Long-Term Performance Data and Analysis of CIS/CIGS Modules Deployed Outdoors

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Outline

- Introduction
  - Rationale for thin-film CIS PV modules: cost - high efficiency
  - Identify loss modes and/or sources in CIS/CIGS modules
- Module deployment &Tests at NREL OTF
  - two manufacturers, types ‘A’ & ‘B’, on 3 separate testbeds
- Analyses 2 types of data,
  - STC & dark I-V standard diode devices
  - Real-time field data analysis
- Conclusions
  - FF degradation is predominant loss mode
    - Type ‘A’ can show very low rate to moderate loss rates
      - Series-resistance increases symptomatic of A modules
    - Type ‘B’ can show very low loss rate to nominal loss rate
      - Shunt increases & other subtle changes or failure mechanisms
  - Transient behavior observed especially after dark storage

Introduction

- Thin-film PV technologies (CIGS, CdTe, a-Si/nc-Si) are expected to achieve and compete for lowest cost per watt vs. bulk technologies (c-Si, poly-c-Si) largely because of economy in and costs of semiconductor materials usage;

- Copper indium diselenide (CIS) and/or gallium-alloyed CIGS photovoltaic (PV) modules achieve some of highest PV conversion efficiency of the thin-films:
  - Current state-of-the-art CIGS efficiency at Standard Test Conditions (STC):
    - cells attain 19.9%
    - modules (~ 0.4 - 0.5 m^2) attain ~12%
- CIGS PV module stability issues need addressing
  - issues under damp/dry heat exposure
  - high-voltage bias applications for electrical power

Introduction: performance & reliability loss modes

- FF losses:
  - Series resistance (Rse) increases:
    - degradation of top TCO (ZnO) resistivity
    - CdS/CIS interface
  - Shunt conductance (Gsh)
  - Diode qualities (A, J_0) & recombination
- Voc losses:
  - electronic carrier effects in CIS,
  - band offsets,CdS/CIS interface
- Isc loss modes not obvious, but possibilities:
  - transparency of top TCO, EVA
  - Rse increases are very large

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Experimental Tests at OTF

- Two manufacturers of modules ‘A’ & ‘B’
  - glass/Mo/CIGS/CdS/ZnO/glass laminates
  - type A deployed beginning in 1988, 5 vintages
  - type B deployment began 2002
  - Other CIS manufacturers also at OTF but not reported
- Study CIS/CIGS modules deployed on 3 testbeds:
  - Single units, free-standing, long-term exposure, loaded at Pmax (STC) with fixed resistor, 9 total
  - High Voltage Stress Testbed (HVST2) Array
    - consists of 2, bipolar strings, nominally ± 300 VDC open circuit
    - 12 type ‘A’ CIGS modules per string, 24 total
    - I-V traces monitored & loaded continuously with DAS
  - Performance & Energy Ratings Testbed (PERT)
    - I-V traces monitored & loaded continuously with DAS
    - A module 1997, B module 2002

PERT & HVST2 Array Module Deployment

- Performance & Energy Ratings Testbed (PERT)
  - Open-air steel frame mounts, face due south, tilted at 40° latitude with respect to horizontal
  - Meteorologic resources (Irr, module & air temps., etc)
- Array: High-voltage stress test (HVST2)
  - Same sensors as PERT, plus RH
  - Elevated, frames electrically floated to measure HV leakage currents

PERT: viewed looking west

HVST2 array: viewed looking east

Long-term free-standing single module deployment

- loaded with fixed resistor,
- 9 modules total
- Also tilted at latitude angle, facing south
- open-air steel rack mounts

1988 A module installed 20 years

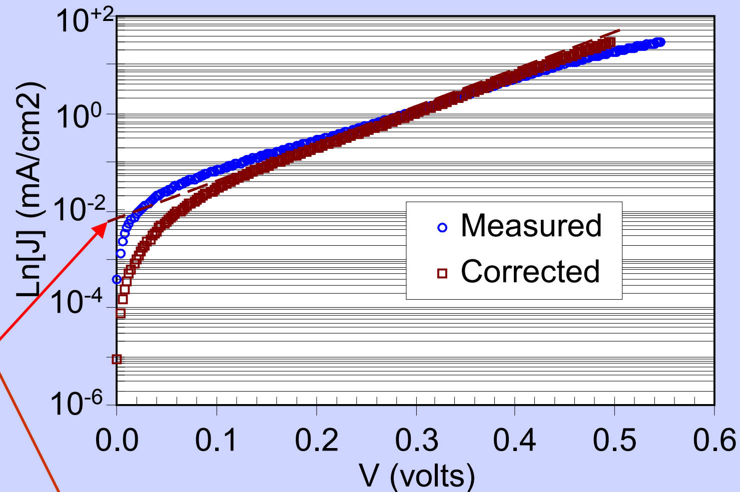
Long-term exposure rack seen looking east

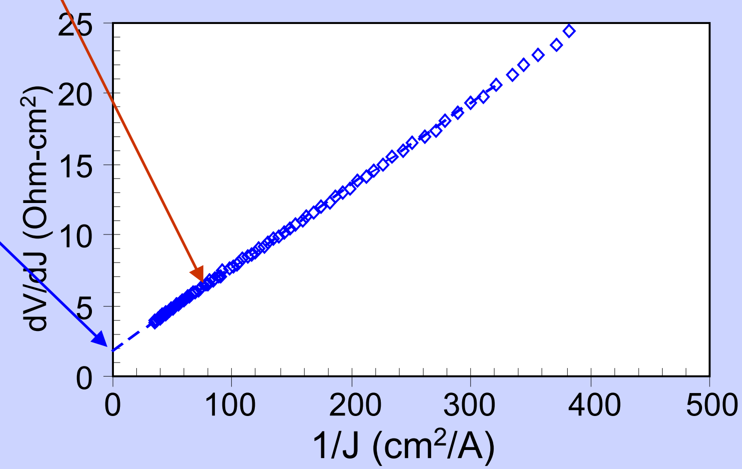
Data Analysis: STC or dark at 25°C

- Single I-V curves at STC or dark at 25°C
  - STC data: SPIRE, LACSS or SOMS
    - LACSS & SOMS use P/S to drive I-V traces
  - Module data normalized to unit area cell (J-V):
    - dividing voltage by series cell count (Ncell)
    - dividing current by area per cell (Acell = AperArea / Ncell)
  - Standard PV device diode circuit model with
    - parasitic series resistance (Rse) and shunt conductance (Gsh)
    - determined Rse, Gsh (dark) allows raw data to be corrected and then to derive A, J_0

Diode Analysis: Rse, diode Q, Gsh, J_0

- Diode Eq. $J = J_0 * [\, e^{q(V-RseJ)/AkT} - 1\,] + G_{SH}V - J_L$
  - Derive 3-pnt slopes dV/dJ (Rse) or dJ/dV (Gsh) & correct data for series & shunt
    - *dV/dJ vs. 1/J or 1/(J+J_{light})*
      - ⇨ Intercept = Rse,
      - ⇨ slope = A (k_BT/q)
    - Gsh: from dJ/dV minimum near 0 V
    - *V –> Vcor = V -RseJ, J –> Jcor = J - GV*
    - *Ln(J_{cor})-V_{cor} => J_0,*
    - *Also A* => slope V vs. LnJ



