JACKSONVILLE 2019

EVALUATING THE INCIDENT ENERGY OF ARCS IN PHOTOVOLTAIC DC SYSTEMS:
COMPARISON BETWEEN CALCULATED AND EXPERIMENTAL DATA

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IEEE IAS ELECTRICAL SAFETY WORKSHOP

Outline

- PV Solar System Characteristics
- DC Incident Energy –
  - NFPA 70E [1],
  - Maximum Power [2],
  - Stokes/Oppenlander [3]
- PV Solar Arc Experiments
- Comparison – Modeled vs. Measured Data
  - (order of magnitude difference)

Why Are We Discussing Arc Energy Hazards in PV Systems?

550 MW PV Plant [4]

- Ensure workers wear proper PPE but are not over protected

- States & Utilities looking to increase RE portfolios
- PV Systems in the hundreds of megawatts
- Thousands of acres

- Largest PV inverters approximately 1-MW

Not All DC Systems Are the Same

- PV Systems are different than other types of DC systems
  - e.g., Capacitors, Transit Systems, Batteries, …
- Ensure PV workers appropriately protected from the hazards
- Studies should be conducted on each type of DC system (IEEE-1584 [5])

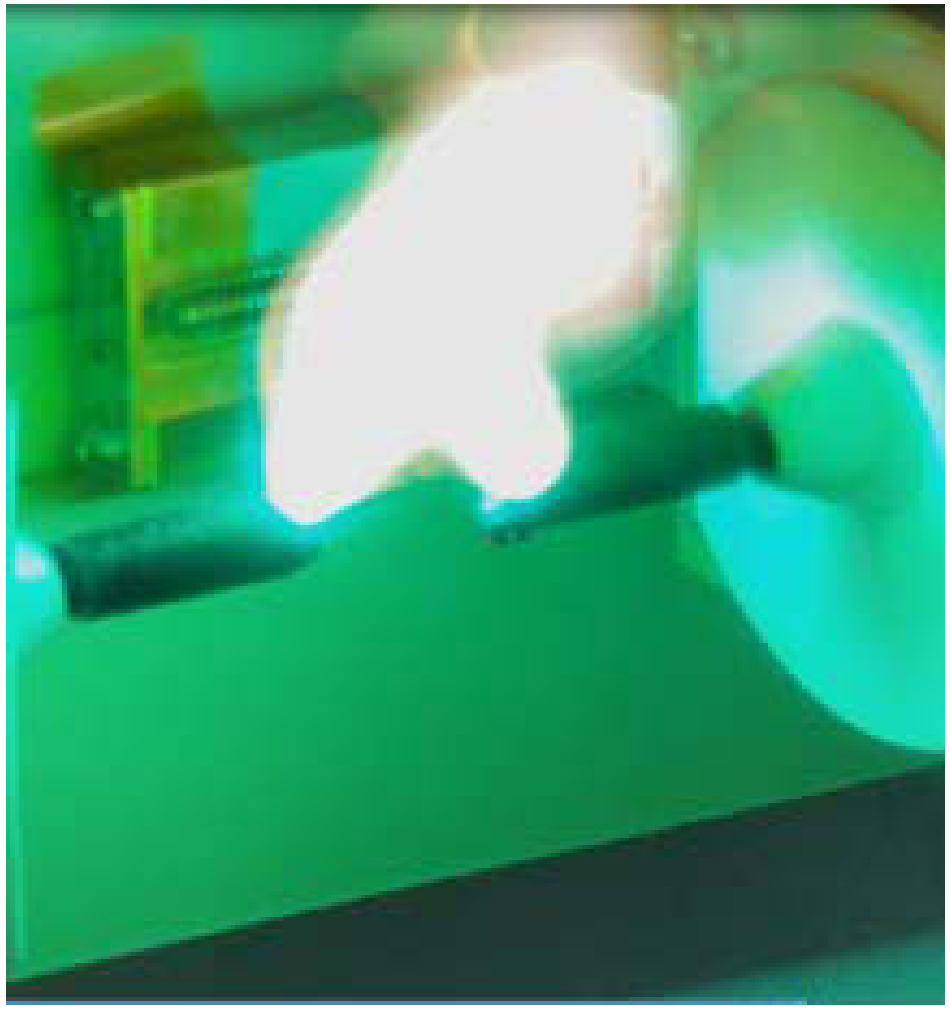
DC Laser Supply, LLNL NIF

DC Transit System, NREL

Battery Bank, NREL

Why is PV Incident Energy Different?

- Solar DC Systems have unique characteristics
- PV Systems are current and voltage limited
- PV Incident Energy Calculations
  are more than Voltage * Current * Time



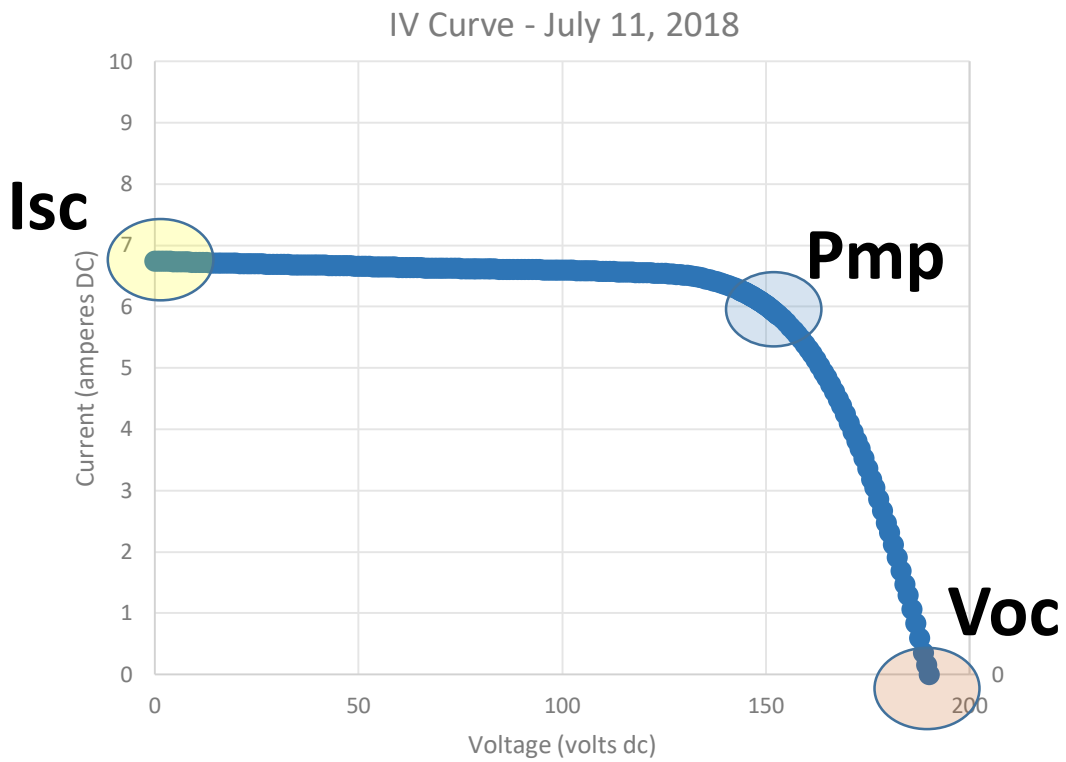
Source: NREL

PV Characteristics

- Solar System Operational Parameters
- Environmental Parameters
- How to Determine Maximum Voltage, Current
- Arc Parameters

