Stability Of CIS/CIGS Modules At The Outdoor Test Facility Over Two Decades

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33rd IEEE PVSC, San Diego, CA
Thursday, May 15, 2008
1:30 –3:00 PM

NREL/PR-520-43255
Presented at the 33rd IEEE Photovoltaic Specialist Conference held May 11-16, 2008 in San Diego, California

Outline

- Introduction
  - Rationale for thin-film CIS PV modules: cost & high efficiency
  - Loss modes in CIS/CIGS modules
- Experimental Tests at NREL OTF
  - Multiple modules from two manufacturers, types ‘A’ & ‘B’
  - Modules deployed on 3 separate testbeds
- Analyses
  - 3 types of data and data analysis
- Data
- Conclusions
  - FF degradation is predominant loss mode
    - Type ‘A’ can show very low loss rate to moderately loss rate
      - Series-resistance increases emblematic of A modules failure mechanism
    - Type ‘B’ can show very low loss rate to nominal loss rate
      - Shunt increases & other changes emblematic of B modules failure mechanisms
  - Some transient behavior observed especially in Voc
- Acknowledgements

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 attain ~12%
- ☐ CIGS PV module stability is a key issue that needs to be addressed (as well by other thin-film technologies) in order to achieve low levelized cost of electrical power

Introduction: Stability Heat/Humidity Stress

- ☐ FF losses:
  - Rse increases may result due to:
    - degradation of top TCO (ZnO) resistivity due to chemical reaction (especially if doped with Al)
    - Increase in CB offset/barrier height at CdS/CIS interface through which electrons must travel
  - Gsh changes: may either increase/decrease due to point defects
- ☐ Voc losses:
  - Change in doping density in CIS
  - Induction of deep acceptor states/traps in bulk
  - Decrease in VB offset/barrier height at CdS/CIS interface & increase in interface recombination
- ☐ Isc losses:
  - Not typically observed, but can arise if :
    - transparency of top TCO degrades
    - Rse increases are very large

Experimental Tests

- ☐ Two types of modules ‘A’ & ‘B’
  - glass/Mo/CIGS/CdS/ZnO/glass laminates
  - type A began to deploy in array field at OTF in 1988
  - type B began deploying at OTF in 2002
- ☐ Study CIS/CIGS modules deployed on 3 testbeds:
  - Single, free-standing, long-term exposure, loaded at Pmax (STC) with fixed resistor, 8 total
  - High Voltage Stress Testbed (HVST2) Array
    - consists of bipolar strings, nominally ± 300 VDC
    - 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

Analysis of Data

- ❑ Single I-V curves at STC or dark at 25°C
  - ➢ Module data reduced to unit area cell level (J-V) by:
    - ❖ 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) allow raw data to be corrected and then to derive A, J_0

$$J = J_0 * [\, e^{(V-RseJ)/AkT} - 1 \,] - G_{SH}V - J_L$$

Dark J-V

$$dV/dJ = R_{se} + (AkT/q) \;/\; J$$

$$V - R_{se} * J = (AkT/q) * Log[\, 1 + (J + G_{sh} * V) / J_0 \,]$$

Light J-V

$$dV/dJ = R_{se} + (AkT/q) \;/\, [\, J_L + J \,]$$

$$V - R_{se} * J = (AkT/q) * Log[\, 1 + (J + J_L + G_{sh} * V) / J_0 \,]$$

Analysis of Data

- PERT real-time outdoor data measured in-situ with DAS
  - I-V power parameters (Voc, FF, etc.) data derived from traces segregated into narrow irradiance bands 500±25, 1000±25 W/m^2.
  - Linear temperature corrections determined to power parameters by performing regression of data in 30 day intervals
  - Changes in power parameters vs. time calculated
- HVST2 array real-time outdoor data measured in-situ with DAS for each string done same as PERT except only at one irradiance window 1000±25 W/m^2.

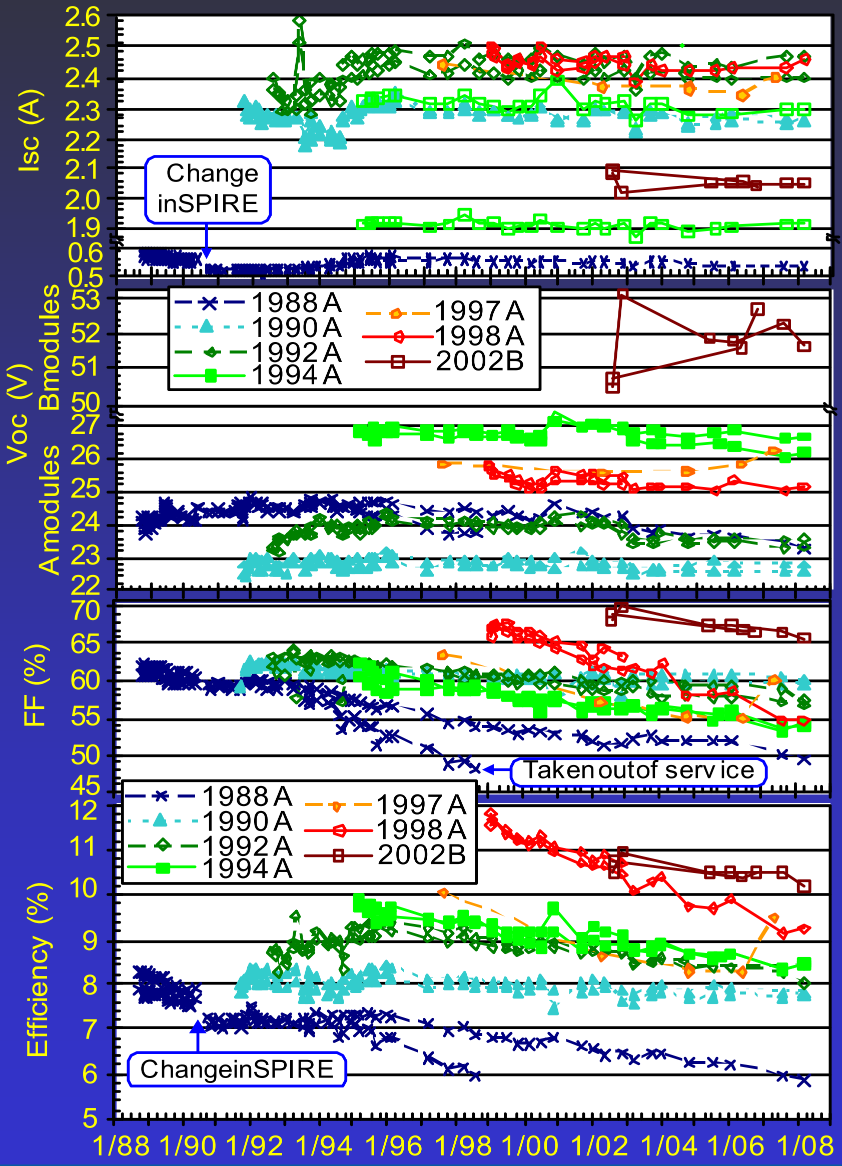
Analysis of Data

- ☐ HVST2 array: PVUSA Test Conditions Regression
  - ➢ Perform regression of power vs. irradiance, air temp., wind speed conditions for coefficients A, B, C & D monthly, for data where irradiance > 800 W/m^2
  - ➢ monthly calculated coefficients (A, B, C, D) then used to evaluate rated power (P_{PTC}) at PVUSA conditions
    - ❖ $E_0 = 1000$ W/m^2 , Tair = 20°C, Ws = 1 m/s

