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Arc-Fault Photovoltaic Reliability and Plasma Physics of Failure Investigations

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Overview of Research

Unmitigated arc-faults present fire dangers, shock hazards, and cause system downtime in photovoltaic (PV) systems. The 2011 National Electrical Code® added section 690.11 to require a listed arc-fault protection device on new PV systems. Underwriters Laboratories created the outline of investigation for PV DC arc-fault circuit protection, UL 1699B, for certifying arc-fault circuit interrupters (AFCIs) for arc suppression. Unfortunately, little is known about the physics of failure of arc-fault events, and appropriate trip times, which can vary by location in the PV system, different electrode and polymer encapsulant geometries and materials. In this investigation, analytical and experimental research was performed to study the physics of failure of plasma arc-fault events. A model was developed which determines fire danger with UL 1699B-listed AFCIs and consequences of arc-fault discharges sustained beyond UL 1699B trip time requirements. This model predicts temperatures for varying system configurations and was validated by 100 and 300 W arc-faults experiments where combustion times and temperatures were measured. This investigation then extrapolated burn characteristics using this model to predict polymer ignition times for exposure to arc power levels between 100-1200 W. Experimental tests of other materials and connectors in close proximity to DC-DC plasma discharges was also performed, with Fast Fourier Transform (FFT) analysis conducted to determine arc-fault signatures for AFCIs. Optical emission spectroscopy and thermochemical decomposition analysis were also conducted to assess spectral and chemical degradation of polymer and metalic materials.

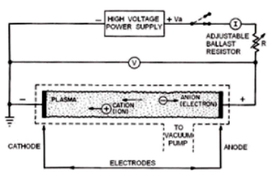
Significance of Work

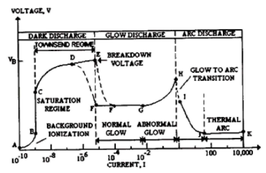
As the worldwide installed capacity of photovoltaic systems continues to grow and age, the number of arc-faults in PV systems is expected to increase. However, the lack of fundamental understanding and nuisance tripping has given rise to the need for better sensing methodologies and Standards. This work provides novel methods for arc-fault characterization, detection and mitigation.

Current & Future Work

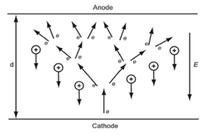
Further research is currently being conducted to explore the physics of failure of materials , as well as new methodologies, such as "signature replay", to reduce nuisance tripping in AFCIs. This work is currently contributing to UL and NEC standards, as well as AFCI device and 1-atm plasma arc-fault generator development, for near-term TA, IP and journal publications submission.

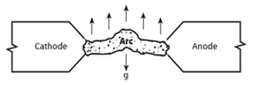
Fundamental Research





Braz. J. Phys. vol.34 no.4b São Paulo Dec. 2004

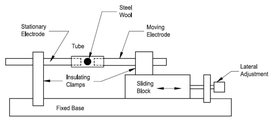


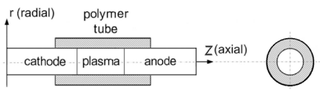


UL 1699B Standard Requirements

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

Plasma Thermal Model





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

$$\dot{Q}_{Plasma}=jE-U(T) \qquad E=\frac{\partial V}{\partial z}=\frac{I}{\sigma A}$$

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

$$F=j_iV_i+j_e\left(\phi_w+\frac{2k_bT}{e}\right) \qquad F=j_e\phi_w$$

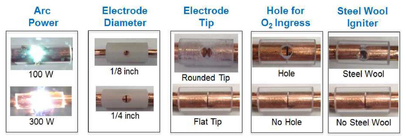
Thermionic current

$$j_{rich}=\xi T^2e^{\frac{-\phi_e}{k_bT}} \qquad j_i=j-j_{rich}$$

$$\boldsymbol{j}=-\sigma\nabla\phi \qquad \nabla\cdot(\sigma\nabla\phi)=0$$

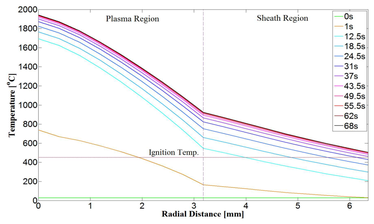
Notable Approximations

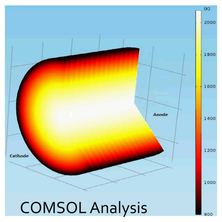
- High & Uniform electrical conductivity throughout the axially-centered column
- Thermodynamic equilibrium & 1-atm low temperature plasma conditions

