Photovoltaic Efficiency Measurements

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Laurence Ottoson
Concentrator Cells : James Kiehl

NCPV

National Center for Photovoltaics

Director: Larry Kazmerski
Deputy Director: Roland Hulstrom
PV Program Manager: Larry Kazmerski
Admininstrative Assistant: Paula Robinson

Electronic Materials & Devices

Manager: John Benner
Admin. Assistant: Carole Allman

High Efficiency Devices & Concentrators
Group Manager: Sarah Kurtz

Silicon Materials & Devices
Group Manager: Howard Branz

Polycrystalline Compound Semiconductors
Group Manager: Rommel Noufi

Process Development & Engineering
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Measurements & Characterization

Manager: Pete Sheldon
Admin. Assistant: Audrey Carapella

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Group Manager: Keith Emery

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Team Leader: Sally (Sarah) Asher

Electro-Optical Characterization
Team Leader: Richard Ahrenkiel

Process Integration Development
Project Leader: Brent Nelson

Engineering, Reliability, & Applications Development

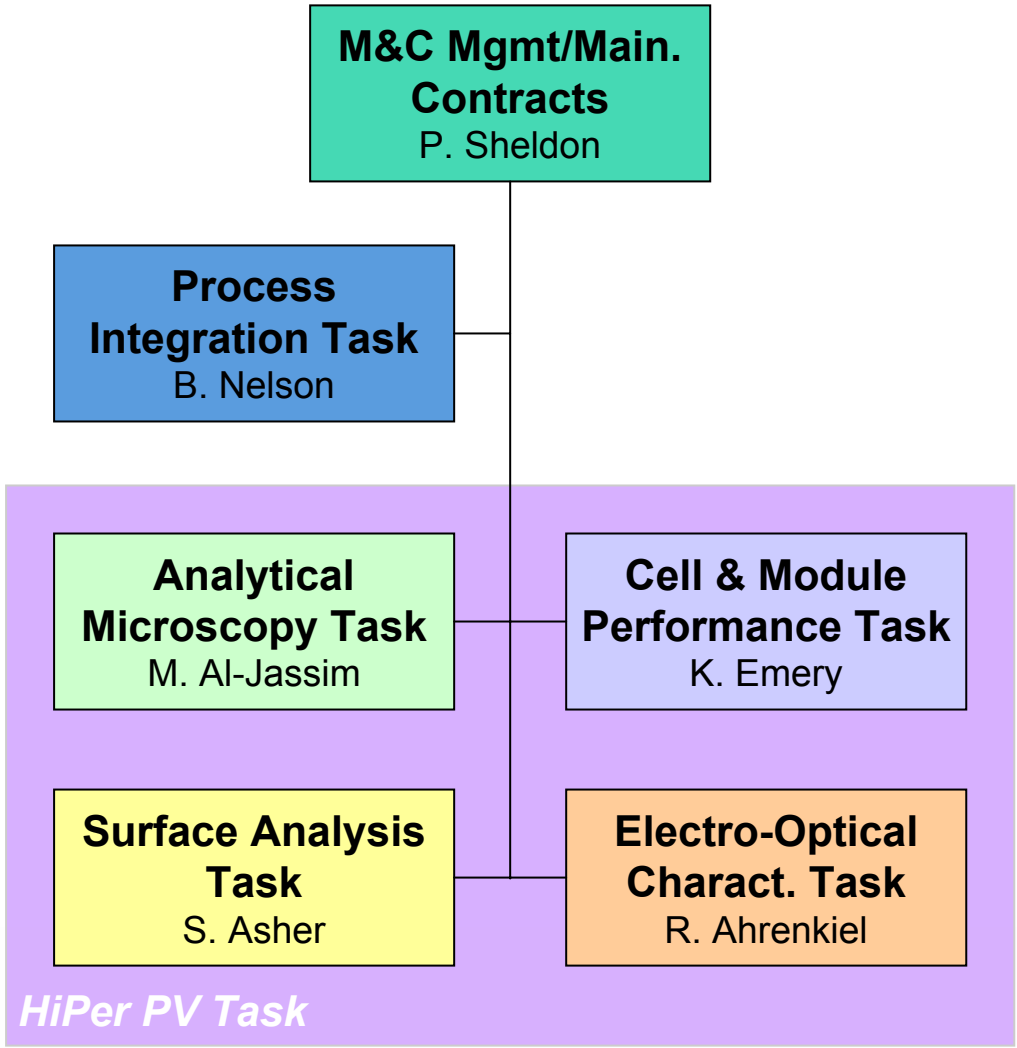
Manager: Roland Hulstrom
Admin. Assistant: Paula Robinson

Performance & Reliability R&D
Group Manager: Carol Riordan

Subcontracted Technology R&D

Applications Development

Measurements Division



Division mission

Support:

Providing routine and specialized measurement and characterization support for research and industry teams in the photovoltaics program. Meet customer needs through rapid and direct response to requests;

Collaborative R&D:

Contributing to and leading collaborative research projects to address critical issues and problems in key PV technology areas;

Technique and Diagnostic Development:

Developing and implementing new and specialized measurement techniques that enhance the ability to understand and advance fundamental photovoltaic R&D. Devising diagnostic tools to advance manufacturing research and development.

Goal - Flat Plate cell & modules

Determine Current *versus* Voltage
under Continuous Illumination
At 25 °C Junction Temperature
1000 W/m^2 Total Irradiance
ASTM or IEC Global Reference
Spectrum

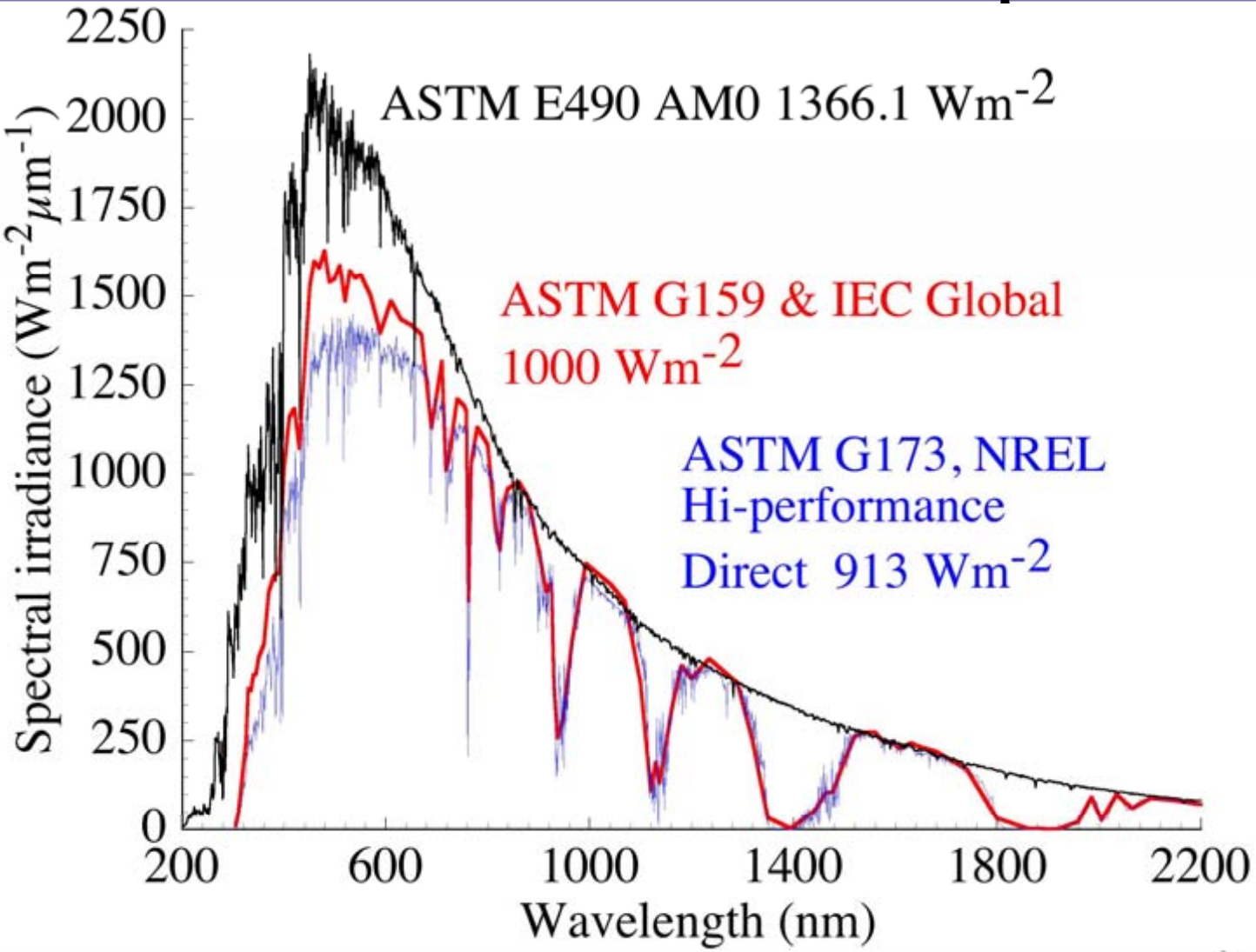
Goal - Concentrator Cells

Determine Current *versus* Voltage
under Continuous Illumination
At 25 °C Junction Temperature
1000 W/m^2 Total Irradiance
ASTM G173 Direct
Reference Spectrum

Goal - Air Mass 0 / Extraterrestrial Cells

Determine Current *versus* Voltage under Continuous Illumination At 25 °C and 1 AU from the sun

Reference Spectra



IV Theory

$$I^{\text{Test, Ref}} = \frac{I^{\text{Test,Source}} I^{\text{Ref,Ref}}}{I^{\text{Ref,Source}} M}$$

$$M = \frac{\int_{\lambda_1}^{\lambda_2} E_{\text{Ref}}(\lambda) S_{\text{Ref}}(\lambda) d\lambda \int_{\lambda_1}^{\lambda_2} E_{\text{Source}}(\lambda) S_{\text{Test}}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{\text{Ref}}(\lambda) S_{\text{Test}}(\lambda) d\lambda \int_{\lambda_1}^{\lambda_2} E_{\text{Source}}(\lambda) S_{\text{Ref}}(\lambda) d\lambda}$$

Source of Differences

Procedural

- Calibration lab - formal
- Internal researchers - variable
- Manufacturers - marketing, Power Mark
- External can not distinguish between calibration lab and internal

Definition

- Area - total, active, aperture, typical, not measured

Data Acquisition System

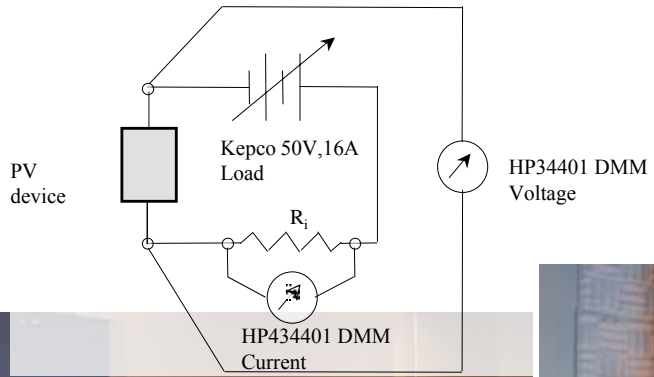
- Voltage bias rate - too fast for pulsed systems
- Voltage bias direction - rarely both directions
  - so hysteresis can not be detected

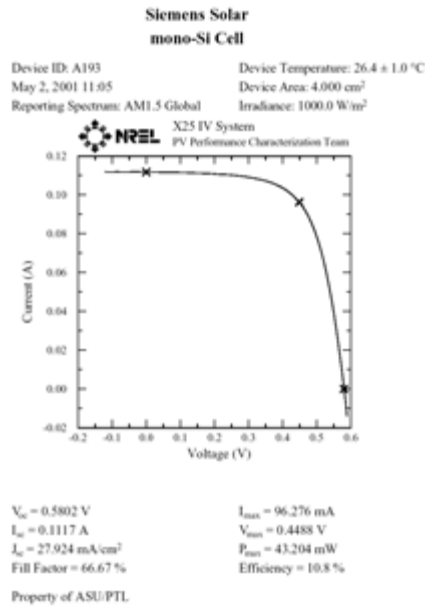
Pre-measurement conditions

- voltage (0V,0A or P_{max}), light, temperature, humidity

1-sun Cells & Modules

Light source	Size/Temperature	Voltage limits	Current limits
0.1 - 20 suns	30 cm x 30 cm	±0.5 mV	±10 pA
filtered 3 kW Xe	5-50 °C	±50 V	±16 A





Spire

Size / Temperature	**Voltage** limits	**Current** limits
61 x 122 cm	0.1 mV	0.5 mA
25 °C (20-50 °C)	100 V	20 A
0.1 to 1.2 suns		