$$P_{max}(E, Tair, Ws) / E = (A + B^*E_0 + C^* T_{air} + D^*W_S)$$

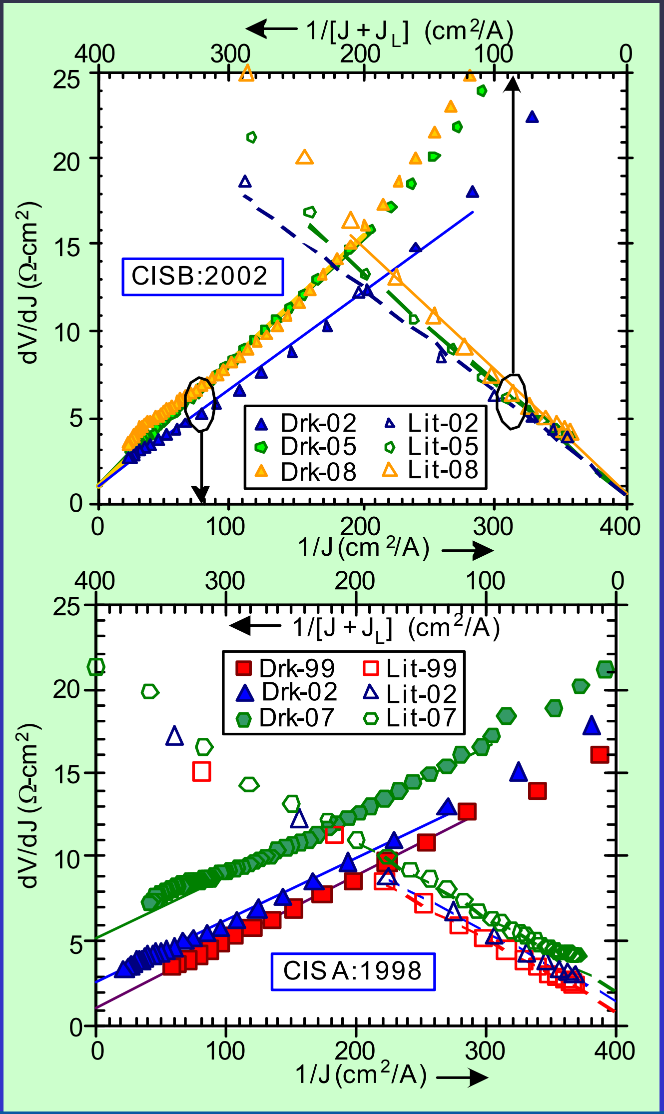
$$P_{PTC} = E_0 * (A + B^*E_0 + C^*T_{air} + D^*W_S)$$

Data: single module stability at STC



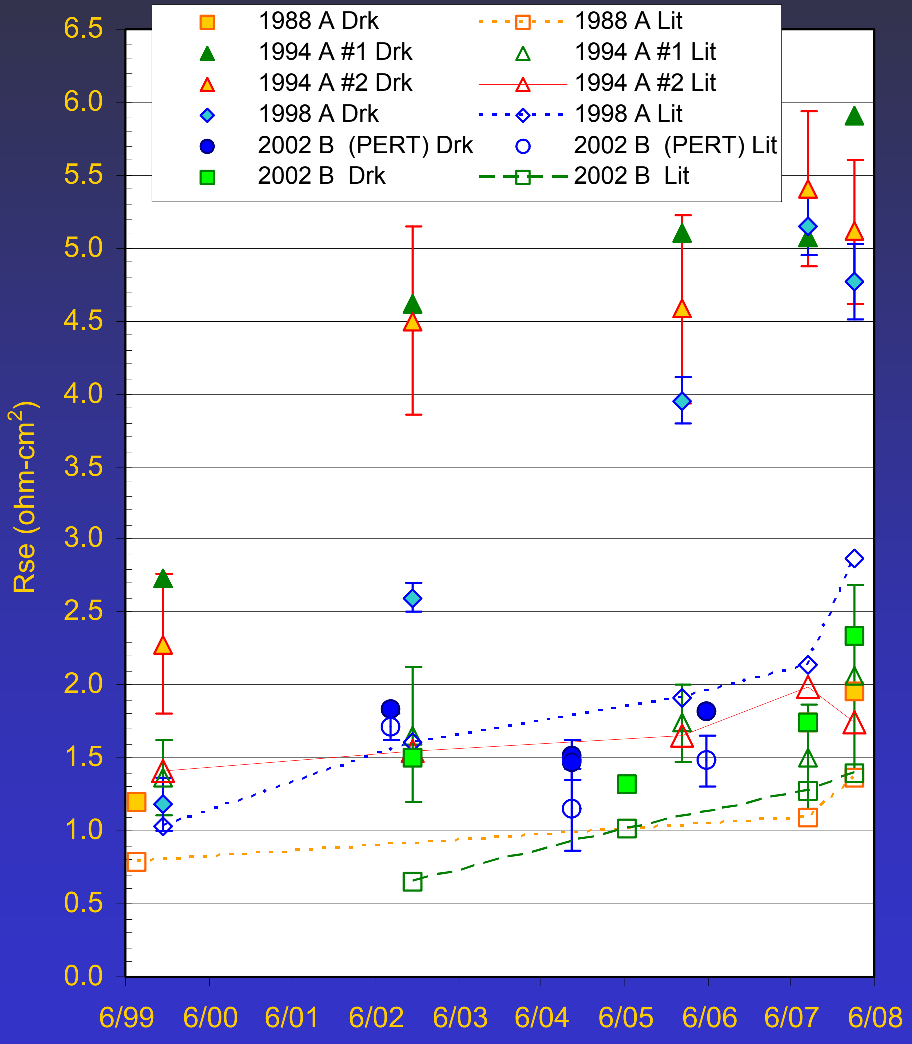
- ❑ Type A 1988, 1990, 1992, 1994, 1998; type B 2002:
  - ➢ Isc, Voc, FF and Efficiency at STC on the SPIRE shown
  - ➢ Type A initial efficiency improved from 8% (1988) to just under 12% (1998)
  - ➢ stability of A modules became more of an issue:
    - ❖ FF losses account for most decline
    - ❖ Voc increases in initial years, partly offset FF losses, but subsequently can degrade
- ❑ Type B module initial efficiency ~11% show slight decline mostly in FF, is also offset by Voc increase

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

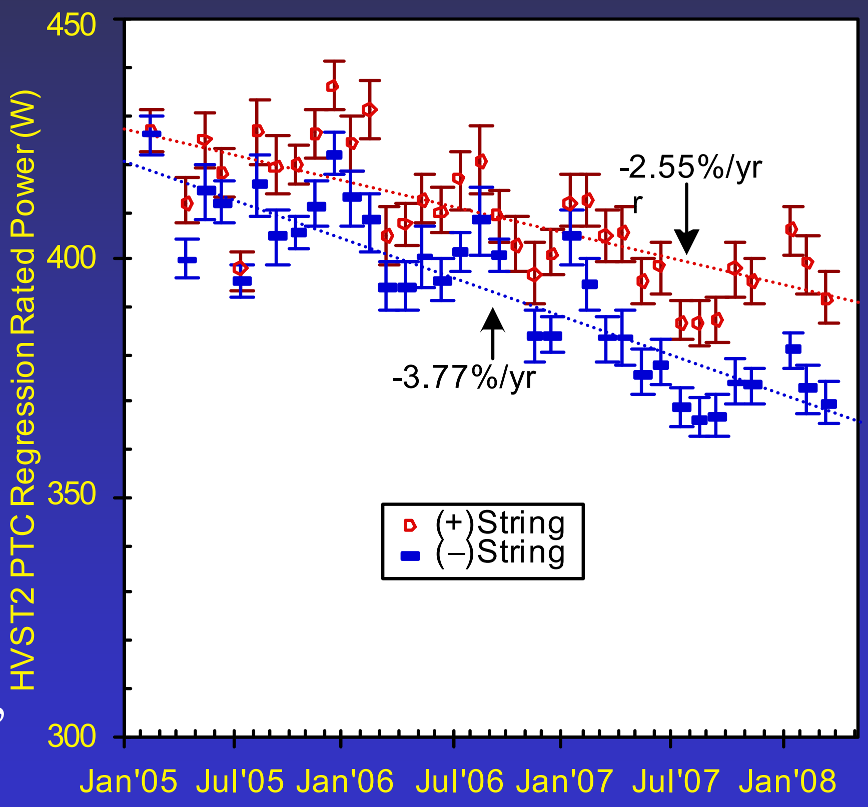
Data: series resistance vs. time (single modules)