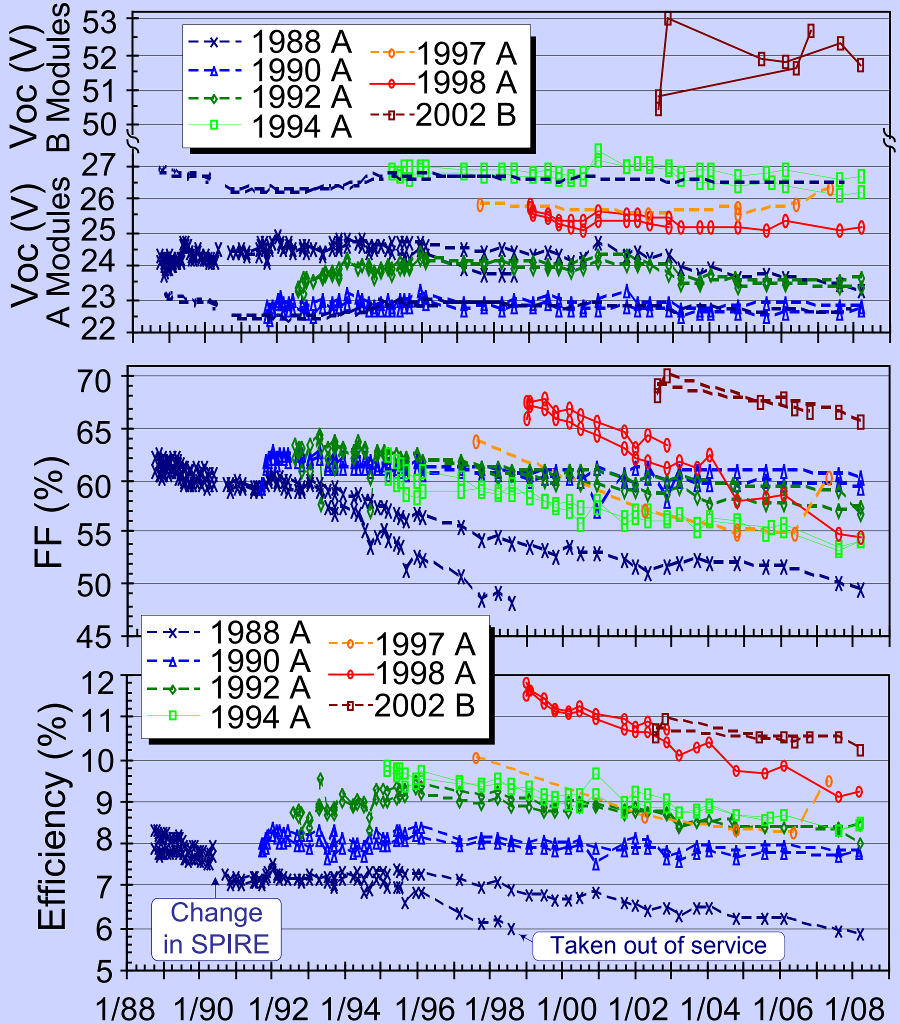


Data Analysis: PERT & HVST2

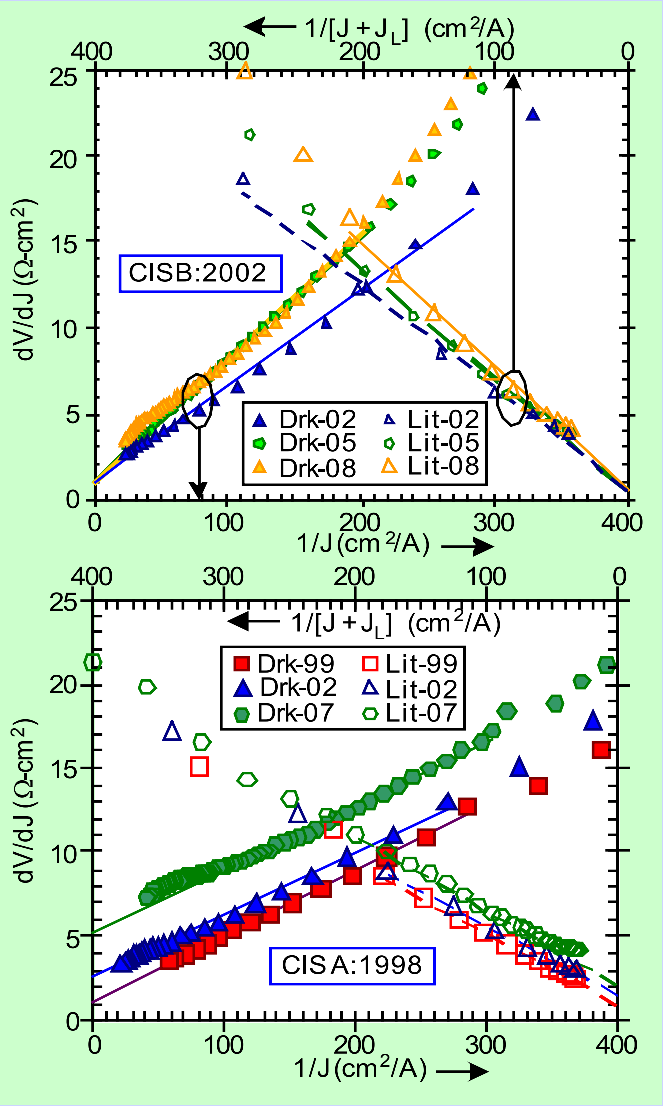
- Real-time outdoor data measured in situ with programmable electronic loads & DAS
  - I-V power parameters (Voc, FF, etc.) data condensed
    - segregated into narrow irradiance bands (±25 W/m^2) for all illumination intensities,
    - Linear regression vs. module temperature (Tmod) each bin:
      - Parameter Y: Y(Tmod) = Y0 + dY/dTmod * Tmod
  - select bands analyzed 250, 500, 1000 W/m^2, vs. time
    - averaged to cover 3 select windows for ±75 W/m^2 span
    - cover most of energy-producing field conditions
  - Data partitioned to 3-month intervals
    - Power parameters, Rseries, diode Q factor derived for each
    - Changes in power parameters vs. time calculate

Single module data at STC (SPIRE or LACSS)

- Manufacturers A & B:
  - A: (5 vintages) 1988, 1990, 1992, 1994, 1998;
  - B: 2002
- A module initial efficiency
  - from 8% (1988) to ~ 11-12% (1998)
  - Low loss rates earlier 1%/yr or less
  - stability became issue when initial efficiency exceeded ~ 9%:
    - FF losses account for most decline
    - Voc increases in initial years, partly offset FF losses, but subsequently can degrade
- B module initial efficiency ~11%
  - slight decline mostly in FF, partly offset by Voc increase during first years