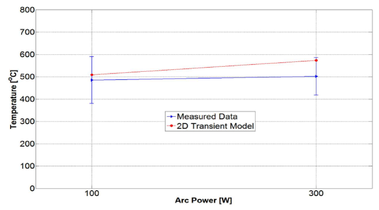


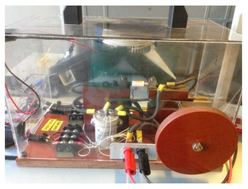
- **Model validated with experimental data for a uniform polycarbonate sheath with a 4.9% and 14.2% error for the 100 and 300 W power levels respectively.**
- **<u>Opportunity</u> for developing & utilization of comprehensive model:**
  1. **Predicting failure mechanisms of devices and materials, of varying geometries, in contact with plasma discharges.**
  2. **Results will be published in upcoming UL1699B and NEC standards.**
  3. **Research to be used in the development of advanced and reliable AFCI devices.**

Notable Results & Conclusions









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

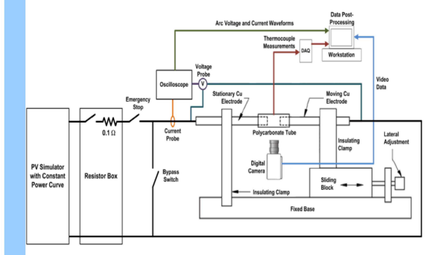
UL 1699B AFCI Maximum Trip Time
T_{melt} = 155°C
$T_{ignition}$ = 450°C

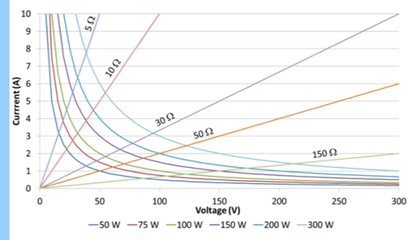
<u>Publications:</u>

- 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, Netherlands. – **Top 20 Paper Award** (out of ~1700 papers)
- Armijo, K.M., Johnson, J., Hibbs, M. and Fresquez, A., **2014**, "Quantifying Photovoltaic Fire Danger Reduction with Arc-Fault Circuit Interrupters," *Progress in Photovoltaics*, **In Press**.

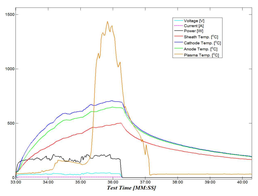
Applied Research

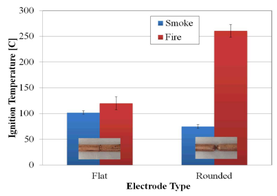
Experimental Setup & Innovative Plasma Generator

