National Renewable Energy Laboratory
Innovation for Our Energy Future

Reliability Challenges for Solar Energy

NREL

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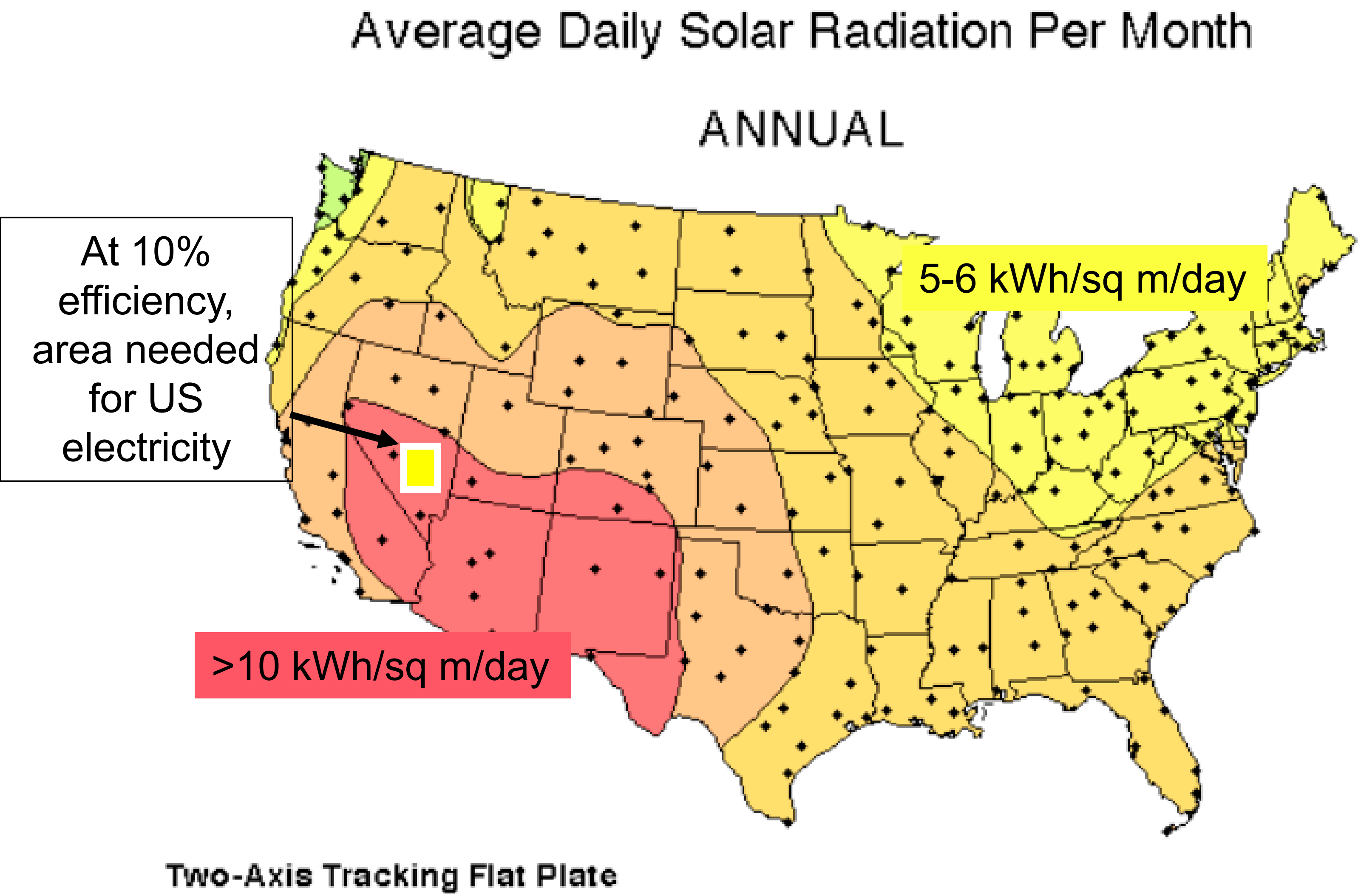
Outline

- Solar – a huge success, but still a long way to go
- Importance of reliability to success of solar
- A little history
- Reliability issues specific to three key approaches
  - Silicon – continuous improvement requires continued testing; quantitative predictions
  - Thin film – uniform, large-area deposition for product development and sensitivity to moisture; metastabilities
  - Concentrator – product development; simultaneous optimization of multiple components

