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Parametric Study of PV Arc-Fault Generation Methods and Analysis of Conducted DC Spectrum

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Sandia National Laboratories

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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**

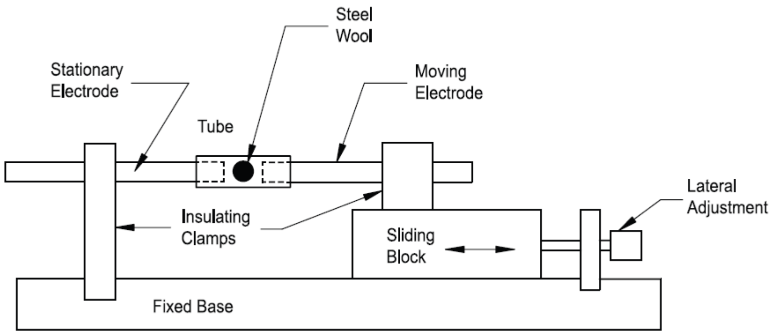
Arc Generation Research Goals

- Determining the most repeatable, 'worst case' tests for adoption by the UL 1699B STP

- The ideal UL 1699B arc-fault generation method:
  - reduces experimental setup complexity
  - improves testing repeatability
  - minimizes arc-fault radio frequency (RF) noise because this is how many arc-fault detectors identify a fault

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 powers between 300-900 W



Arc Powers

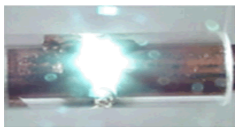
Trip Times

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

Alternative arc-fault generation methods

The following variables were parameterized:

