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An Unlikely Combination of Experiments with a Novel High-Voltage CIGS Photovoltaic Array

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Introduction

- Long-term (2020) goal of the US Solar Program Multi-Year Plan:
  - Commercialization of photovoltaic (PV) modules with 30-year lifetimes or more, capable of sustaining less than 0.5% annual performance degradation rate, and at costs consistent with market-rates of electricity.
- Motivation: quantify the performance, stability and reliability of high efficiency thin-film copper-indium-diselenide (CIS) PV modules in a high-voltage array.

Motivation: PV Module Reliability

- High voltage is a known stress-mechanism that precipitates PV module degradation:
  - In the 1980's, the Jet Propulsion Laboratory (JPL) investigated the connection between high-voltage leakage currents from modules and their degradation:
  - Found that series resistance increases, brought about by electrochemical corrosion of contacts, is a prime failure mechanism induced by high-voltage stress
  - Established key thresholds of accumulated charge that would result in 50% failure in certain PV modules:
    - For crystalline-silicon (c-Si) ranging 1–10 coulombs per linear centimeter (C/cm) of module perimeter,
    - For amorphous-silicon (a-Si) modules 0.1–1 C/cm

Motivation: PV Performance & Stability

- Actual energy production of modules under real field conditions continues to be an issue:
  - Currently only measurements of power at Standard Reporting Conditions (SRC) are used to rate modules
    - But SRC misses most of actual operating conditions
- PV arrays commonly employ inverters and measurements reported usually include only optimum power-point voltage, current and power
  - When performance degrades, measurements of optimum power point voltage & current are usually not enough to discern the failure mode,
  - Would benefit to have more in-depth I-V characterization.

Goals of This Study

- Parameterize current-voltage (I-V) performance over a wide range of illumination & temperatures:
  - 50 – 1150 W/m^2 irradiance, 5° – 65 °C
  - Obtain array temperature coefficients
  - Quantify energy production
- Investigate high-voltage leakage currents from the CIS modules in a high-voltage array:
  - Determine dependence on moisture, temperature, and voltage bias
  - Ascertain corrosion problems if any
- Study long-term power & energy production stability.

HVST2 CIGS Array

- 24 Shell Solar thin-film CIGS modules
  - Nominally ±300 VDC open-circuit & 1 kW total array power
  - Deployed in 2 bipolar strings, 12 modules in each connected in series
  - Each string: aperture area~4.877 m^2, segregated into 2 groups of 6 modules each group for each string
  - Each group of 6 modules perimeter length ~ 1.915 m
  - Efficiency baseline tested at standard test conditions (STC, η_{STC}) prior to deployment:
    - All modules tested between 36 and 44 W power, at STC,
    - Average η_{STC} for the positive (+) and negative (-) strings of the array: respectively, 9.64% and 9.53%.
  - Dry hi-pot and wet hi-pot tests : for both tests, the leakage currents ranged 0.1–0.6 microamps.

HVST2 CIGS Array

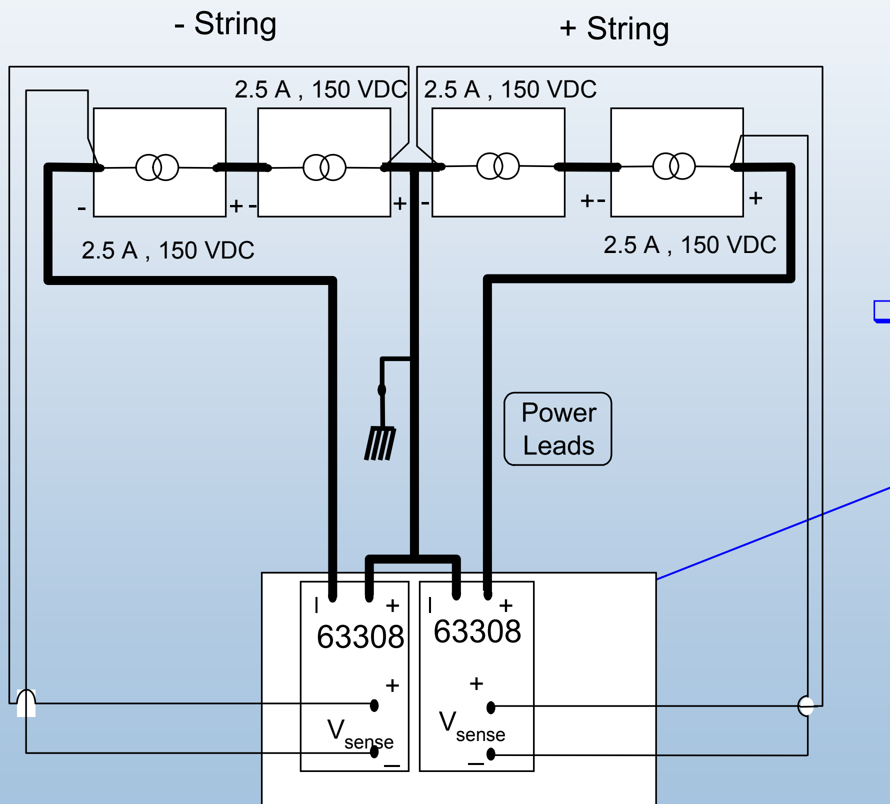
Outdoor Test Facility (OTF)

