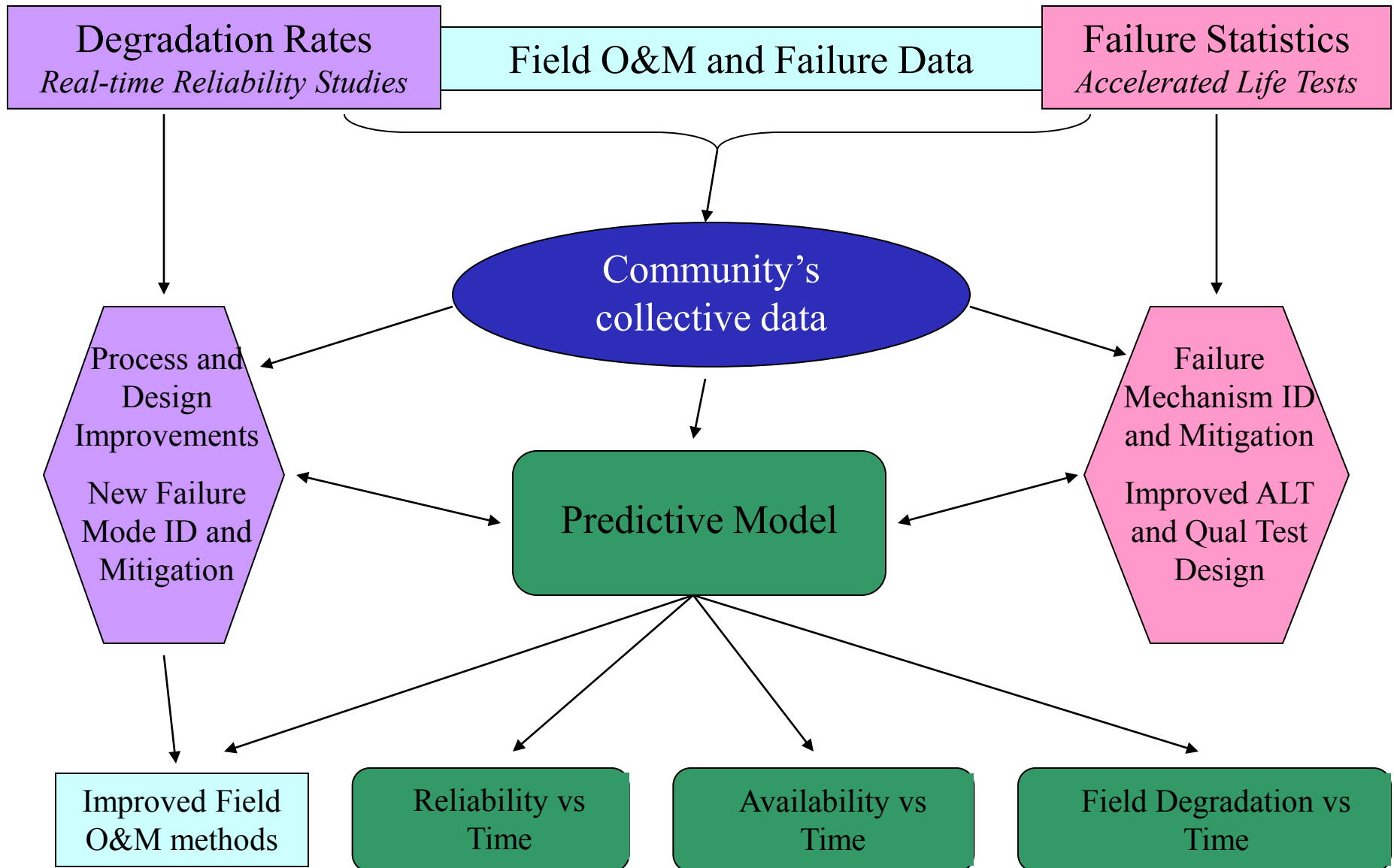
Quality assurance

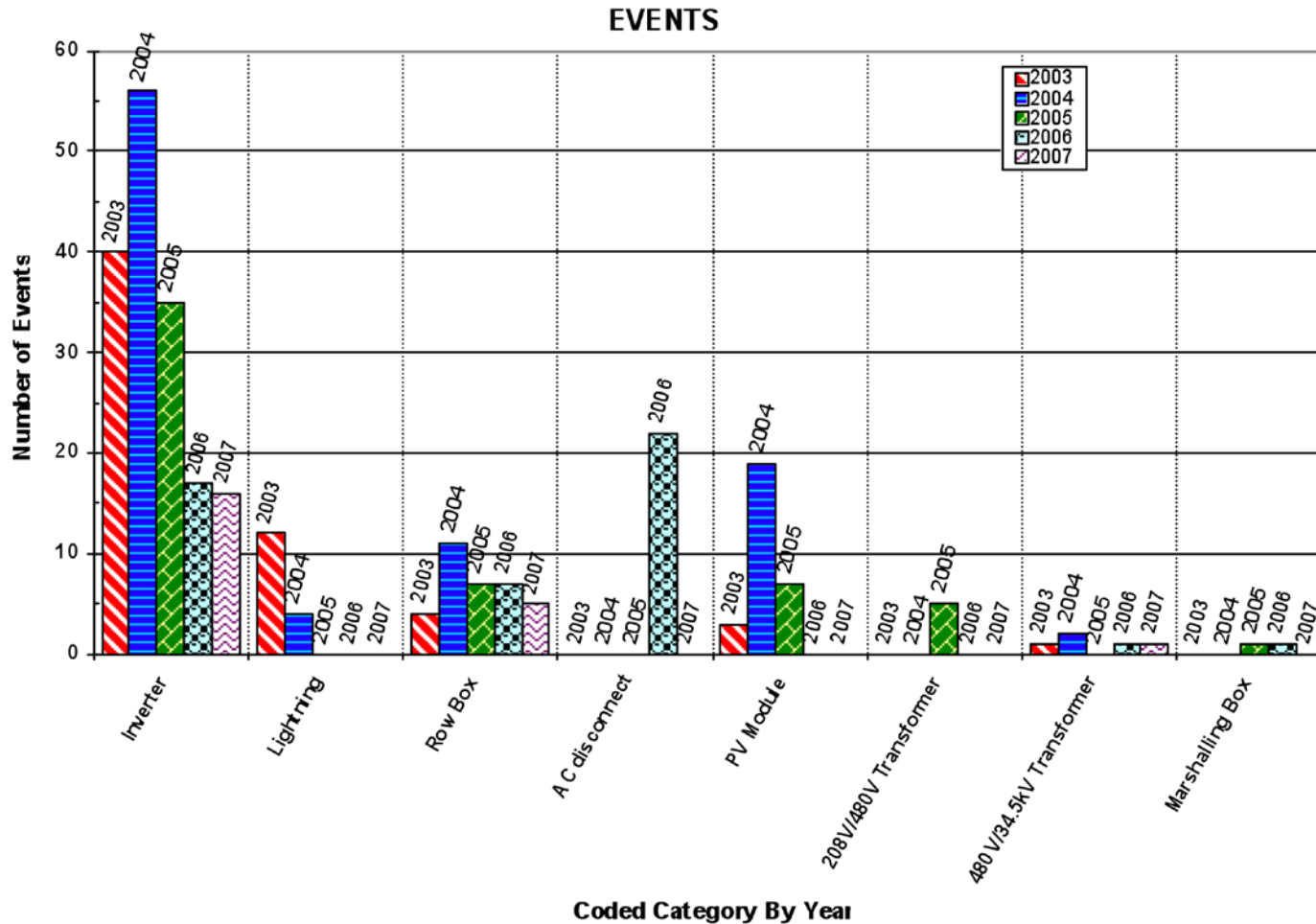
- Test raw and refined materials
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Predict reliability

- Identify useful tests
- Understand all components
- Make predictions





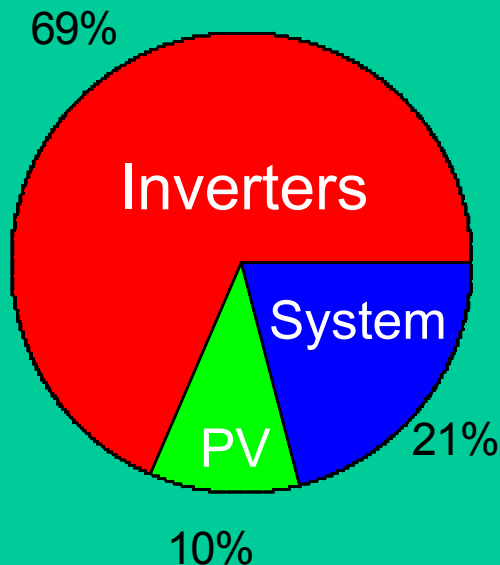
Reliability and availability analysis of a fielded PV system
34th PVSC Elmer Collins



Systems Approach:

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

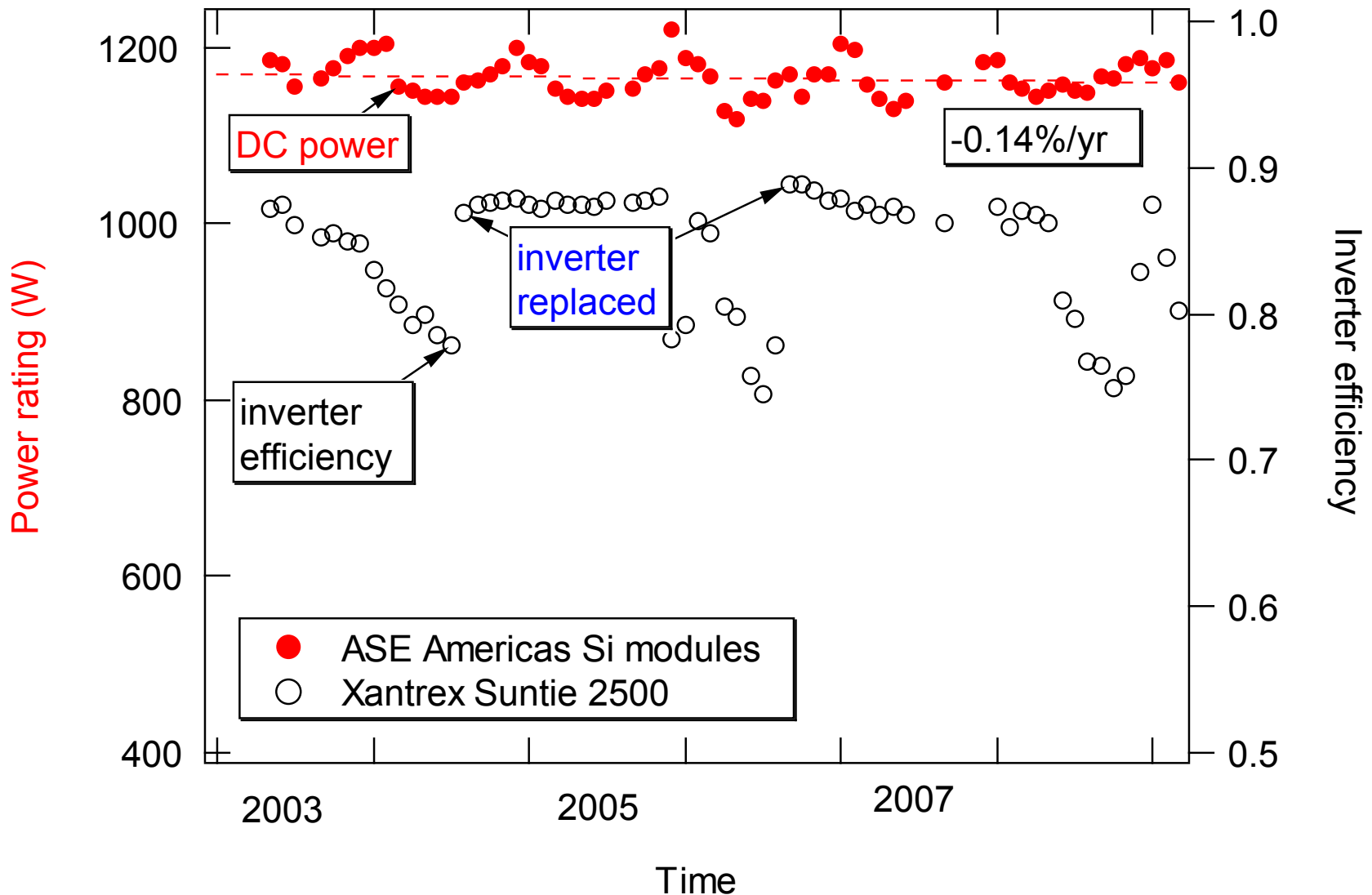
Unscheduled maintenance costs



(Prog. PV 2008; 16:249)