Data: series resistance changes single modules



- Dark & Light Slopes dV/dJ plotted vs.
  - 1/J for dark data read along lower ordinate axis
  - $1/(J+J_{Light})$ for light data, read along upper ordinate axis
  - 2002 B in upper pane ('02, '05, '08) 1998 A in lower pane ('99, '02, '07)
  - For 2002 B no increase in Rse intercept in both dark & light data over time
    - curvature suggestive of other effects
  - For 1998 A substantial increase in Rse intercept in dark (~ 4 Ω-cm^2) & some in light (1-2 Ω-cm^2) data with time

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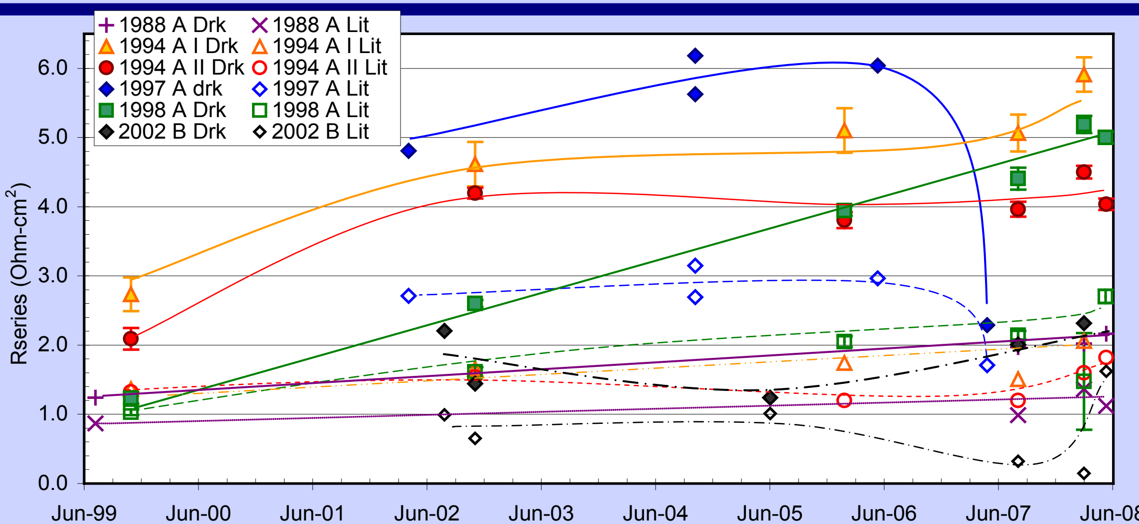
Series resistance data, STC/dark I-V on LACSS

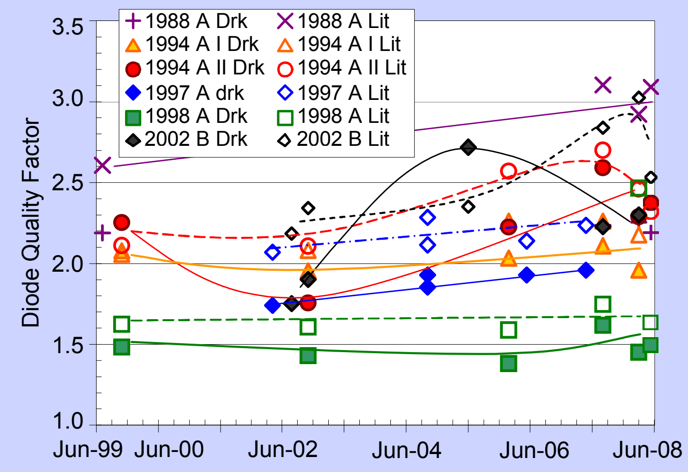


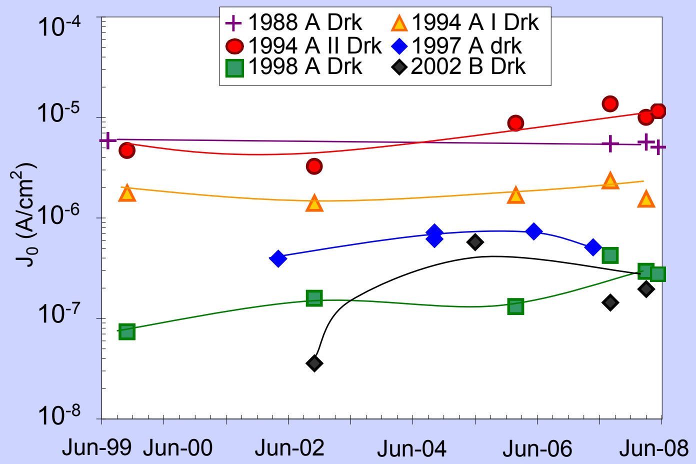
- Dark (filled), Light (open) symbols
- Long-term exposure rack modules shown, with A & B from PERT occasionally tested on LACSS
- Manually drawn trend lines shown as guide

- 1988 A
  - Dark increase ~ 1.2 to 2.0 Ω-cm^2
  - Light increase ~ 0.8 to 1.4 Ω-cm^2
- 1994 A #1 & #2
  - Dark increase ~ 2.1–2.8 to 4.5–6 Ω-cm^2
  - Light increase ~ 1.4 to 2.0 Ω-cm^2
- 1998 A
  - Dark increase: 1.2 to 5 Ω-cm^2
  - light increase: 1 to 2.8 Ω-cm^2
- 1997 A (PERT)
  - Dark increase (2002–06): 1 Ω-cm^2
  - light increase (2002–06): ½ Ω-cm^2
  - (1997 A) substantial metastable drop in Rs of 3.5 or 1 Ω-cm^2 for dark or light, while module lay indoors 1 year
  - Also reflected in performance (in & out)
- 2002 B
  - Dark 1.5 to 2.3 Ω-cm^2
- Light 0.6 to 1.4 Ω-cm^2
- 2002 B (PERT)
  - Dark nearly no change ~ 1.8 Ω-cm^2
  - light nearly no change ~ 1.5 Ω-cm^2
- Rse increases impact type A more than type B because of higher Jsc for A (STC)
  - ~30 mA/cm^2 for A, ~24 mA/cm^2 for B

Diode J_0, A factors, STC/dark I-V on LACSS

- A from dark or light dV/dJ–1/J data;
- J_0 from dark Log(Jcor) –Vcor
- A modules (over 8-years period)
  - Quality factors changes between negligible to 20% increases
  - Dark J_0 increases small, highest factor of x2
- B modules (over 5-year period)
  - Quality factors show more substantial gain, 25%-30%
  - J_0 changes by mult factor up to 40
  - More detail picture show 2-diode type behavior, primary weakening