View Looking East Toward Array

- Current-Voltage (I-V) control & measurements:
  - via programmable e-load
  - I-V traces once every 15min, in 1st quadrant
  - peak-power other times
- Temperatures:
  - type 'T' TC back-of-module one for each +/- string
  - Air Temp. & humidity (RH)
- Modules mounted facing south, at ~40° tilt ~latitude ~39.7°, plane-of-array (POA)
- Irradiance sensed with pyranometers, same POA

HVST2 Array Connection

High Voltage Array: 24 CIGS PV modules
2 strings + / - , with 12 modules per string,
2 groups of 6 modules in series each,
±300 volts Voc , 2.5 amps Isc from each string

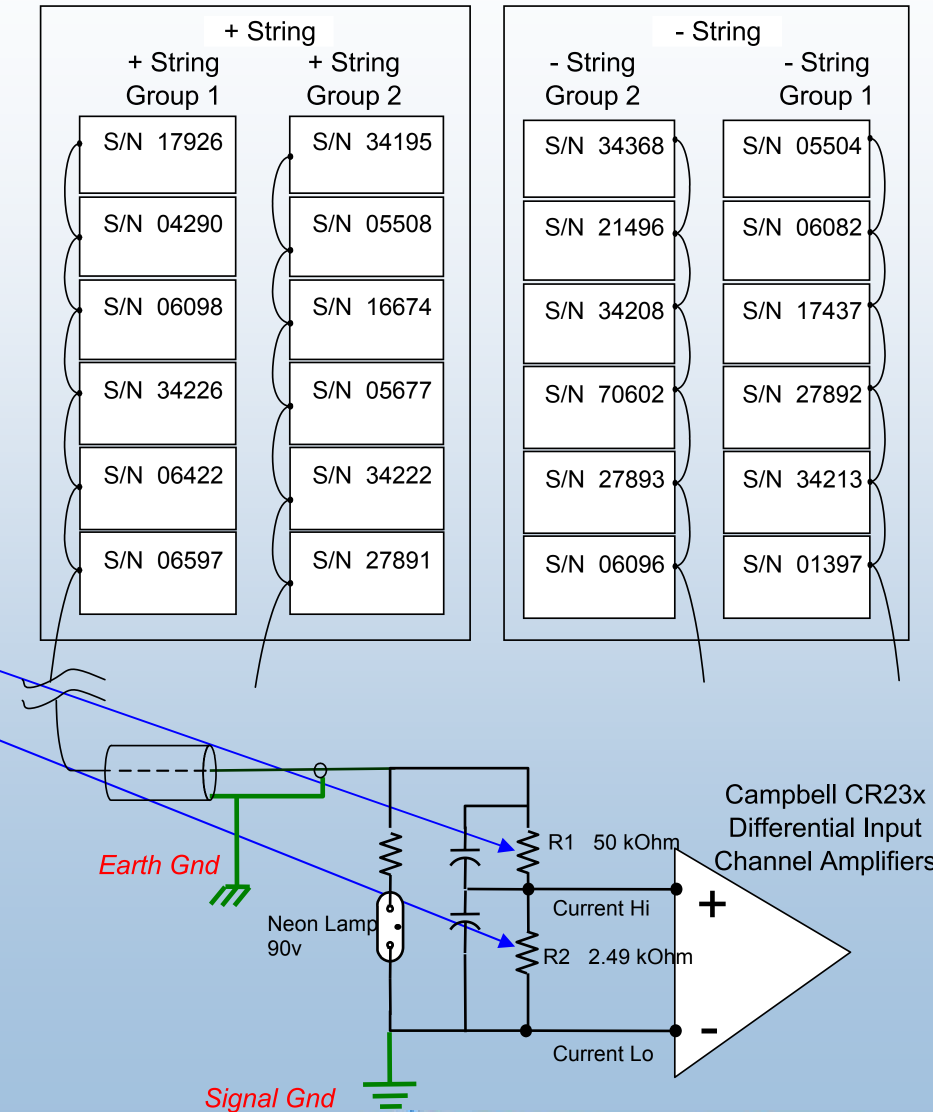


Programmable Electronic Load: Control Modes:
constant current or voltage, resistance Loading

- 24 CIGS modules in positive (+) and negative (-) strings
  - 12 modules per string, 2 groups of 6 modules each per string
  - Frames not grounded at supports, but instead connected to resistive network and then to ground to facilitate leakage current sensing
- Electrical Characterization & Control
  - via dual-channel Programmable Electronic Load (PEL) interfaced to Data Acquisition System (DAS) running Visual BASIC Code
  - PEL is not a power supply/source
  - PEL can control in constant voltage, current or resistance
  - DAS sends varying set-points to PEL to trace I-V curves or track peak power

HVST2 Array Leakage Currents Sensing

- Frames allowed to float and electrically daisy-chained together on support structure
- Electrical connection made to resistive network before ground:
  - Leakage currents pass through 52.5 kOhm resistor combination,
  - Leakage currents appear as voltage across 2.49 kOhm resistor, are sensed by CR23x data-logger differential input channels
  - Arc by-pass to ground provided in case of too much leakage.
- Each group of 6 modules has own sensing circuit
  - Group 1 always higher offset bias being further from ground



Data Analysis

1. Integration of peak-power tracking and irradiance data versus time yielding daily energy output, insolation
2. Accumulation of all I-V trace records, statistical filtering for predominantly clear-sky conditions, followed by segregation into irradiance bins & regression vs. Temp.
3. Integration of the leakage current data through module frames resulting in accumulated daily leakage charge.
4. Efficiency quotients from two distinct angles:
   i. usual I-V trace data representing power measurements from each string, divided by the incident power on each string,
   ii. Effective Efficiency (η_{EFF}) = ratio of the daily energy output from each string divided by the daily insolation energy

$$\eta_{EFF} = \int_{Daily} P_{MAX} \cdot dt \Big/ \left[Area_{String} \cdot \int_{Daily} Irr \cdot dt \right] \qquad (1)$$