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LACSS

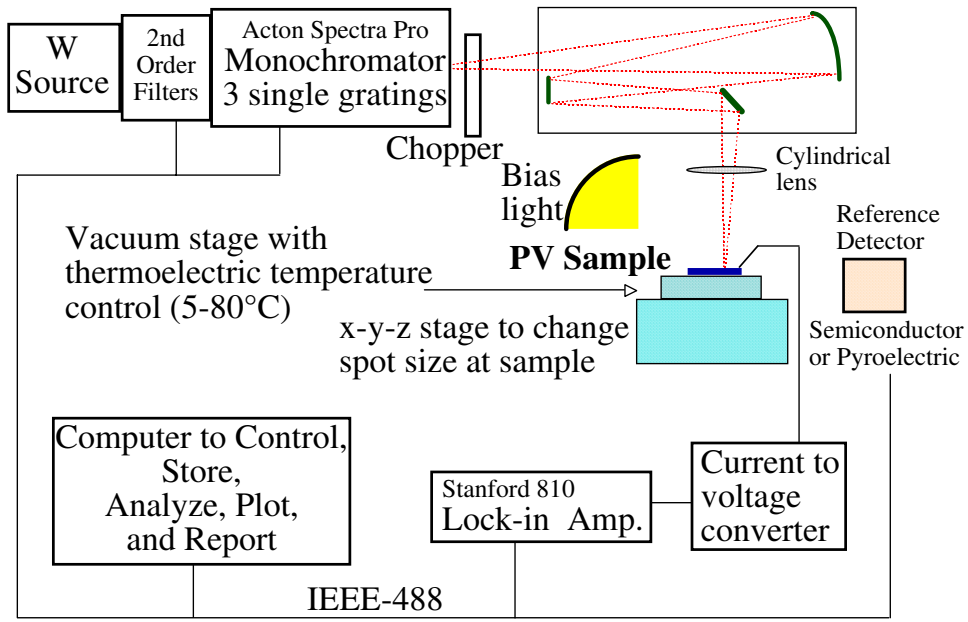
Size	Voltage limits	Current limits
152 cm x 122 cm	±0.5 mV	±1 μA
filtered 25 kW Xe	±300 V	±60 A
0.1 to 20 suns		

Outdoor 1-sun test bed

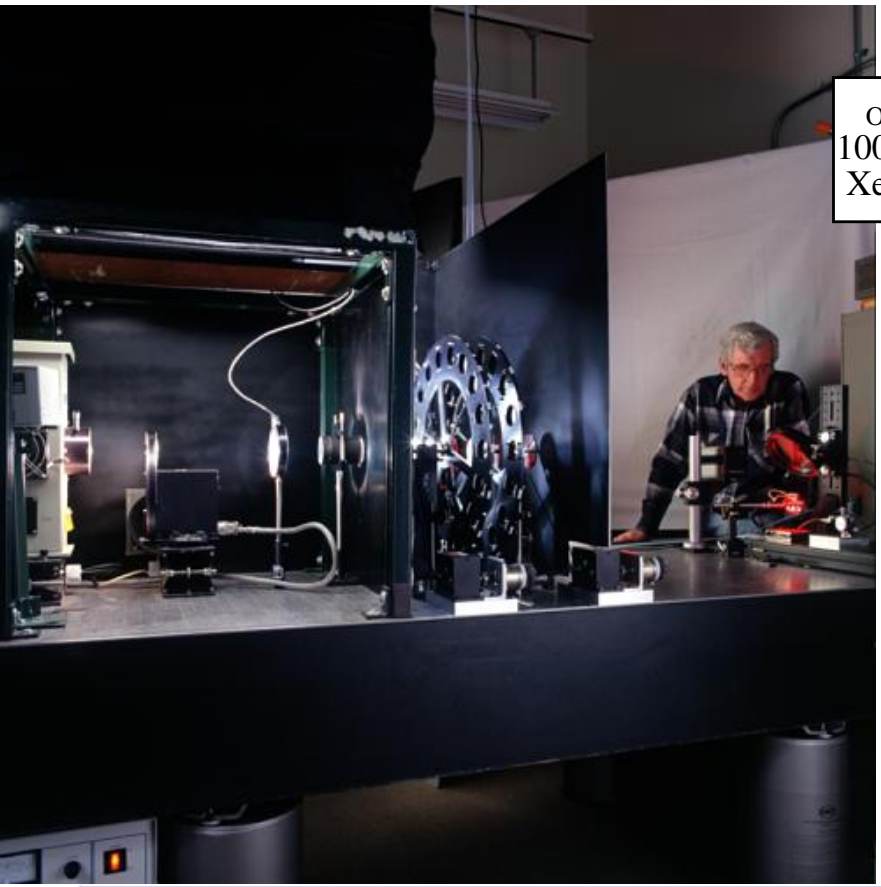
Size	**Voltage** limits	**Current** limits
200 x 300 cm	±0.5 mV	±1 μA
2-axis positioning	±300V	±60 A