Typical PV System Operating Parameters

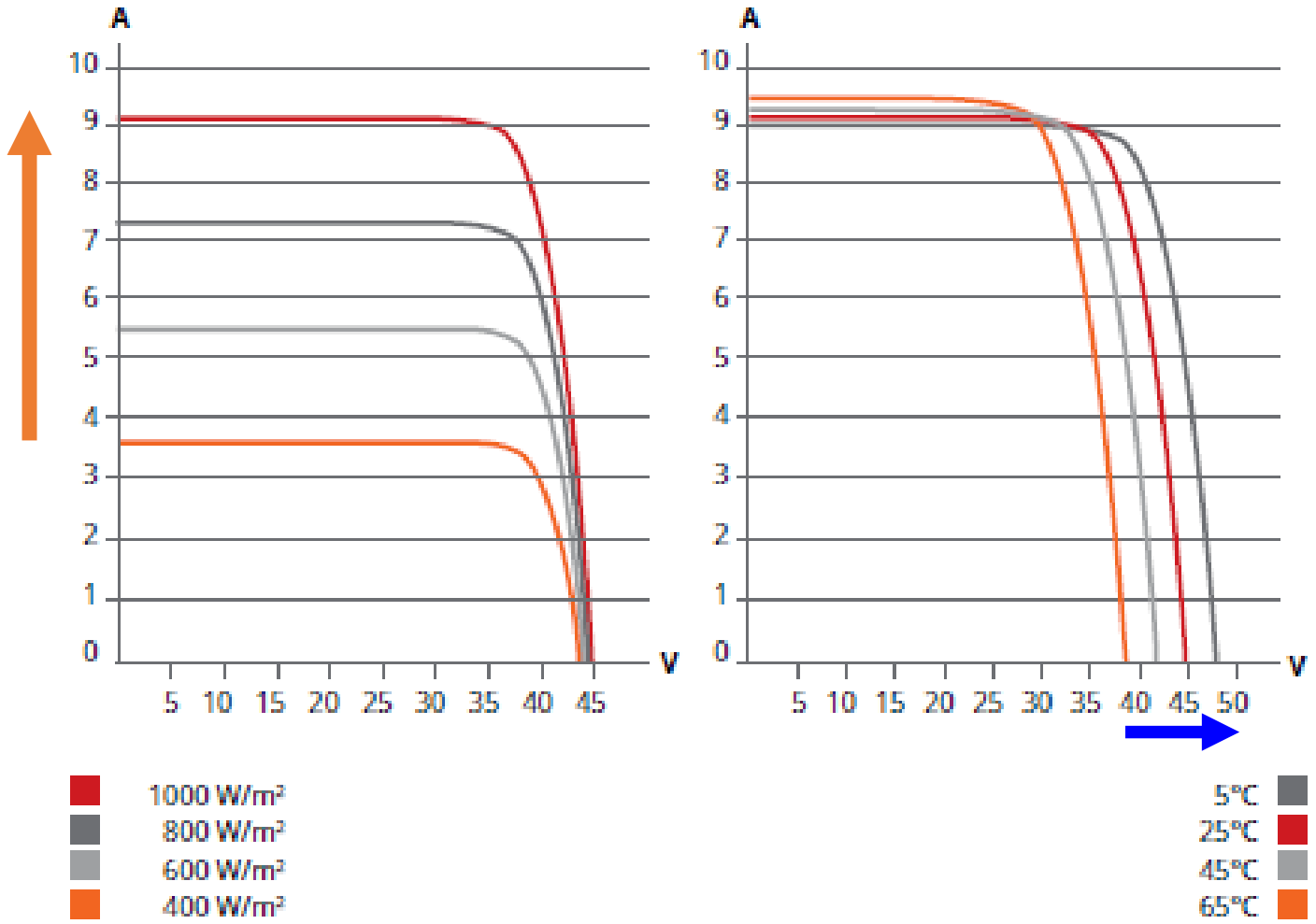
- Current and Voltage IV Curve
- Maximum Power (Pmp) ~ 915 W
- Max. Power Current (Imp) ~ 6 A
- Short-Circuit Current (Isc) ~ 7 A
- Max. Power Voltage (Vmp) ~ 155 V
- Open-Circuit Voltage (Voc) ~ 190 volts



Source: NREL

Typical PV Module Operating Curves

A **SUNNIER** array produces more energy



A **COOLER** array produces more energy

NEC Table 690.7(A)

[12]

Sizing a PV String

Typical Sizing Tool [6] (most string inverter manufacturers offer a sizing tool)

Select your system's parameters

System Components

Inverter Model: Inverter 10kw (240VAC)

- MPPT Setting: Separate MPPTs / Combine to MPPT1
- Max PV System Voltage (Voc): 600V / 1,000V

PV Module

- Manufacturer: Module MFG
- Model *[series]*: 300 Watt Module

Ambient Daytime Temperatures °F / °C

- *Record* Cold: -25 .. -23°C
- *Average* Hottest: 33 .. 35°C

MPP1 Configurations (18A)

# MODULES	1 STRING	2 STRINGS
4	1241	2483
5	1552	3104
6	1862	3724
7	2173	4345
8	2483	4966
9	2793	5587
10	3104	6207
11	3414	6828

String sizing dependent on:

- Inverter parameters
- Module parameters
- Local weather

- Array *could* be larger (DC:AC < ~80%)
- Optimal Configuration
- Array *may* be Oversized (DC:AC > ~118%)
- Max PV Current > Max Usable Input Current

In Denver, record low was -25°C [7], string limited to 11 modules (Voc ~ 592 V)