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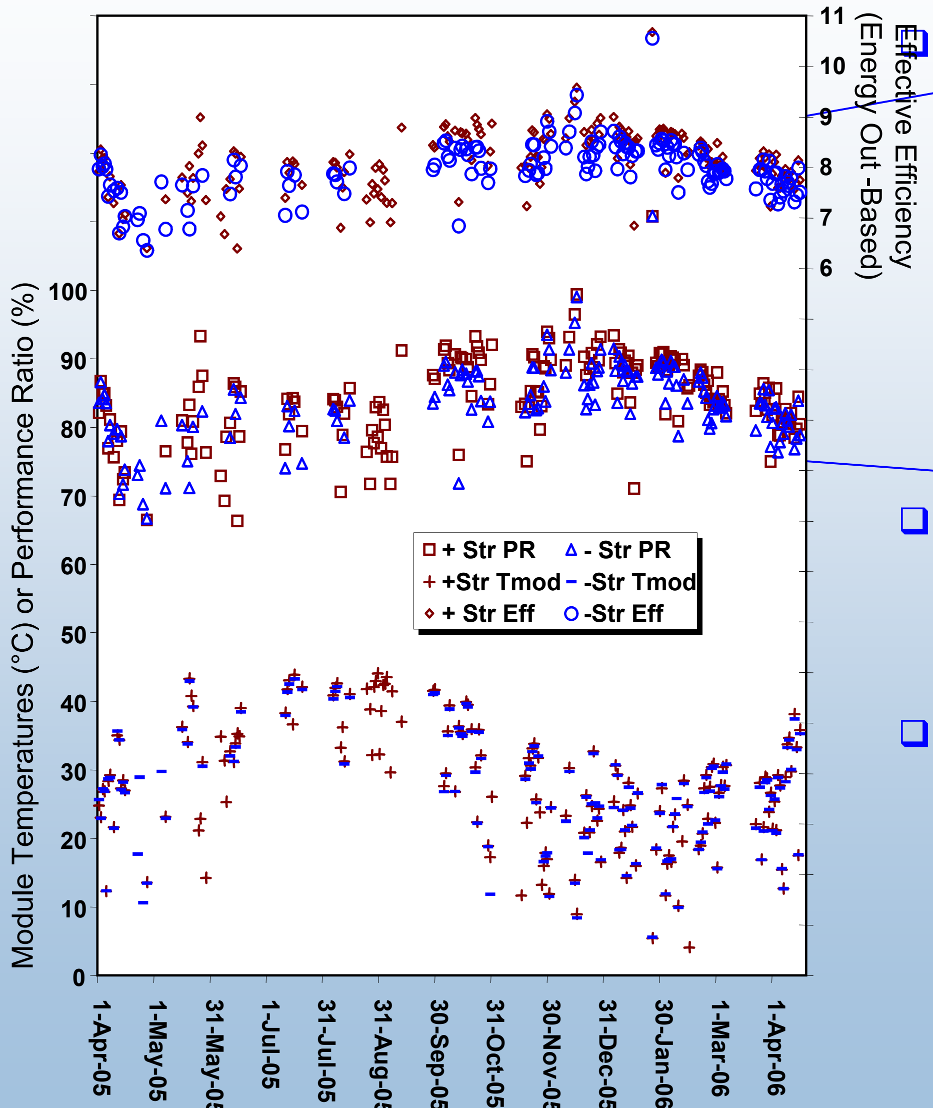
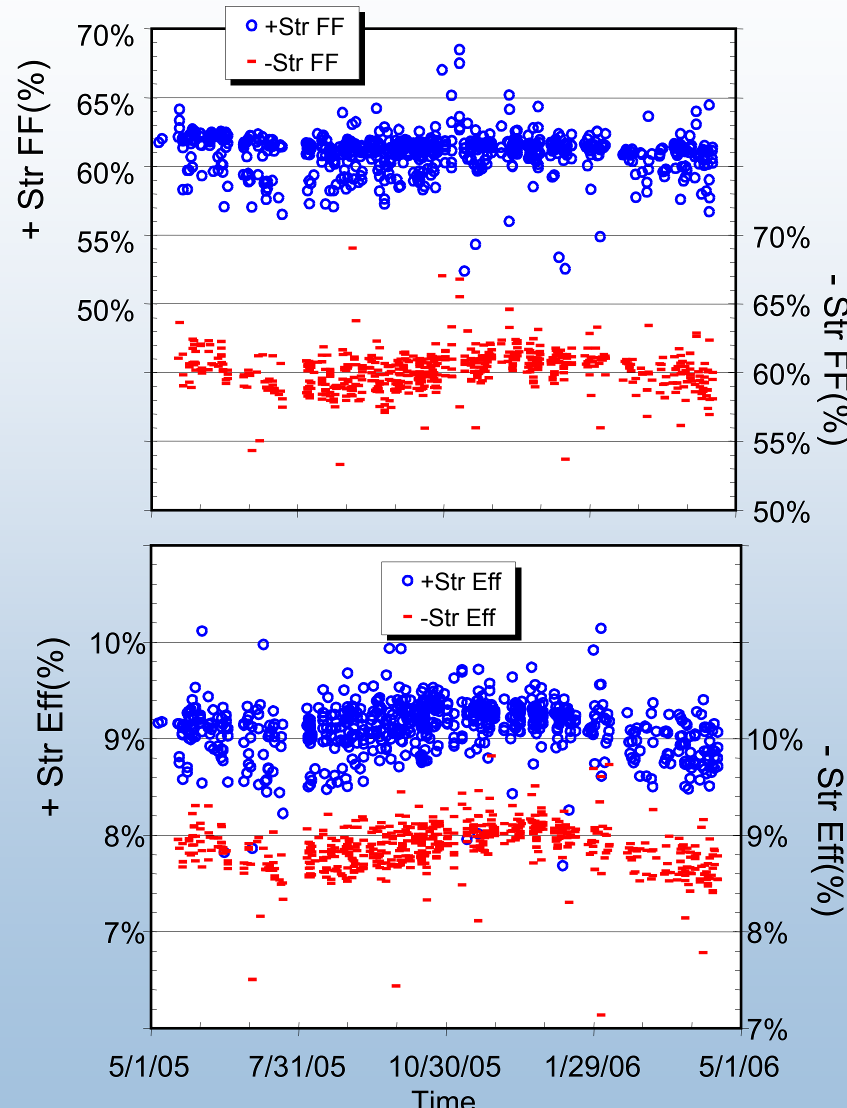
Peak Power Tracking Data



- Top: Effective efficiency (η_{EFF}) derived daily from energy output (time-integrated power)
  - Not temperature corrected due to integration and convolution of all field conditions occurring daily
  - Varies seasonally ~7%-9½%
- Mid: Performance ratio (PR)
  - PR = η_{EFF} / η_{STC} energy-based, vary 70%-95% of η_{STC}
- Bottom: +/- strings sampled average daytime module temperatures
  - η_{EFF} is function of temperature,
  - $(1/\eta_{EFF})\, d\eta_{EFF}/dT_{air}$ ~ -0.38%/°C
    - T_{air} –> average daytime air temp.

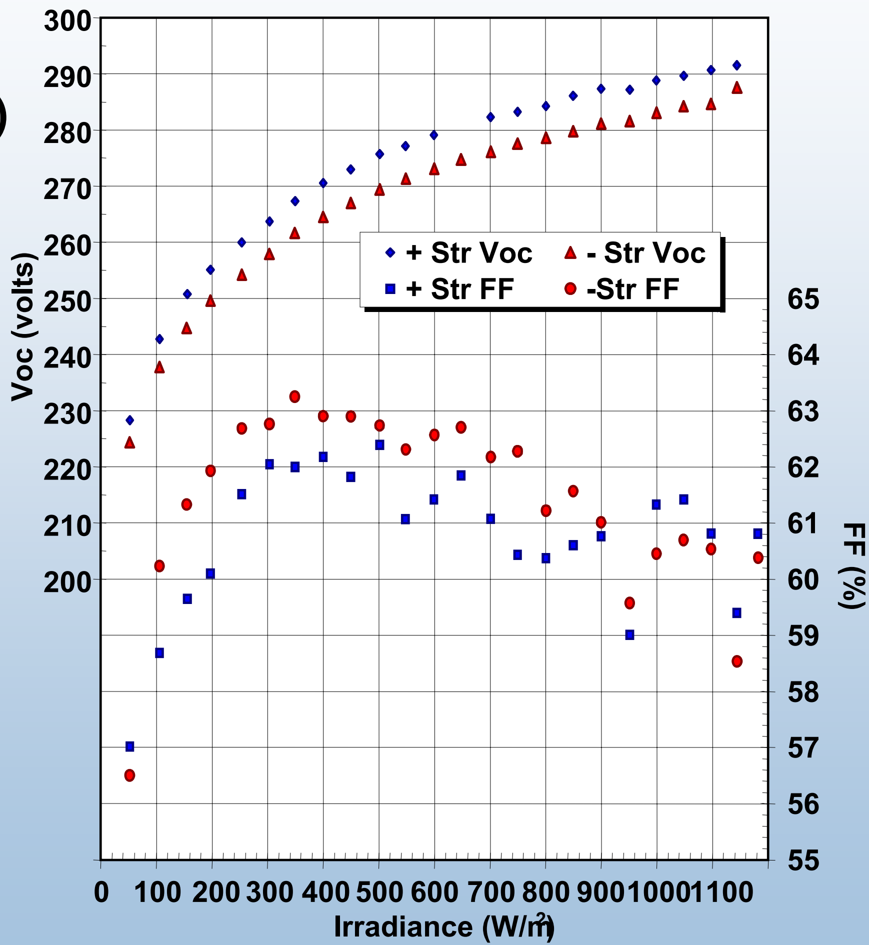
Performance From Full I-V Traces

- FF (top) and Efficiency (bottom) from full I-V traces, corrected to 25°C temperature, for irradiance = 1000±50 W/m^2 depicted
  - No statistically significant changes in efficiency or FF with time in 1st year
  - Seasonal variations observed
  - + string: 9.1% ± 0.3% efficiency, 61%-62% FF
  - - string: 8.9% ± 0.3%, efficiency, ~60% FF
- Actual FF determination allows closer scrutiny in event of degradation (e.g., series, shunt resistances).