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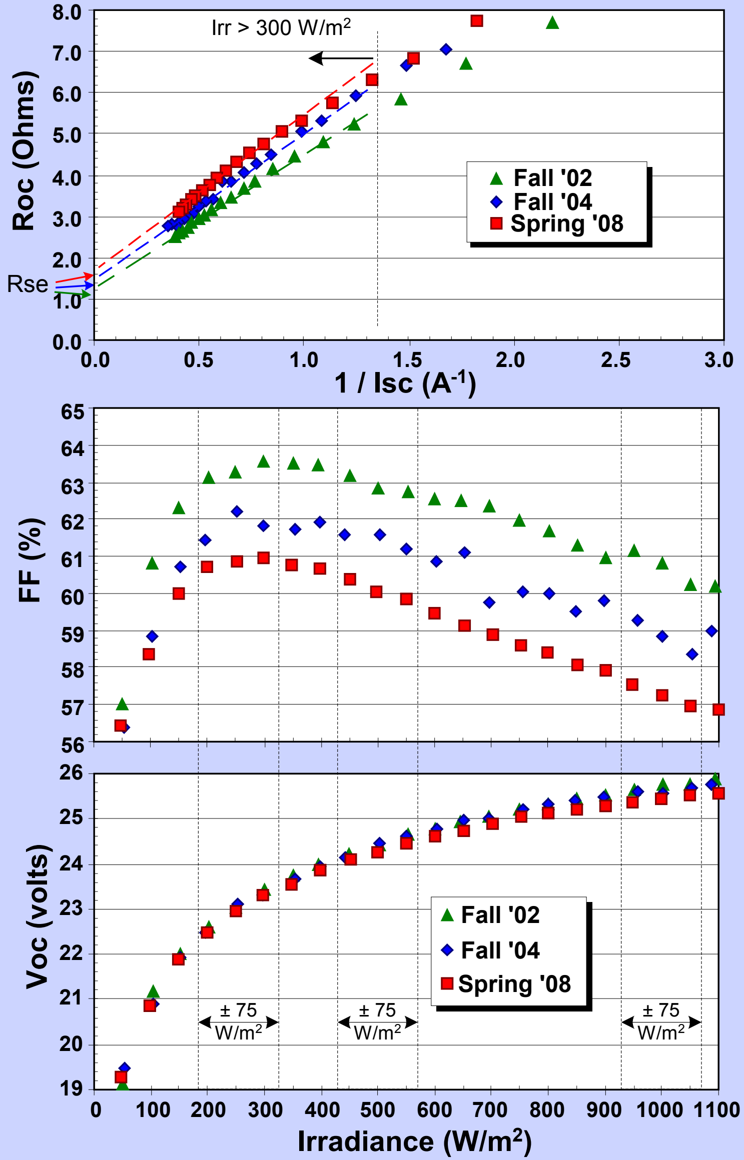
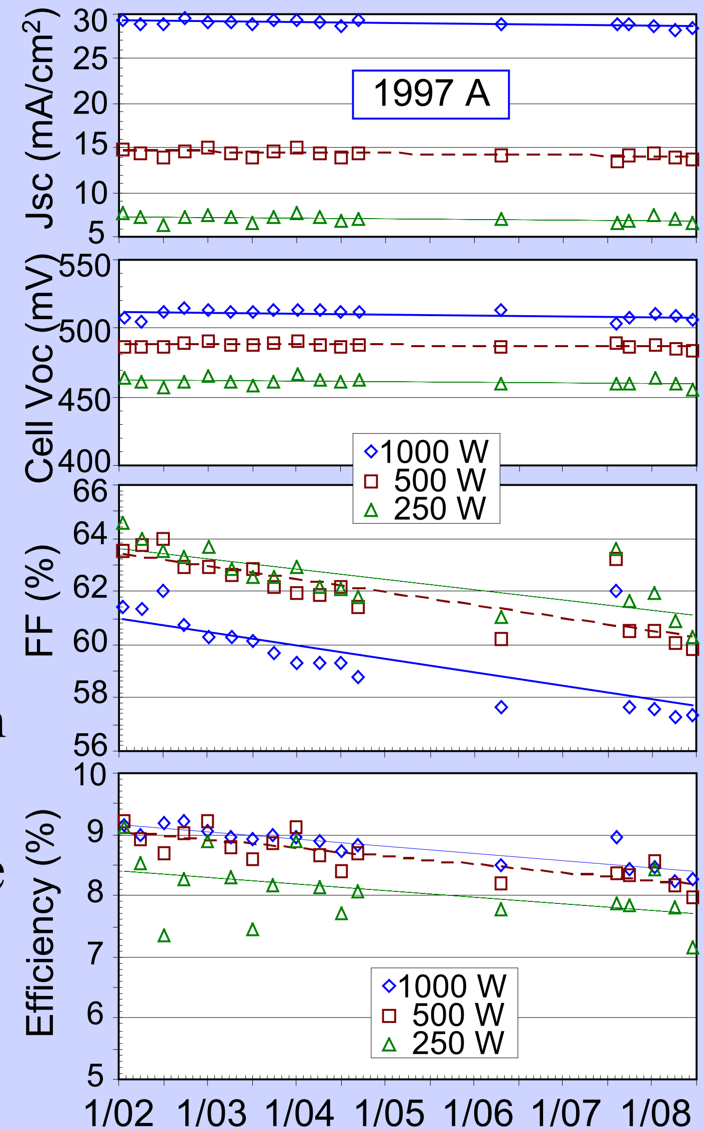
Sample PERT 1997 A Data: Across Irradiance



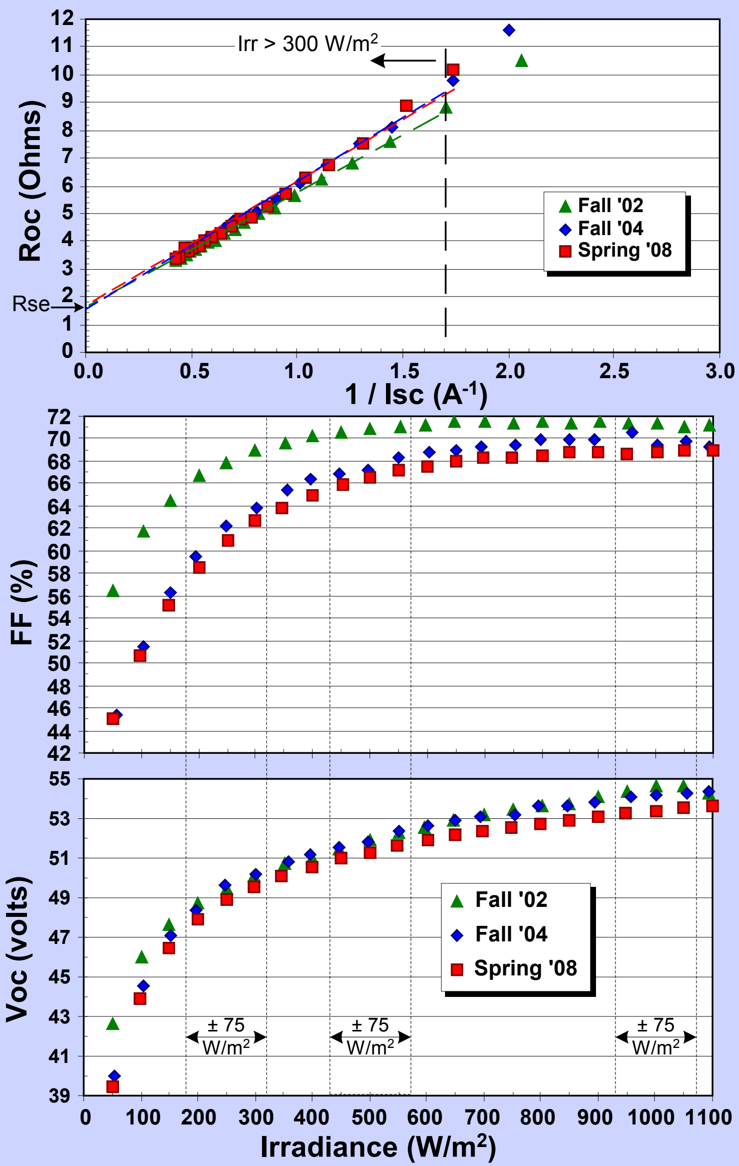
- Roc(Irr), FF(Irr) & Voc(Irr) from top to bottom
  - Segregated data by irradiance bins ±25 W/m^2,
  - Linear regression with Tmod, evaluated at 25°C;
  - data partitioned into 3-month semesters 2002-08
  - Examine 3 irradiance ranges, each spanning ±75 W/m^2 , at low (250 W/m^2), mid (500 W/m^2) , & high (1000 W/m^2) intensities
- Sample data for Fall 2002, Fall 2004 & Spring 2008
- Voc vs. Irradiance data: slight drop with time,
- FF vs. Irradiance data
  - Peak in FF at 250 W/m^2, followed by linear decline toward high irradiance typical of many modules consistent with compromise between series resistance loss vs. optical transparency
  - exhibit 5% relative decline for all irradiance above 250 W/m^2, consistent with series resistance (Rse) increase
- Roc vs. 1/ Isc data intercept gives Rse
  - increase of about 0.6 ohms, or 50% relative