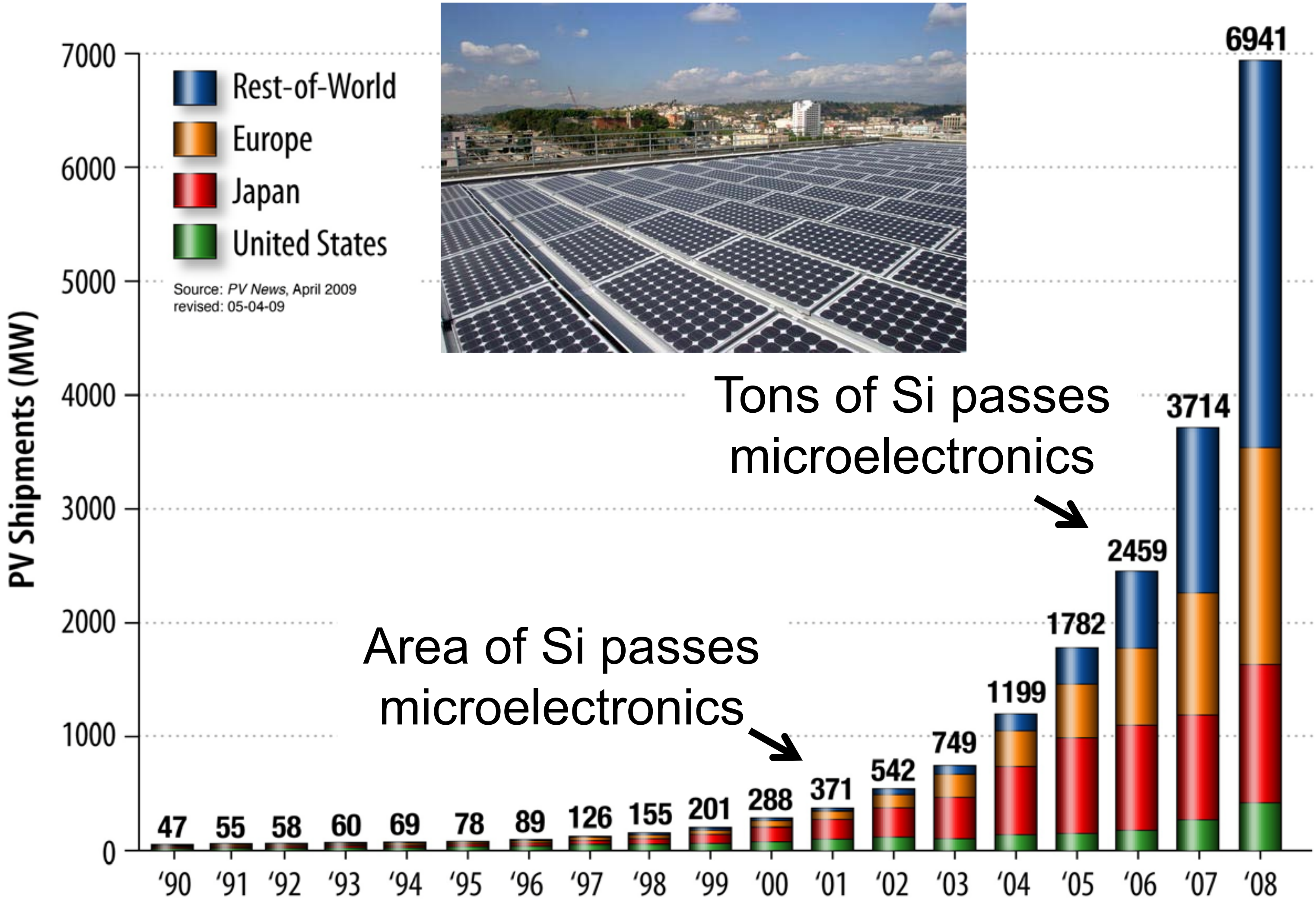
Solar energy is abundant

Convenient truth: small area can supply our energy needs

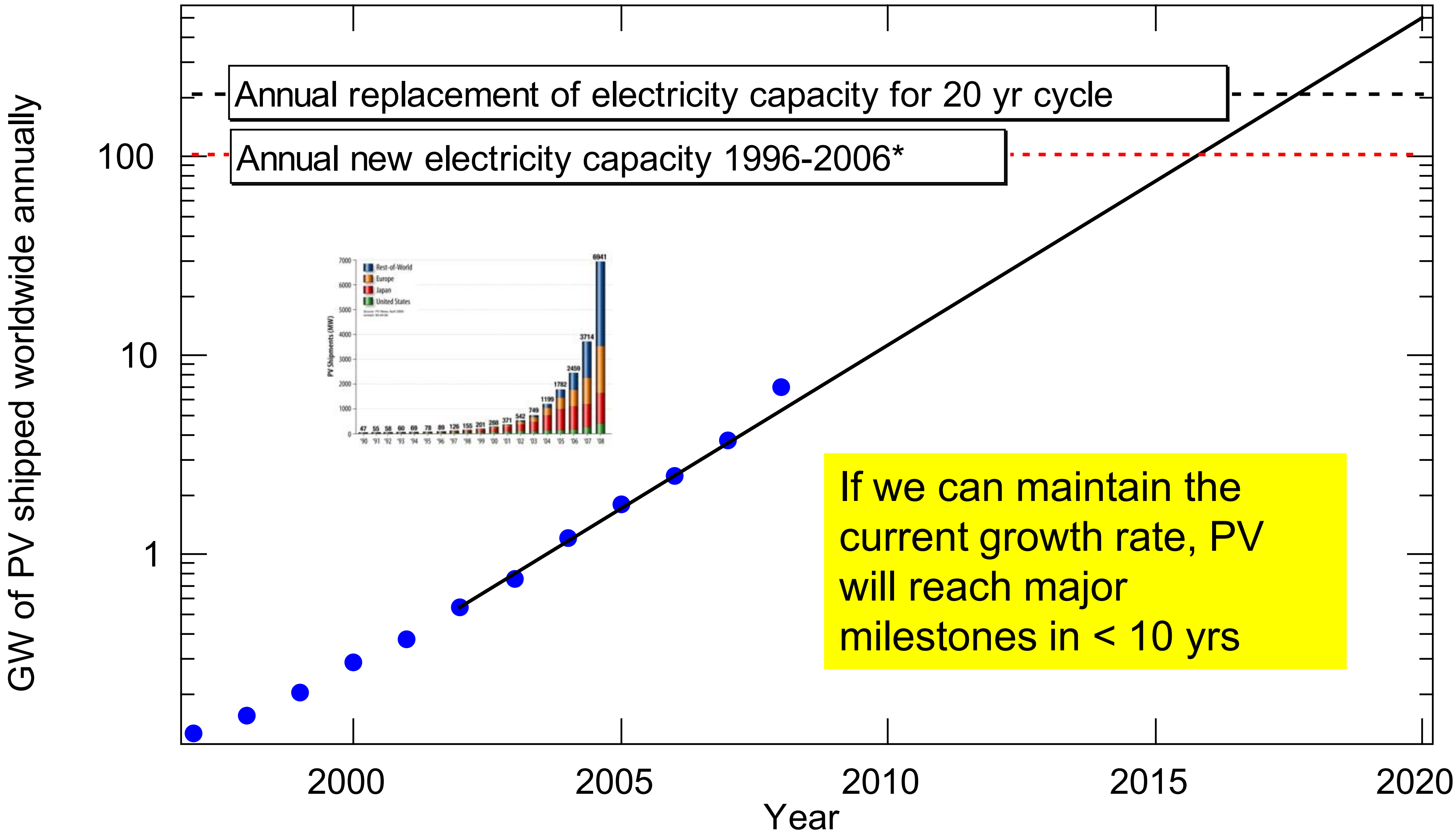


Sunlight reaching earth in 1 hour is enough to power the world for 1 year

Growth of photovoltaic (PV) industry

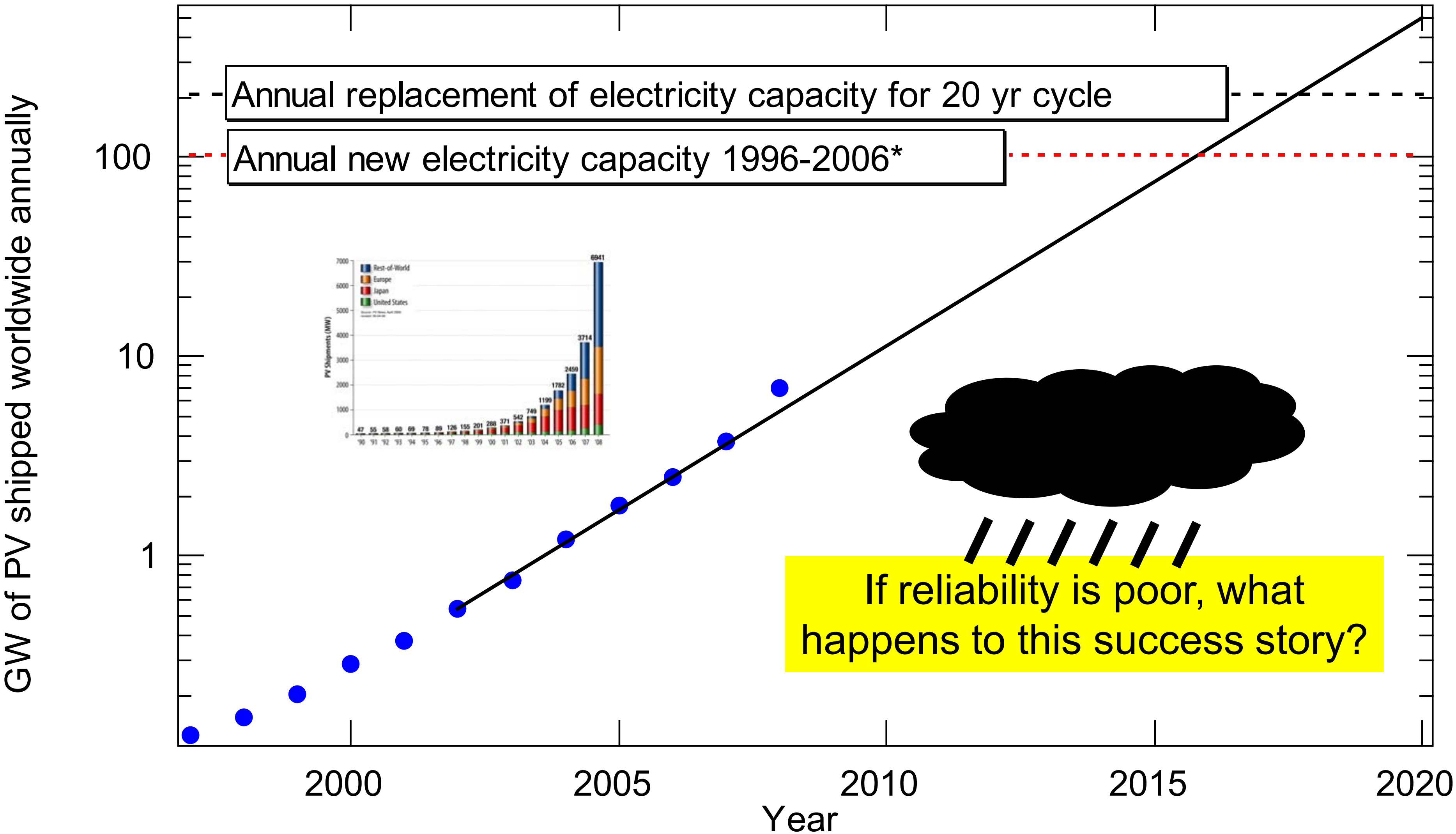


Growth of PV industry



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

Growth of PV industry



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

How to satisfy the investor?

Historically, degradation & failure mechanisms have been found in the field that were not found in accelerated testing

Predictive models need to be validated with field data

Big challenge: How can we give 30-year predictions for degradation & failure rates when the product has only been in the field for 1-2 years?

