SAND2021-4288PE

High/Low Power R&D Arc & Ground-Fault Detection/Mitigation

Dr. Kenneth M. Armijo

Sandia National Laboratories

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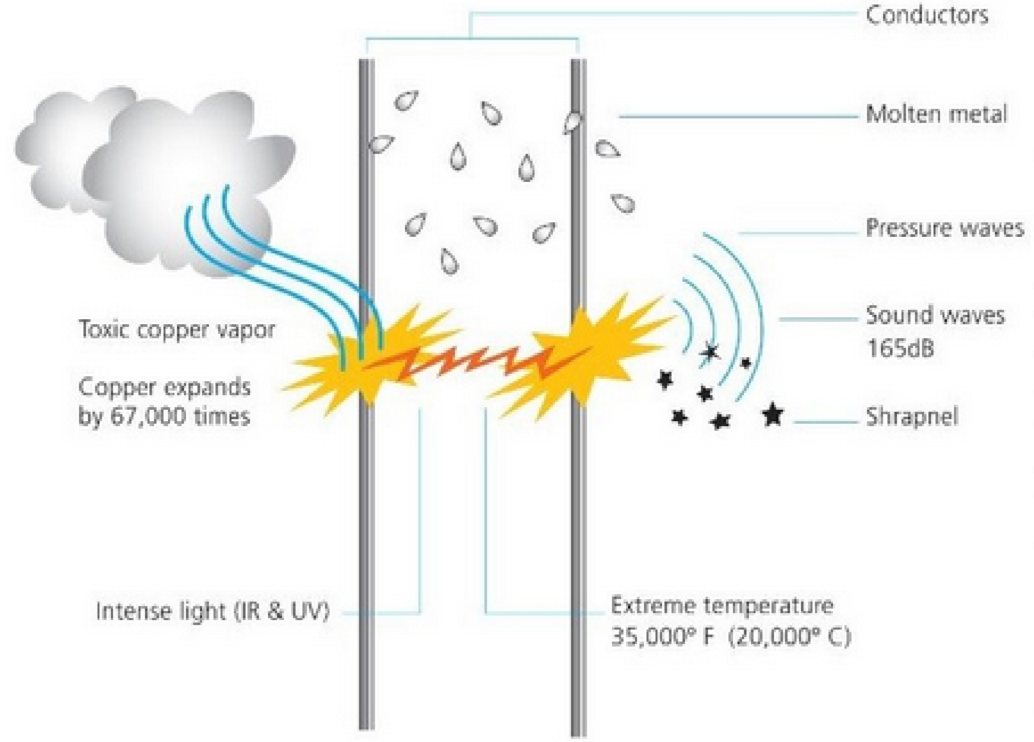
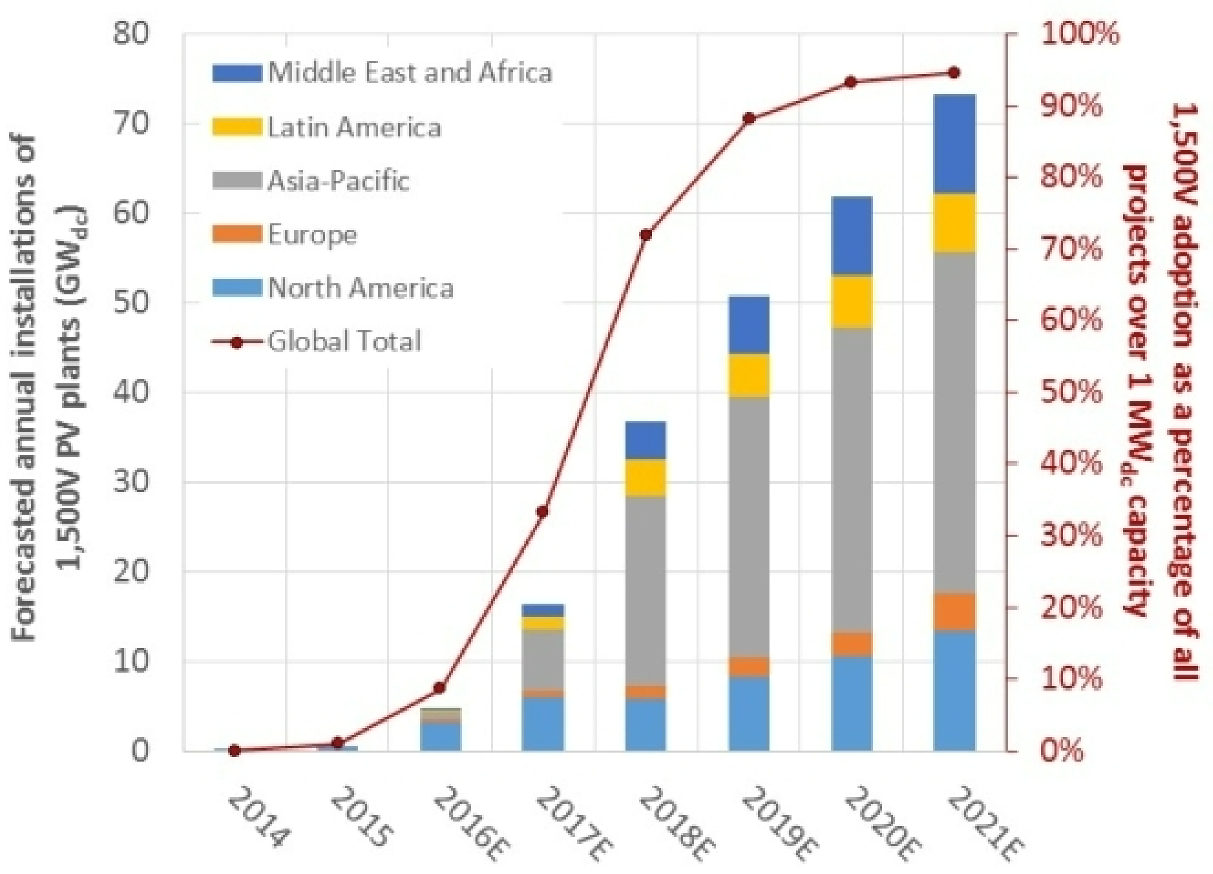
Thermal Arc/Ground Fault Research