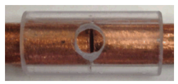
Arc Power



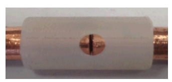
100 W

300 W

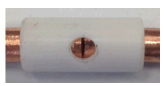
Sheath Material



Polycarbonate

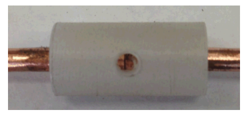


PET

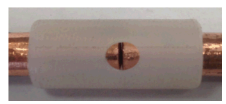


Nylon 6,6

Electrode Diameter

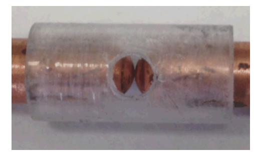


1/8 inch

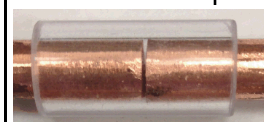


1/4 inch

Electrode Tip

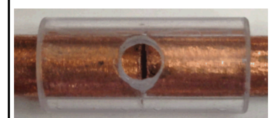


Rounded Tip

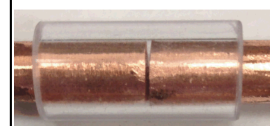


Flat Tip

Hole for O_2 Ingress

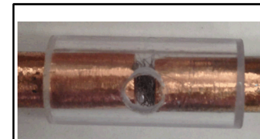


Hole

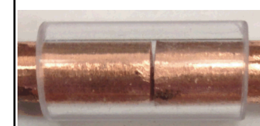


No Hole

Steel Wool Igniter



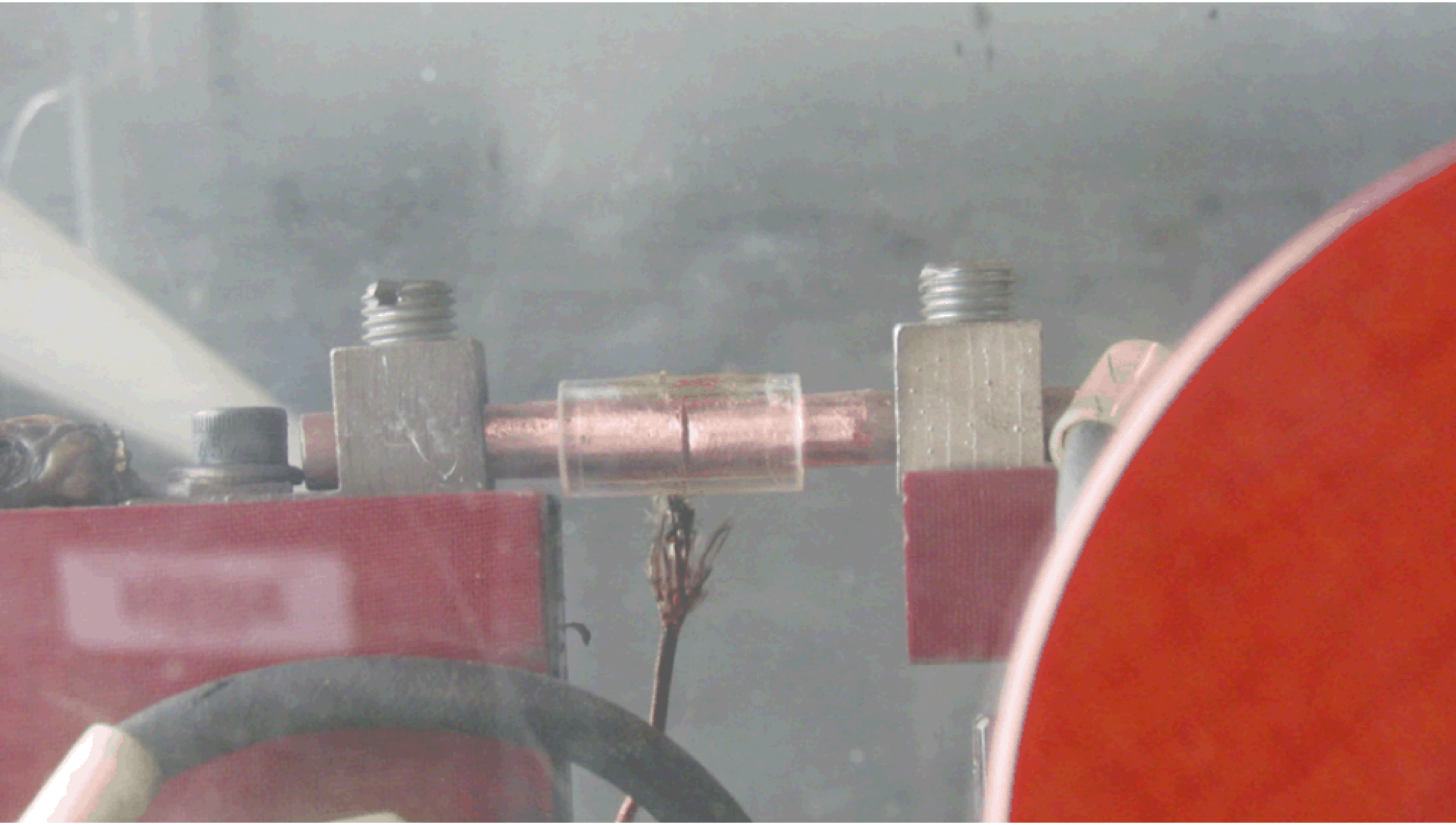
Steel Wool



No Steel Wool

Test Number	Arc Power	Polymer	Electrode Diameter	Electrode Tip	Hole	Steel Wool
1 (UL 1699B)	300 W	Polycarbonate	1/4"	Flat	No	Yes
2	300 W	Polycarbonate	1/4"	Flat	Yes	Yes
3	300 W	Polycarbonate	1/4"	Flat	No	No
4	300 W	Polycarbonate	1/4"	Flat	Yes	No
5	300 W	PET	1/4"	Flat	Yes	No
6	300 W	Nylon 6,6	1/4"	Flat	Yes	No
7	100 W	Polycarbonate	1/4"	Flat	No	No
8	100 W	Polycarbonate	1/4"	Flat	Yes	No
9	100 W	Nylon 6,6	1/4"	Flat	No	No
10	100 W	Nylon 6,6	1/4"	Flat	Yes	No
11	100 W	PET	1/4"	Flat	No	No
12	100 W	PET	1/4"	Flat	Yes	No
13	100 W	Polycarbonate	1/4"	Round	Yes	No
14	100 W	Polycarbonate	1/8"	Flat	Yes	No
15	100 W	PET	1/8"	Flat	Yes	No
16	100 W	Nylon 6,6	1/8"	Flat	Yes	No
17	300 W	Polycarbonate	1/8"	Flat	Yes	No