PERT 1997 A Data: Power Parameters vs. time

- Data in 3 irradiance bands, low to high irradiance, plotted vs. time
  - Voc & Jsc normalized to cell level
  - Performance (δEff /δt) loss rates
    - 1.3 %/yr to 1.5 %/yr all 3 bands
  - FF degradation rates dominate loss
    - 0.6 %/yr to 0.8 %/yr
    - Lower FF at high irradiance coupled with higher FF at low irradiance consistent with series resistance as failure mode
  - Jsc decline next discernable loss mode
    - 0.4%/yr at 1000 W/m^2, or 0.7%/yr lower irradiance



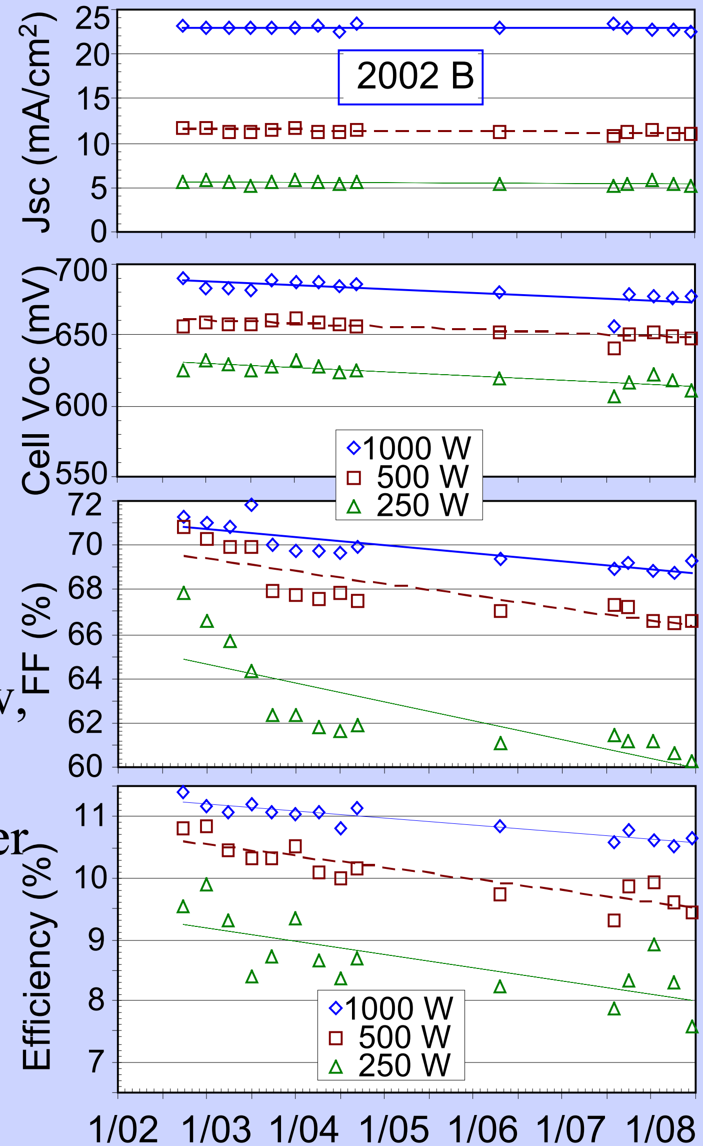
Sample PERT 2002 B Data: Across Irradiance



- ❑ Roc(Irr), FF(Irr) & Voc(Irr) from top to bottom
  - ➢ Segregated data by irradiance bins ±25 W/m^2,
  - ➢ Linear regression with Tmod, evaluated at 25°C;
  - ➢ data partitioned into 3-month semesters 2002-08
  - ➢ Examine 3 irradiance ranges, each spanning ±75 W/m^2 , at low (250 W/m^2), mid (500 W/m^2) , & high (1000 W/m^2) intensities
- ❑ Sample data for Fall 2002, Fall 2004 & Spring 2008
- ❑ Voc vs. Irradiance data: small but discernable drop vs. time lately
- ❑ FF vs. Irradiance data, between 2002 and 2008
  - ➢ Plateau behavior in FF from low to high increasing irradiance, not typically consistent with series resistance loss mode, but Gsh losses
  - ➢ 10 % relative decline at 250 W/m^2,
  - ➢ 5 % relative decline at 500 W/m^2,
  - ➢ 3 % relative decline at 1000 W/m^2,
- ❑ Rse: Roc vs. 1/Isc data intercept
  - ➢ No apparent significant increase

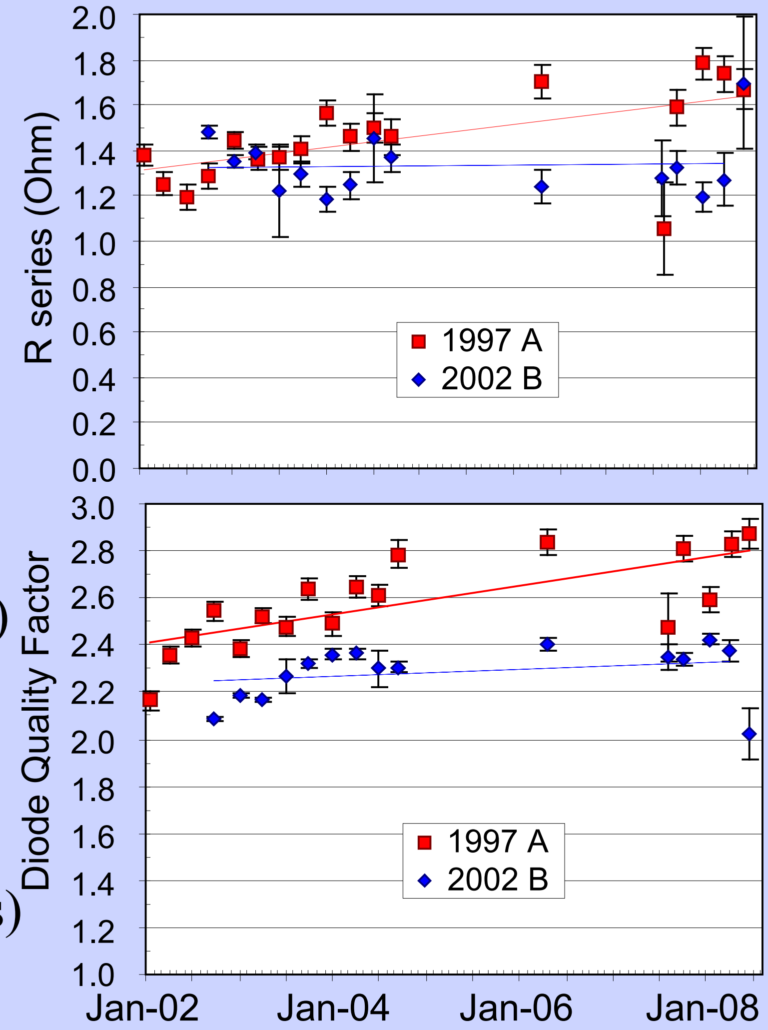
PERT 2002 B Data: Power Parameters vs. time

- Data in 3 irradiance bands, low to high irradiance, plotted vs. time
  - Voc & Jsc normalized to cell level
  - Performance (δEff /δt) loss rates
    - -2.3 %/yr low, -1.8 %/yr mid, -1.0 %/yr high irradiance
  - FF degradation rates dominate performance loss rates
    - -1.31 %/yr, -0.80 %/yr, -0.51 %/yr at low, mid, high irradiance
    - Low & mid irradiance losses appear larger initially
  - Voc declines ~ -0.4%/yr
  - Jsc declines -0.7%/yr at low & mid



PERT 1997 A & 2002 B: Rse, A Data vs. time

- Rseries extrapolated for Irr > 300 W/m^2 for each set Roc(Irr)-1/Isc(Irr) each semester,
  - if regression includes lower Irr does not alter results significantly except scatter
- A module
  - Rseries degrades (increases) 0.4 to 0.5 ohms in over 6 years
  - Point at Aug-2007 correlates with metastable performance
  - Diode quality factor degrades (increases) at rate ~ 2.5 %/yr
- B module
  - Rseries: statistically no change
  - Diode quality factor degrades (increases) at rate ~ 0.7 %/yr



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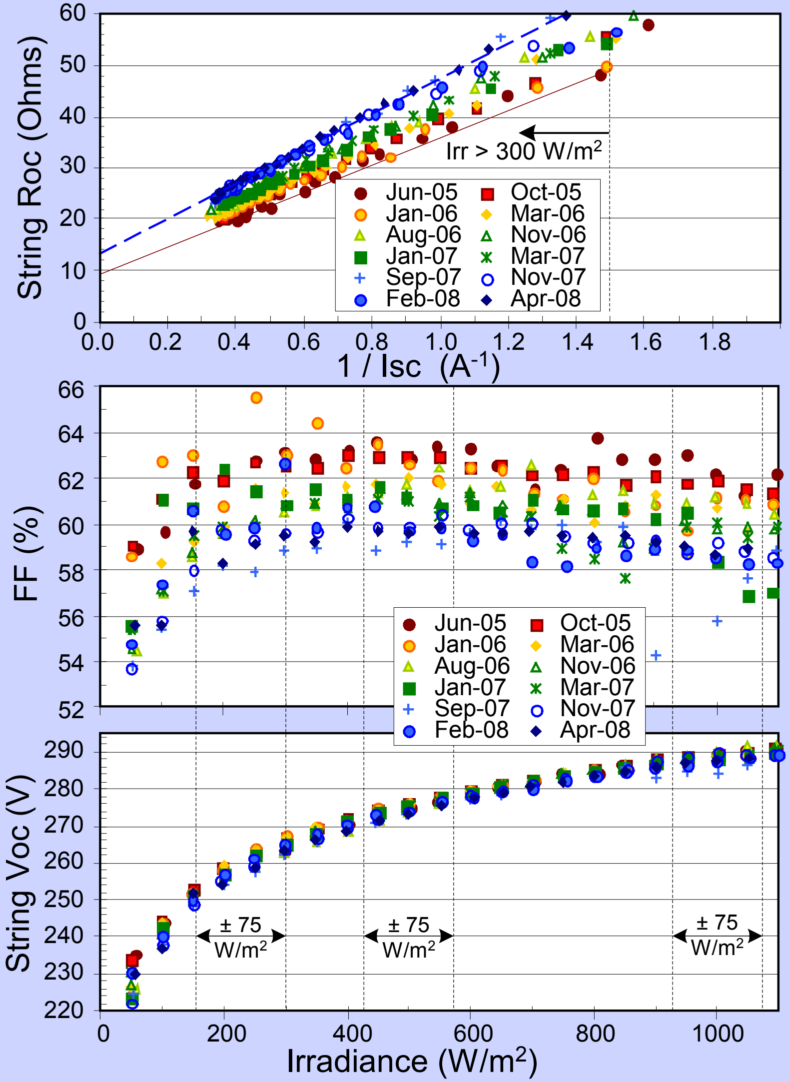
(+ String) Sample HVST2 Data : Across Irradiance



- ❑ Roc(Irr), FF(Irr) & Voc(Irr) from top to bottom
  - ➢ segregated data by irradiance bins ±25 W/m², 3 irradiance ranges, at low, mid, & high intensities, regression to evaluate parameters at 25°C
- ❑ data for Jun’05 thru Apr’08 color coded in rainbow-spectral-sequence:
  - ➢ red ⇔earlier ‘05, blue ⇔ latter ‘08
- ❑ Voc vs. Irradiance data:
  - ➢ slight but palpable drop vs. time
- ❑ FF vs. Irradiance data exhibit 10% relative decline between Jun’05 and Apr’08
- ❑ Rse: Roc vs. 1/Isc data intercept
  - ➢ Obvious shift in Rse to higher values vs. time by ~ 4-5 ohms

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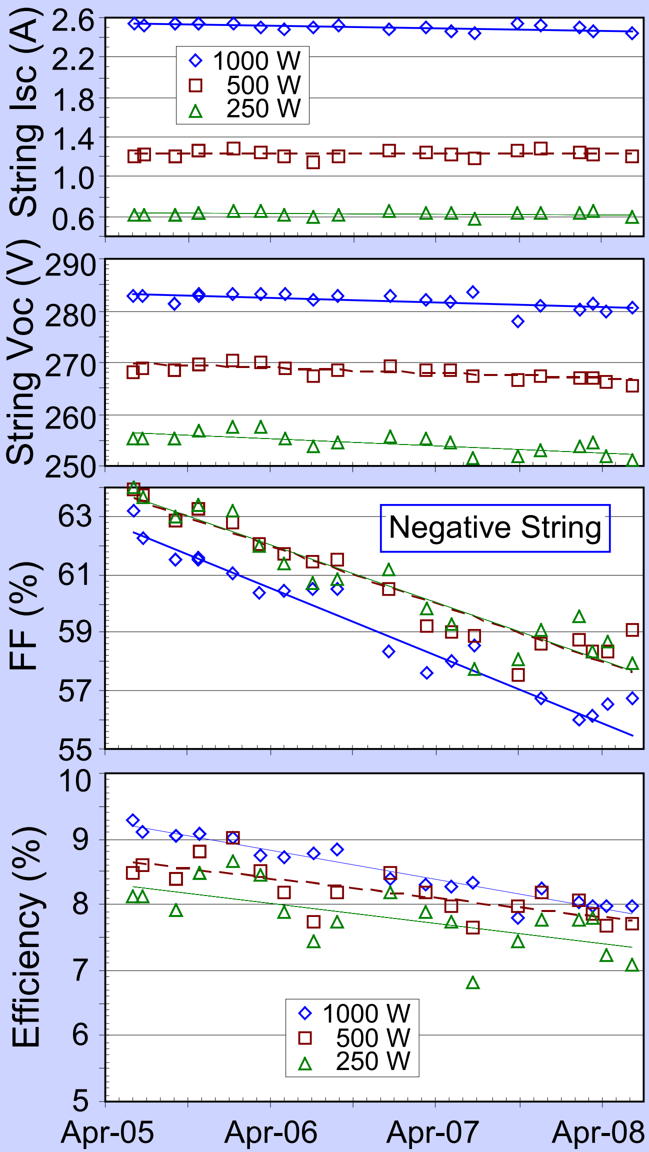
HVST2 array Power Parameters vs. time: (– string)

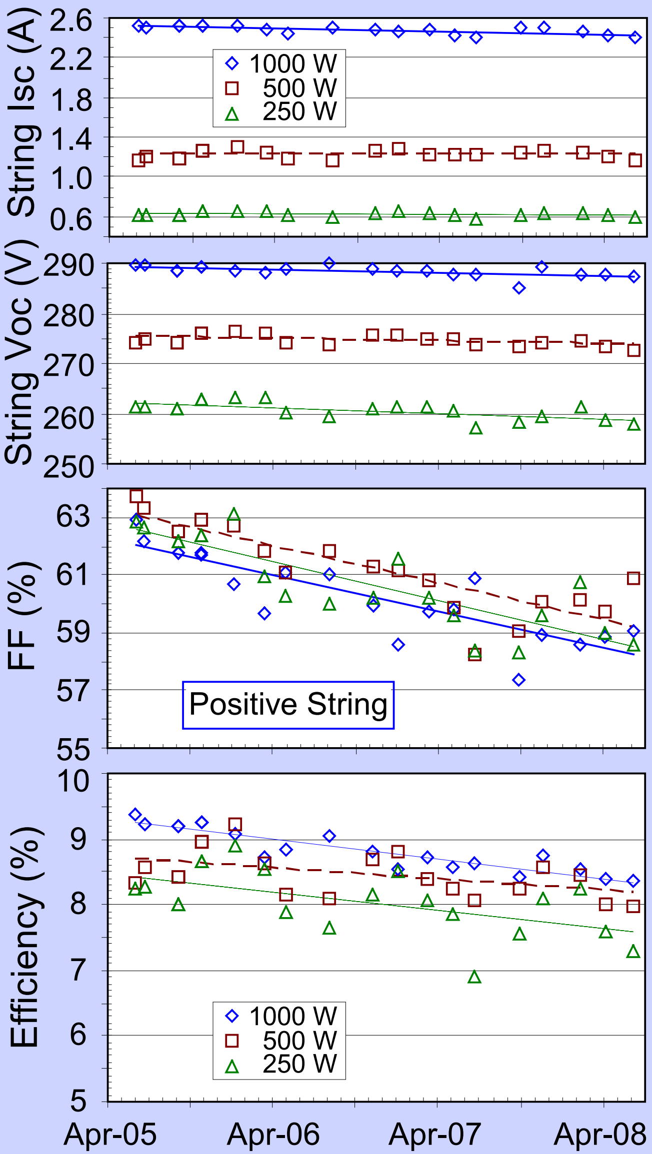


- Data in 3 select irradiance bands shown,
  - adjacent bands averaged, span ±75 W/m^2
  - Time span: Apr. 2005 – Jul. 2008
- Efficiency loss rates moderately high
- FF degradation rates lead
- Voc degradation also discernable
  - initial ~ 284 V (6 V less than + string)
- Some Isc loss rate at high irradiance

Negative string summary loss rates

	250 W/m^2 (%/yr)	500 W/m^2 (%/yr)	1000 W/m^2 (%/yr)
Eff	-3.7 ±0.95	-3.4 ±0.68	-4.8 ±0.29
FF	-3.1 ±0.24	-3.1 ±0.22	-3.7 ±0.30
Voc	-0.52 ±0.12	-0.36 ±0.07	-0.30 ±0.09
Isc	-0.24 ±0.76	0.15 ±0.66	-0.99 ±0.21

HVST2 array Power Parameters vs. time: (+ string)