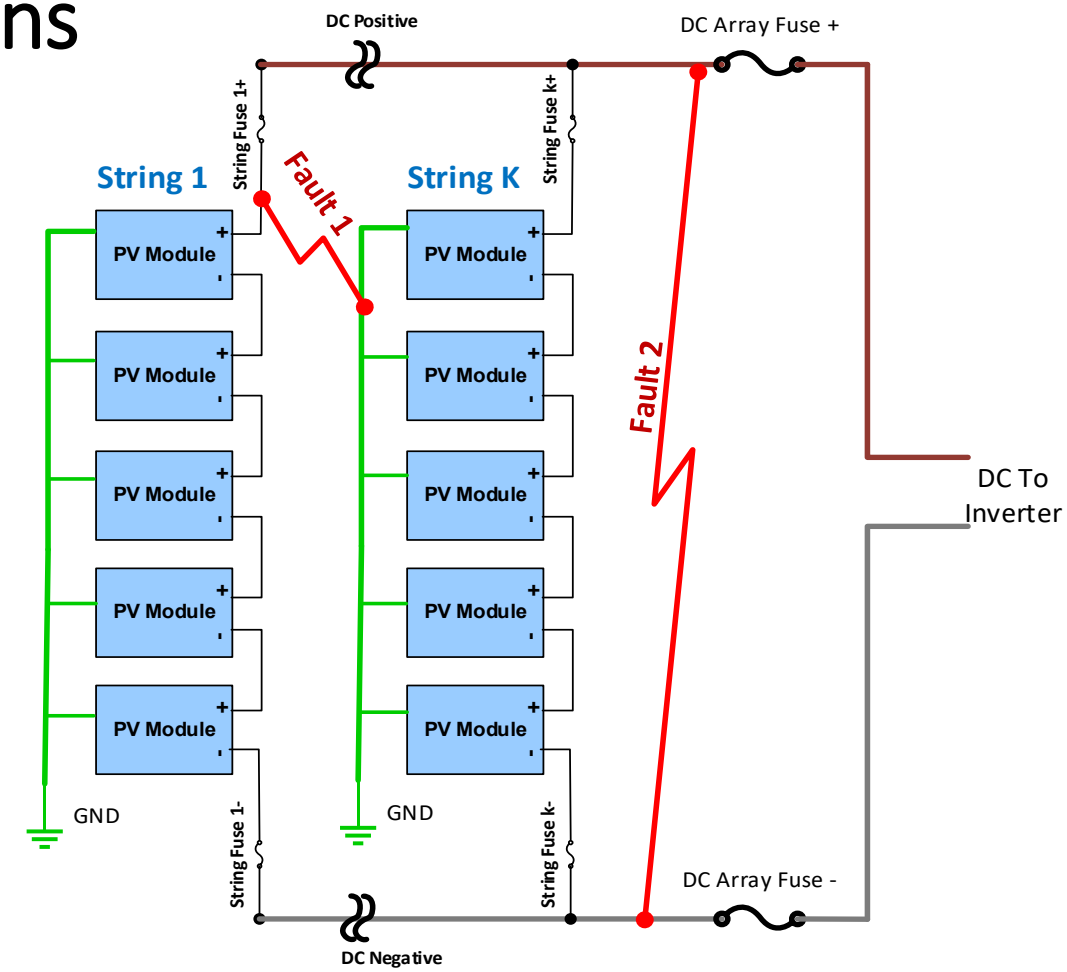
In Phoenix, record low was +1°C, string limited to 12 modules (Voc ~ 596 V)

PV System - Possible DC Arc Locations

Most faults can be categorized as:

- Line to Ground
- Line to Line
- Module to Module
- String to String

Note: *String fuses protect against backfeed & array faults*



Source: NREL

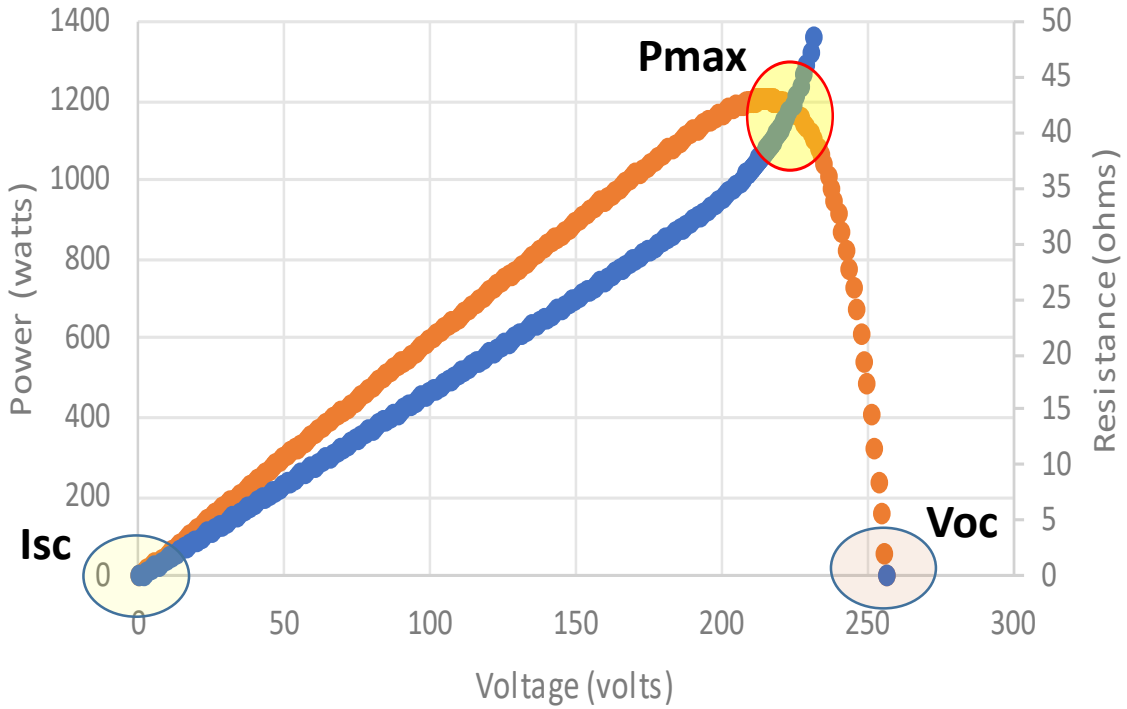
PV System – Resistance

Typical Power-Voltage Curve

- 1400W System

Resistance of PV System

- 45 ohms at MPPT



IV Curve – 1400W PV System, NREL

DC Arc Energy Calculations

- Losses and Error in Incident Energy Models for PV Systems
- NFPA 70E, Annex D[1]
- Maxim Power Incident Energy [2]
- Stokes/Oppenlander [3]