Videos of Arc-fault Tests

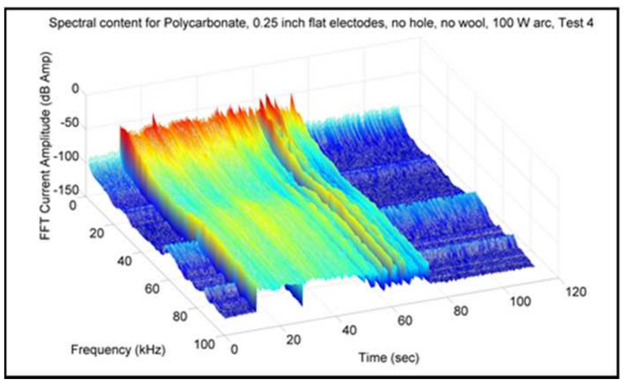


Arc-fault Noise Signatures

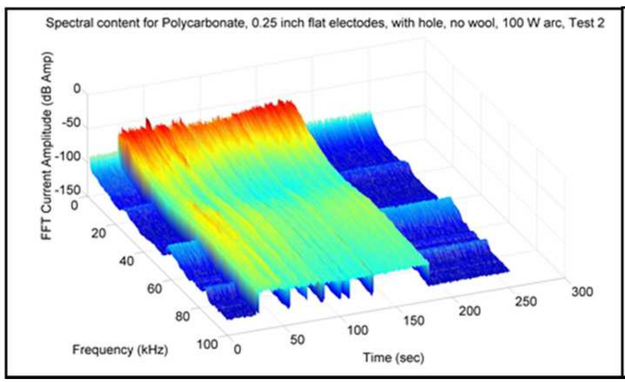
- Discrete Fourier Transforms (DFTs) of the DC current during the arc-fault tests were saved at a rate of ~0.28 DFTs/sec.
- Arc stability and polymer pyrolyzation determine arc-fault noise patterns
  - If liquid polymer, steel wool, or copper dust from electrode enter plasma stream the arc can flicker or self-extinguish
  - Only the first 2 seconds are of importance because the AFCI must trip by that point to pass UL 1699B.