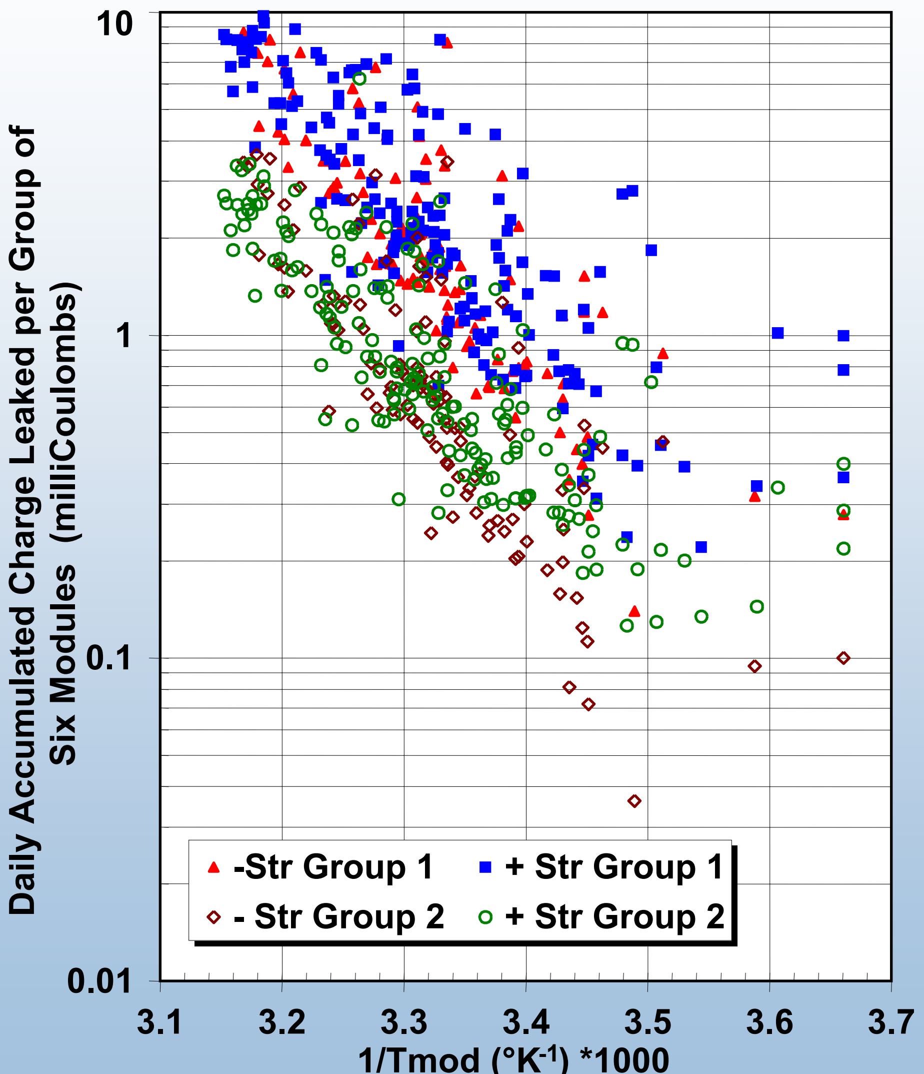


Voc & FF From Full I-V Traces

- Dependence analyzed across all irradiance every 50 W/m^2, corrected to 25°C module temperature (Tmod)
  - Voc shows logarithmic type dependence with irradiance
    - Coefficients *(1/Voc) dVoc/dTmod* vary ~ -0.37 to -0.30 %/°C
  - FF data, seem to peak at ~ 300 W/m^2, then decrease with increasing irradiance
    - Consistent with series-resistance limited behavior
    - Drops off at low irradiance
    - Coefficients *(1/FF) dFF/dTmod* vary ~ -0.05 to +0.20 %/°C going from high to low irradiance