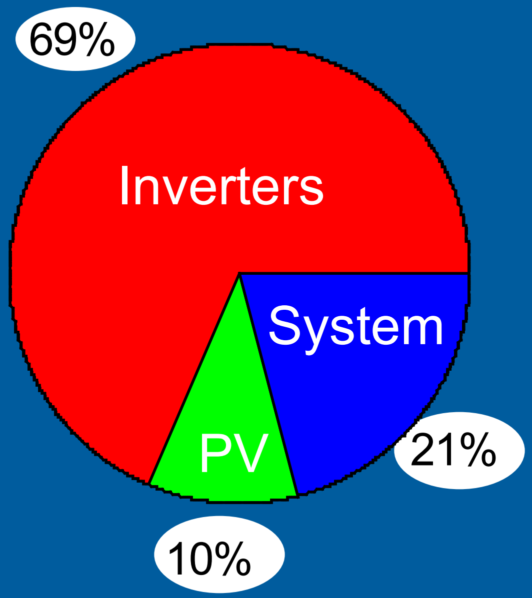
History of Si module qualification test: JPL (Jet Propulsion Lab) Block buys

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
- Studies of c-Si modules show that module failures are small (inverters dominate when cost is low)

Unscheduled maintenance costs



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

Currently, most reports imply that c-Si module failures are dominated by improper installation, lightning strikes, critters, etc.

Today's qualification standards are similar

IEC 61215 - Crystalline silicon design qualification includes 18 test procedures

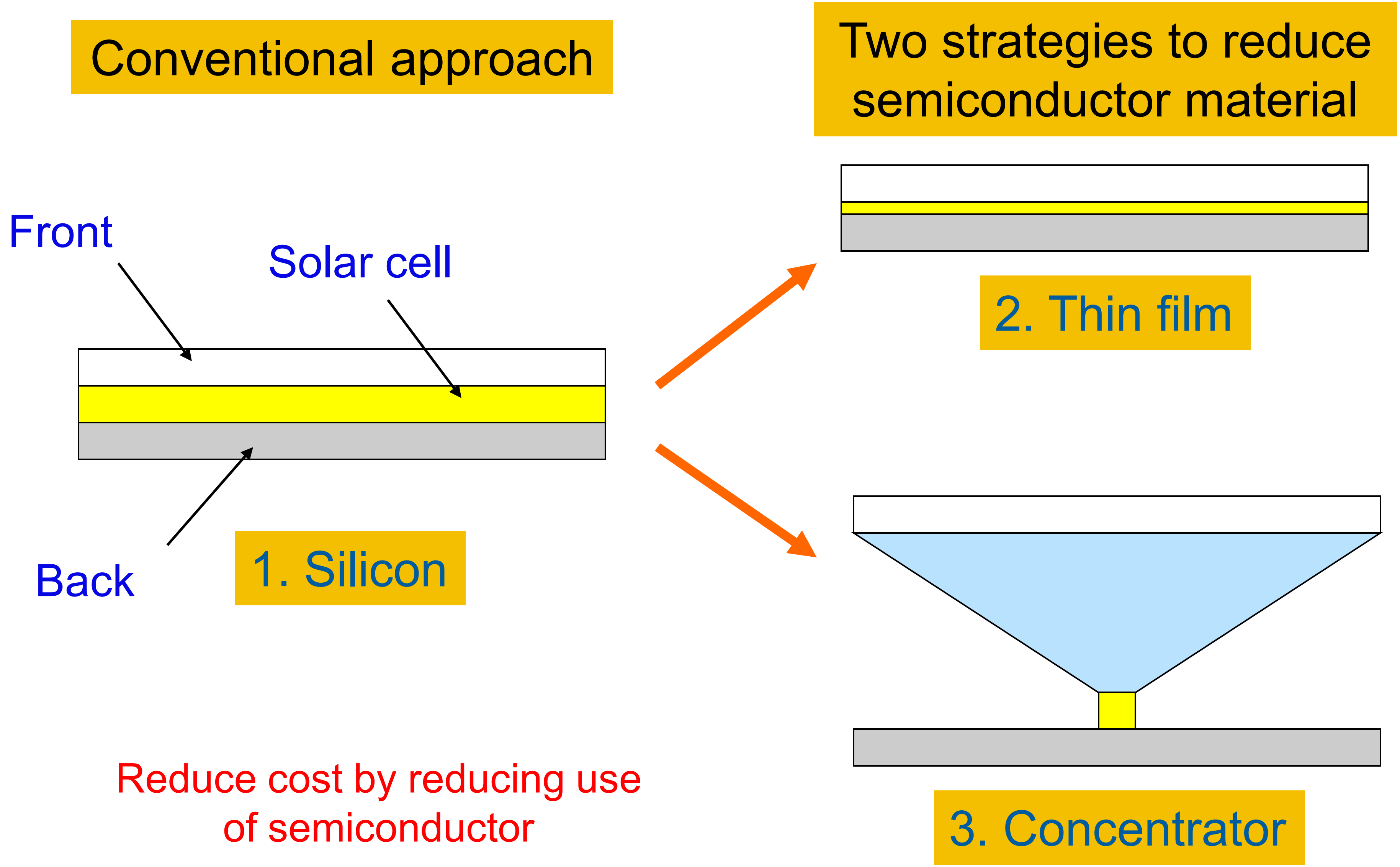
- Thermal cycling - 200 cycles -40°C to +85°C
- Humidity freeze - 10 cycles +85°C, 85% RH to -40°C
- Damp heat - 1000 hrs at +85°C, 85% RH
- Wet leakage current - Wet insulation resistance X area > 40 MΩm^2 at 500 V or system voltage
- Requirement is typically to retain 95% of original power production

IEC 61646 (thin film) and IEC62108 (CPV) are similar

Review: Osterwald & McMahon, Progress in PV **17**, p11 (2009)

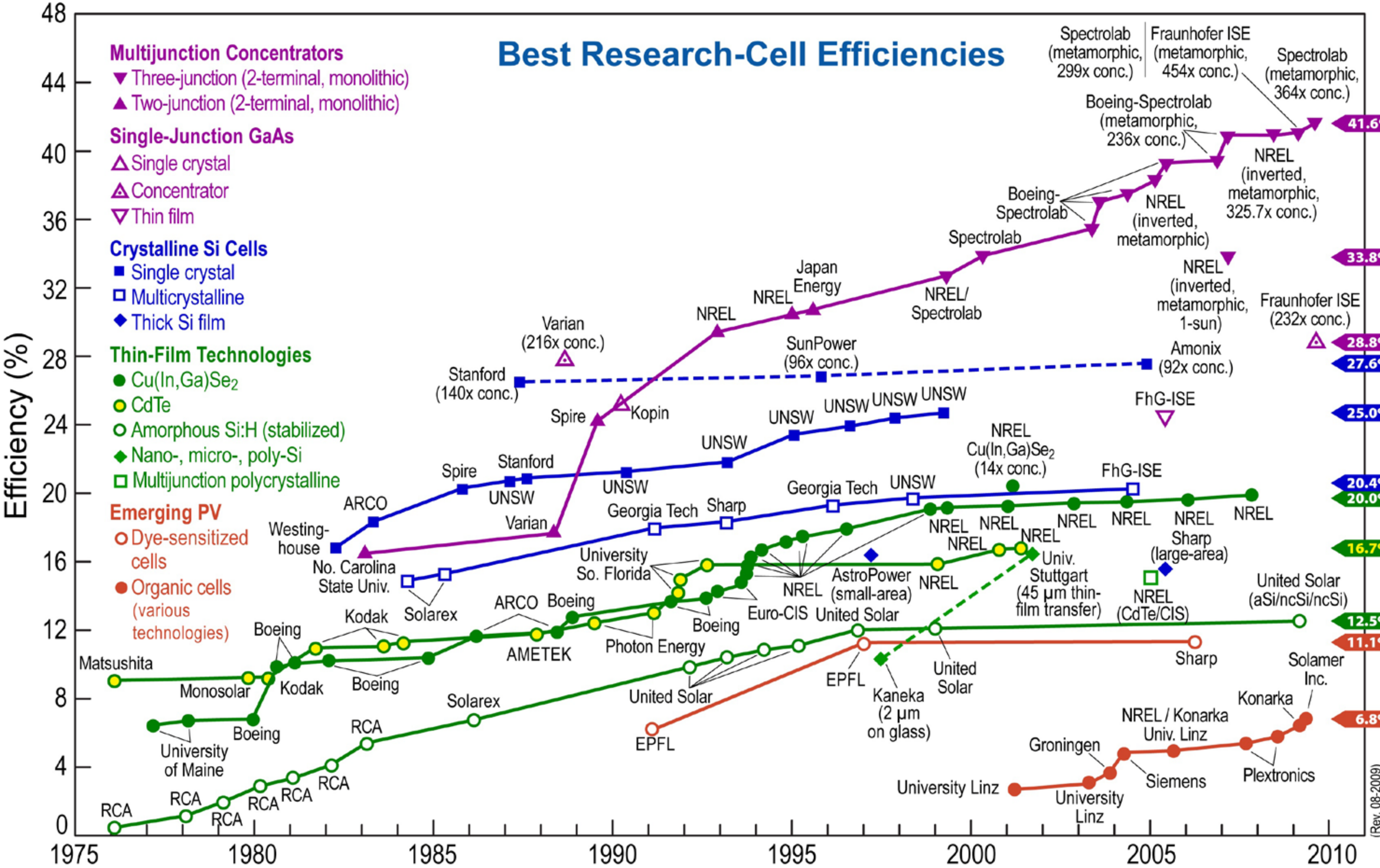
www.iec.ch

Three key approaches to photovoltaic (PV) panels



Reduce cost by reducing use of semiconductor

Many technology choices



One “winner” or many technologies?

Alkaline

Nickel cadmium

Nickel metal hydride

Lead acid

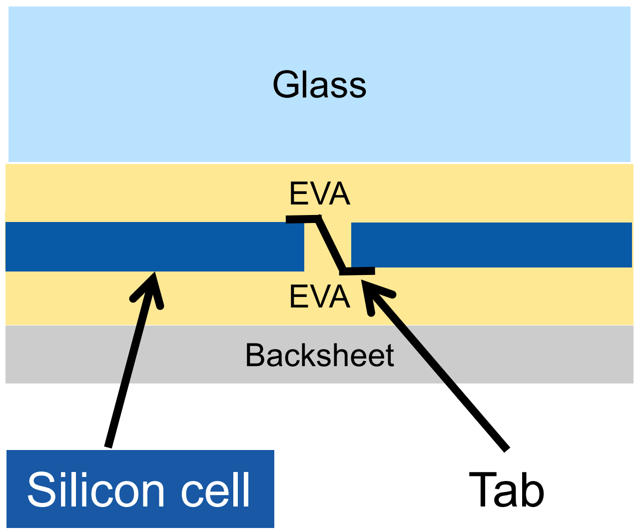
Lithium ion

Different technologies for different applications

Lithium

Silicon modules

Si module cross section



Common encapsulation materials
EVA - Ethylene vinyl acetate
PET - polyethylene terephthalate
PVF - poly vinyl fluoride

Silicon modules – remaining challenges

New materials (reduce cost, improve performance) – will these have same reliability; how to test for?

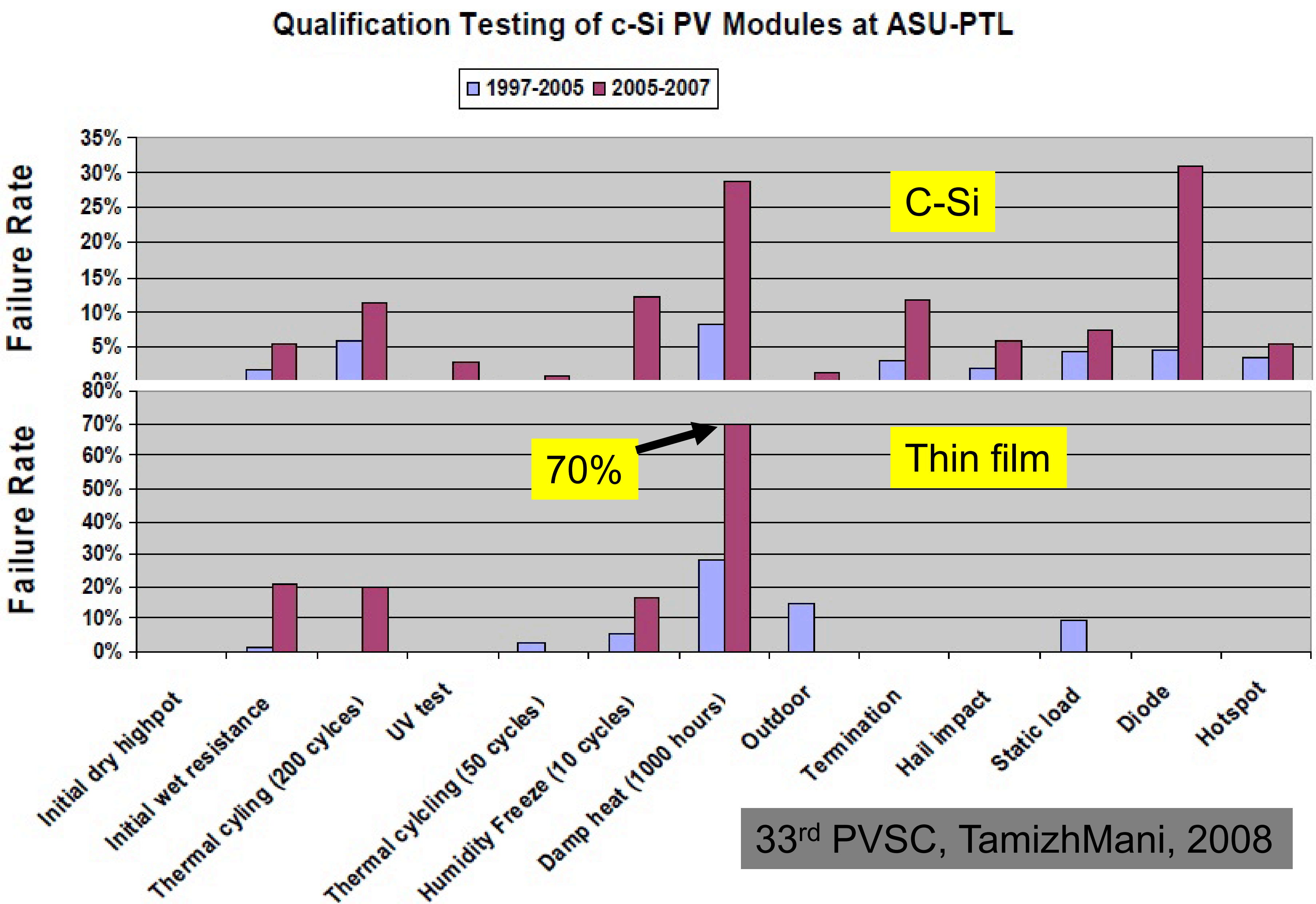
Continued quality assurance (e.g. impurities in Si give light-induced degradation)

Arcing, grounding, power conditioning, other system-related problems

Confident, long-term, quantitative predictions

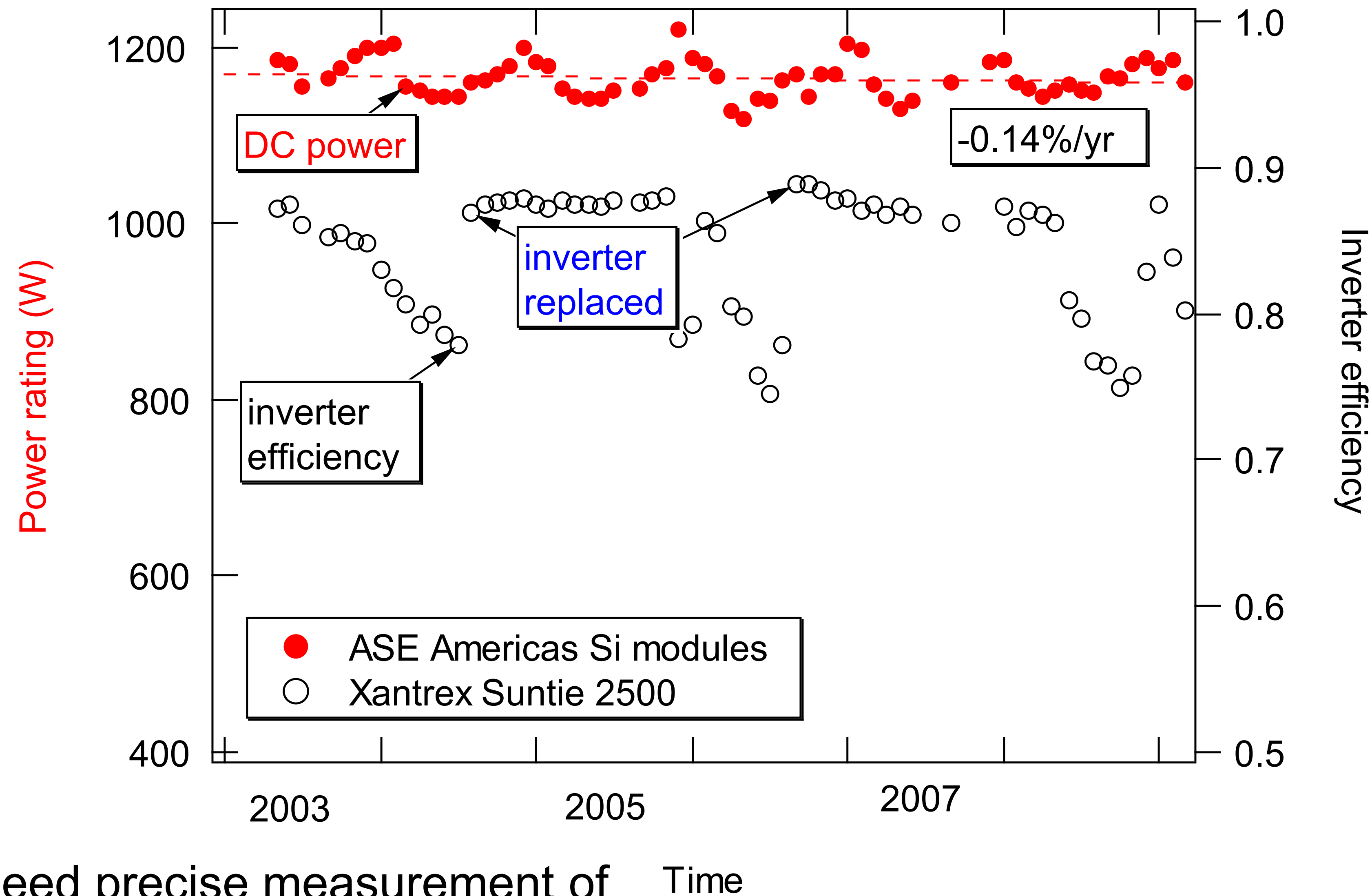
Typical module degradation rates are 0.5±0.5%/yr (difficult to measure); field module failure rates are often < 0.1%/yr