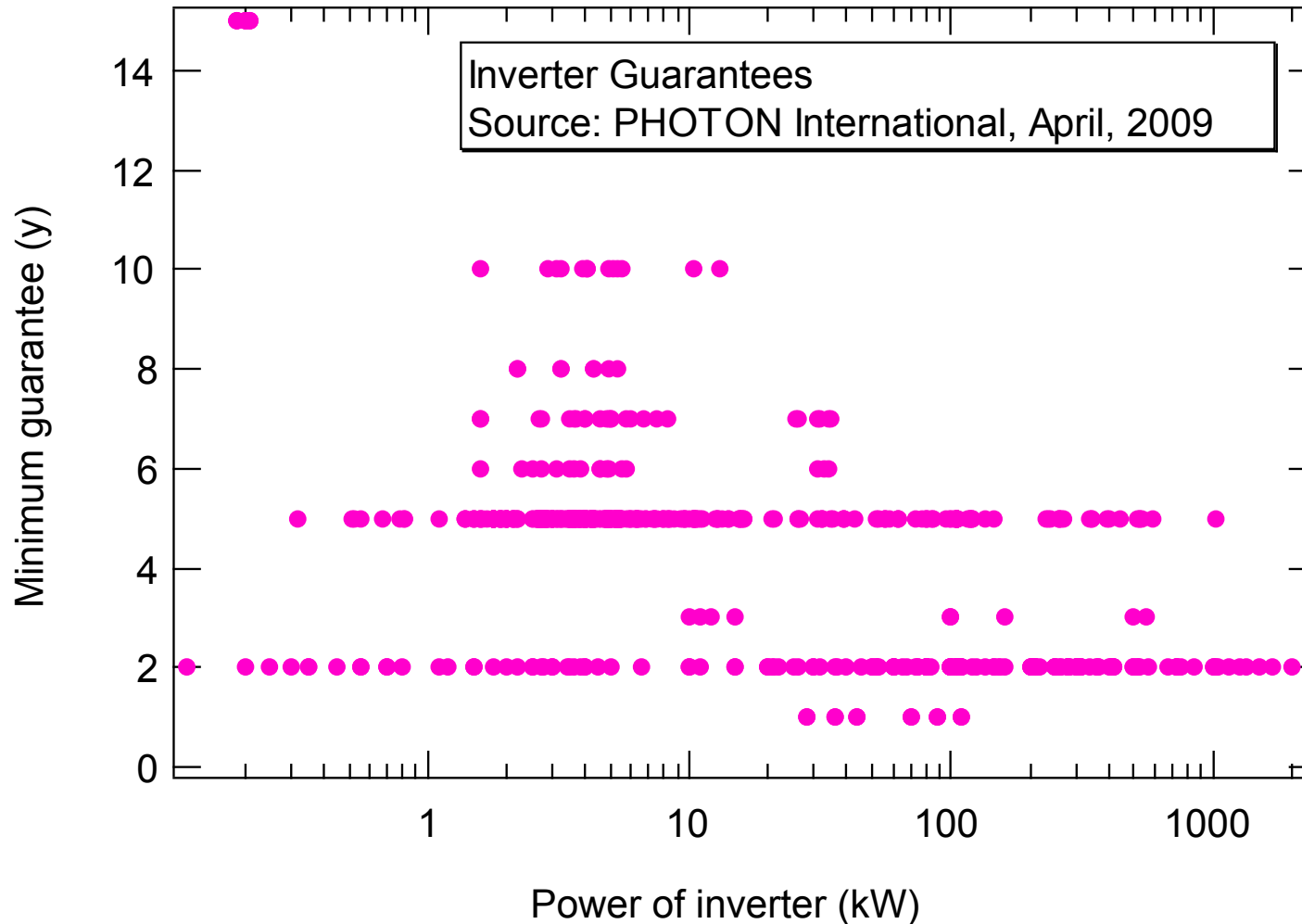
Studies of c-Si systems typically show few module failures; Inverters typically dominate O&M cost

Reliable Si modules are demonstrated, but not guaranteed





Inverters are improving, but still need more



Limited
warranties
may be
longer

Qualification/p
erformance
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

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

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.

Location	Test duration	Module Tech.	Degradation rate (%/year)
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Vazquez, Prog. in PV (2008)