- ❑ Dark (filled symbols), Light (open symbols)
- ❑ 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 ~ 2.3–2.8 to 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
- ❑ 2002 B
  - ➢ Dark 1.5 to 2.3 Ω-cm^2
  - ➢ Light 0.6 to 1.4 Ω-cm^2
- ❑ 2002 PERT B (2002 to 2006)
  - ➢ 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
  - ➢ ~30 mA/cm^2 for A-type, 1-sun
  - ➢ ~24 mA/cm^2 for B-type, 1-sun

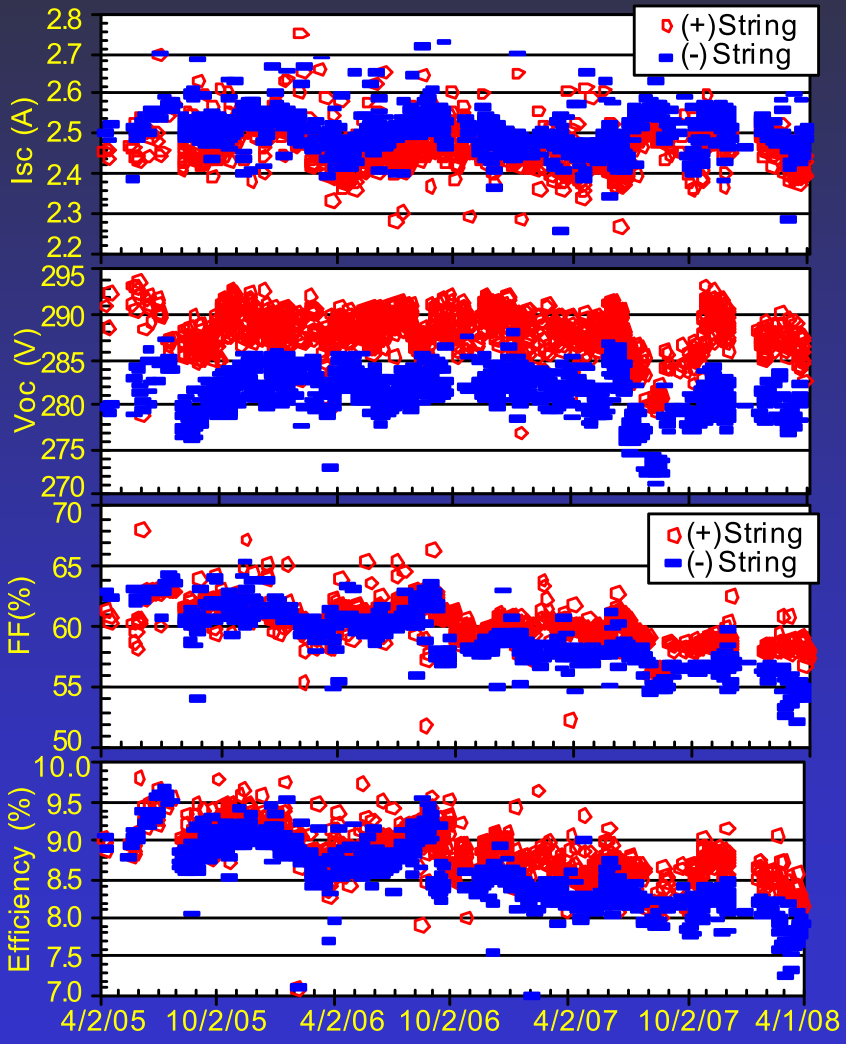
Data: HVST2 Array PTC Regression

- 24 Type A 2004 CIGS modules
  - 12 per string in positive (+) & negative (–) configuration
- PTC rated power: start out with ~425 W each string in Feb. 2005
- Degradation rate is un-even:
  - + string ~ -2.5 %/yr (relative)
  - – string ~ -3.8 %/yr (relative)
- PTC regression analysis rating mitigates environmentally-induced fluctuations in performance (like temperature cycles) but not entirely, as evidence of higher/lower power cycles in winter/summer are still observed