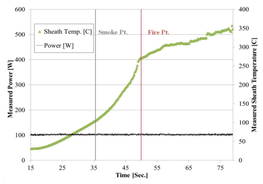


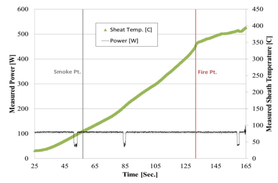


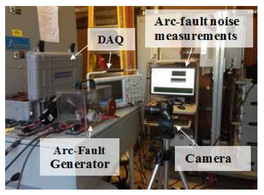
Experimental Thermal Results

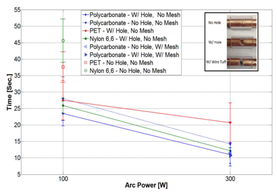








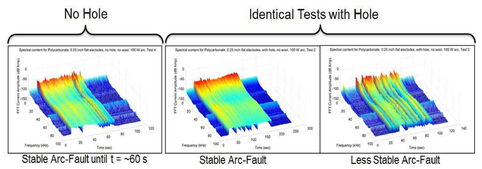


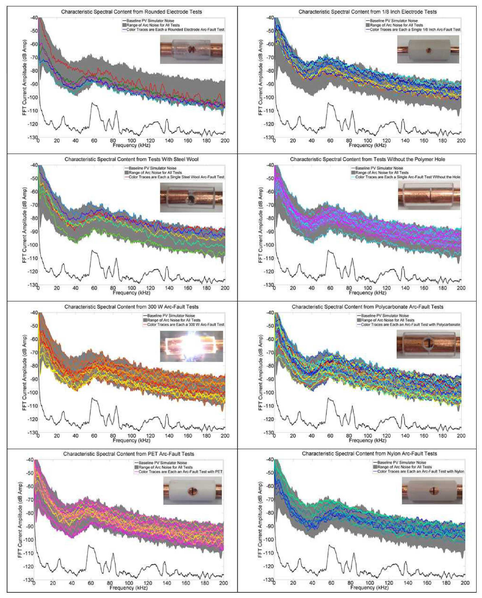


POLYMER IGNITION TIME SUMMARY OF ARC-FAULT EXPERIMENTS WITH A PV SIMULATOR AND ARC-FAULT GENERATOR

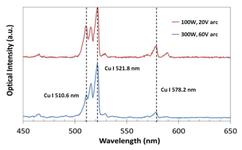
Arc Power	Polymer Type	Electrode Diameter	Electrode Tip Type	Contains Oxygen Ingress Hole	Contains Steel Tuft	Average Smoke Ignition Time [Sec.]	Standard Deviation Smoke Ignition Time[Sec.]	Minimum Smoke Ignition Time [Sec.]	Average Fire Ignition Time [Sec.]	Standard Deviation Fire Ignition Time [Sec.]	Minimum Fire Ignition Time [Sec.]	% of Samples Reaching Fire Ignition
300 W	Polycarbonate	1/4"	Flat	No	Yes	11.5	3.2	7.0	16.6	10.7	11.0	100%
300 W	Polycarbonate	1/4"	Flat	Yes	Yes	10.7	4.6	8.1	10.3	7.5	4.0	100%
300 W	Polycarbonate	1/4"	Flat	No	No	16.2	6.7	6.3	14.1	9.0	6.0	100%
300 W	Polycarbonate	1/4"	Flat	Yes	No	11.0	3.5	6.5	11.8	5.9	11.0	100%
300 W	PET	1/4"	Flat	Yes	No	13.2	3.6	8.51	14.3	1.9	13.0	100%
300 W	Nylon 6,6	1/4"	Flat	Yes	No	12.2	0.9	11.4	24.3	16.5	14.0	100%
100 W	Polycarbonate	1/4"	Flat	No	No	28.0	6.6	19.4	69.0	41.4	39.0	100%
100 W	Polycarbonate	1/4"	Flat	Yes	No	23.1	3.8	19.2	22.0	12.7	13.0	80%
100 W	Nylon 6,6	1/4"	Flat	No	No	45.6	6.6	19.8	108.0	2.8	104.0	22%
100 W	Nylon 6,6	1/4"	Flat	Yes	No	25.9	5.6	19.7	88.5	6.4	84.0	14%
100 W	PET	1/4"	Flat	No	No	37.6	4.6	22.1	120.9	14.4	108.5	63%
100 W	PET	1/4"	Flat	Yes	No	27.5	6.0	16.5	75.3	38.6	21.0	86%
100 W	Polycarbonate	1/4"	Round	Yes	No	19.4	12.5	6.5	107.0	17.0	95.0	40%
100 W	Polycarbonate	1/8"	Flat	Yes	No	29.1	3.0	20.0	21.7	4.5	17.0	100%
100 W	PET	1/8"	Flat	Yes	No	15.0	4.0	9.0	14.0	3.5	10.0	100%
100 W	Nylon 6,6	1/8"	Flat	Yes	No	20.4	5.4	12.1	86.5	21.9	71.0	100%
300 W	Polycarbonate	1/8"	Flat	Yes	No	10.5	6.8	2.5	10.3	6.0	1.0	100%

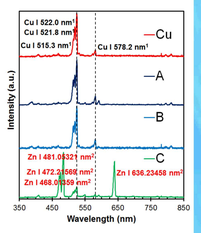
FFT & AFCI Current Spectrum Results

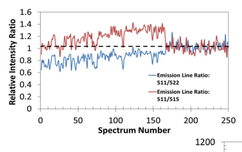


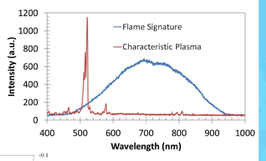


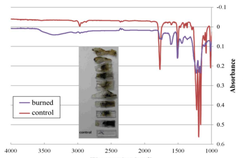
Optical Spectrum Emission & Chemical Degradation Analysis

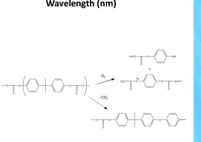


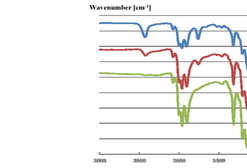












- **Based on fire & minimum 2.5 second smoke detection time, it is suggested UL 1699B include a two second trip time requirement for 100 W arcs to ensure AFCIs detect low power arc-faults**
- **Results suggest a 16.1% and 22.9% decrease in combustion times for the 100 W and 300 W polycarbonate tests with an oxygen-ingress hole.**
- **Chemical analysis showed oxidation reactions (combustion) occur during arc faults and changes in appearance of polymers are not due to just melting.**

<u>Publications:</u>

- Armijo, K.M., Hibbs, M., Johnson, J. and Fresquez, A., **2014**, "Characterizing fire danger from low power PV arc-faults", *40th PVSC Conference*, Denver, CO.
- Johnson, J. and Armijo, K.M., **2014**, "Parametric Study of PV Arc-Fault Generation Methods and Analysis of Conducted DC Spectrum", *40th PVSC Conference*, Denver, CO.
- Yang, B.B., Johnson, J., Armijo, K.M., Taylor, J.M. and Sorensen, N.R., **2014**, "Arc Fault Risk Assessment/Degradation Model for Photovoltaic Connectors, *40th PVSC Conference*, Denver, CO.
- Contributions in upcoming revised publication of UL1699B Standard.

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration