SAND2014-19244PE

Quantifying PV Fire Danger Reduction with Arc-Fault Circuit Interrupters

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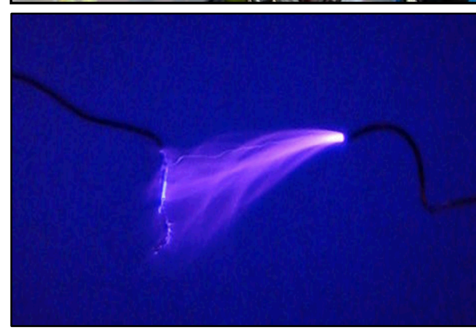


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29th European PV Solar Energy Conference & Exhibition
23 September, 2014
Amsterdam, The Netherlands

SANDIA REVIEW & APPROVAL NUMBER: 2014-XXXXC

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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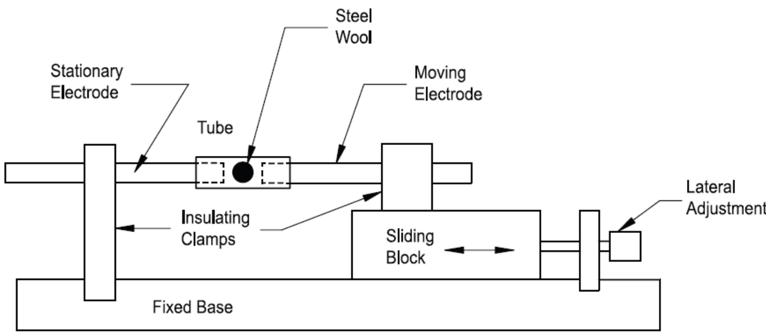
Arc-Fault Codes and Standards

- *National Electrical Code® (NEC)* 690.11
  - 2011 *NEC* requires arc-fault mitigation for PV systems on/penetrating a building
  - 2014 *NEC* requires arc-fault mitigation for all PV systems
- Arc-fault circuit interrupters are listed using Underwriters Laboratories (UL) 1699B, *"Outline of Investigation for Photovoltaic (PV) DC Arc-Fault Circuit Protection"*
  - Not a standard yet! Needs to be improved and voted on by the UL Standards Technical Panel (STP) first.
  - To move UL 1699B to a certification standard, the outline of investigation must be improved.
  - The Sept 2013 STP meeting identified the following areas for development:
    - Arc-fault testing parameters (e.g., inclusion of ballast resistors, capacitors, etc.)
    - DC power supplies for PV simulation
    - Unwanted tripping tests
    - **Arc generation methods**
- Development of an Arc-Fault Model for evaluating thermal degradation mechanisms and reliability of materials and systems in PV systems from DC-DC plasma discharges

Arc-fault generation in UL 1699B

- Currently UL 1699B requires the arc to be created with a tuff of steel wool between the ¼" Cu electrodes
- Electrodes are set to a fixed gap
- 4 tests are required with arc power levels between 300-900 W



Arc Powers

Trip Times

Arcing current (amps)[a, d]	Arcing voltage[b] (volts)	Average Arcing Watts [a]	Approximate electrode, inches (mm) [b]	Max time (sec) [c]
7	43	300	1/16 (1.6)	2
7	71	500	3/16 (4.8)	1.5
14	46	650	1/8 (3.2)	1.2
14	64	900	1/4 (6.4)	0.8

Arc Generation Research Goals

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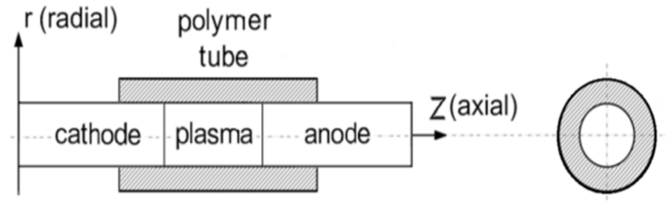
- **Primary Goal:**
  - Determine trip time for low power arc-faults
  - Arc-Fault Plasma Physics Model for varying geometries and power loads
- **Secondary Goals**
  - Measure arc/sheath temperatures
  - Investigate chemical/spectral degradation
- **Findings:**
  - Model Validation found for 100W and 300W Arcs.
  - Results suggest a 16.1% and 22.9% decrease in combustion times for the 100 W and 300 W polycarbonate tests with an oxygen-ingress hole.
  - Electrode geometry can severely impact arc ignition time
  - “Pull-apart” method was found more reliable in facilitating stable arcs, however inclusion of wire mesh according to UL1699B facilitated lower ignition times.
  - Recommendations have been made to UL and a revised version of the UL1699B guidelines is underway.

Arc-Fault Plasma Model Development

- Numerical Model for a transient, 2D DC-DC Discharge Plasma event.
  - Implicit FEA Methodology
  - Radiative and Natural Convective BC's
  - Air Medium with 5mm Gap Spacing
  - Plasma and Sheath Control Volume
- Collision dominated DC discharge plasma with mean free paths for all reaction species smaller than the macro characteristic lengths.
- Approximations made:
  - High and uniform electrical conductivity throughout the axially-centered column
  - 1 atm Low Temperature Plasma
  - Plasma Thermodynamic Equilibrium Conditions.



Energy Balance

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{Q}_{Plasma} = \rho C_p \frac{\partial T}{\partial t}$$

Ohmic Heating

$$\dot{Q}_{Plasma} = j\boldsymbol{E} - U(T)$$

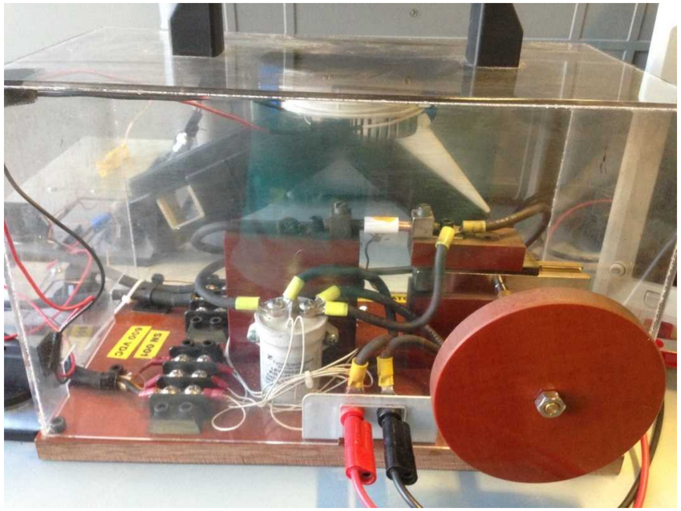
$$\boldsymbol{E} = \frac{\partial V}{\partial z} = \frac{I}{\sigma A}$$

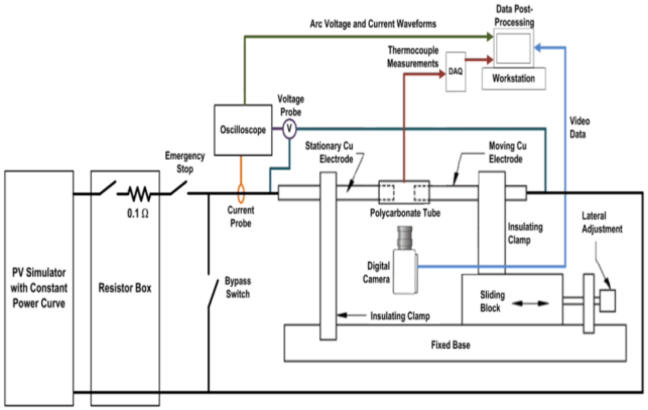
Cathode/Plasma Interface & Cooling by Thermionic Emission of Electrons and Heating by Ion Bombardment of the electrodes

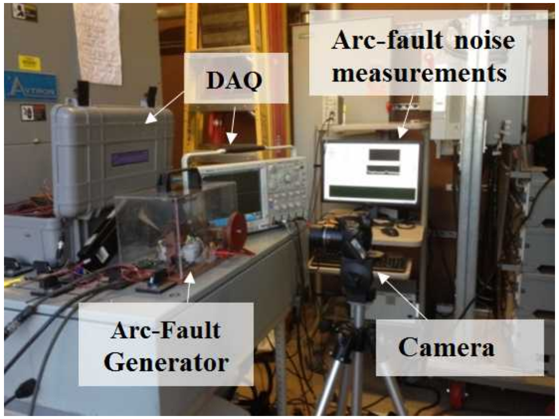
$$F = j_i V_i + j_e\left(\phi_w + \frac{2k_b T}{e}\right) \qquad F = j_e \phi_w$$

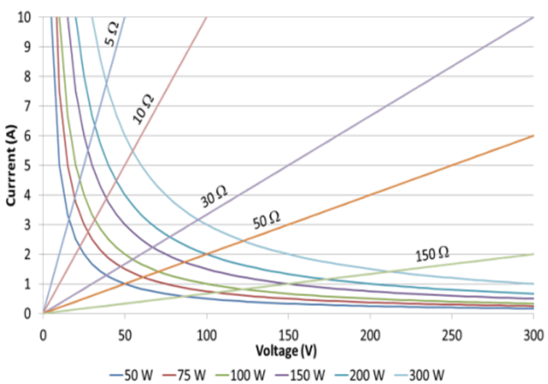
Experimental Methodology

- Customized PV Simulator provided power to a developed Arc-Fault Generator.
  - A power resistor was employed to avoid shorting
- Smoke detector, thermal measurements and high speed camera used for measuring ignition times.
- Spectral Analysis Performed
  - J. Johnson and K.M. Armijo, J. Progress in Photovoltaics, **2014**,
  - B. Yang, et. al., 40th PVSC, **2014**, Denver, CO.
  - J. Johnson and K.M. Armijo., 40th PVSC, **2014**, Denver, CO.