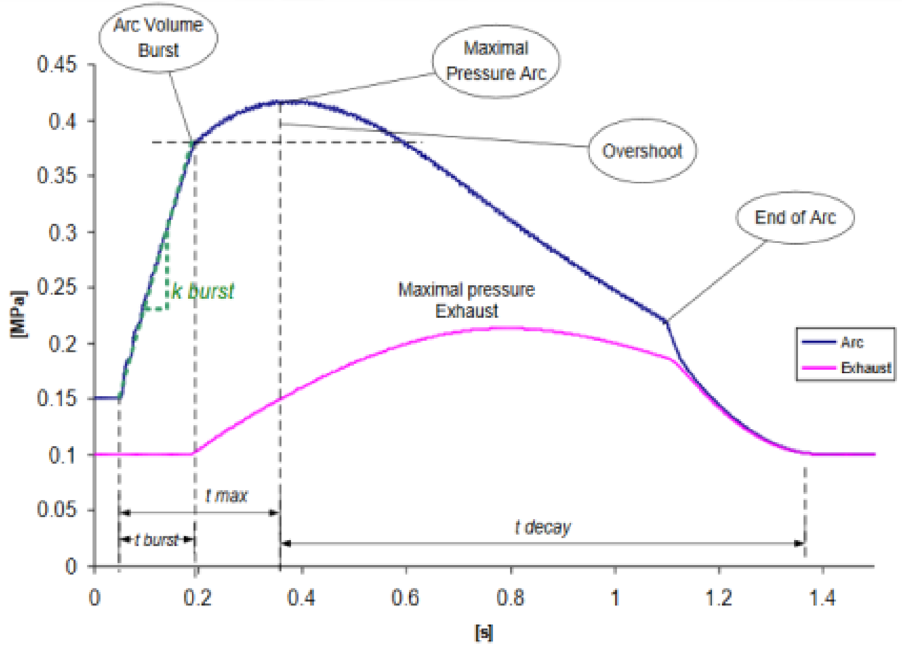
- Arc & Ground faults in PV & DC systems linked to dozens of PV fires around the world.
- Increased solar PV installations & higher system voltage levels ⟶ increased fire potential
- Electrical fires are result of high-temperature plasmas produced as current passes across separated, damaged conductors.



Increasing PV Voltage & Propensity for Fires



Forecasted capacity installation and percent adoption of 1,500V_{DC} utility-scale PV plants. Data: GTM Research



Commercial Bldg. Arc-Fault Fire

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2020, Armijo, K.M., et al., "Localized Arc-Plasma Model for High-Voltage Photovoltaic Power Systems," *47th Photovoltaics Specialist Conference (PVSC)*, Calgary, Canada.

DC (PV) and AC (Nuclear Energy) High-Energy Arc-Fault (HEAF) events

Photovoltaics (600-1,500VDC)

Bakersfield CA, April 5 2009

"… the ground-fault protection device was unable to interrupt the current, **allowing arc faults to be formed**, spreading sparks to surrounding materials, **causing ignition.**"

-- Commercial Roof-Mounted Photovoltaic System Installation Best Practice Review and All Hazard Assessment, The Fire Protection Research Foundation, Feb. 2014

Nuclear Energy (480V, 410V, 6900V and 10kV)-AC

San Onofre Nuclear Generating Station, Feb. 3 2001

"There was a **failure of the main contacts** of a 25 year old 4.16 kV breaker to close fully, **causing a HEAF event**… the **fire persisted for three hours** until water was applied."

-- Brown et al., SAND2008-4820, High energy arcing fault fires in switchgear equipment, a literature review