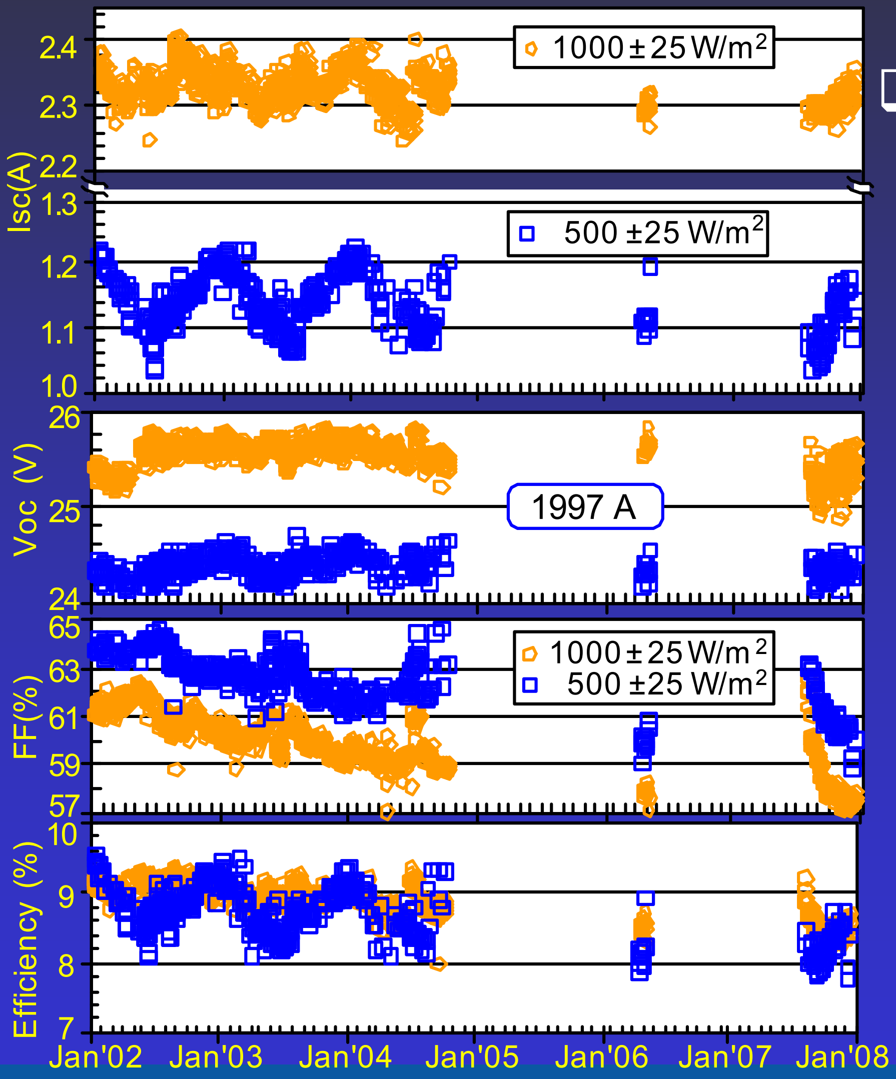


Data: HVST2 Array data at 1000 ± 25 W/m^2

- ☐ 24 Type A 2004 CIGS modules
- ☐ Bipolar (+/-) strings I-V power parameters, corrected to 25°C temperature vs. time shown:
  - ➢ Isc, Voc, FF & Eff top to bottom
- ☐ Efficiency of each string clearly declining between 2005 and 2008, relative loss rates:
  - ➢ + string ~ -2.9 %/year
  - ➢ – string ~ -4.7%/year
- ☐ FF losses account for most of changes:
  - ➢ + string ~ -2 %/year
  - ➢ – string ~ -4 %/year
- ☐ Voc declines ~ -0.2%/yr to -0.4%/yr

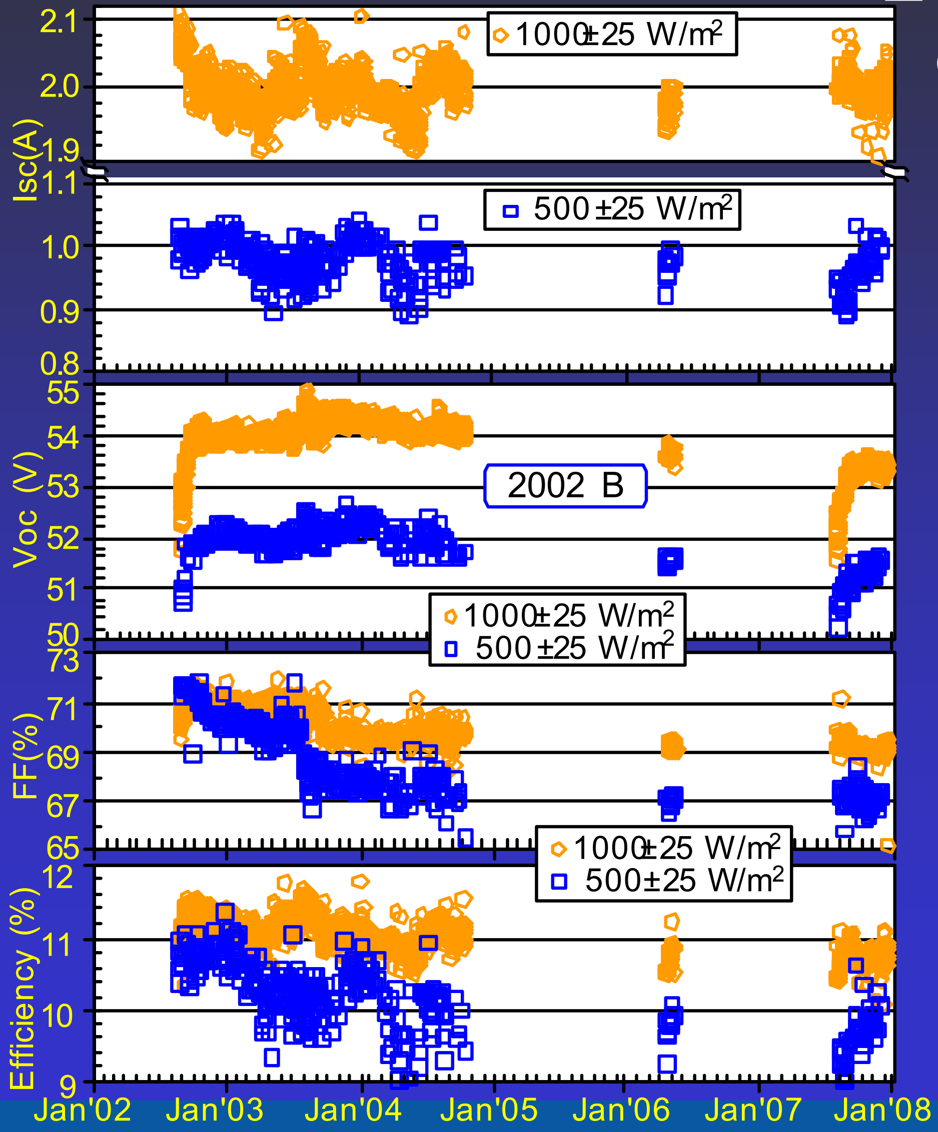


Data: PERT type ‘A’ at 500 & 1000 ± 25 W/m^2



- 1997 A I-V power parameters, corrected to 25°C temp. vs. time:
- Isc, Voc, FF & efficiency shown from top to bottom
  - FF losses lead degradation rates
  - similar loss rates for FF data in 500 & 1000 W/m^2 irradiance windows, -0.71%/yr & -0.75 %/yr , respectively
    - consistent with series resistance source
  - Data gap in 2006-07: module lay indoors
    - Transient improvement in FF, ~5%, just after re-deployment in 2007

Data: PERT type ‘B’ at 500 & 1000 ± 25 W/m^2



- ❑ 2002 B I-V power parameters, corrected to 25°C temp. vs. time
  - ➢ Isc, Voc, FF & efficiency shown from top to bottom
  - ➢ Uneven loss rates for FF data in 500 & 1000 W/m^2 irradiance windows:
    - ❖ -0.93%/yr & -0.49 %/yr , respectively
    - ❖ Consistent with shunt-related increases with time as source
  - ➢ Transient improvement in Voc by 1-2 V with re-deployment after low light level storage in 2002 & 2007

Conclusions: Performance Loss Rates

- Loss rates type A modules:
  - range from negligible (-0.3%/yr), to nominal (1%/yr) and moderate (2%/yr) for later types
  - FF worsens due to series resistance increases
  - Moderate larger loss rates observed when deployed at high-voltage bias:
    - + HV bias ~ -2.5%/yr to -2.8%/yr