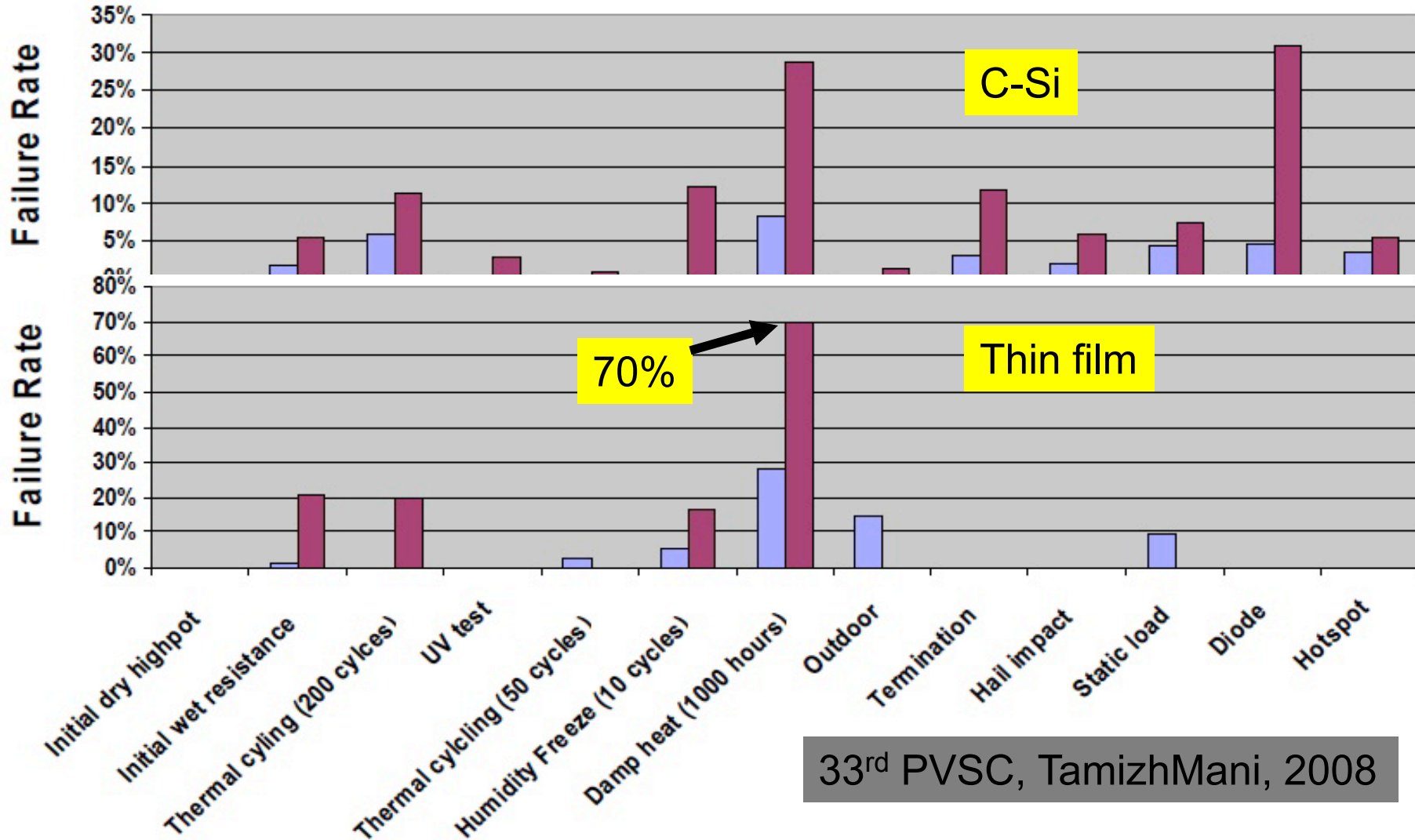
Perth (Australia)	16–19 months	c-Si	0.5–2.7
<i>Temperate climate</i>		p-Si	1.0–2.9
		a-Si	18.8
		CIS	12.6
Mesa, Arizona (USA)	2.4–4 years	c-Si	0.4
<i>Desert climate</i>	2.4–2.7 years	p-Si	0.53
	2.7–6.7 years	a-Si	1.16 (6.7 year) to 3.52 (2.7 year)
Trinidad, California (USA)	11 years	c-Si	0.4
<i>Cool coastal climate</i>			
Hamamatsu (Japan)	10 years	c-Si	0.62
<i>Temperate climate</i>			
Golden, Colorado (USA)	8 years	c-Si	0.75
<i>Mountain continental climate</i>			
Ispra (Italy)	22 years	p-Si	0.3 (Silicone)
<i>Temperate climate</i>			
		c-Si	0.67 (EVA)
Lugano (Switzerland)	20 years	c-Si	0.53
<i>Temperate climate</i>			
Negev desert (Israel)	3–4 years	p-Si	1.3
<i>Desert climate</i>			

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



Qualification Testing of c-Si PV Modules at ASU-PTL

1997-2005 2005-2007





Current/recent studies

With highlights of presentations at SPIE this week



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)

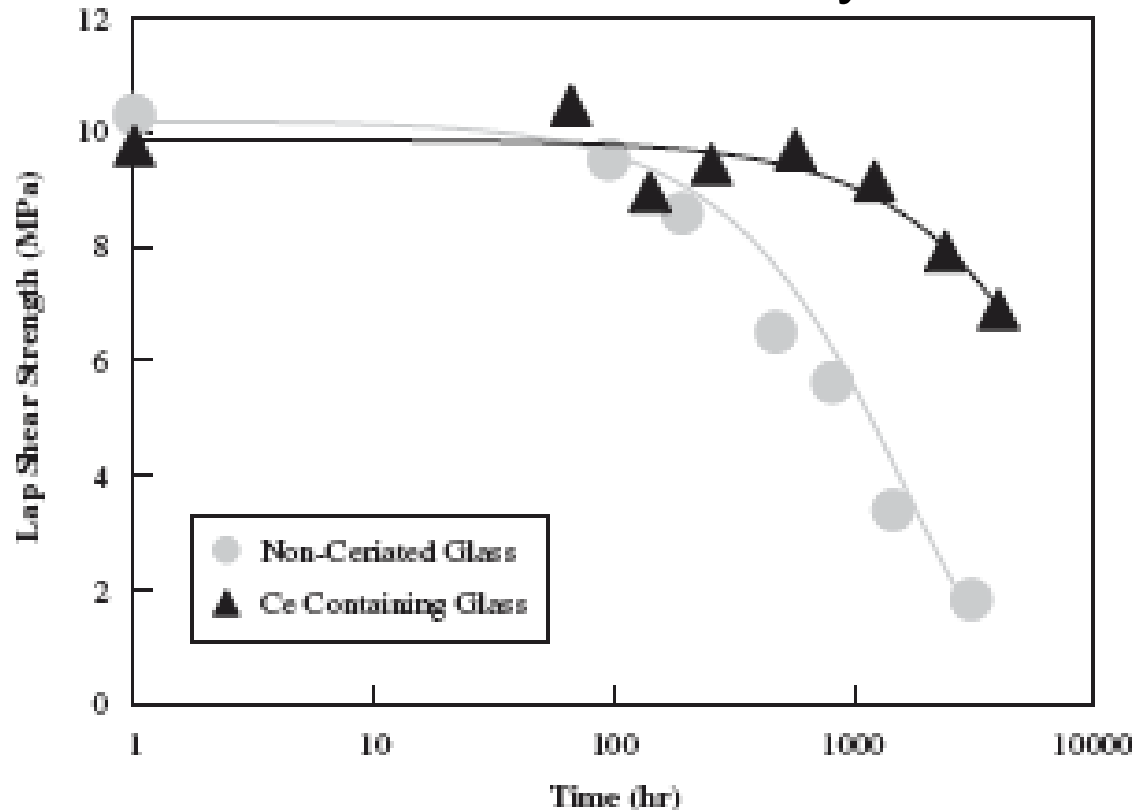
Outdoor monitoring and high voltage bias testing of PV modules as
necessary test for assuring long-term reliability
Thurs. 3:50 pm Neelkanth Dhere (7412-28)