Grating QE

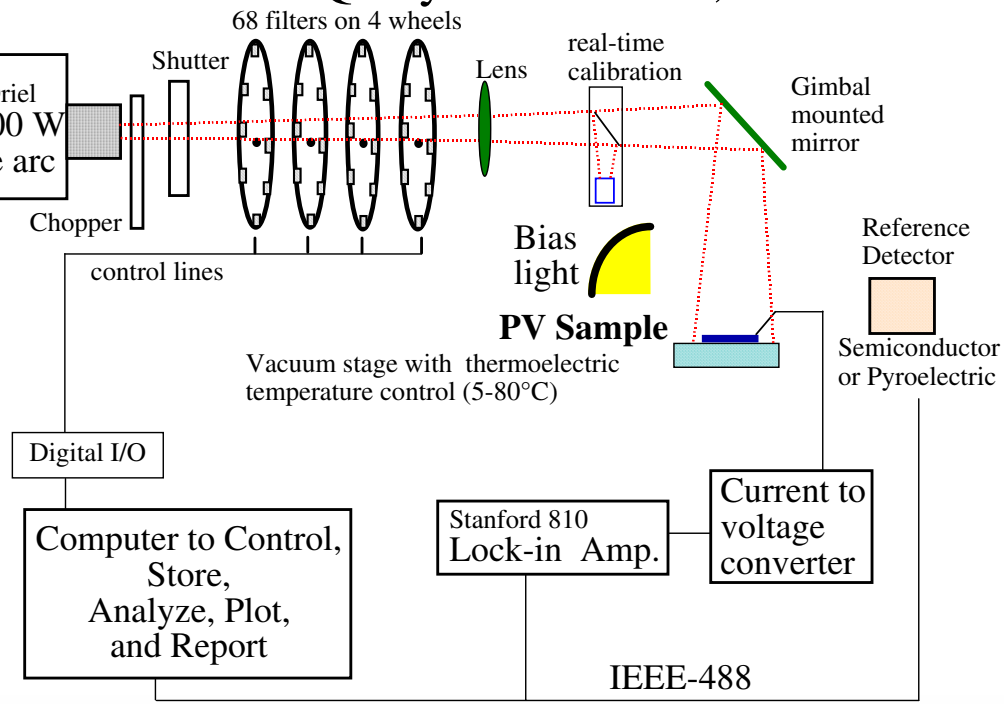
NREL Grating QE system 400 - 2,800 nm



Filter QE

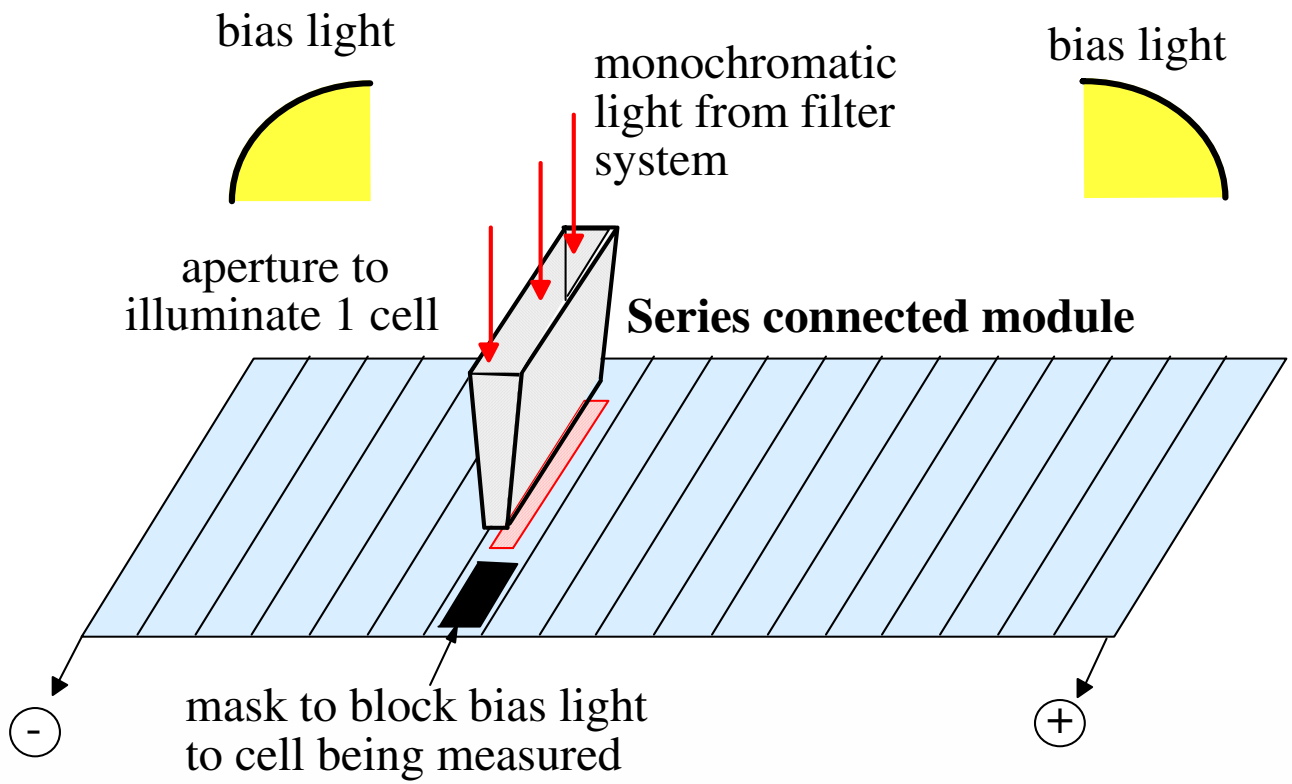


NREL Filter QE system 280 - 2,000 nm



Module / Multi-Junction Responsivity

Apparatus to measure the QE of a given cell in a thin-film module



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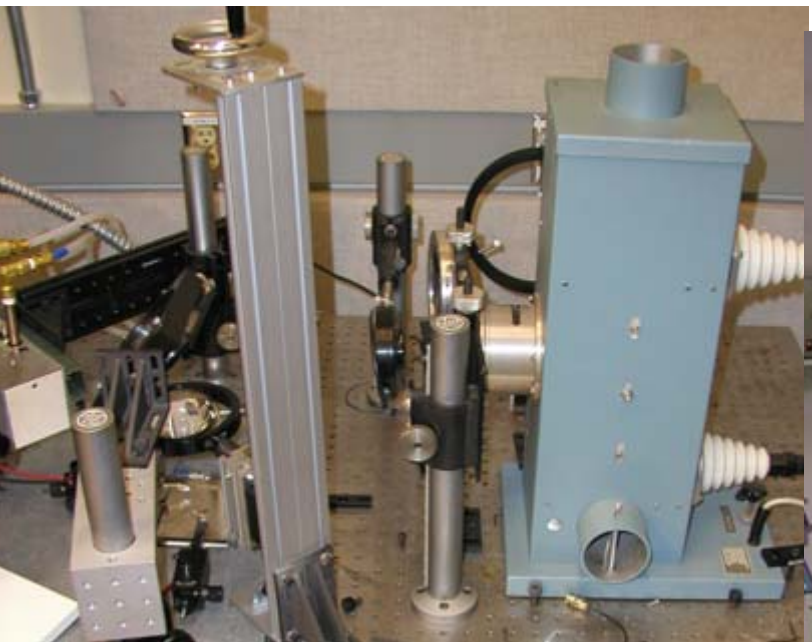
Concentrator Cells

I-V Applications

Test bed	Light source		Voltage	Current
		size/temperature	limits	limits
Continuous	1 kW Xe or	~ 1cm diameter	±0.1 mV	±1 μA
Concentrator	7 kW tungsten	for Xe, 5 x 10 cm	±10V	±10 A
	1 to 200 suns	for IR lamp, 5-80 °C		
Spectrolab HIPSS	1 ms Xe flash	2 cm x 20 cm	0.1 mV	500 μA
		1 to 2000 suns	100 V	50 A



PVUSA style regression for rapid analysis (<1min) of field data

Multiple Linear Regression

Select Test Bed-->

Roof

Get new data?

No Yes

Then-->

Press To Continue

Power Rating Test Conditions

Formula Selector

Wind Speed [m/s]