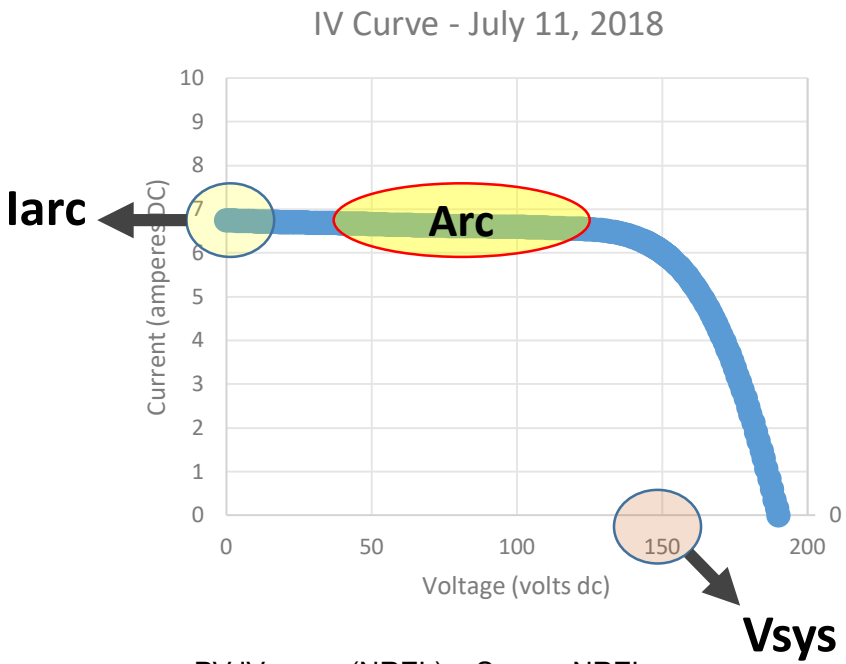
PV Arc Energy Calculations

- Heat Transfer Assumptions
  - Light, Heat, Sound Energy Assumed to all contribute to Incident Energy [3]
  - No losses accounted for in models
- PV Systems Don't Operate at Maximum Power During Faults
  - PV Modules and Systems **must** operate along their IV Curve
  - During arc events, PV system voltage will be decreased

DC Incident Energy Models – 70E Annex D, D.5 [1]

$$I_{arc} = 0.5 * I_{bf} \quad (1)$$

$$IE_m = \frac{(0.01 * V_{sys} * I_{arc} * T_{arc})}{D^2} \quad (2)$$



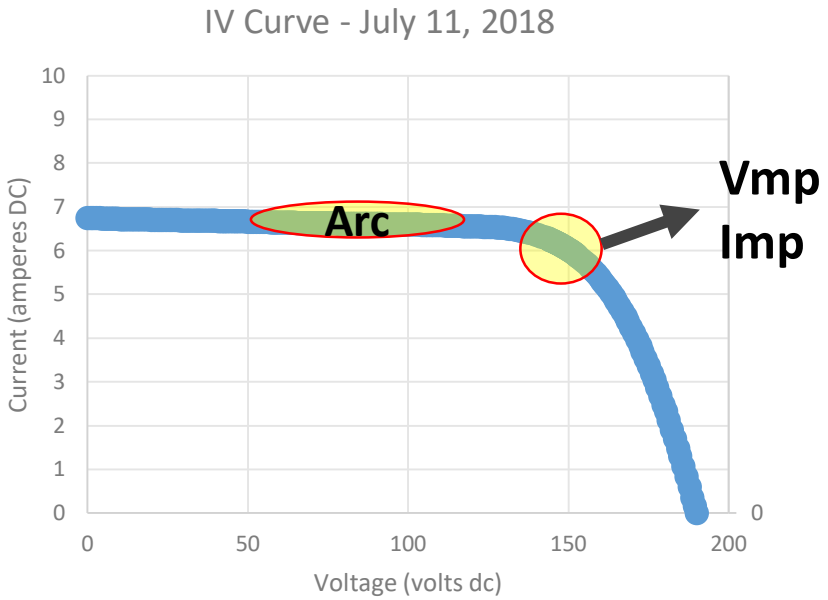
PV IV curve (NREL) - Source NREL

where:

V_{sys} – voltage system (volts)
I_{arc} – current arc (amperes)
I_{bf} - bolted fault current (amperes)
Z_g – arc gap (cm)
T_{arc} – arc time (seconds)
D – working distance (cm)
IE_m – incident energy max power (W/cm^2)

DC Incident Energy Models – Maximum Power (Doan) [2]

$$E_{I.E.} = \frac{(0.239 * V_{mp} * I_{mp} * t_{arc})}{4 * pi * d^2} \quad (3)$$



PV IV curve (NREL) - Source NREL

where:

V_{mp} *– open circuit voltage (volts)*

I_{mp} *– short circuit current (amperes)*

t_{arc} *– arc time (seconds)*

d *– working distance (cm)*

$E_{I.E.}$ *– incident energy (w/cm²)*

DC Incident Energy Models – Stokes/Oppenlander [3]

$$I_t = 10 + 0.2 * Z_g \quad (4)$$

$$V_{arc} = \left(20 + 0.5348 * Z_g\right) * I_{arc}^{0.12} \quad (5)$$

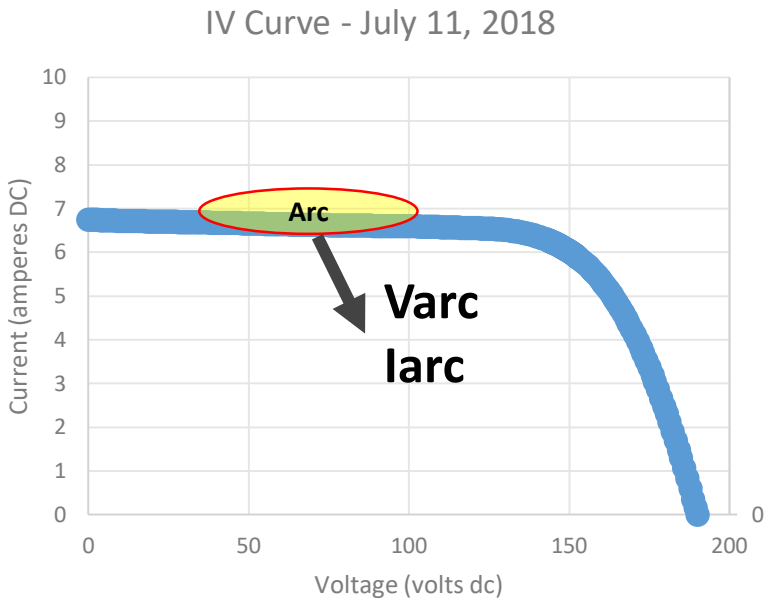
$$R_{arc} = \frac{\left(20+0.5348*Z_g\right)}{I_{arc}^{0.88}} \quad (6)$$

$$E_{arc} = I_{arc}^2 * R_{arc} * t_{arc} \quad (7)$$

$$E_{I.E.} = \frac{E_{arc}}{(4*pi*d^2)} \quad (8)$$

where:

V_{arc} – *voltage arc (volts)*
I_{arc} – *current arc (amperes)*
Z_g – *arc gap (mm)*
R_{arc} – *arc resistance (ohms)*
d – *working distance (mm)*
E_{arc} – *energy (watt-seconds)*
$E_{I.E.}$ – *incident energy (w/cm²)*

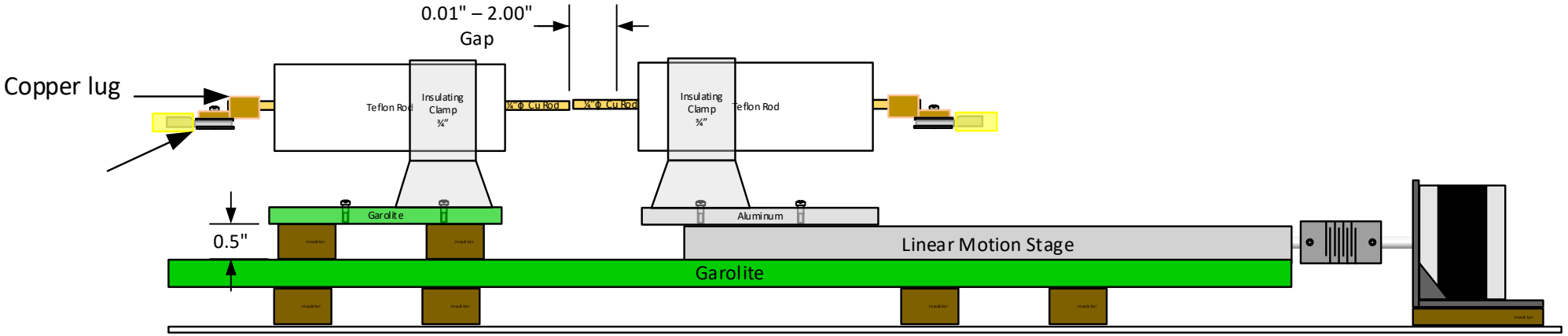


PV IV curve (NREL) - Source NREL

Arc Energy Testing Apparatus

- Voltage and Current Monitoring
- Arc Energy Sensors
- Arc Device
- Future Upgrades

Arc Device - Electrodes

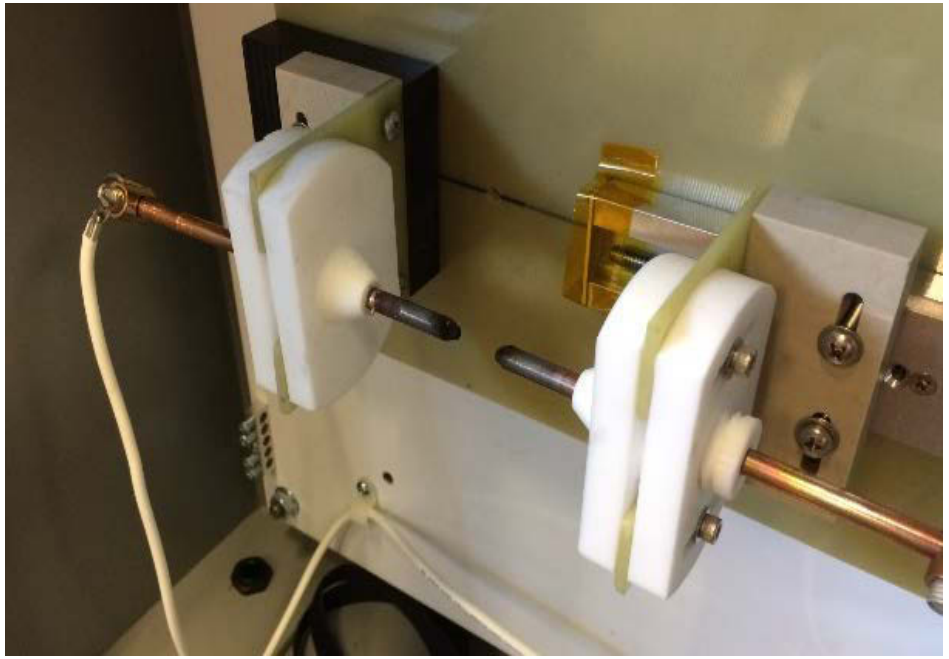


DC Arc Device, NREL

- Linear Motion Stage
- Insulating Materials
- Copper Electrodes
- Arc Gap – 0.01” to 2.00” – Adjustable

Arc Device - Physical

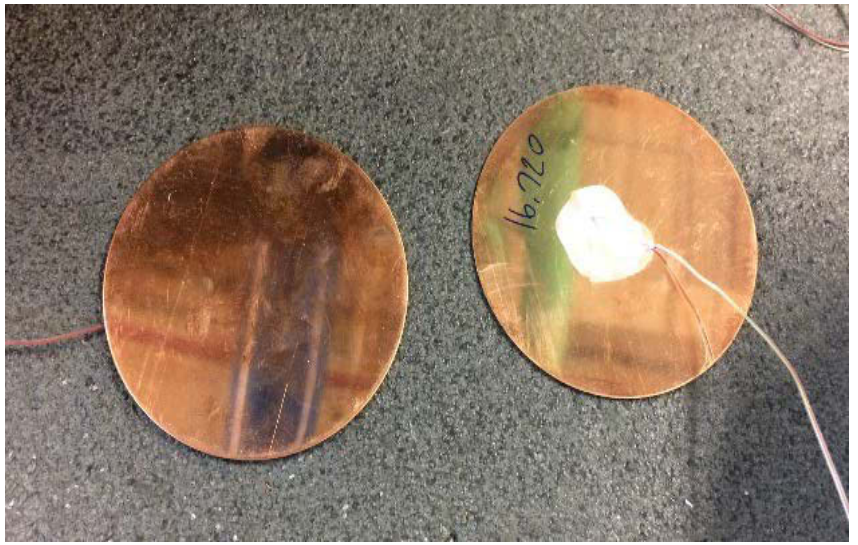
- High Voltage Wiring
- Pure Copper Electrodes (1/4” diameter)
- Initial Tests were started shorted