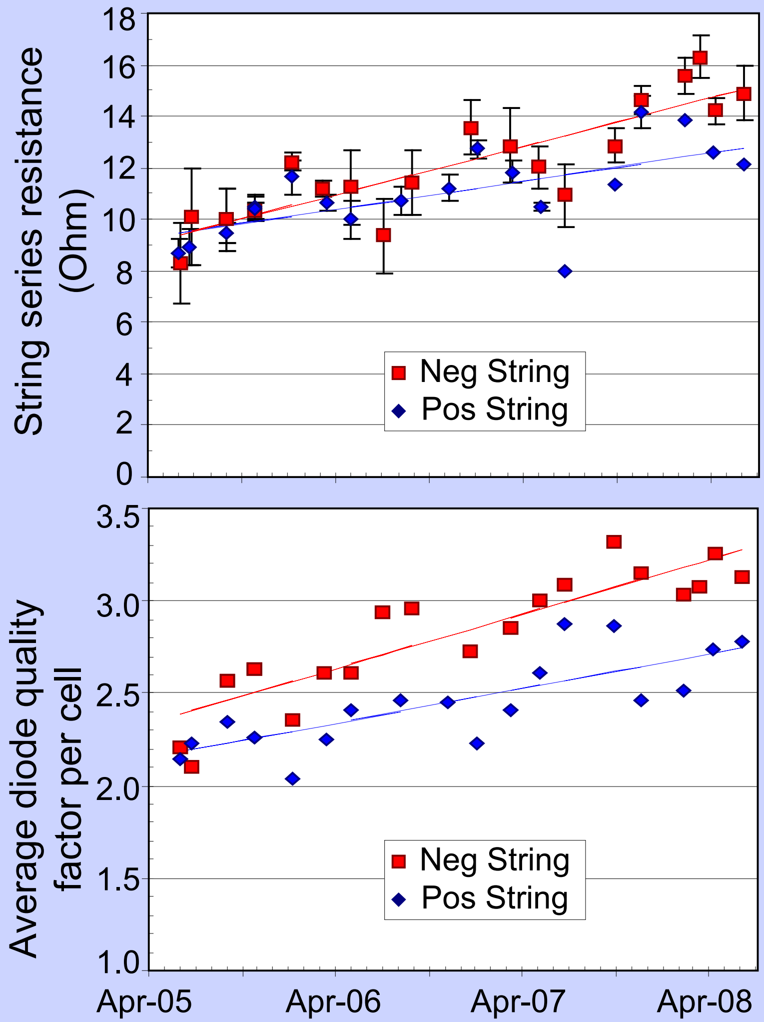


- Data in 3 select irradiance bands shown,
  - adjacent bands averaged, span ±75 W/m^2
  - Time span: Apr. 2005 – Jul. 2008
- Efficiency loss rates moderately high, but discernable lower than for negative string
- FF degradation rates lead, then Voc
- Most loss rates smaller than for Voc loss lower than negative at high irradiance
- Isc loss at high irradiance

Positive string summary loss rates

	250 W/m^2 (%/yr)	500 W/m^2 (%/yr)	1000 W/m^2 (%/yr)
Eff	-3.3 ±1.15	-2.0 ±0.83	-3.3 ±0.34
FF	-2.2 ±0.31	-2.0 ±0.29	-2.0 ±0.30
Voc	-0.45 ±0.12	-0.20 ±0.07	-0.21 ±0.07
Isc	-0.93 ±0.86	0.33 ±0.77	-1.13 ±0.29

HVST2 ± strings: Rse, A Data vs. time



- Rseries 2005 to 2008
  - Both strings start out at nearly identical values (~ 9 ohms), but increase 4-6 ohms with time
    - Growth in negative string's Rse outpaces the positive string by 2 ohms in 3 years
  - intercept derived for Irr > 300 W/m^2
    - but including lower intensities produces similar results with larger scatter
- Diode Q factors degradation (growth) rates:
  - -string: 12 %/yr
  - +string 7.5 %/yr

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Conclusions: Performance Loss Rates @ STC

- Long-term exposure rack modules:
  - Type A, SPIRE
    - (1 of 1988, 2 each 1990, 1992, 1994, 1998)
    - Predominantly FF losses via Rse increases, followed by Voc loss
    - Isc losses likely not significant
  - Type 2002 B
    - (2 modules SPIRE & LACSS, includes one on PERT)
    - Loss rate in FF counter-balanced by increase rate in Voc

Module Type	ΔVoc/Voc (%/yr)	ΔIsc/Isc (%/yr)	ΔFF/FF (%/yr)	Δ Eff / Eff (%/yr)	TIMELINE
1988 A	-0.25%	0.36%	-1.09%	-0.90%	Nov-90 –Mar-08
1990 A	-0.02%	0.01%	-0.24%	-0.26%	Oct-91–Mar-08
1992 A	-0.05%	0.19%	-0.55%	-0.43%	Aug-92–Mar-08
1994 A	-0.08%	-0.11%	-0.84%	-1.01%	Mar-95–Mar-08
1998 A	-0.24%	-0.15%	-1.89%	-2.19%	Jan-99–Mar-08
2002 B	0.57%	-0.16%	-0.83%	-0.40%	Aug-02–Mar-08

Conclusions: Performance Loss Rates PERT

- Average * loss rate 1997 A: -1.4 %/yr,
  - FF declines from Rse increase dominate performance loss
  - Jsc decline next more important sizeable loss

	Module	250 W/m^2 (%/yr)	500 W/m^2 (%/yr)	1000 W/m^2 (%/yr)
Eff	**1997 A**	-1.3 ± 0.08	-1.5 ±0.04	-1.3 ±0.03
FF		-0.60 ±0.13	-0.75 ±0.13	-0.84 ±0.20
Voc		-0.07 ±0.00	-0.05 ±0.00	-0.13 ±0.00
Jsc		-0.68 ±0.06	-0.71 ±0.06	-0.37 ±0.04

- Average * loss rate 2002 B: -1.7 %/yr
  - FF declines dominate performance loss, likely from shunt increase,
  - Jsc decline next important sizeable loss, but Voc loss larger at high irradiance

	Module	250 W/m^2 (%/yr)	500 W/m^2 (%/yr)	1000 W/m^2 (%/yr)
Eff	**2002 B**	-2.3 ±0.09	-1.8 ±0.04	-1.0 ±0.02
FF		-1.31 ±0.29	-0.80 ±0.15	-0.51 ±0.09
Voc		-0.45 ±0.00	-0.35 ±0.00	-0.38 ±0.00
Jsc		-0.74 ±0.04	-0.72 ±0.04	-0.13 ±0.05

* Average over 3 irradiance windows (250 W/m^2, 500 W/m^2, 1000 W/m^2)

Conclusions: Performance Loss Rates HVST2

- Decline rates averaged ✱ Negative string degradation at -4.0 %/yr

	250 W/m^2 (%/yr)	500 W/m^2 (%/yr)	1000 W/m^2 (%/yr)
Eff	-3.7 ±0.95	-3.4 ±0.68	-4.8 ±0.29
FF	-3.1 ±0.24	-3.1 ±0.22	-3.7 ±0.30
Voc	-0.52 ±0.12	-0.36 ±0.07	-0.30 ±0.09
Isc	-0.24 ±0.76	0.15 ±0.66	-0.99 ±0.21

- Decline rates averaged ✱ Positive string degradation at -2.9 %/yr

	250 W/m^2 (%/yr)	500 W/m^2 (%/yr)	1000 W/m^2 (%/yr)
Eff	-3.3 ±1.15	-2.0 ±0.83	-3.3 ±0.34
FF	-2.2 ±0.31	-2.0 ±0.29	-2.0 ±0.30
Voc	-0.45 ±0.12	-0.20 ±0.07	-0.21 ±0.07
Isc	-0.93 ±0.86	0.33 ±0.77	-1.13 ±0.29

- High-voltage stress may lead to higher degradation in these A (2003) modules
  - Higher loss may also be result of manufacturer process, probably both
- FF decline & Rseries increases dominate performance loss/failure mode:
  - 11%/yr and 20%/yr, for the positive and negative strings, respectively
- Degradation rates consistent with earlier analysis done via PTC regression method

✱ Average over 3 irradiance windows (250 W/m^2, 500 W/m^2, 1000 W/m^2)

Acknowledgements

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- Thank you for your attention