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



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



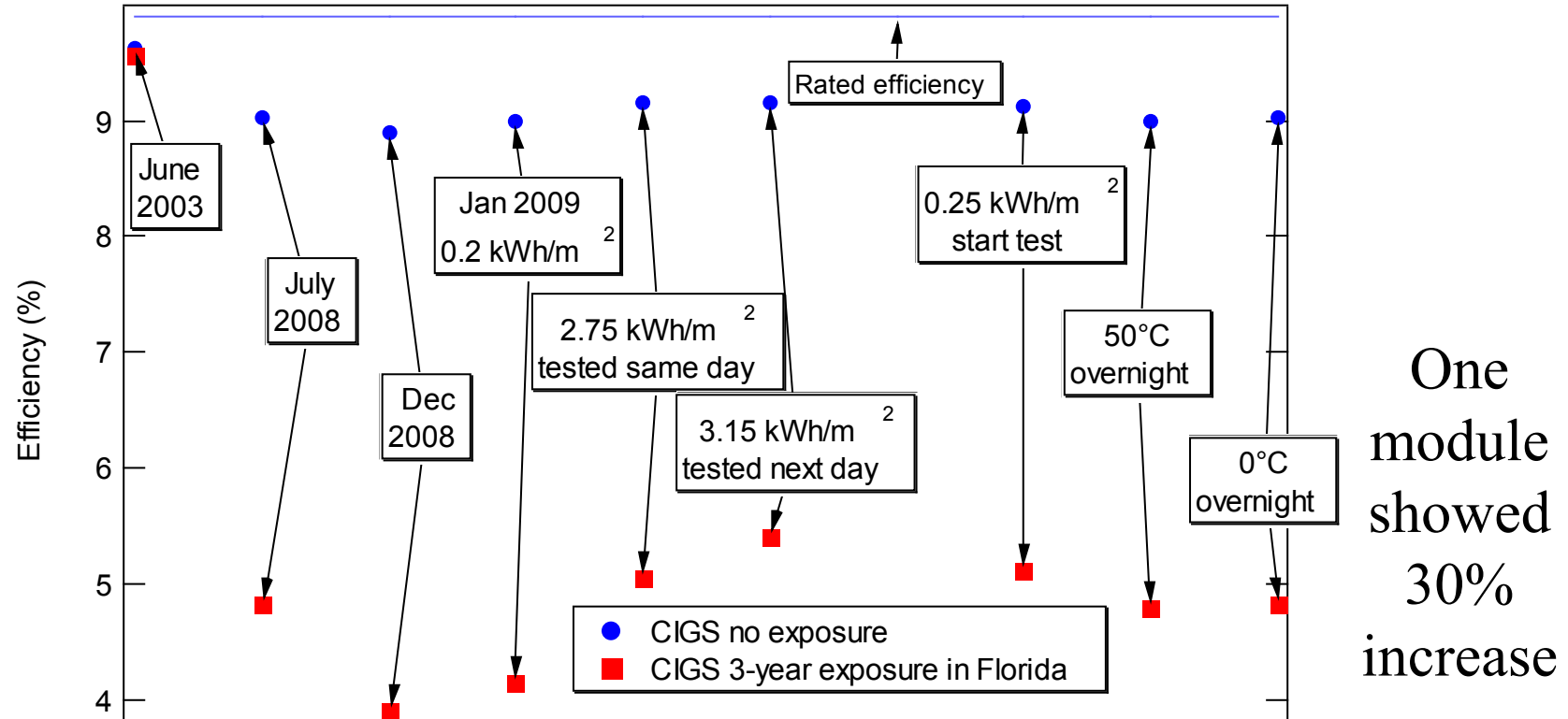
60°C/60% humidity; 2.5 suns UV

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

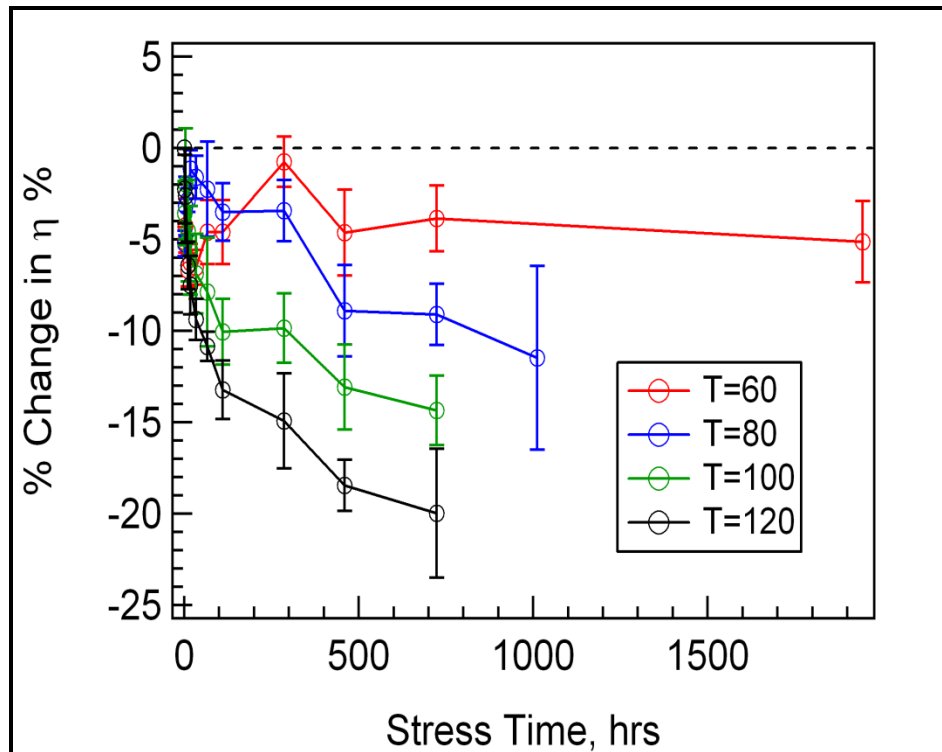