DC Arc Device, NREL Source: NREL

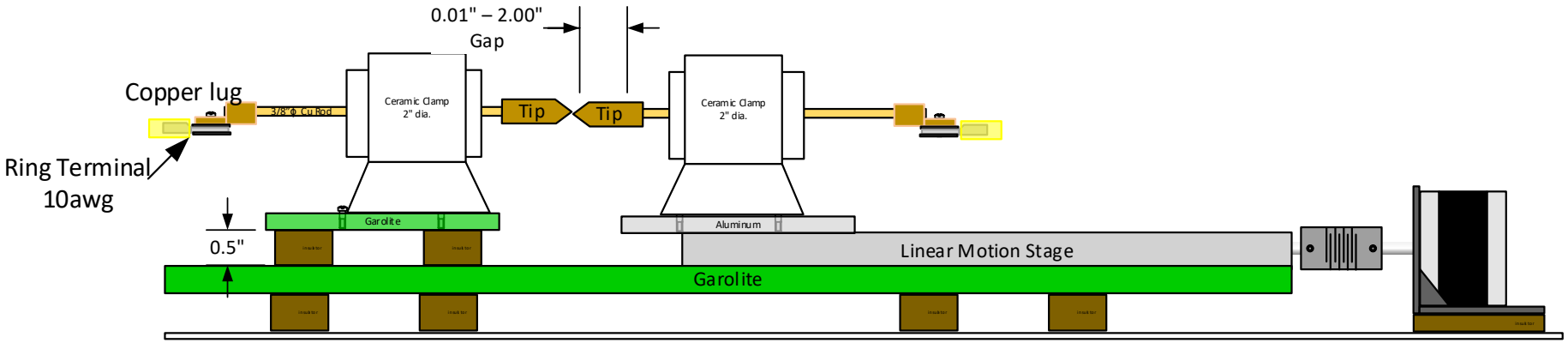
Calorimeters – Copper Discs

- 3” diameter, 1/16” thick pure copper discs
- Type K- Thermocouples
- Precision Weighed
- Verified Readings for Temperature (+/- 0.05°C)
- Insulated, Painted Flat Black
- Built and calibrated to ASTM/F1959/F1959 , ASTM/E457-08, [8],[9]



Copper Calorimeter Discs, NREL Source: NREL

Arc Device - Upgrades



DC Arc Device, Upgrades, NREL

- Electrodes: 3/8” Diameter
- Other Configurations – Rectangular, Round
- Ceramic Insulated Holders

Arc Device - Upgrades

- Other Configurations – Rectangular, Round, Direction
- Adjustable Bus and Box Configurations