Arc-fault Parametric Generation

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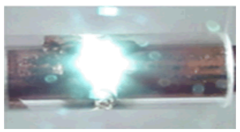
The following variables were parameterized:

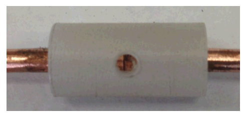
Arc Power



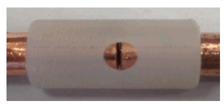
100 W

300 W

Electrode Diameter

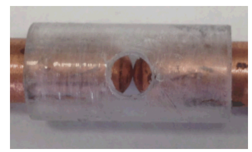


1/8 inch

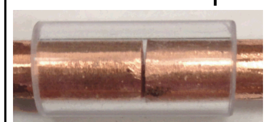


1/4 inch

Electrode Tip

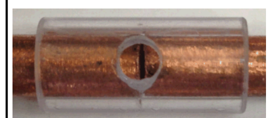


Rounded Tip

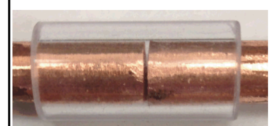


Flat Tip

Hole for O_2 Ingress

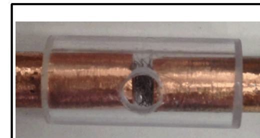


Hole



No Hole

Steel Wool Igniter

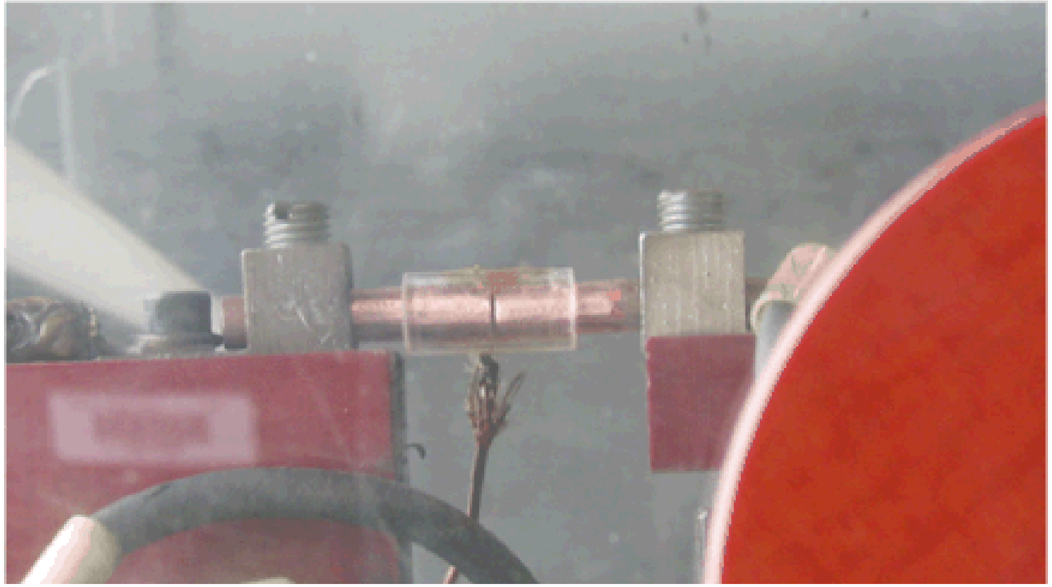


Steel Wool

No Steel Wool

Test Number	Arc Power	Electrode Diameter	Electrode Tip	Hole	Avg. Fire Ignition Time [Sec.]	Standard Deviation Fire Ignition Time [Sec.]
1 (UL 1699B)	300 W	1/4”	Flat	No	14.6	10.7
2	300 W	1/4”	Flat	Yes	11.8	5.9
3	300 W	1/4”	Flat	No	14.1	9.0
4	100 W	1/4”	Flat	No	69.0	41.1
5	100 W	1/4”	Flat	Yes	22.0	12.7
6	100 W	1/4”	Round	Yes	107.0	17.0
7	100 W	1/8”	Flat	Yes	21.7	4.5
8	300 W	1/8”	Flat	Yes	10.3	4.0