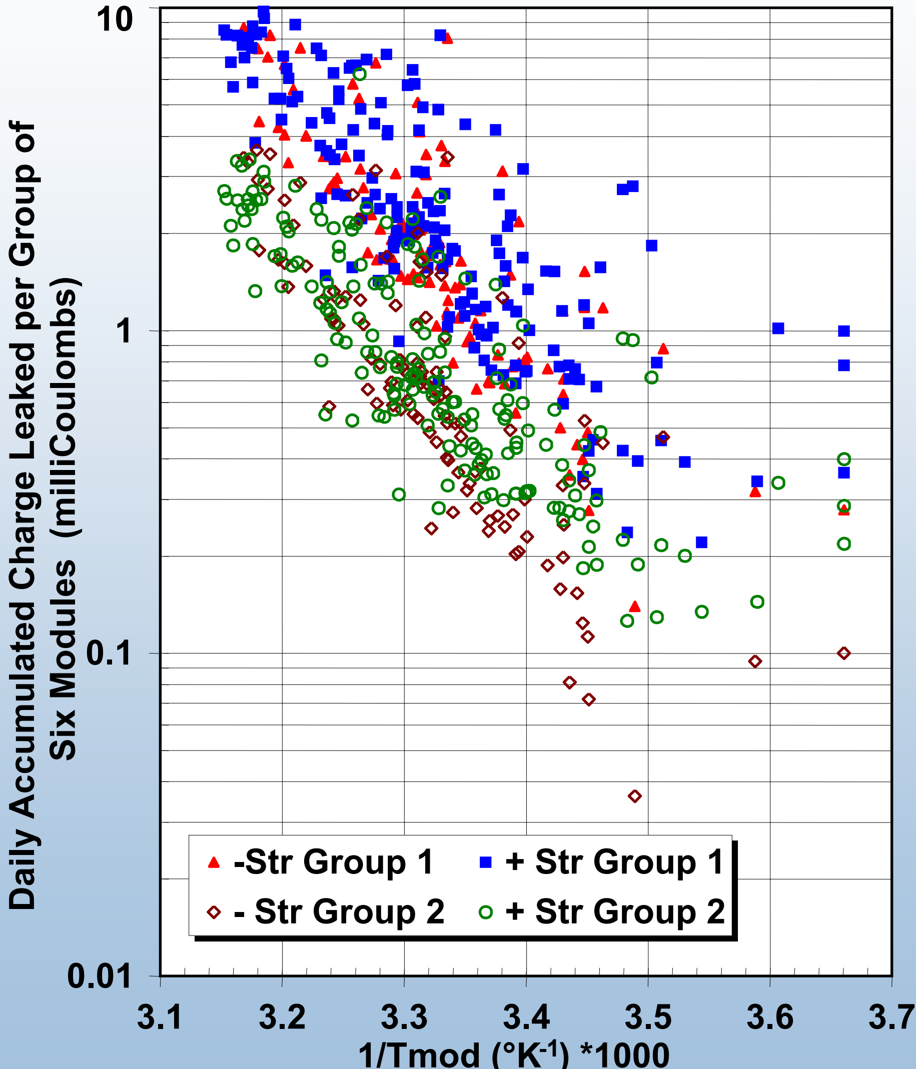


Leakage Currents



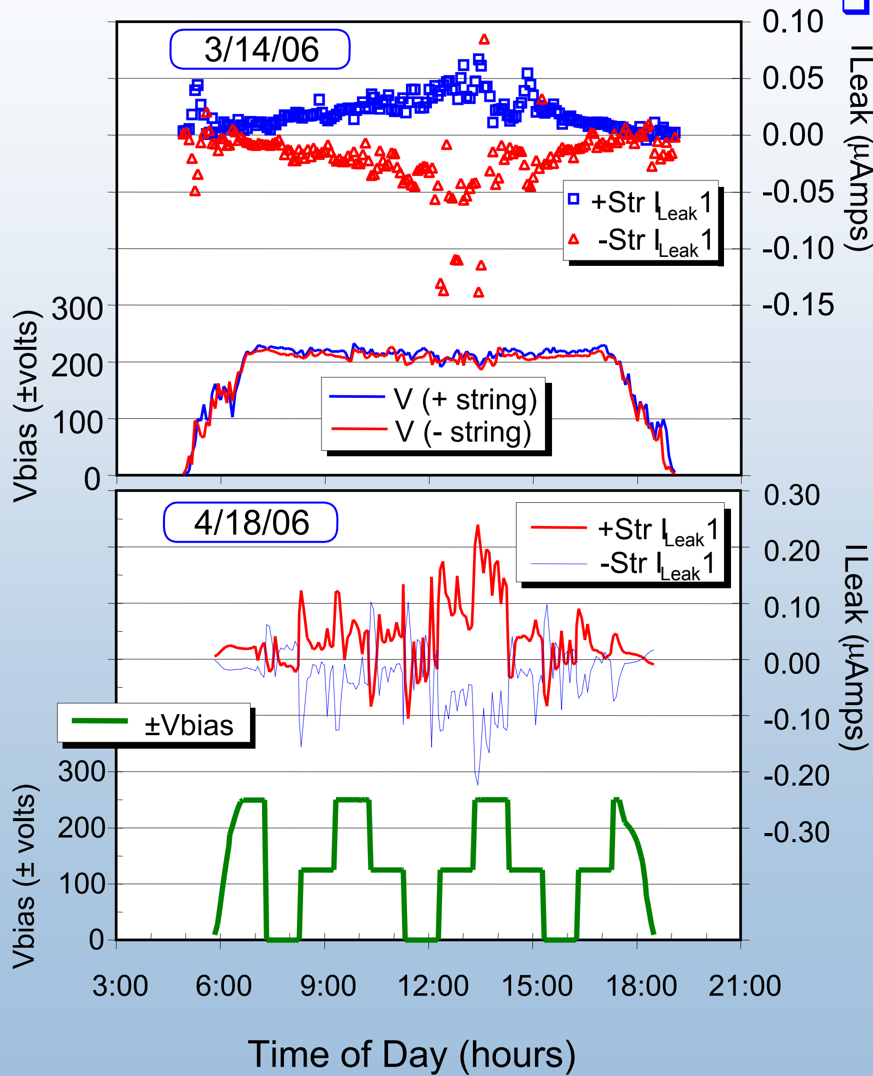
- Q_L = Daily integrated leakage charge: $Q_{Leak} = \int_{Daily} I_{Leak} \cdot dt$
- Computed & plotted for each group of 6 modules vs. average daytime temperatures
- Plotted on Arrhenius Graph
  - Appears thermally activated
  - Scale 0.01-10 milliCoulombs
- Variations or scatter:
  - Sizes of group-1 Q_L are ~2.8 - 2.9 * Group-2 Q_L, reflects partition of voltages between modules & higher offset bias for group 1
  - Humidity, integration over day convolutes multiple humidity values

Leakage Charge: Activation and Size



- Q_L = integrated leakage charge
- Thermal Activation energies:
  - 0.6-0.78 eV
  - consistent with leakage conduction through soda-lime glass
- For largest leakage ~10 mC, Tmod average ~23-30°C
  - Not a problem in Colorado due to our cold dry climate
  - In hotter climate, say with 200 days/year at these temperatures,
    - In 10 years, would accumulate ~20 Coulombs leakage for each group of 6 modules or about 0.1 C/cm
    - 0.1 C/cm => is right at threshold for 50% failure rate determined by JPL for a-Si thin-film modules

Leakage Currents: Response to Array Bias



- Response of high-voltage leakage currents to bias vs. time of day shown for ± groups 1 on two days
  - Peak-power tracking at top, & stepped-voltage vs. time profile at bottom,
  - Corresponding $\pm V_{bias}$ shown, read at left, leakage currents read at right
  - For stepped-bias, response appears qualitatively different:
    - Forcing effect in phase with large step increments in bias
    - Leakage exhibit transients and larger value by ~ 2x over peak power
    - Currents actually flip polarity for several minutes when decrementing, but not when incrementing
      - Ion motion & relaxation in glass

Conclusions

- Performance characterized from both power and energy output considerations:

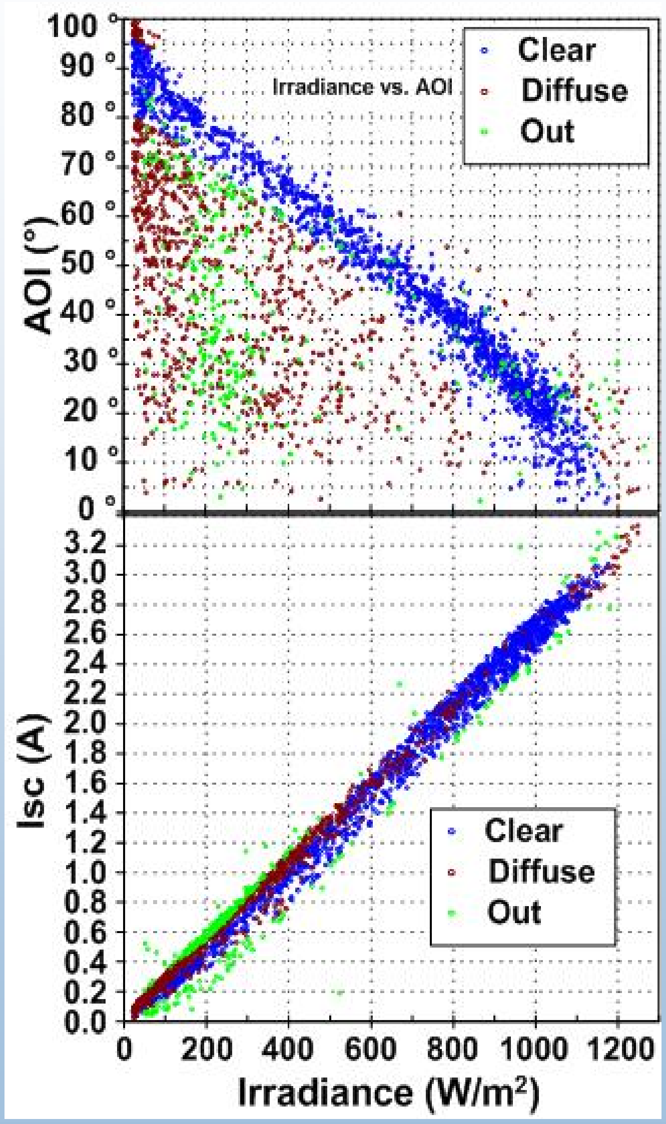
String	Average Air Temp.	Average Module Temp.	Irradiance or Insolation	Eff (%) Method	PR
+	14	28	6.12 kW-hrs/m^2/day	8.12 Energy	84.3%
+	Temp. Corrected	25	1001.5 Wm^2	9.11 Power	94.5%
-	13	27	6.18 kW-hrs/m^2/day	7.95 Energy	83.5%
-	Temp. Corrected	25	1001.4 Wm^2	8.87 Power	93.1%

  - Significance of energy-based effective efficiency, rows 2, 4:
    - Average insolation * effective efficiency (at 13°-14°C Average daytime air temperature) = delivered energy output per day
    - We present energy-based performance temperature coefficient:
      - -0.38%/°C vs. average daytime air temperatures
- Stability:
  - Does not appear to be degrading statistically or otherwise

Conclusions

- Leakage Currents:
  - Measured and characterized
  - Appear thermally activated
  - May point to potential corrosion problems in hot environments, where average daytime air temperatures are at, or exceed 25-30 °C for 200 days or more per year, after 10 years.

Appendix: IV Trace Statistical Filtering for Clear sky vs. Diffuse Illumination



- Two conditions applied: Isc is linear with Irr & Irr=Irr(cos(AOI))
- Irr ~ k_2*cos(AOI) ± 2 σ
  - differentiates between predominantly clear vs. diffuse
  - Works well , but at larger AOI the diffuse starts to become dominant over direct beam
- Isc ~ k_1*Irr ± 2 σ
  - mitigates data traced w. rapid changes in Irr and/or obscuration by snow
  - Carried out in piecewise intervals