1.0

Standard Dev

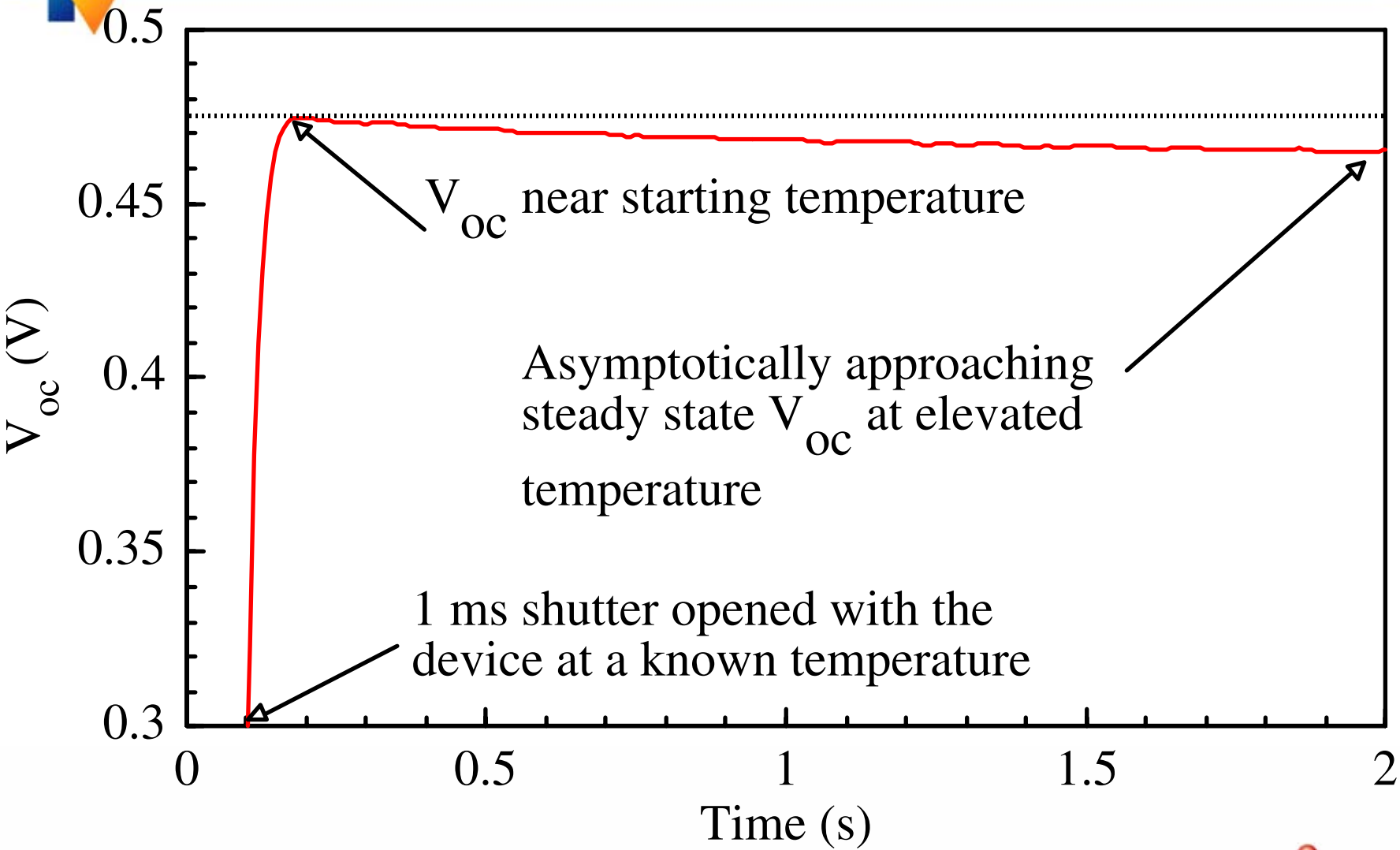
Scroll Down for more Charts

Light trap

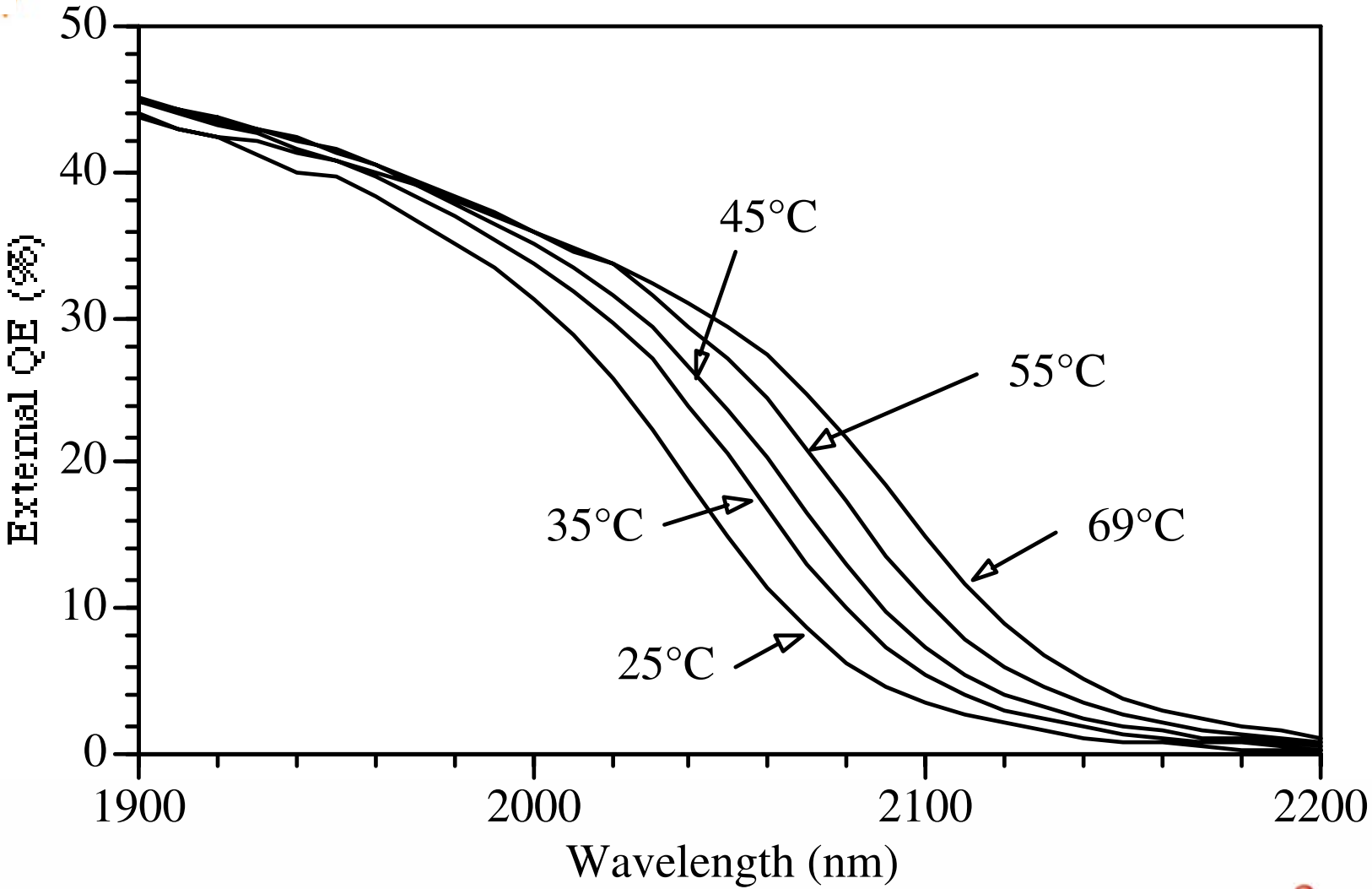
A mono-crystalline solar cell's efficiency improves when encapsulated because the encapsulation utilizes a white border providing additional light to the cell via internal reflections.

Mask area cm^2	Border mm	Voc mV	Isc A	FF %	η %
unmasked	--	603.3	1.346	60.63	14.1
82.8	32	602.4	1.298	61.39	13.7
64.0	21	601.7	1.265	61.36	13.3
51.8	13	600.8	1.222	61.86	13.0
37.2	2	597.8	1.147	62.39	12.2
34.8	0	597.8	1.095	62.95	11.8

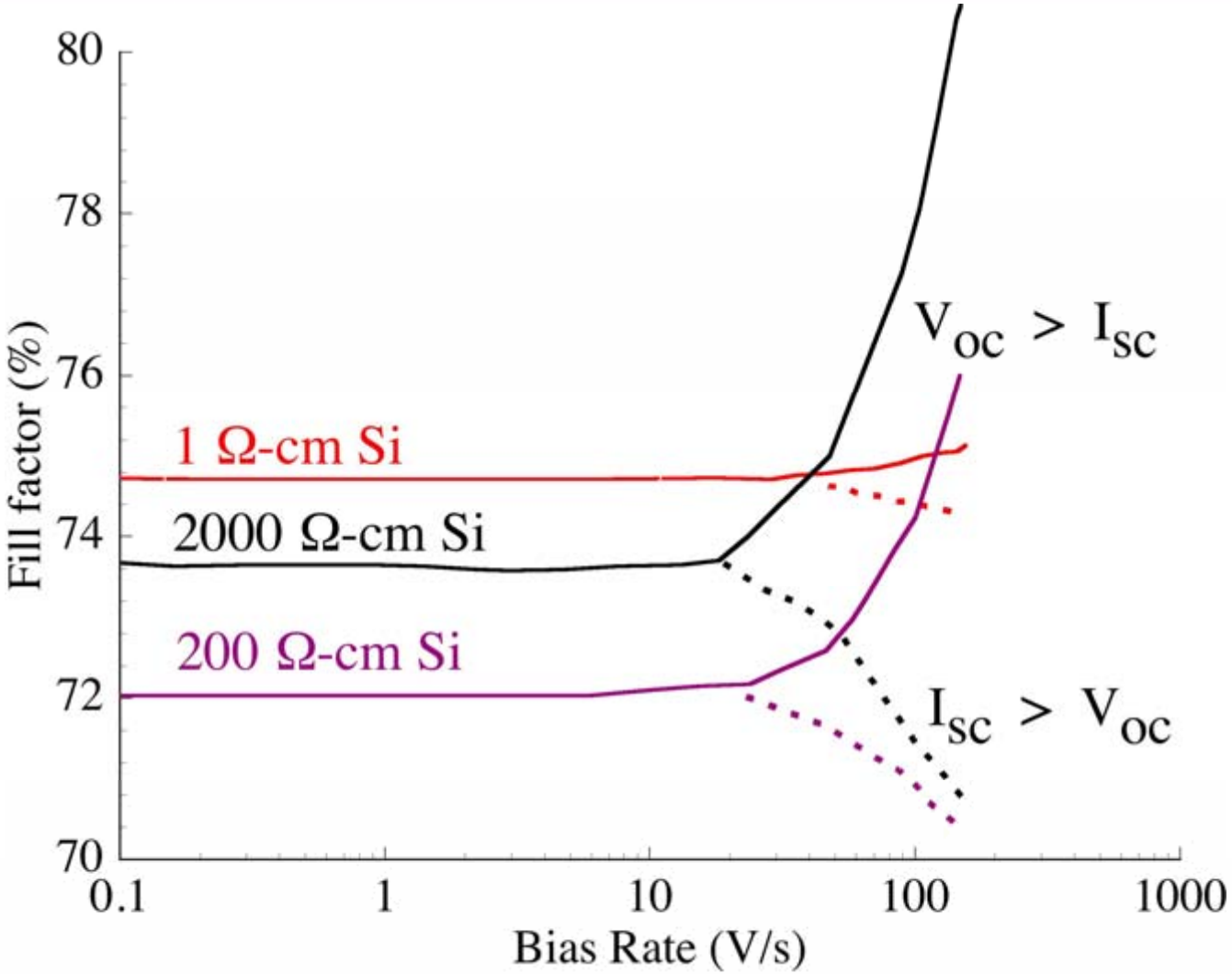
Voc TEMP


0.5
0.45
0.4
0.35
0.3
V_{oc} (V)
0
0.5
1
1.5
2
Time (s)
V_{oc} near starting temperature
Asymptotically approaching steady state V_{oc} at elevated temperature
1 ms shutter opened with the device at a known temperature

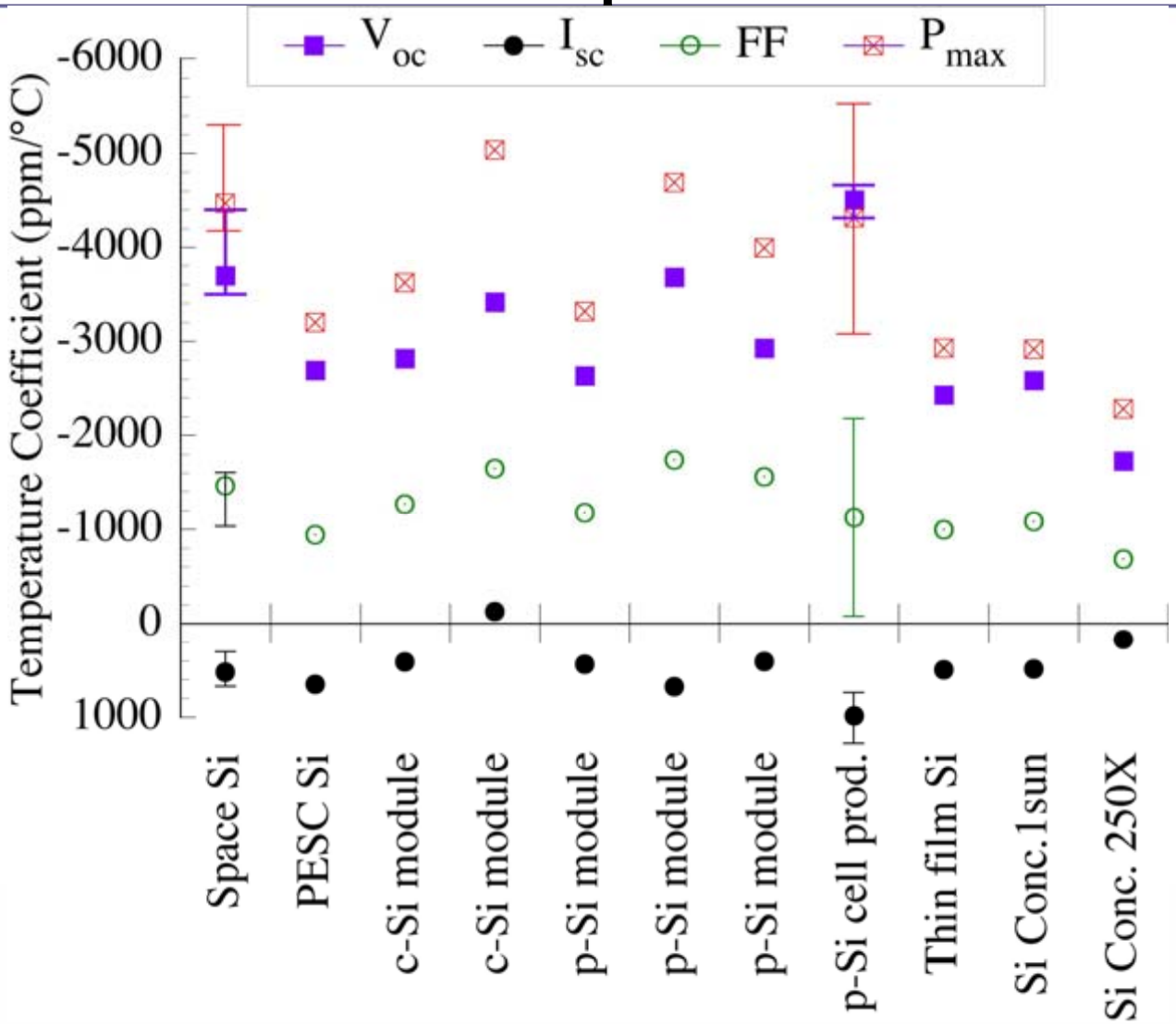
Isc TEMP


External QE (%)
50
40
30
20
10
0
1900
2000
2100
2200
Wavelength (nm)
45°C
55°C
35°C
69°C
25°C

Bias rate, direction



Temperature Coefficient



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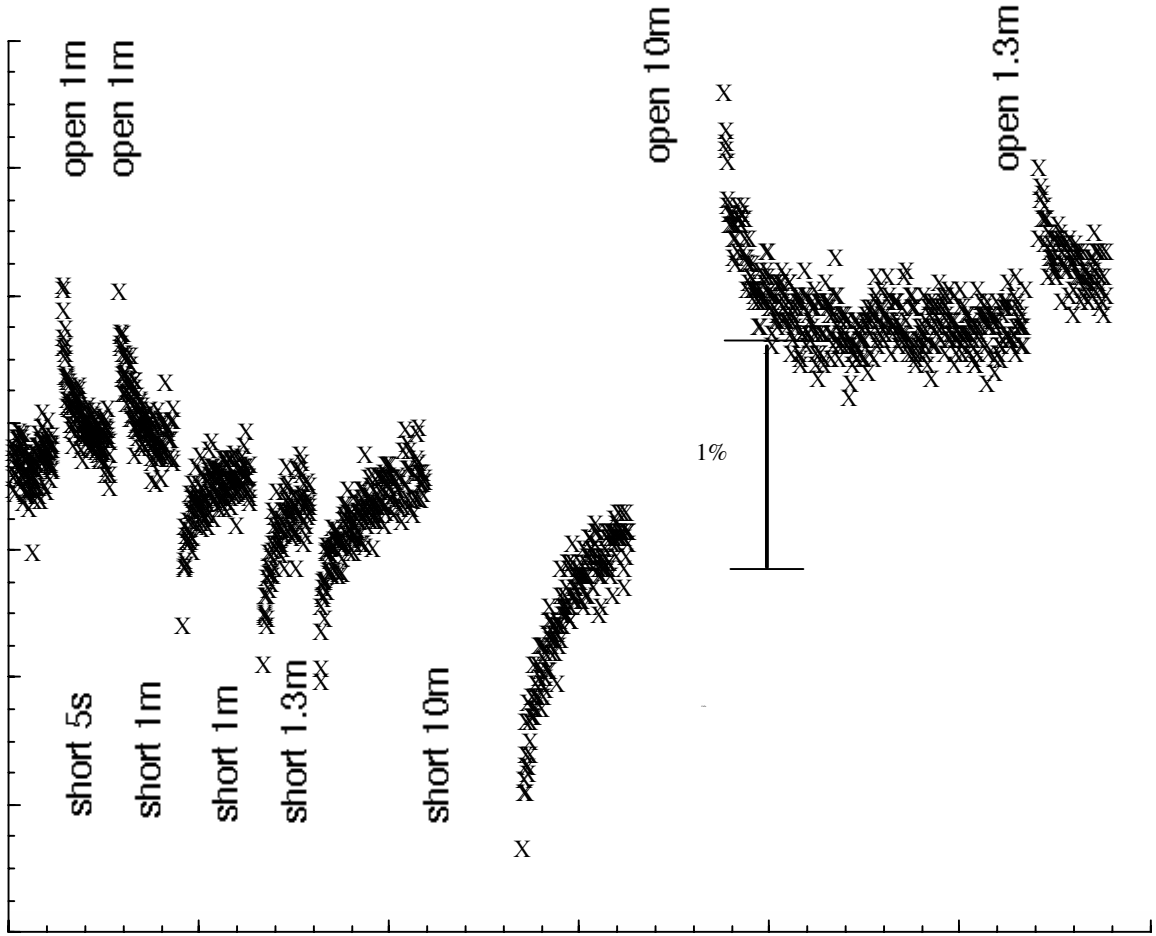
CdTe Transients