Striving for a standard protocol for preconditioning or stabilization of polycrystalline thin-film PV modules

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)



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

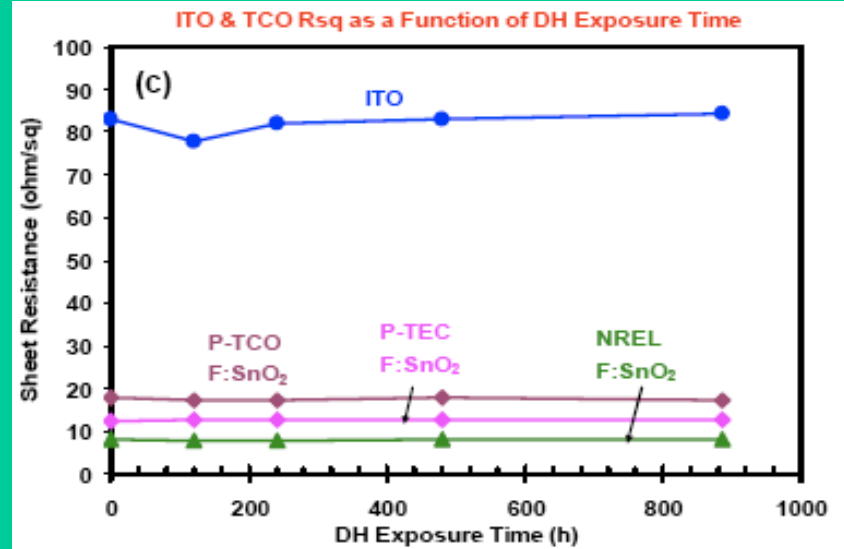
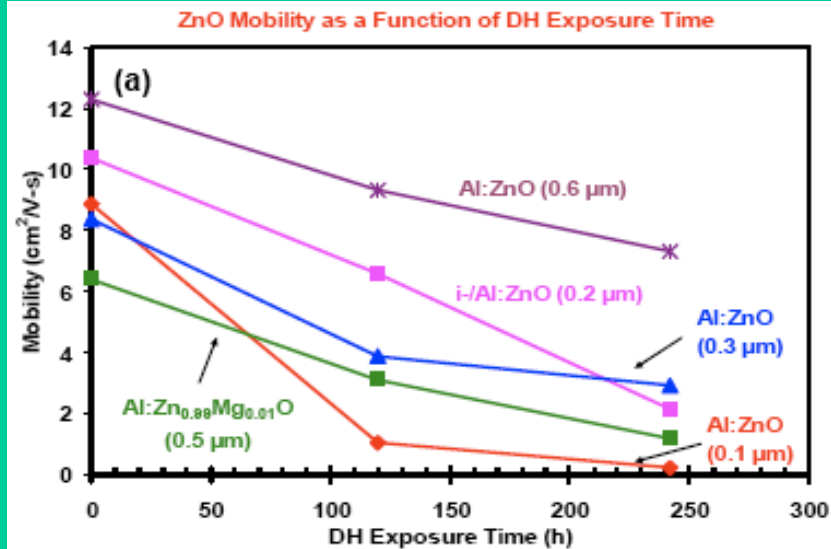
Thurs. 11:40 am Victor Karpov (7412-21)