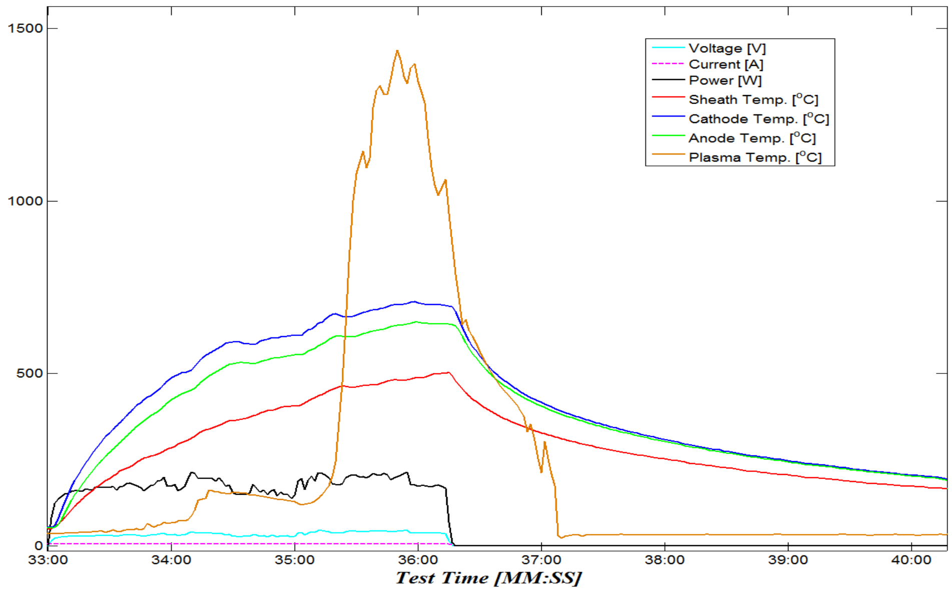
100W Arc-fault Test

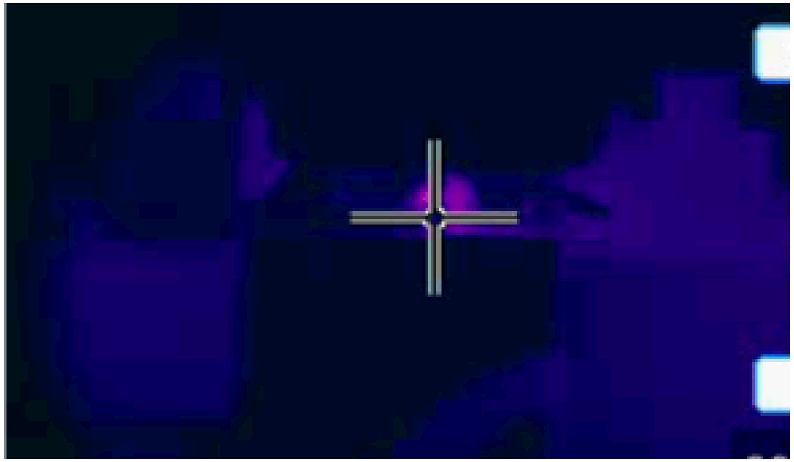


This will be a Video

Polycarbonate tube with no hole. Possibly fire at 7.26 s, but no sustained external flame until after 92.04 s.

Arc Thermal Degradation Results





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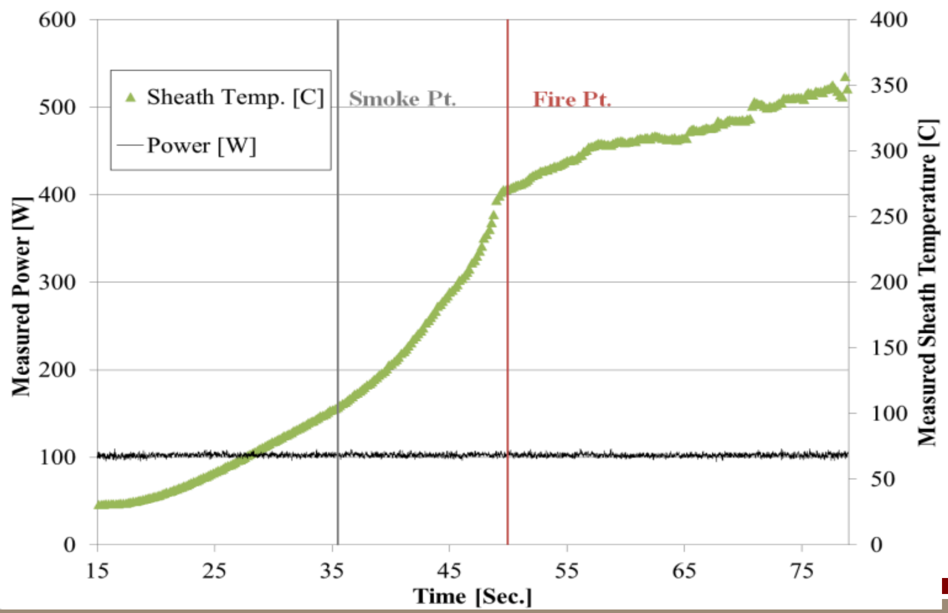
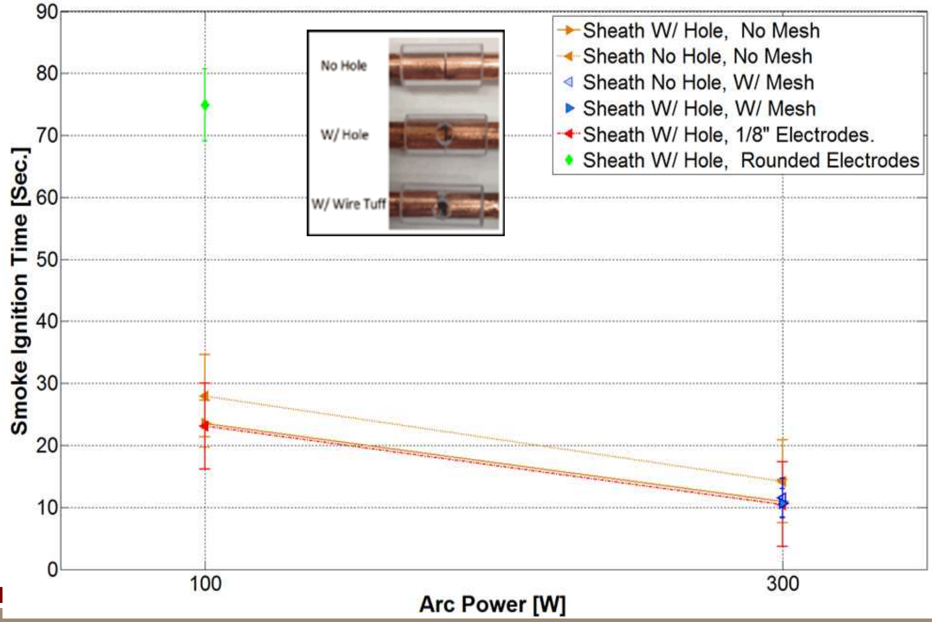
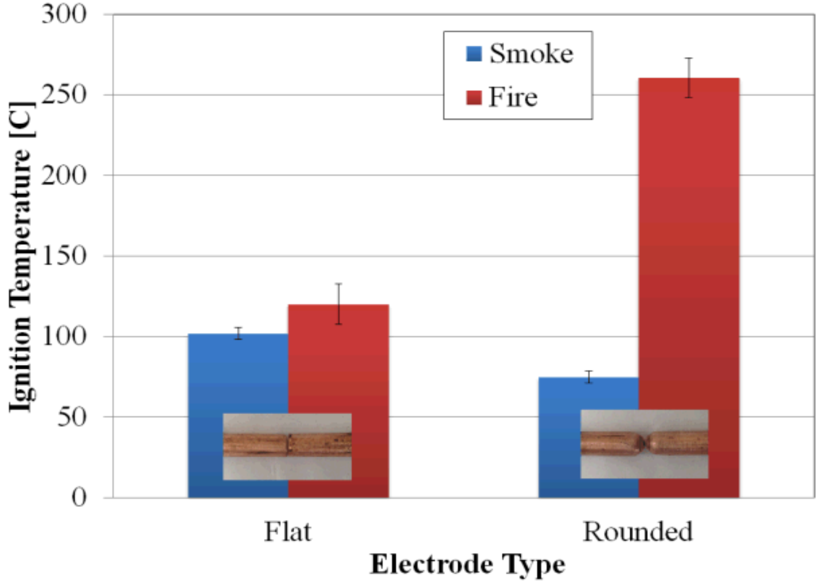
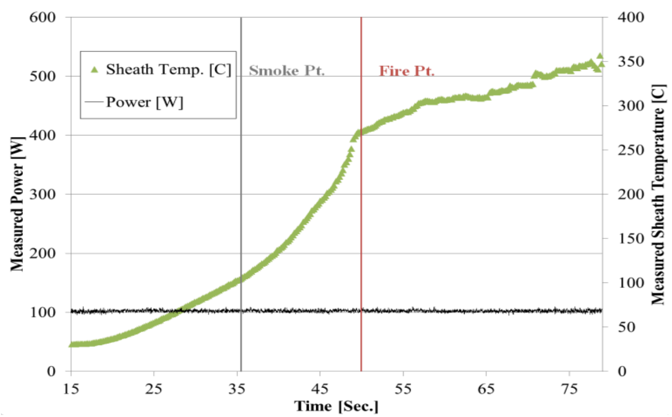