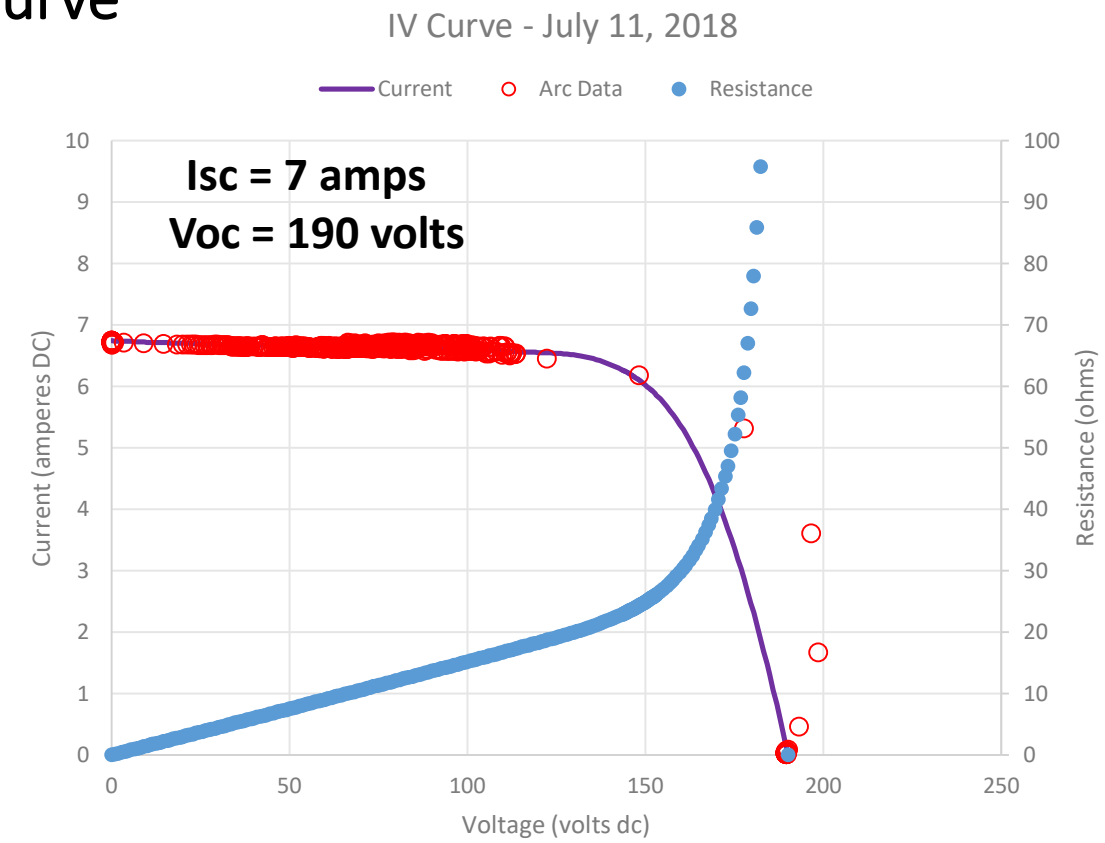
Source: NREL

Arc Energy Experimental Data

- Small Systems < 20kW DC Arc Event Data
- Comparison to Modeled Data

PV Arc Event – Imposed on Operating IV Curve

- **Red circles** – DC Arc Event
- Never reached Maximum Power Point

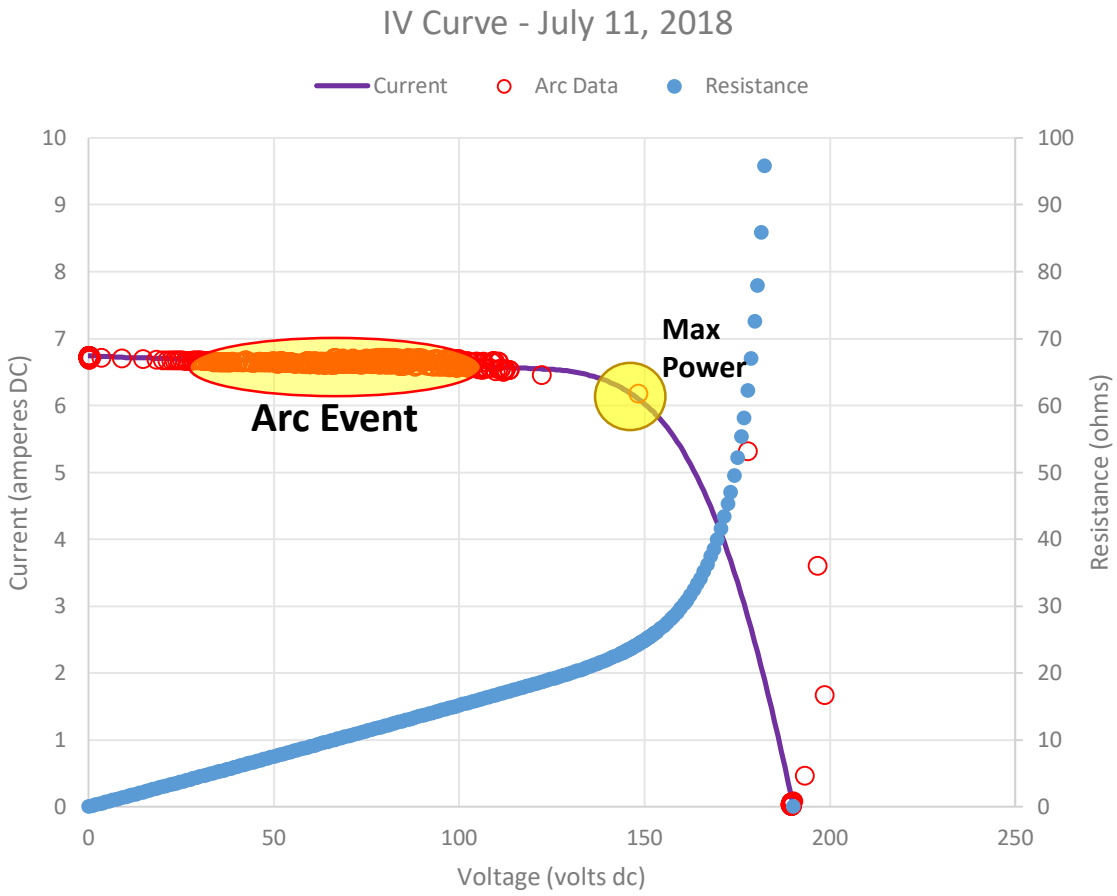


Arc Data Superimposed on Operating IV Curve, NREL

Arc Event vs. IV Operating Point

- **Arc Event** – 25 seconds
- Points Fall Well Below MPPT.
  (Red Oval – labeled Arc Event)
- Inductive Kick when disconnected
- Arc Resistance is < 20 ohms
  - Significantly less than MPPT resistance
  - Non-zero fault resistance

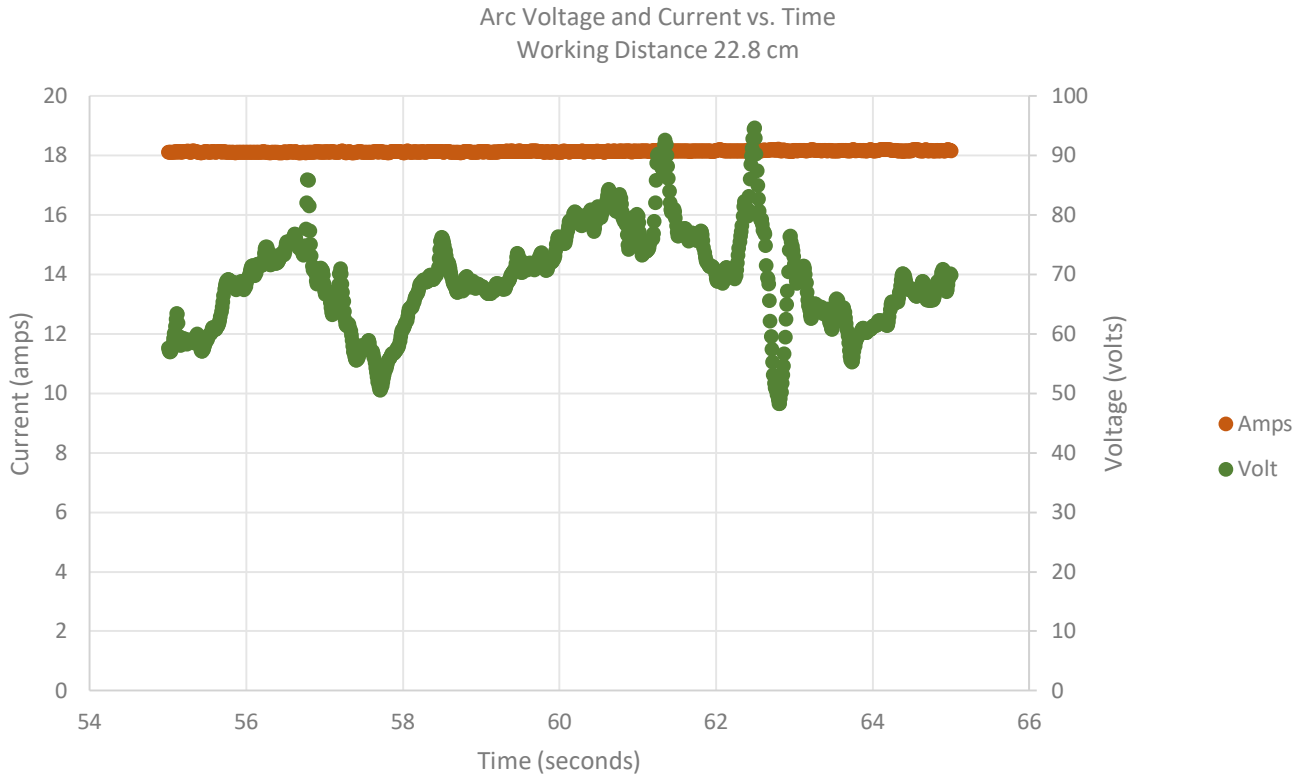
Isc = 7 amps **Iarc = 6.9A**
Voc = 190 volts **Varc = 75V**



Arc Data Superimposed on Operating IV Curve, NREL

Arc Event – Voltage and Current Data

- Working Distance: 22.8 cm (9 inch)
- **Current Fairly Constant**
  - Isc = 18 amps
  - Iarc = 18 amps
- **Voltage Varies**
  - Voc = 650 VDC
  - Varc = 75 VDC (95 Max)