No Hole

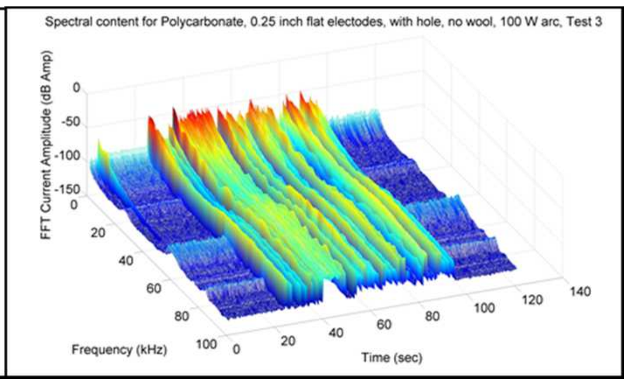
Identical Tests with Hole



Stable Arc-Fault until t = ~60 s

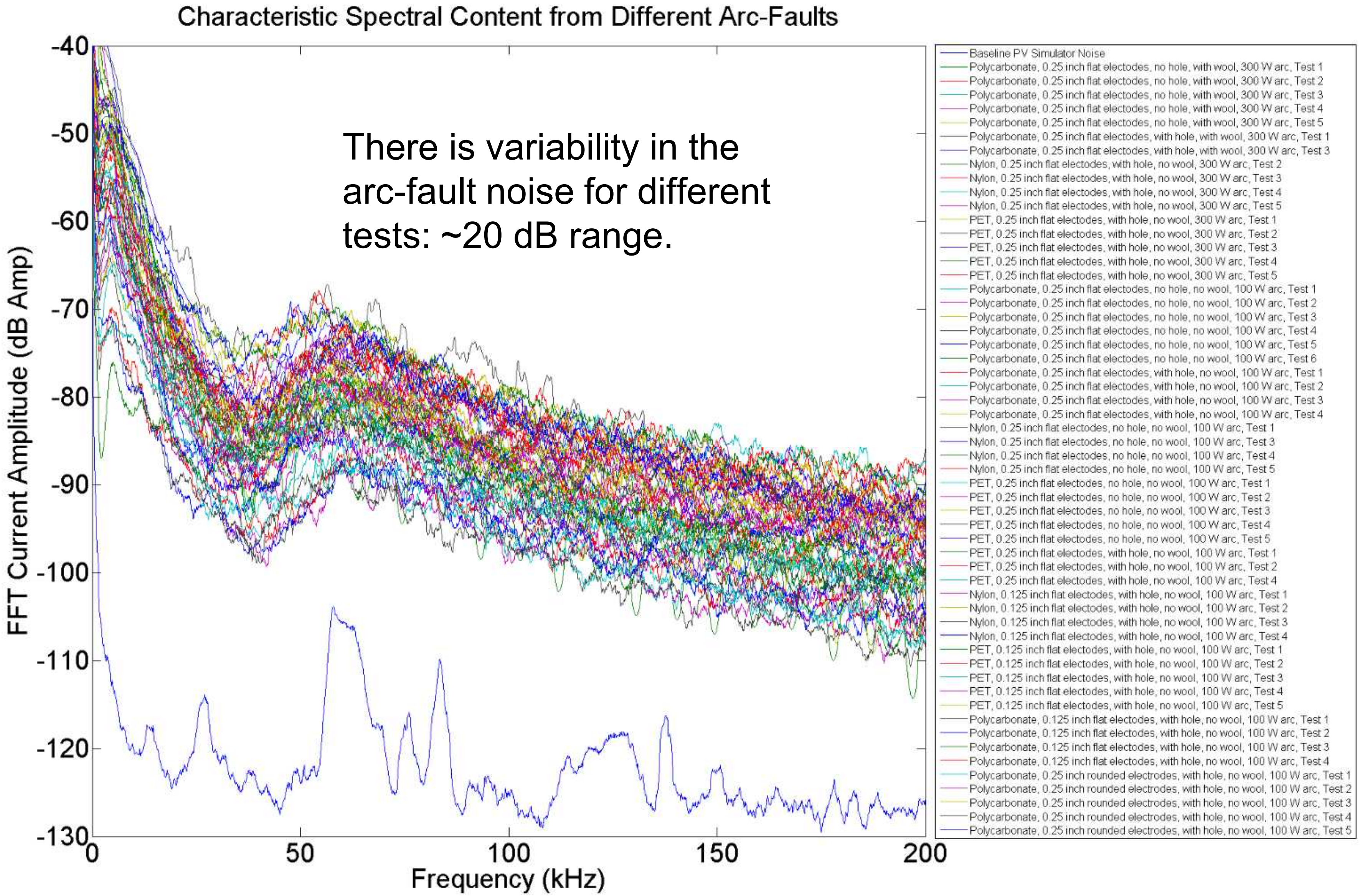


Stable Arc-Fault

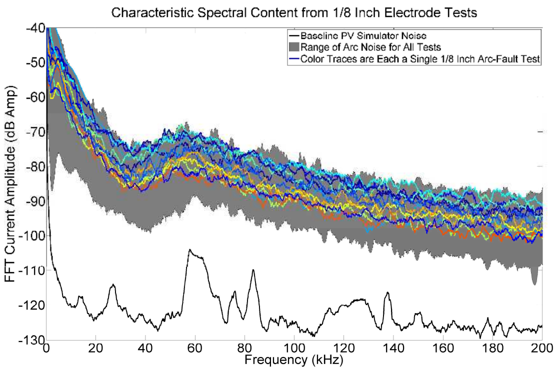


Less Stable Arc-Fault

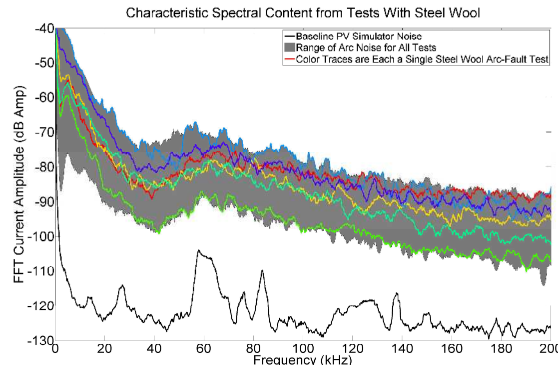
Arc-Fault Noise at *Initiation*



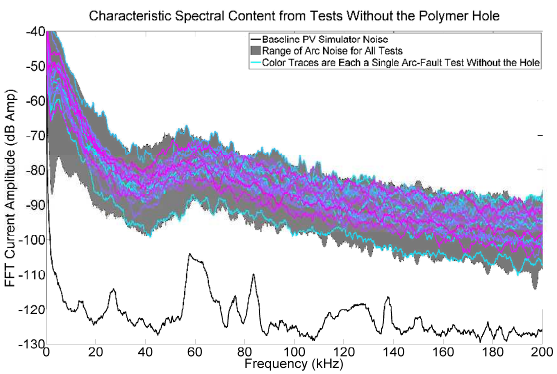
Factors for Noise Generation



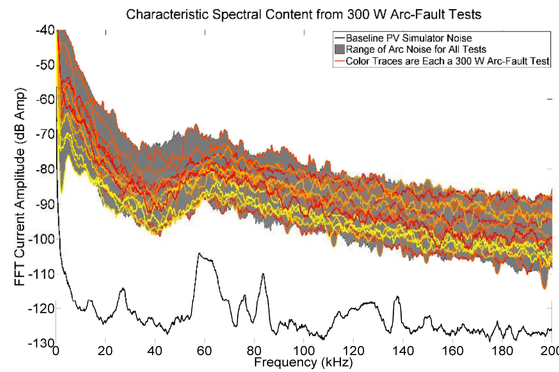