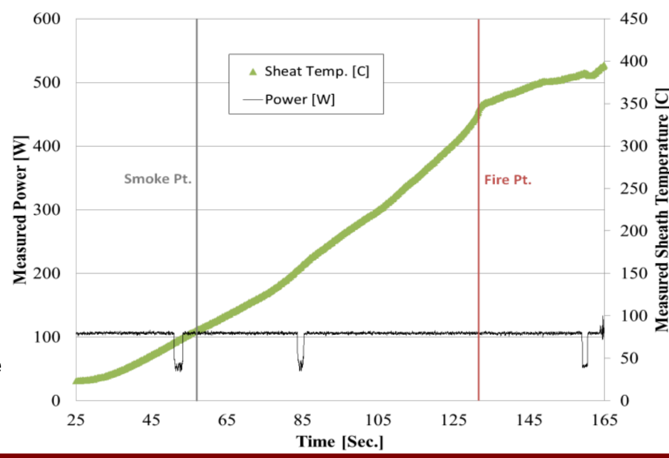


Rounded vs. Flat-Tip Electrodes

- Results found a 17.4% reduction in smoke ignition time, as well as a 26.6% decrease in measured smoke ignition sheath temperatures btw flat and rounded-tip electrodes respectively.
- Rounded-Tip Electrodes increased arc stability but had a lower occurrence of fires due to rapid melting.
  - Holes were included for these tests.