CIS Transients

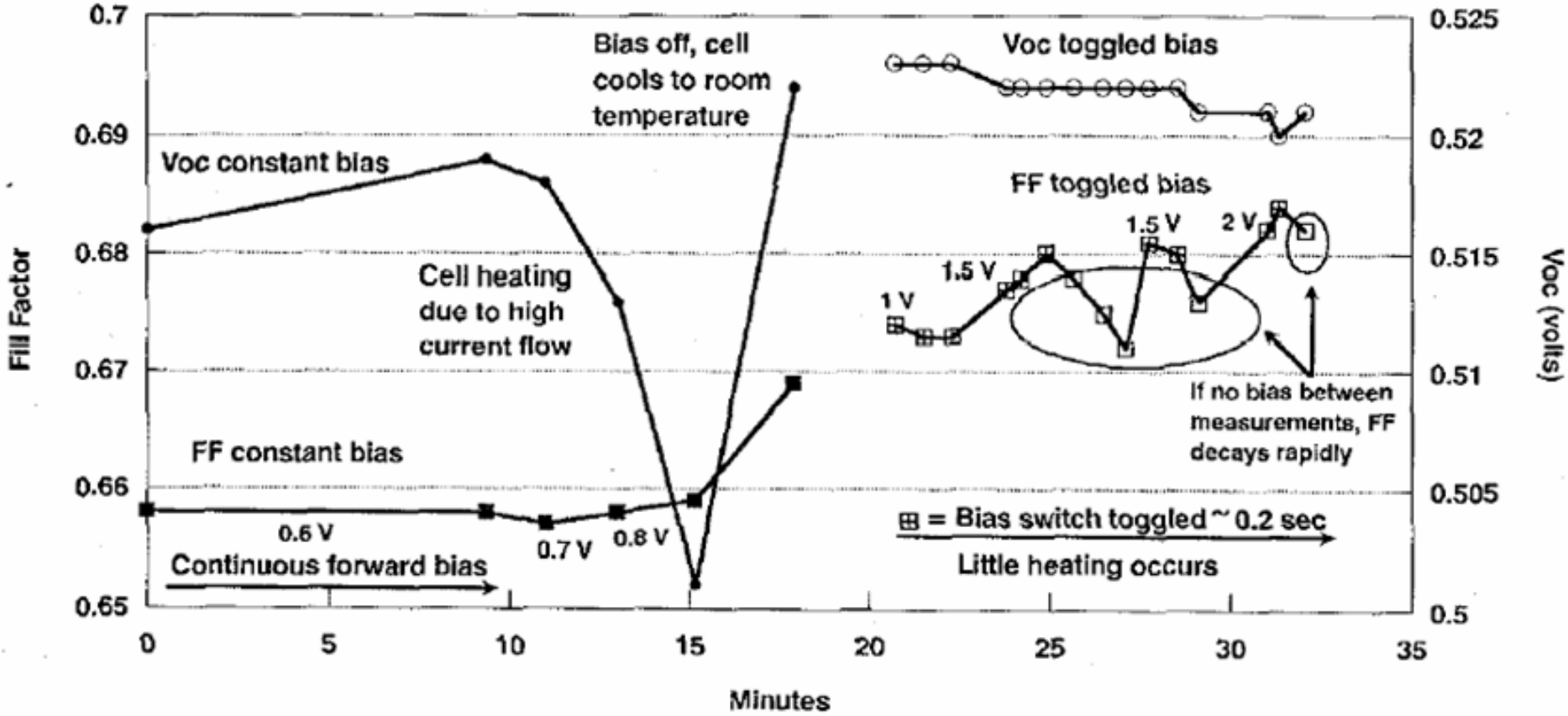


Fig. 3. Different dark forward bias methods applied to a cell that had previously been light soaked until the efficiency stopped increasing.

No changes in I_{sc}

a-Si

Low light,low temp in winter -> degradation

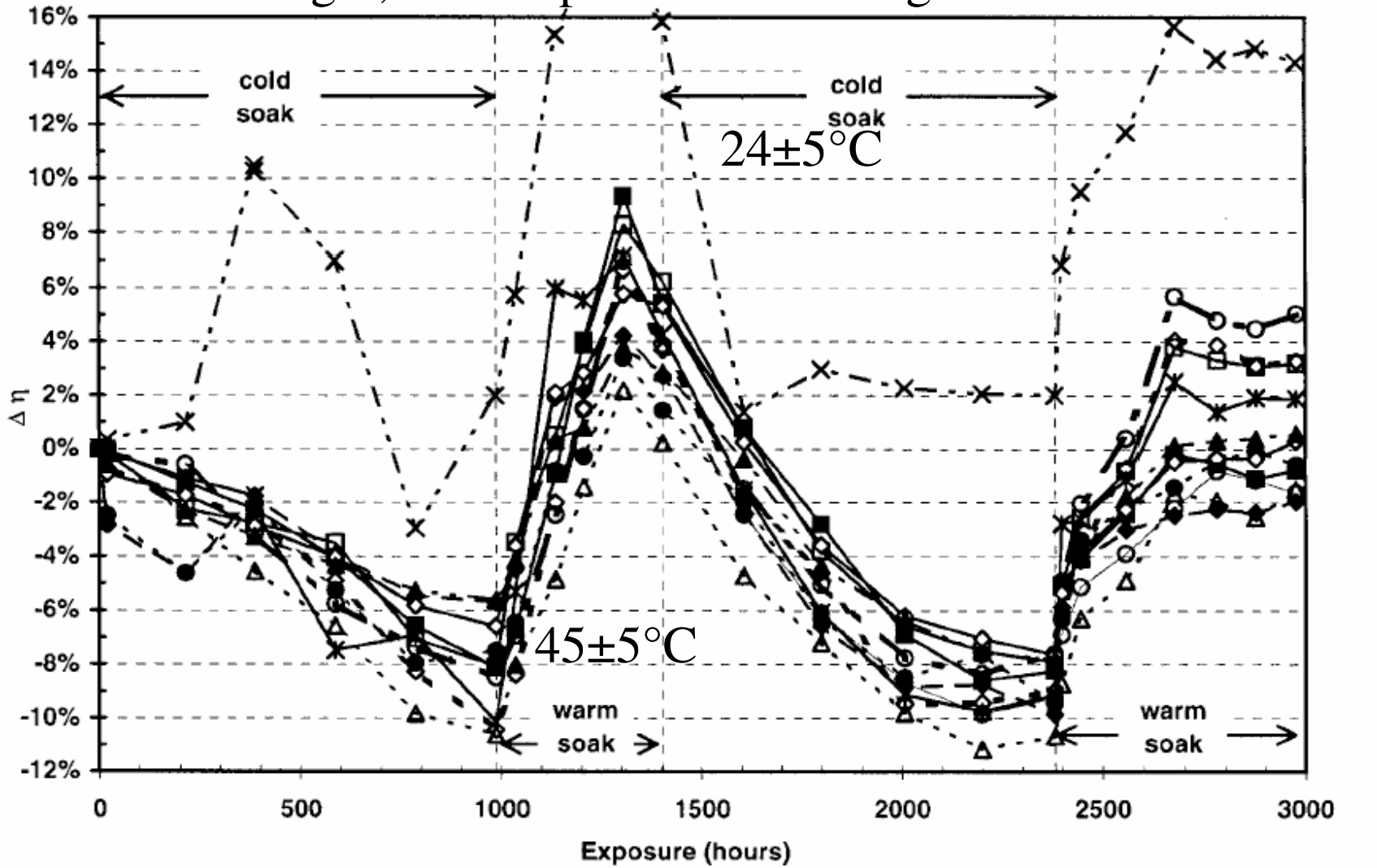


Figure 11. Relative efficiency changes ($\Delta\eta$) vs light exposure for both cold and warm soaks and both cycles I and II, compared to start-of-test values

Summary

From the Moody Blues

"Just what the truth is I can't say anymore, because…"

However;
As a calibration lab you want the "TRUTH" from me so I will report a value with an estimated uncertainty with 95% confidence.