Smaller electrodes produce high noise signatures due to increased off-gassing rates and oxygen depletion.



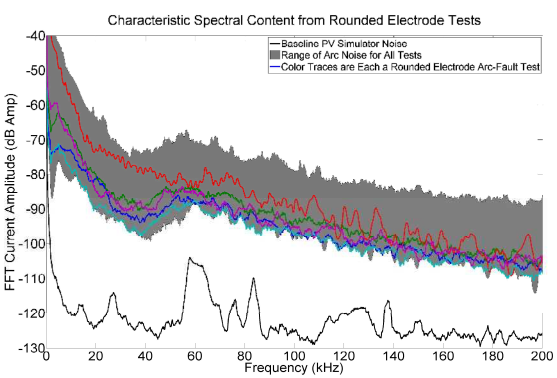
Steel wool tests had a large noise range but the wool tended to produce signatures toward the upper end of the spectral band.



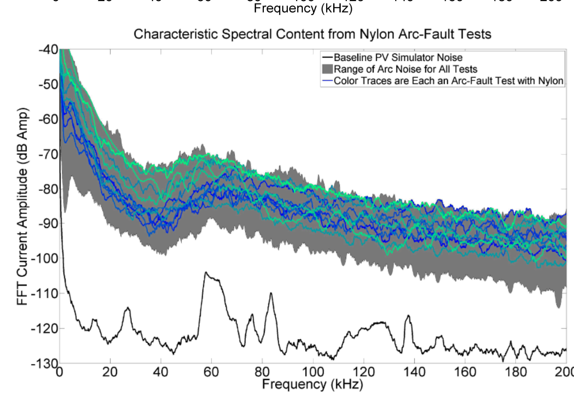
Holes produced slightly cleaner burning arc-faults, possibly because of the increased presence of oxygen.



Higher power arc-faults tend to create more stable, cleaner burning, *slightly* less noisy arcs.



Rounded electrodes tend to produce less arc-fault noise because the arc-fault is 'cleanly' established at the center of the electrodes.



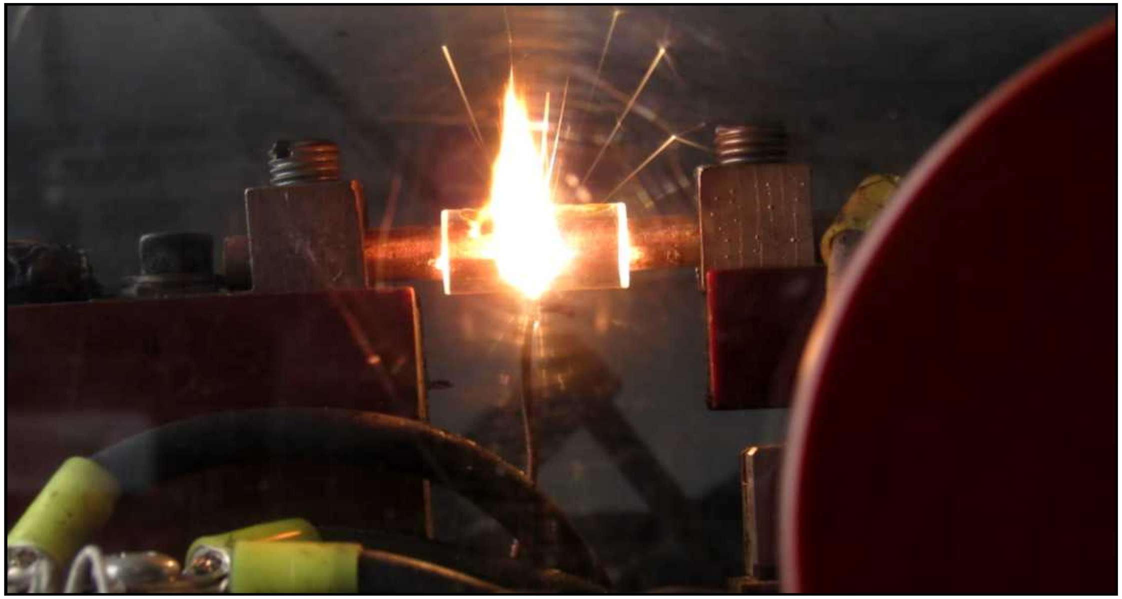
Arc-faults with Nylon 6,6 created more noise than the polycarbonate and PET tests.

Conclusions

- A parametric study of various geometries, materials, and powers was conducted to determine repeatable arc-fault certification tests for UL 1699B.
- Frequency-based arc-fault detection would be the most difficult with the following:
  - Larger (1/4”) diameter electrodes. Plus 1/8” tend to melt and weld at 300 W.
  - “Pull-apart” generation method (no steel wool) . This is also more repeatable than using steel wool.
  - A hole in polymer sheath. More setup time, but arcing is more consistent and repeatable.
  - Rounded electrode tips. Not recommended because the machining time is onerous for test operator.
  - 300 W power. Hard to tell, but it may have slightly less conducted noise.
- A 100 W arc-fault test has been recommended by the UL 1699B Arc Generator Task Group because low power arcs cause fires and AFCIs using time-based methods would have difficulty with this scenario. (Frequency-based methods would not.)
  - To establish low power arcs, the pull apart method is most consistent. To compensate for the variability in operator-selected gap sizes, a ±30% arc power tolerance is recommended.
  - A hole will be allowed for more consistent arcing.
  - Flat electrodes are preferred because creating rounded-tip electrodes with tight tolerances is difficult.
- Stay tuned for 1699B changes after the Sept 2014 STP meeting!

Acknowledgements

- Photovoltaics Solar Evaluation Laboratory
- Distributed Energy Generation Laboratory
- Department of Energy
- Underwriters Laboratory



Questions?