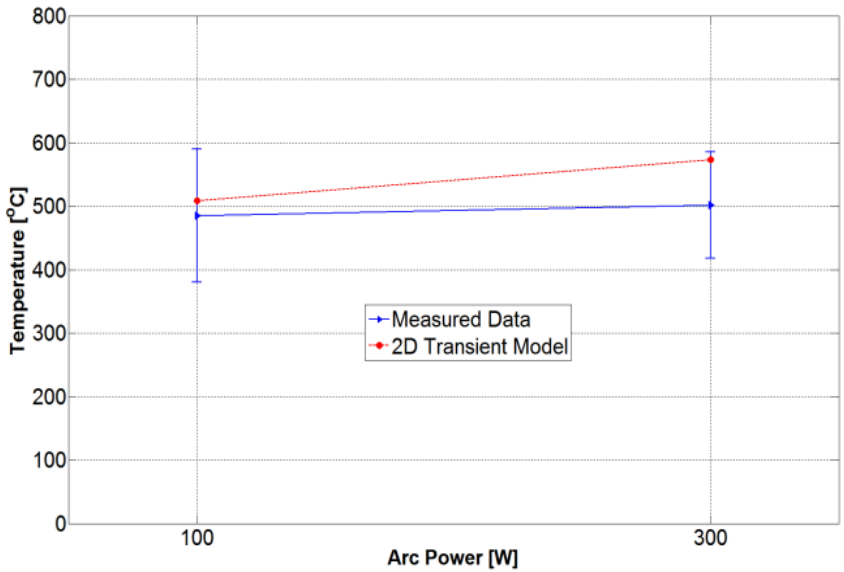


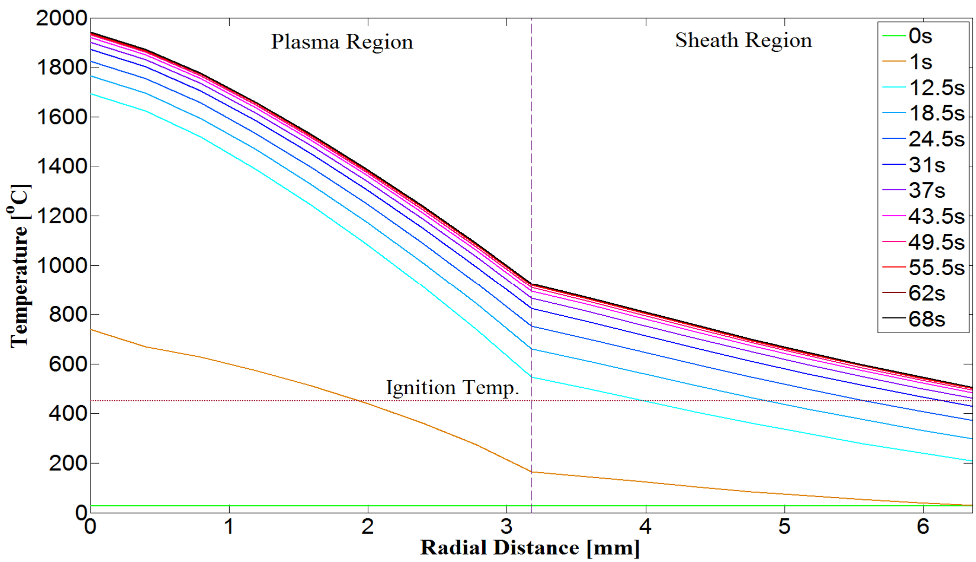


Armijo, K.M., Johnson, J., Hibbs, M. and Fresquez, A., **2014**, "Quantifying Photovoltaic Fire Danger Reduction with Arc-Fault Circuit Interrupters", *29th EUPVSEC Conference*, Amsterdam, The Netherlands

Model Results

- 100 W input power-level exhibited a 4.9% uncertainty and the 300 W case had 14.2% uncertainty after 69 s found to be the average arc-extinguish time.
- Average low temperature variations of 0.87% and 0.68% were found across the respective plasma and sheath regions.
- Larger radial variations were found with avg. temperatures of 788.7°C and 346.7°C observed across the plasma and sheath regions respectively.





Arc Duration Trip Time

- Parametric transient temperatures determined for the (bulk) median radial temperature through the sheath.
- As the arc power increases there is less time before the polymer reaches the ignition temperature.
- Results suggest increasing arc-power levels can have impacts on ignition time scales, which requires rapid and accurate AFCI responses.
- UL 1699B defines the maximum AFCI trip time according to: $t_{trip} = min\left(2, \frac{750}{i_{arc} \cdot V_{arc}}\right)$