Past success does not guarantee future success



33rd PVSC, TamizhMani, 2008

Measurement of degradation rates takes years



Need precise measurement of irradiance, temperature, etc.

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 v

Vazquez, Prog. in PV (2008)

Location	Test duration	Module Tech.	Degradation rate (%/year)
Perth (Australia)	16–19 months	c-Si	0·5–2·7
Temperate climate		p-Si	1·0–2·9
		a-Si	18·8
		CIS	12·6
Mesa, Arizona (USA)	2·4–4 years	c-Si	0·4
Desert climate	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, Califomia (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

Thin-film approaches on the market

CuIn(Ga)Se

CdTe

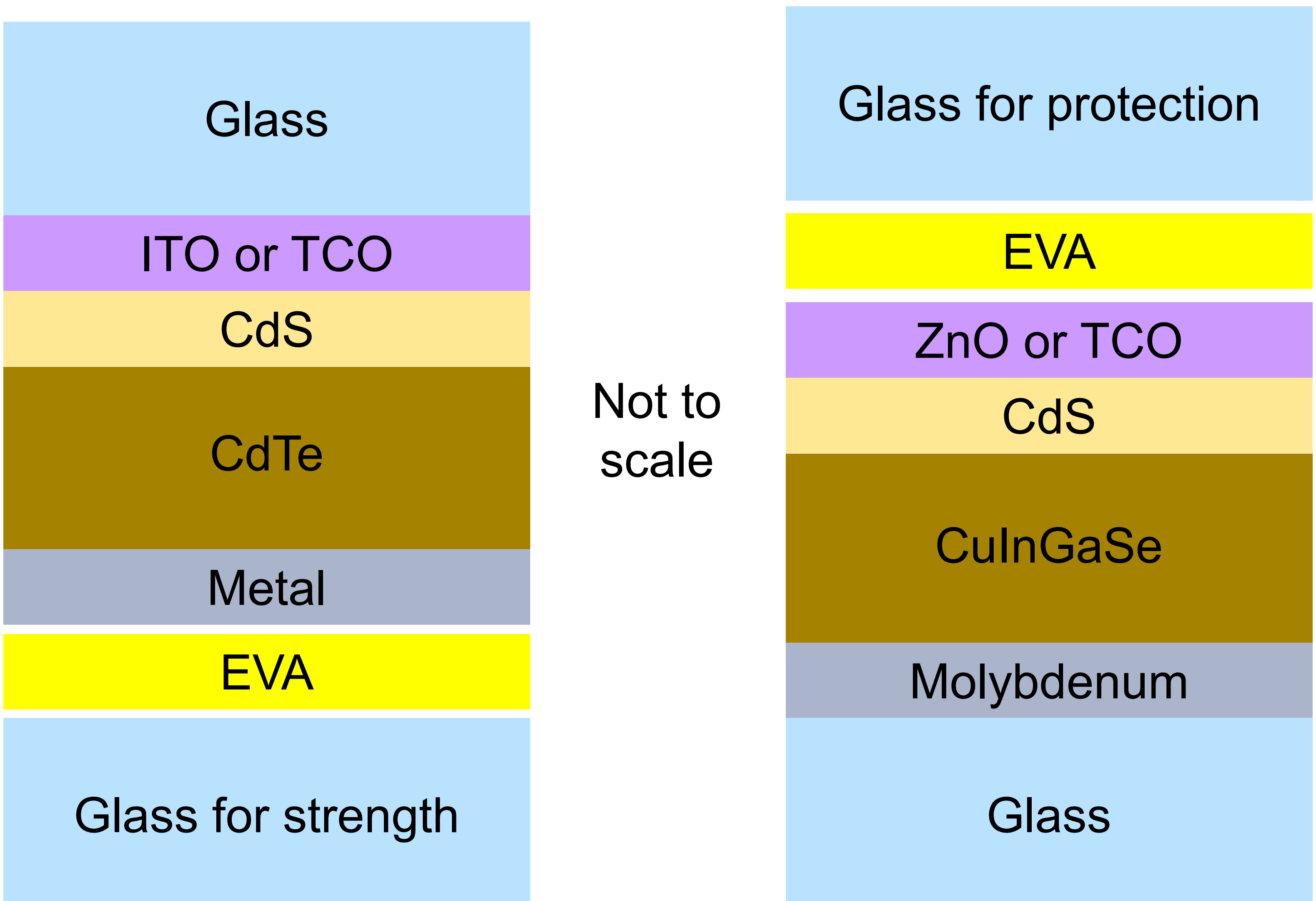
Amorphous silicon

Large variety of approaches is challenge to reliability engineer

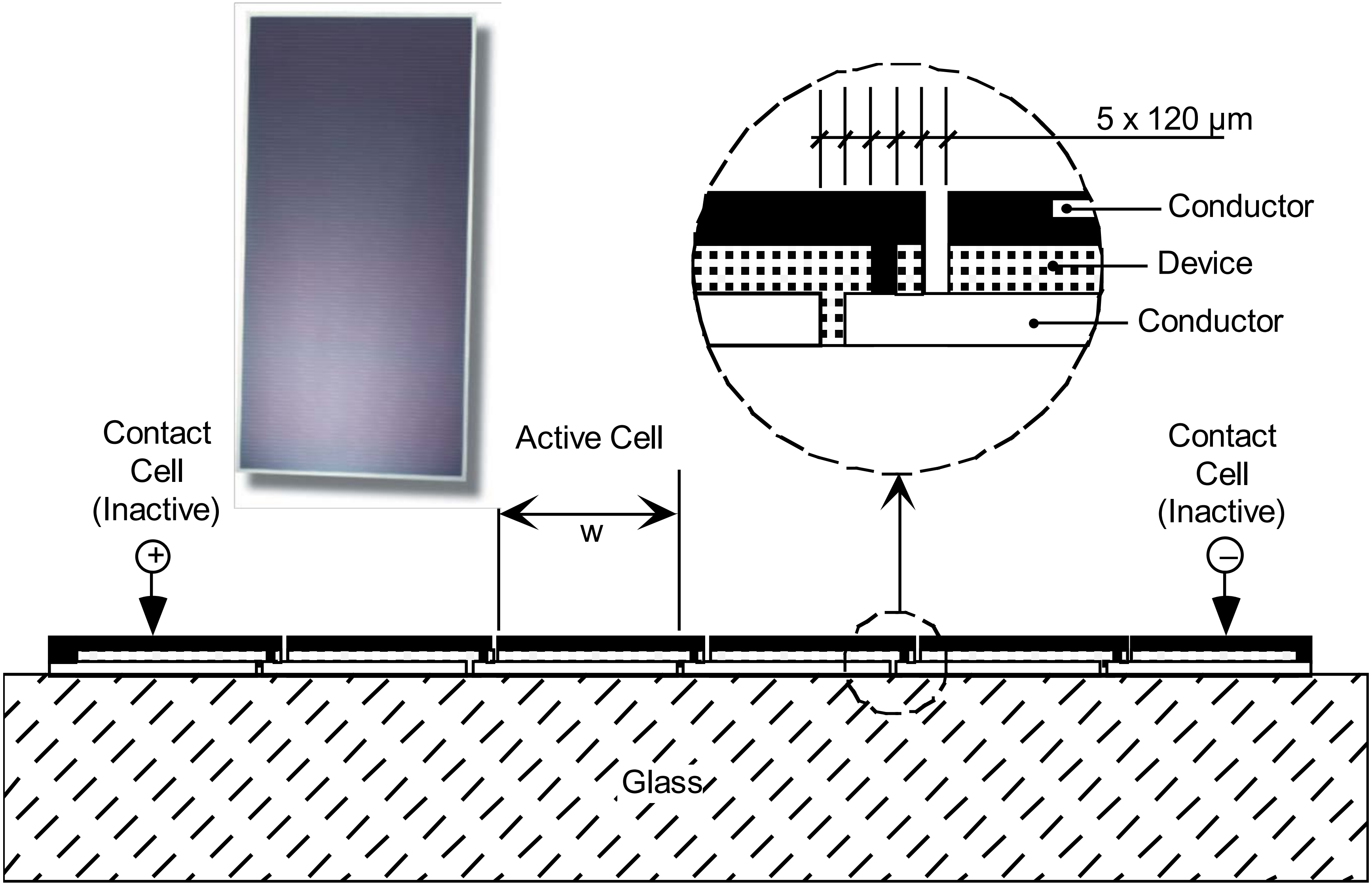
Typical thin-film structures

CdTe uses superstrate

CuInGaSe uses substrate



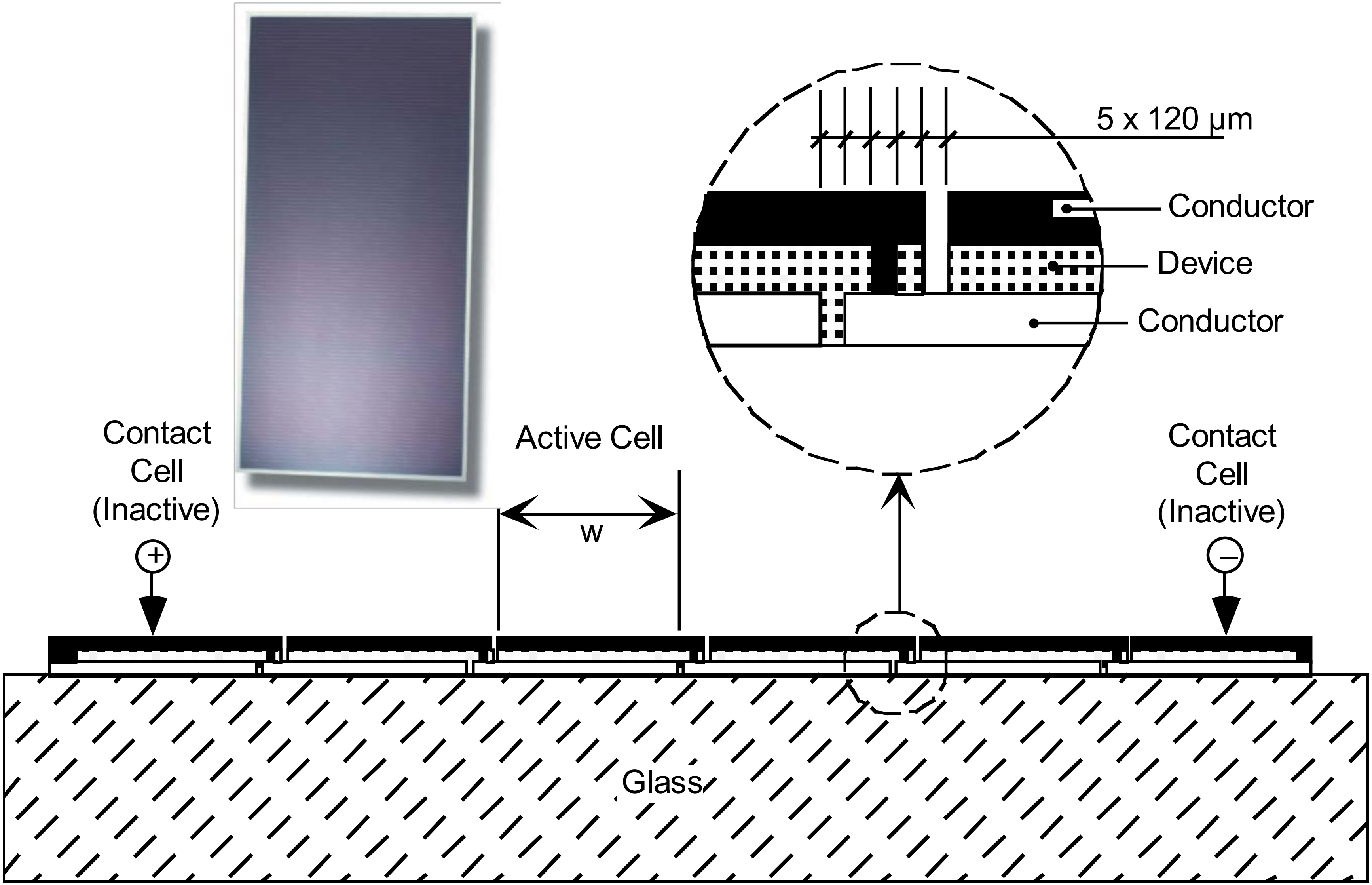
Monolithic module integration



Hurdle for thin films: uniformity of deposition

Quality assurance remains a big problem for thin-film products

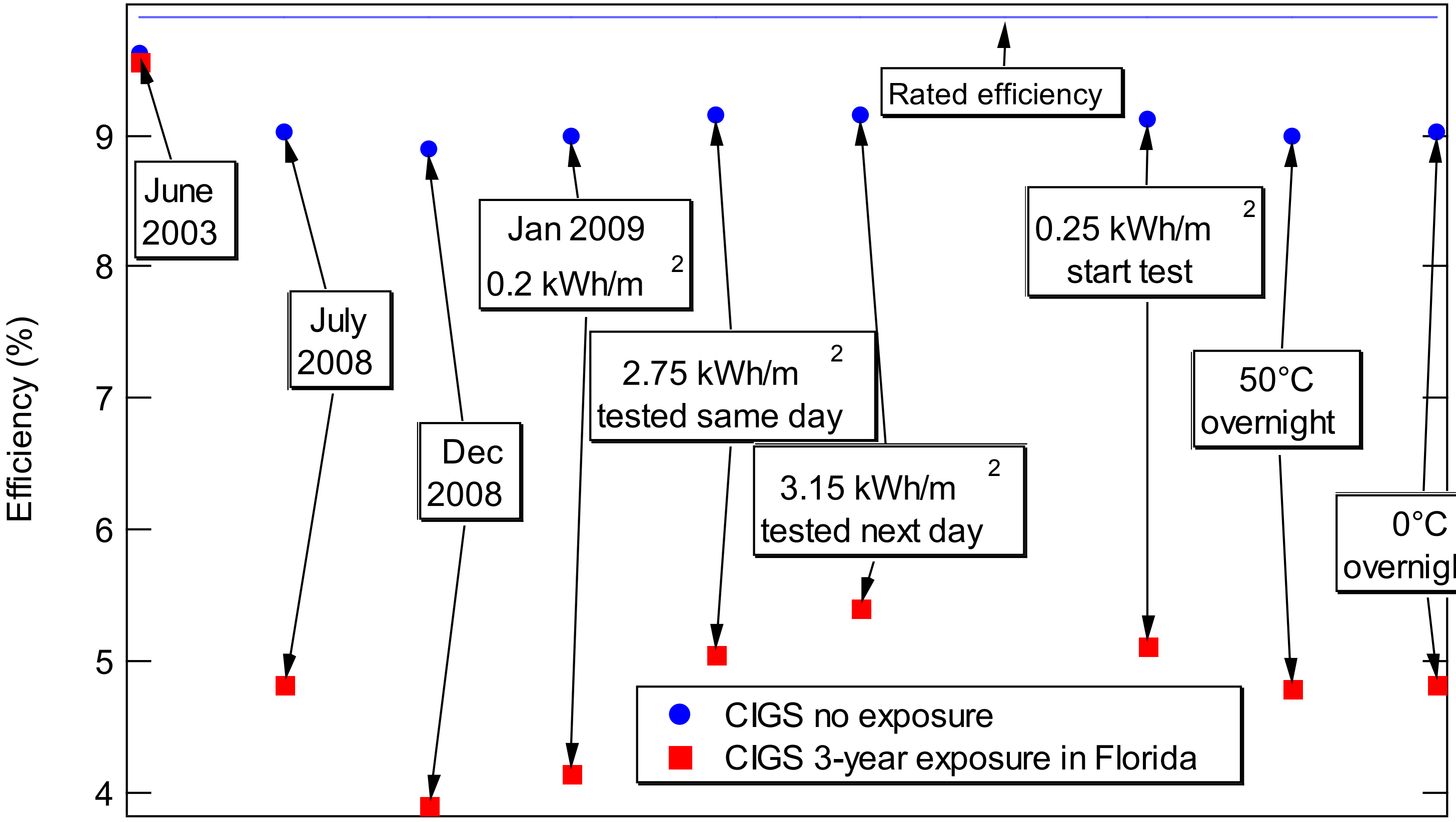
Hurdle for thin films: uniformity of interconnections