The effect of metal foil tape degradation on the long-term reliability of PV modules

Thurs. 3:30 pm Rob Sorensen (7412-27)



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



ITO and SnO₂ are stable in 85% humidity, 85°C

Pern, 2008

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

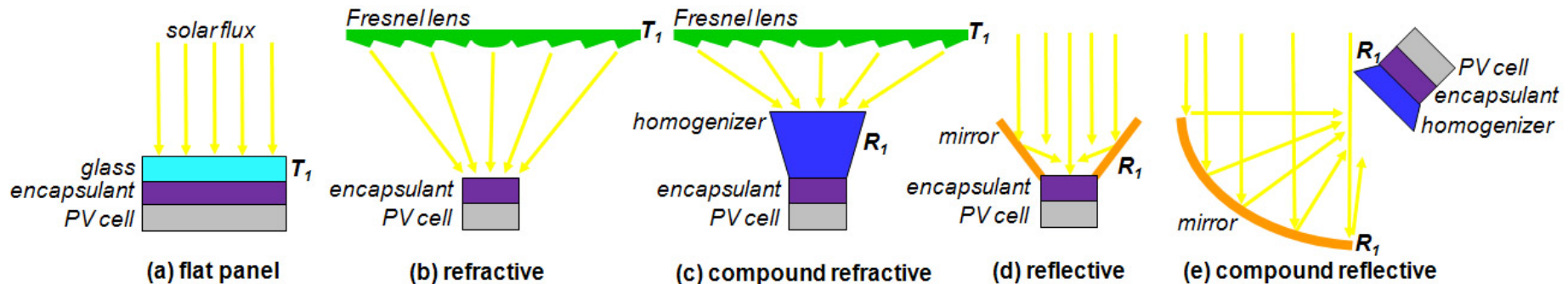
Thurs. 10:55 am Rajalakshmi Sundaramoorthy (7412-19)

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?



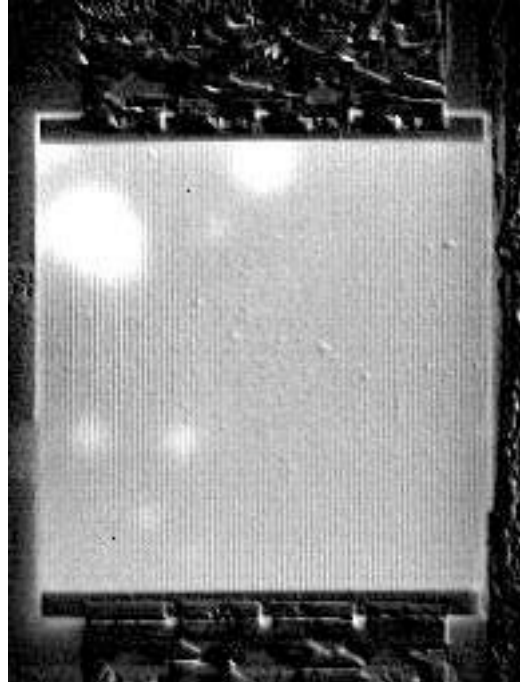
Analysis of transmitted optical spectrum enabling accelerated testing of CPV designs

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)



IR image of void in die attach

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



- 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 for
your attention!

Thank you to :

Dave Albin
Glenn Alers
Nick Bosco
Joe del Cueto
Chris Deline
Ed Gelak
Steve Glick
Peter Hacke
Dirk Jordan
Mike Kempe
Tom Moricone
Bill Marion
David Miller
Matt Muller
John Pern
Jose Rodriguez
Bill Sekulic
Ryan Smith
Kent Terwilliger
David Trudell

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Mike Mundt
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Peggy Rhodes
Jeff Mahn
Rob Sorensen
Many others

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