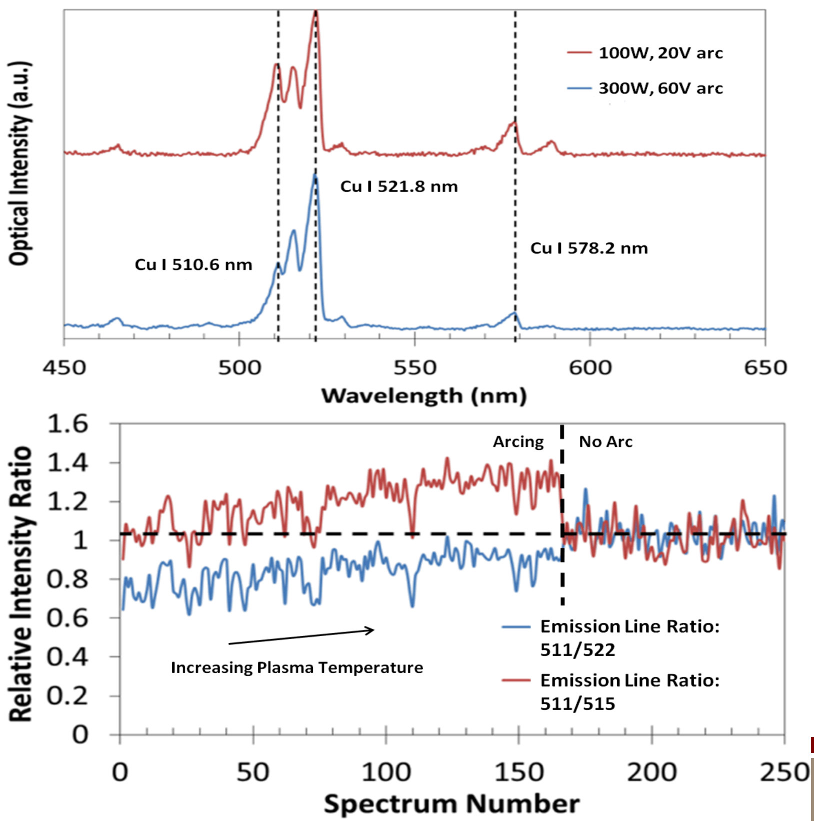
Arc Power [W]	Arc Duration Time [sec.]										
	0.20	0.40	0.63	0.83	1.15	1.50	2.00	4.00	6.00	8.00	10.00
100	25.79	27.03	33.06	41.94	61.23	86.90	128.03	297.40	425.27	499.96	538.53
300	25.91	28.87	40.87	58.66	98.42	153.16	242.46	556.19	694.35	743.50	760.65
500	26.05	30.78	49.15	76.87	140.46	229.68	372.76	754.14	861.42	890.81	898.93
650	26.13	32.00	54.49	88.81	168.60	280.93	455.90	846.23	936.74	958.79	964.23
900	26.27	33.99	63.38	108.97	216.57	367.08	584.86	961.27	1031.54	1046.20	1049.29
1200	26.44	36.37	74.23	133.93	276.20	470.04	719.73	1062.64	1116.78	1126.49	1128.25

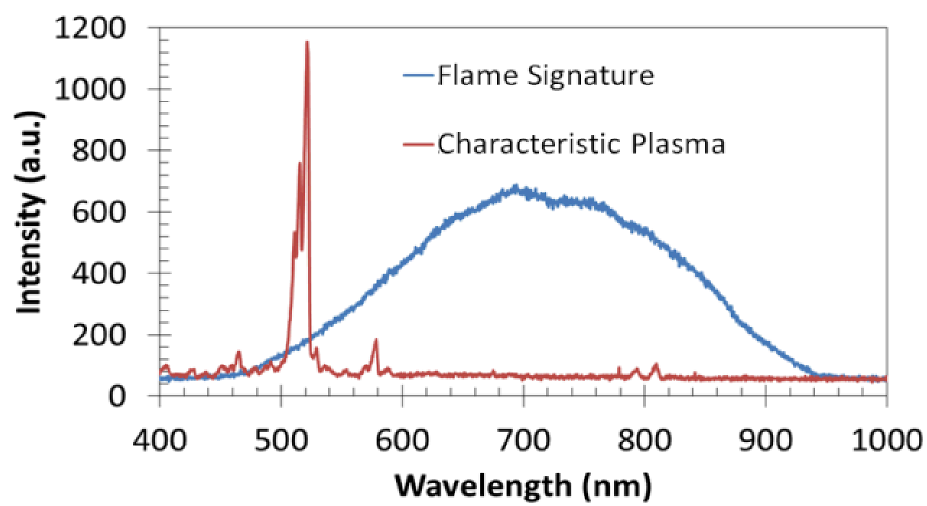
Material Under Non-Destructive State
Material Undergoing Melting
Material Undergoing Fire Ignition

UL 1699B AFCI Maximum Trip Time
$T_{melt} = 155^oC$
$T_{ignition} = 450^oC$

Optical Emission Spectrum Analysis

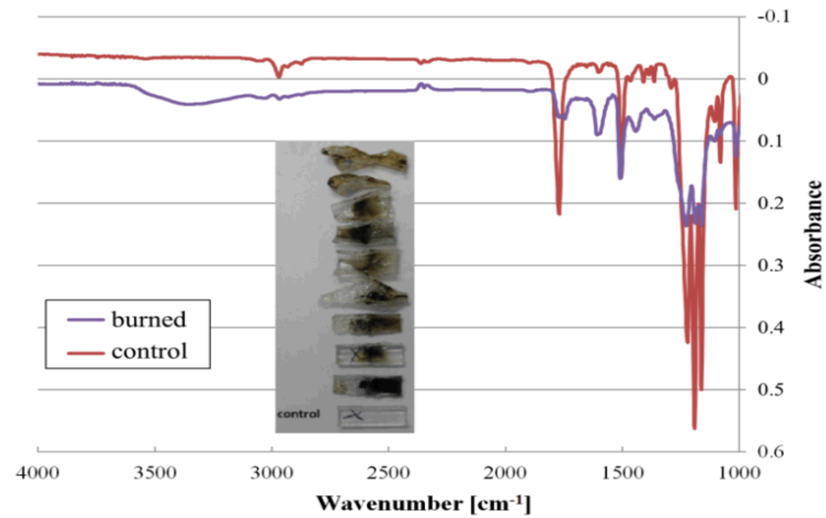
- To further validate the model, understand the plasma discharge process, and predict material degradation mechanisms, measurements of the plasma electron temperature are necessary.
- During the 100 W arc discharge increases of 24% and 30% were observed for the 511/522 and 511/515 ratios, respectively.
  - These increases indicate rising plasma temperatures as a function of time, but further investigations are needed for quantitative analysis.

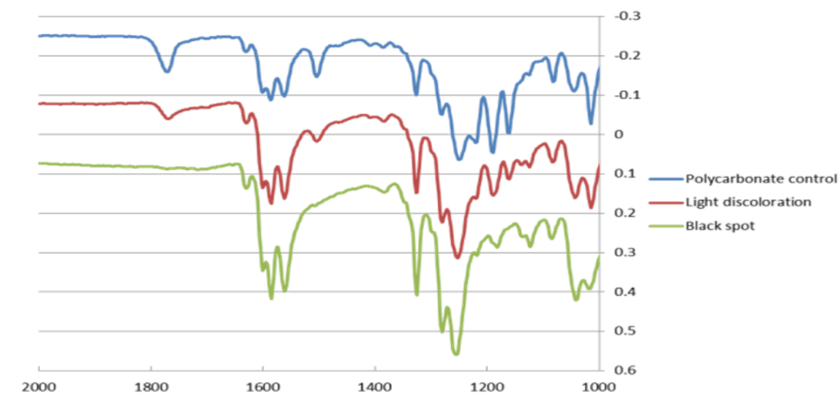


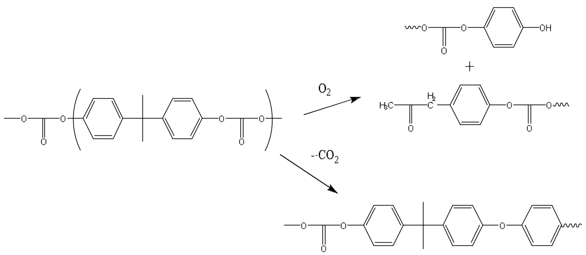


Chemical Degradation Mechanisms

- Chemical analysis showed oxidation reactions (combustion) occur during arc faults and changes in appearance of polymers are not due to just melting.
- Overall, results found similar spectral decomposition between respective grouped samples that experienced fire ignition.
- Some spectral evidence of increased oxidation of the polycarbonate sheaths over the PET and nylon samples were found.
  - This excessive degradation may explain lower ignition times found by polycarbonate sheath materials.







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Conclusions

- Transient 2D FEA model developed and validated for 100W and 300W Arc-Fault DC-DC Plasma Discharges
  - Model validated with experimental data for a uniform polycarbonate sheath with a 4.9% and 14.2% error for the 100 and 300 W power levels respectively.
- A parametric study of various geometries, and power levels was conducted to determine repeatable arc-fault ignition qualification times and certification tests for UL 1699B.
- The results of this study have determined:
  - Low Power (>100W) arcs cause fires in polymers common to PV systems
  - A trip time of less than 2 seconds is recommended for the suppression of fire ignition during arc-faults.
  - Larger (1/4”) diameter electrodes: Had overall longer ignition times to the 1/8” diameter electrodes.
  - “Pull-apart” generation method (no steel wool): Increased arc stability, though longer ignition times
  - A hole in polymer sheath: Overall decreased ignition times, and greater arc stability.
  - Rounded electrode tips: Increased arc stability, however facilitated longer ignition times.
  - 300 W power: Much lower ignition times overall compared to the 100W arcs.
- Optical emission spectroscopy found useful for arc discharge characterization, where characterization using novel approach include optical emission as indicator of arc formation, elemental analysis from characteristic emission lines, and an optical signature of flame.
- Stay tuned for 1699B changes after the Sept 2014 STP meeting!

Acknowledgements

- Sandia Nat'l Labs - Photovoltaics Solar Evaluation Laboratory
- Sandia Nat'l Labs - Distributed Energy Generation Laboratory
- Department of Energy
- Underwriters Laboratory

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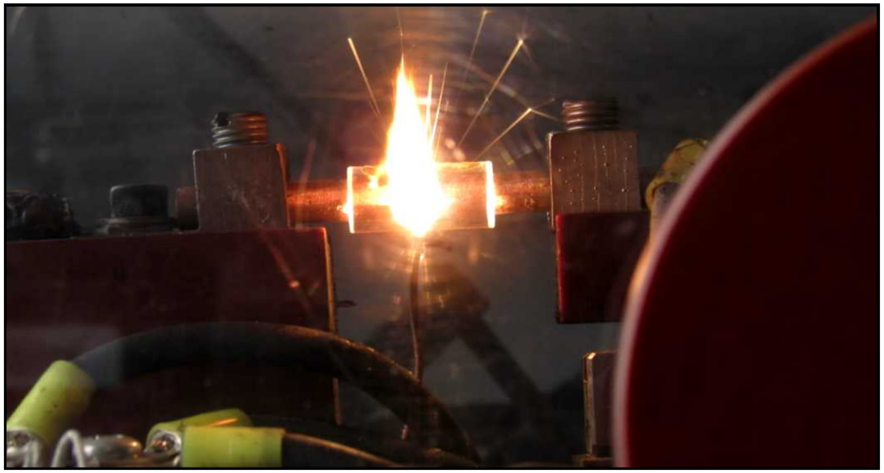

Questions?