Quality assurance remains a big problem for thin-film products

Metastability: Reversible vs irreversible changes

- Amorphous silicon degrades in light and recovers when annealed in the dark
- CIGS and CdTe can show transients



As high as 30% metastability has been observed

Flexible CIGS requires reduced sensitivity to moisture

ZnO (and other transparent conductors) react with moisture, causing increase in series resistance

Two strategies:

- Harden the cell (e.g. Sundaramoorthy, et al 34th PVSC)
- Harden the packaging (barrier coatings)

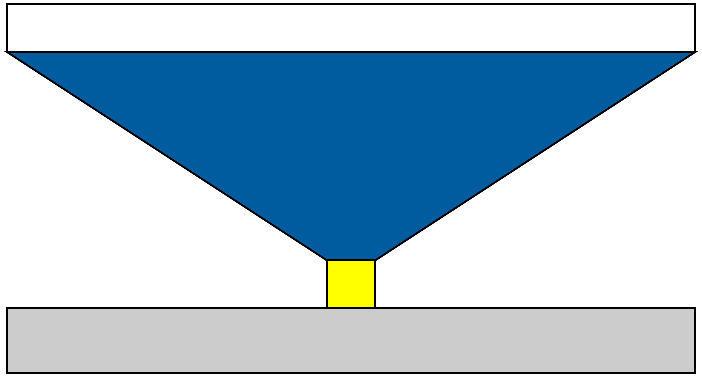
Many possible failure mechanisms

- CdTe has shown instability of back contact (diffusion?)
- Edge seal may allow water into glass/glass module
- Partial shunts or conducting diodes may be seen at scribe lines or other defected areas
- Adhesion to glass can be problem
- Role of sodium is important in CuInGaSe modules, but sodium can move
- Currently, the biggest effort with CuInGaSe is to try to put it on a flexible substrate – requires excellent barrier coating unless cell can be hardened to moisture

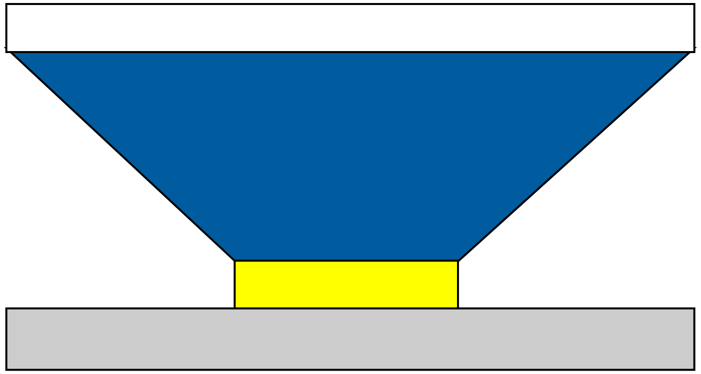
Range of concentrator approaches

Amonix

JX Crystals



High concentration
- 35% - 40% cells
- 400X – 1500 X



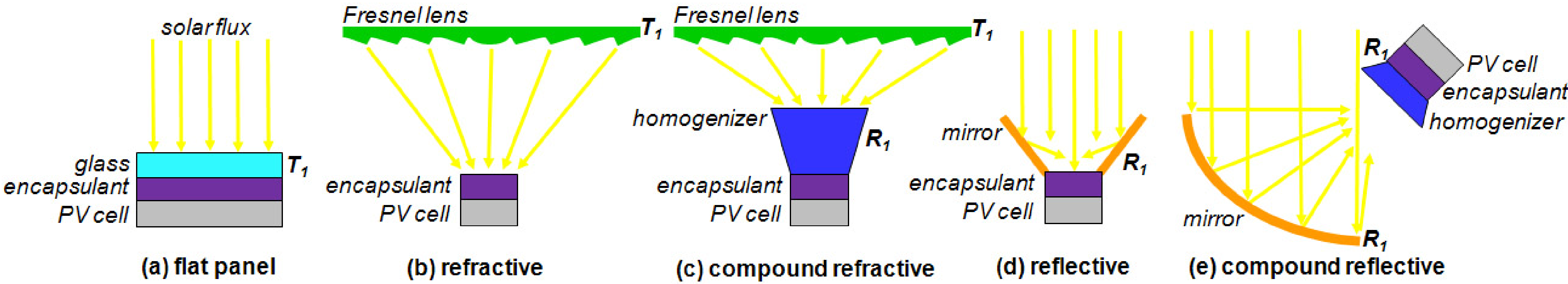
Low concentration
- 15% - 25% cells
- 2X – 100 X

CPV challenges – many interactions

CPV can fail in many ways, but it can be difficult to understand where the problem is and to fix the problem without creating a new problem

- Tracking – optics must be aligned with the sun
- Optics – durability can be problem, soiling; optics affect rest of system
- Cell – must be encapsulated, but not affected by UV; size of cell affects rest of system
- Heat sink – must be electrically isolated, but excellent thermal contact
- Modularity may be benefit!

UV transmission depends on design

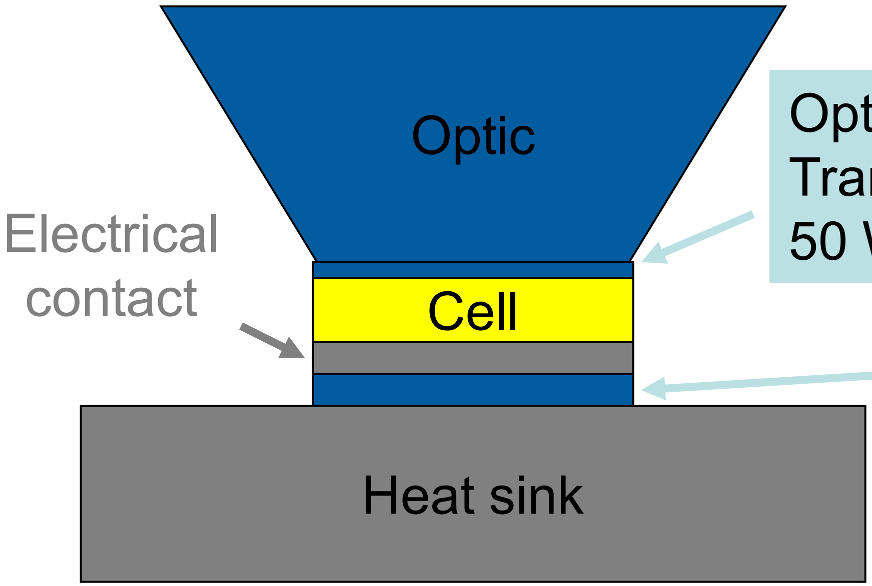


Low UV

High UV

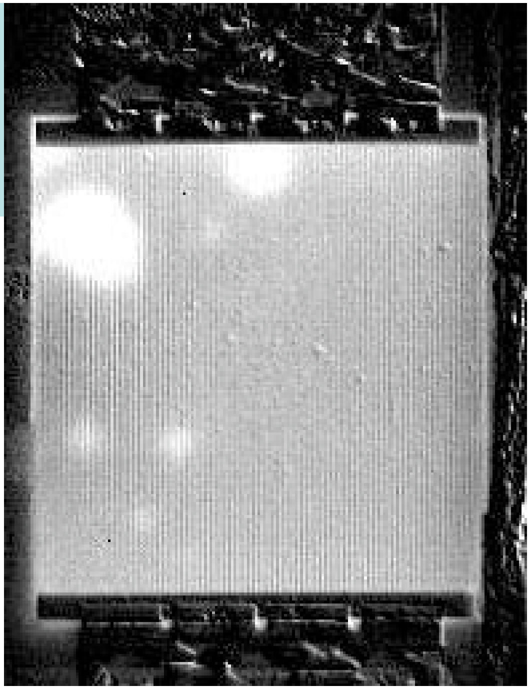
Analysis of transmitted optical spectrum enabling accelerated testing of CPV designs
SPIE 2009 David Miller, et al

Bonds to heat sink and optics



Optical bond with 100%
Transmission
50 W/sq cm

Small ΔT (<10°C)
Electrical isolation
No voids
T cycle OK



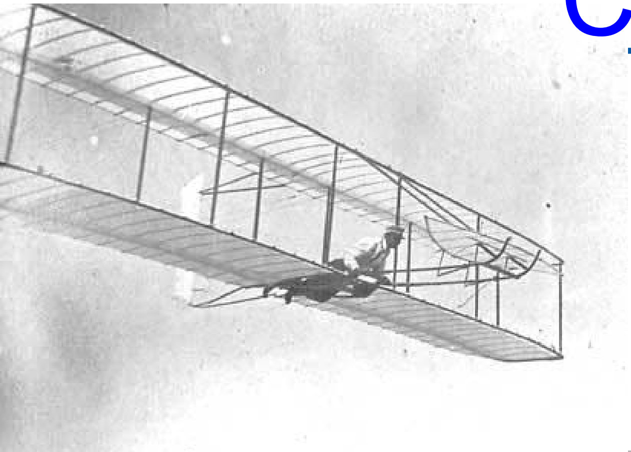
IR image of void in die attach
Bosco, et al 34th PVSC

- Borrowing experience from power electronics and DBC (direct bonded copper) makes this a smaller issue
- Intense UV may be a substantial problem, but optics may not transmit UV

Concentrators – reliability challenges

- Wide variety of designs
- Qualification test is not well established
- Companies spend time developing their own accelerated tests to speed product development cycles
- Very few companies have heritage with field testing
- Response to different stress conditions not well understood (sand, etc.)
- Everyone wants to bring a product to market immediately

Concentrator technology

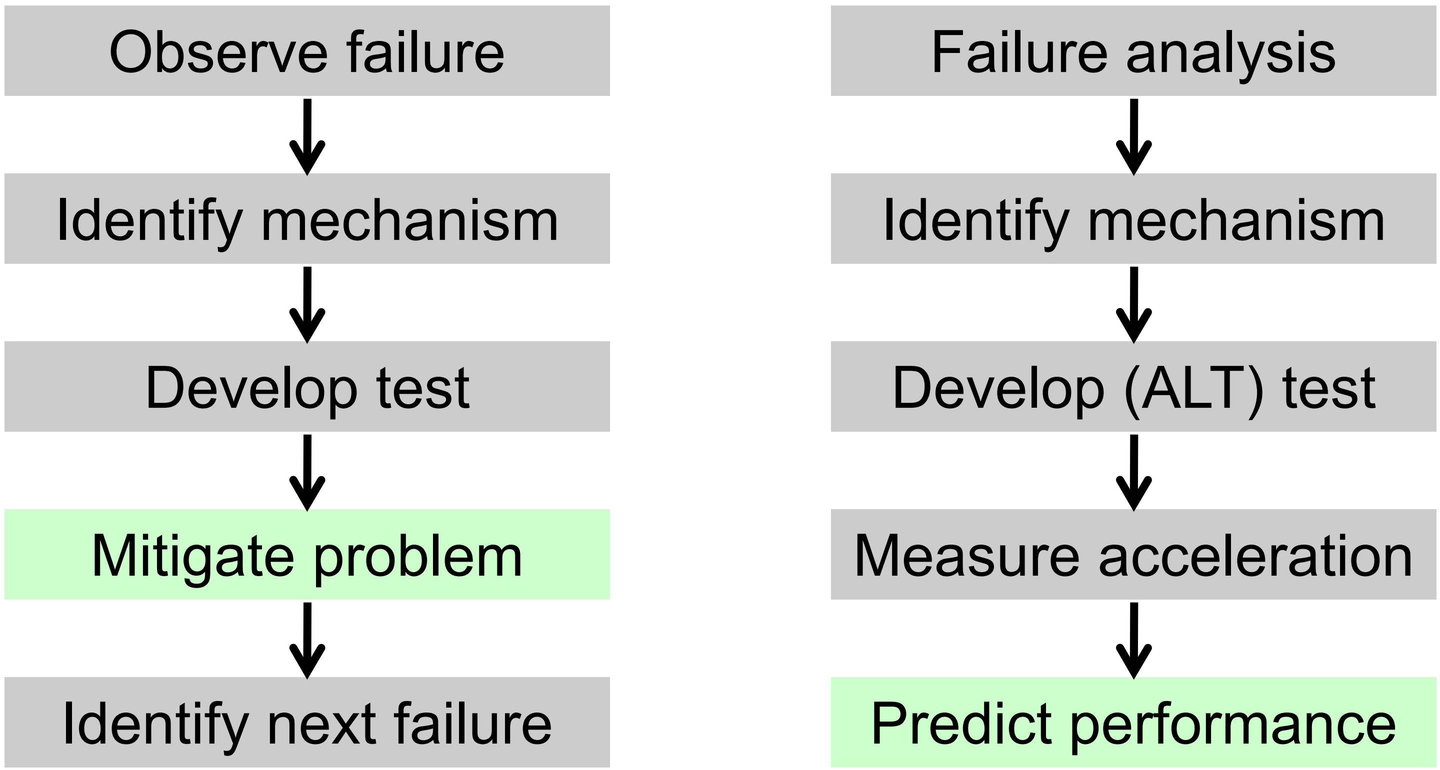


Creative optical designs?

PV is growing up!

Prototype

Mature product

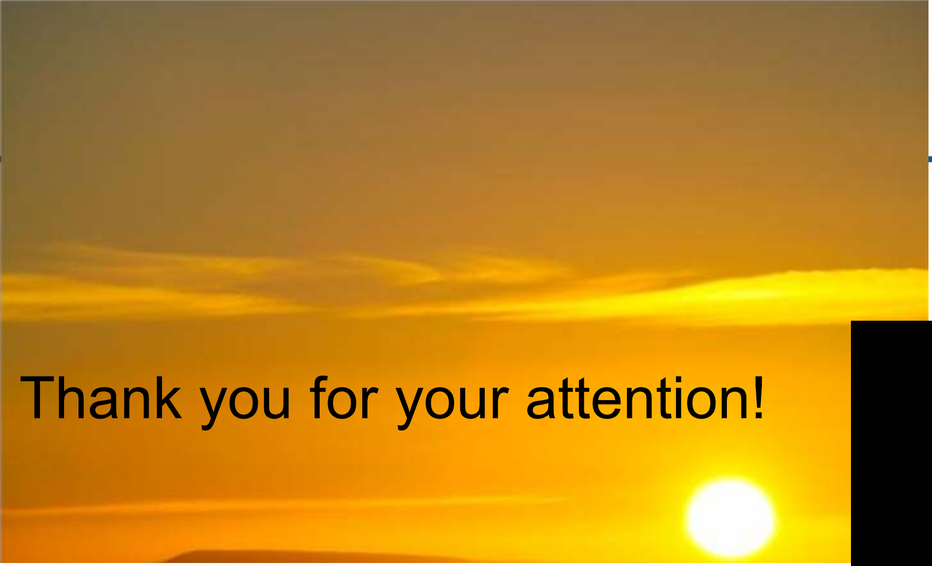


When do we move from focus on mitigation to focus on prediction?

Summary

- Solar is growing rapidly and could become a significant source of electricity within our lifetimes
- Silicon modules are performing well in the field; reliability testing of new designs is still important
- CdTe and CuInGaSe modules are sensitive to moisture, so must be carefully sealed; only amorphous Si modules are available in flexible form
- Concentrator PV is in product development stage, but is benefiting from expertise in other industries
- How do we predict 30 years of performance for product that has been in the field < 1-2 years?

Planet powered by renewable energy By year 2100 or before?



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