    - – HV bias ~ -3.8%/yr to -4.7%/yr
- Loss rates type B modules:
  - Not significant from STC data, due to
    - opposing FF & Voc trends
    - Not as much Rse increase & lower Jsc
  - FF loss mode more tied to shunt conductance increases:
    - Nominal ~ -1%/yr from PERT data around 1000 W/m^2 irradiance
    - Slightly larger ~ -1.8%/yr from PERT data at 500 W/m^2 irradiance

Type	ΔEff/Eff$_0$ (%/yr)	±95% (%/yr)	TEST CONDITION	TimeLine
1988 A	-0.90	0.13	STC	Nov-90 – Mar-08
1990 A	-0.27	0.15	STC	Oct-91 – Mar-08
1992 A	-0.43	0.20	STC	Aug-92 – Mar-08
1994 A	-1.01	0.22	STC	Mar-95 – Mar-08
1998 A	-2.19	0.22	STC	Jan-99 – Nov-02
2002B	-0.67	3.30	STC	Aug-02 – Mar-08
1997 A	-2.10	1.06	STC	Aug-97 – May-07
1997 A	-1.35	0.14	500 PERT	Jan-02 – Dec-07
1997 A	-1.27	0.04	1000PERT	Jan-02 – Dec-07
2002B	-1.80	0.16	500 PERT	Aug-02 – Dec-07
2002B	-0.89	0.14	1000PERT	Aug-02 – Dec-07
2004 A	-2.87	0.15	1000HVST2 POS.STR.	Apr-05 – Mar-08
2004 A	-4.68	0.15	1000HVST2 NEGSTR.	Apr-05 – Mar-08
2004 A	-2.55	0.86	PTC HVST2 POS.STR.	Apr-05 – Mar-08
2004 A	-3.77	0.82	PTC HVST2 NEG.STR.	Apr-05 – Mar-08

Acknowledgements

- ☐ Contributing Coauthors
  - Ben Kroposki
  - Carl Osterwald
  - Steve Rummel
  - Alan Anderberg

- ☐ This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-99GO10337

Thank you for your consideration