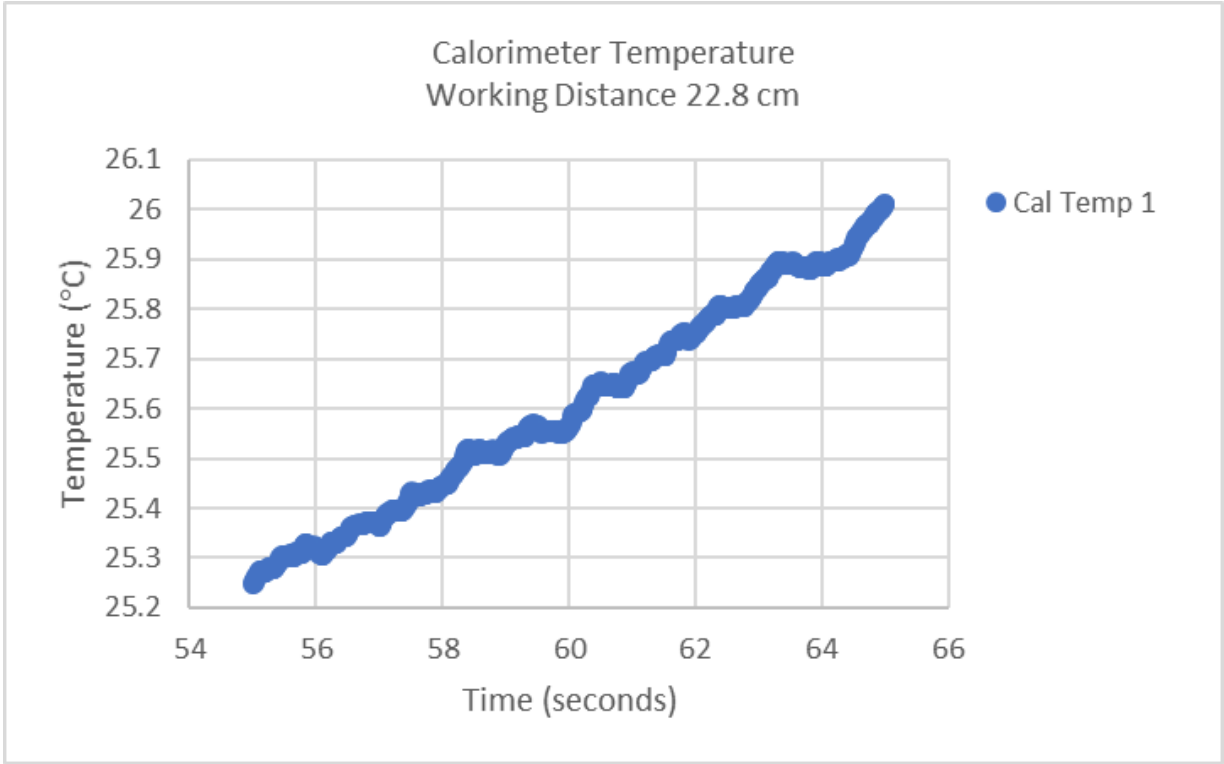
Arc Voltage and Current, 10 Second Arc, NREL

Arc Event – Measured Incident Energy

- **Temperature Rise** (Energy)
  - Less than 0.05°C/Second

  Or
  - 0.03 cal./cm^2 over 2 seconds

- Less Energy than 500 watt Calibration Lamp (Quartz Halogen)
  - 12” distance



Arc Calorimeter Data, 5kW PV System, 22.8cm (9 inch) Working distance, 10 Second Arc, NREL

Arc Testing Results – Experimental vs Models

Test#	Power (Watts DC)	Work Dist (cm)	NREL Data (cal/cm^2)	70E (cal/cm^2)	Stokes/Oppenlander (cal/cm^2)	Maximum Power (cal/cm^2)	Error (Multiplier)	Error (%)
			Experimental		Modeled			
1	8365	46	0.0043	0.053	0.076	0.090	12	-92
2	8552	46	0.0092	0.055	0.078	0.093	6	-83
3	8690	46	0.0077	0.056	0.079	0.094	7	-86
4	8843	23	0.0299	0.227	0.322	0.380	8	-87
5	8875	23	0.0271	0.227	0.323	0.380	8	-88
6	8703	15	0.0354	0.501	0.713	0.843	14	-93
7	11549	46	0.0196	0.079	0.105	0.154	4	-75

Notes:

Tests Run at NREL, Golden, Colorado

Voc around 650VDC, Run 7 at 460VDC

Isc around 18 amps, Run 7 at 36 amps

**** All Experimental Arc Data is approximately 10 times less than modeled data ****

Data Discussions

- Arc Energy Modeled vs Experimental
- Understanding Modeled parameters
- Future Work

Arc Models – Compared to Experimental Data

Model Data

- Assume All Energy Transferred to Worker
- Use Maximum Power Voltage and Current or higher
  - Most Use Wrong Voltage
  - Most Use Wrong Current

Experimental Data

- Thermal Energy Transferred to Sensors (There are losses)
- Follow IV Curve and Depend Largely on Arc Resistance for Operating Point
- ** **Arc Follows IV Cur**ve **

Arc Follows IV Curve

Arc Models – Parameters

Model Data

- Voltage
  - Either Open Circuit or Max Power
- Current
  - Use either Short Circuit or Max Power

Experimental Data

- Voltage
  - Not probable for Solar Device to operate at these points during arc
- Current
  - Operates slightly less than **Isc** or Short Circuit Current

Future Work – NREL PV DC Arc Testing

- Build new Arc Jig
  - Using Ceramic Electrode Holders
  - ½” expendable copper tips
  - Allow for different bus configurations and electrode tips
- Improve Temperature Data Collection
  - New faster logging circuitry
  - New calorimeters, more sensitive
- More Test data for 5-30 kW PV strings and systems
- Help Improve and/or change 70E calculation methodology (dependent on DC generation type)

Need Models for the Different DC Systems

- IEEE 1584 may need to develop models for the different DC systems:
- PV, Capacitors, Fuel Cells, Batteries, DC power supplies…
  - Different Operating Characteristics

550 MW PV Plant [4]

Battery Bank, Source: NREL

Fuel Cell, Source: NREL

DC Laser Supply, Source: LLNL NIF

Other Relevant PV DC Arc Testing Work

EPRI PV DC arc model validation work:

High Power – 1MW PV system DC Arc experimental data

- Direct Current Arc-Flash Hazards of Solar Photovoltaic Systems [10]
- DC Arc Flash on Photovoltaic Equipment [11]

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References

[1] Standard for Electrical Safety in the Workplace, NFPA 70E, 2018.

[2] D. Doan, "Arc Flash Calculations for Exposures to DC Systems," IEEE Transactions of Industry Applications, Vol. 46, No. 6, November/December 2010.

[3] R.F. Ammerman, T. Gammon, P.K. Sen, "DC-Arc Models and Incident-Energy Calculations," IEEE Transactions of Industry Applications, Vol. 46, No. 5, September/October 2010.

[4] BHE Renewables.

[5] IEEE Std 1584 2018 – IEEE Guide for Performing Arc-Flash Hazard Calculations, 2018.

[6] Fronius String Configuration Tool: https://www3.fronius.com/froniusdownload/tool.html

[7] Solar ABCs Solar Design Temps: www.solarabcs.org/about/publications/reports/expedited-permit/map/map_intro.html

[8] ASTM/F1959/F1959 – 14, "Standard Test Method for Determining the Arc Rating of Materials for Clothing," January 2017.

[9] ASTM E457 08(2015) – Standard Test Method for Measuring Heat Transfer Using a Thermal Capacitance (Slug) Calorimeter

[10] Direct Current Arc-Flash Hazards of Solar Photovoltaic Systems, EPRI, October 2018, https://www.epri.com/#/pages/product/000000003002014641/?lang=en-US

[11] DC Arc Flash on Photovoltaic Equipment, EPRI, June 2018, https://www.epri.com/#/pages/product/000000003002014124/?lang=en-US

[12] P. McNutt, W. Sekulic, G. Dreifuerst, Solar PV DC Systems: Basics & Safety, Fort Worth, TX, IEEE ESW 2018.

[13] EFCOG Best Practices - #194: DC Arc-Flash Calculator, https://efcog.org/best-practices/

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Questions?

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