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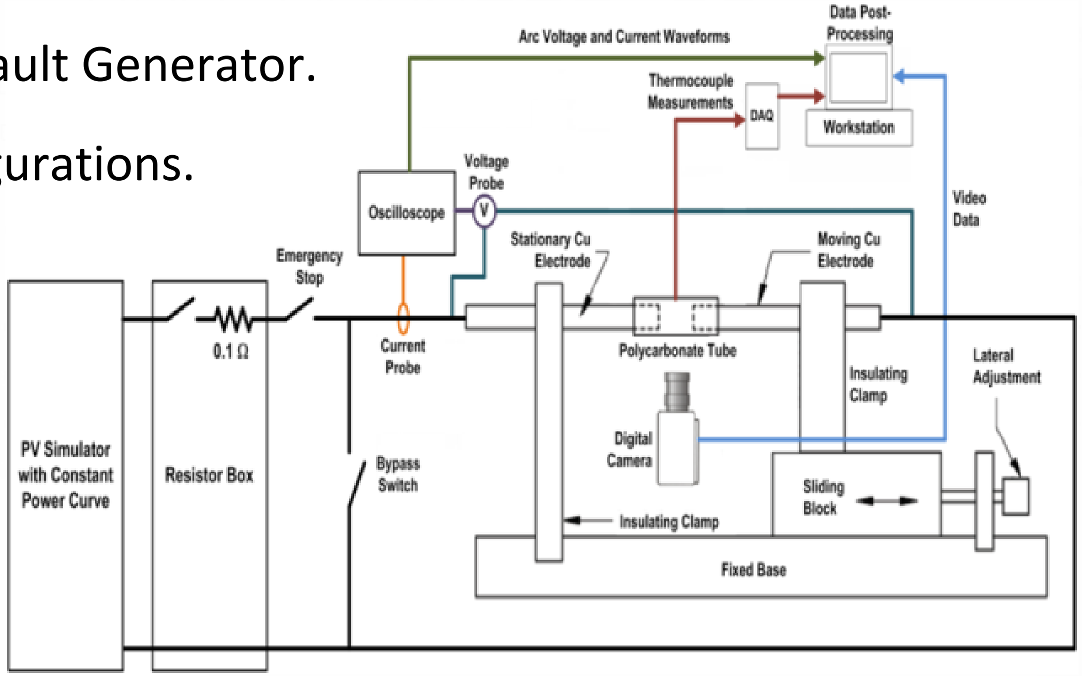
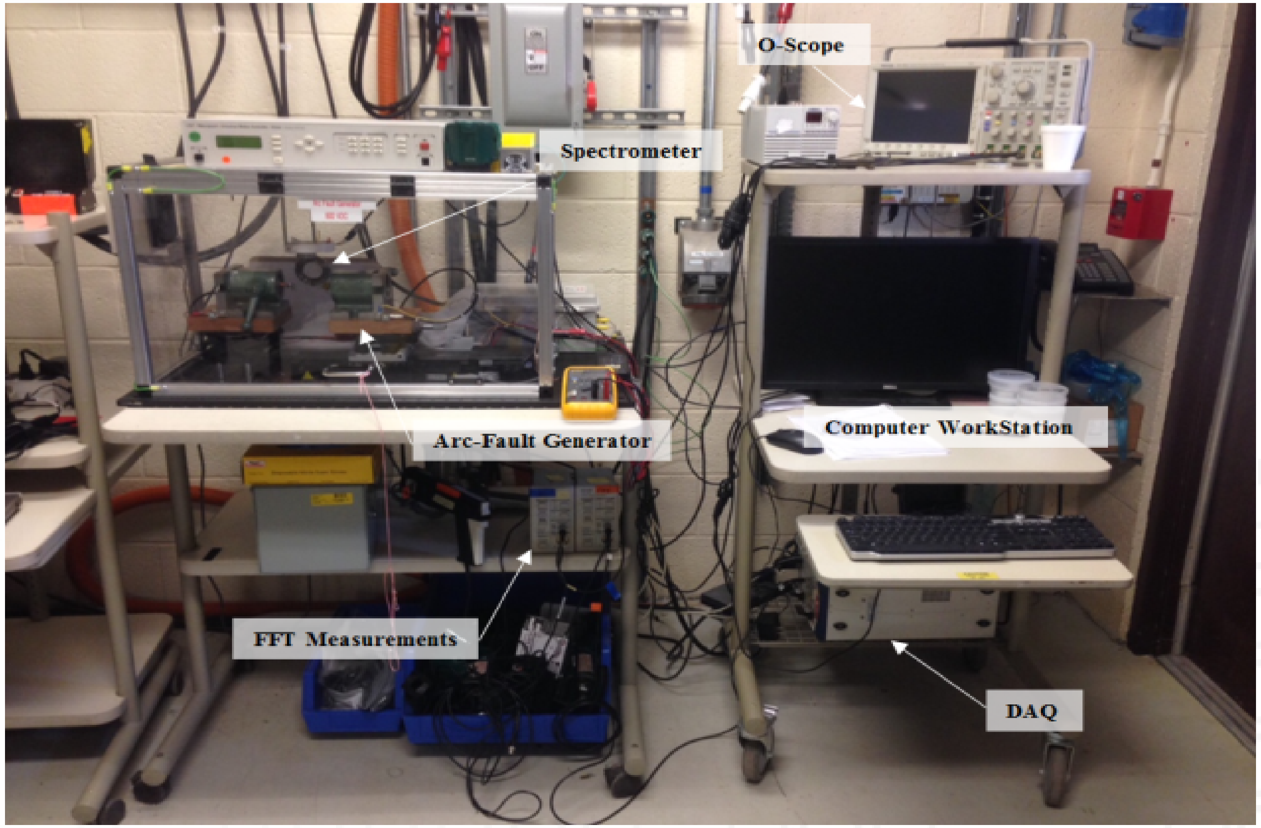
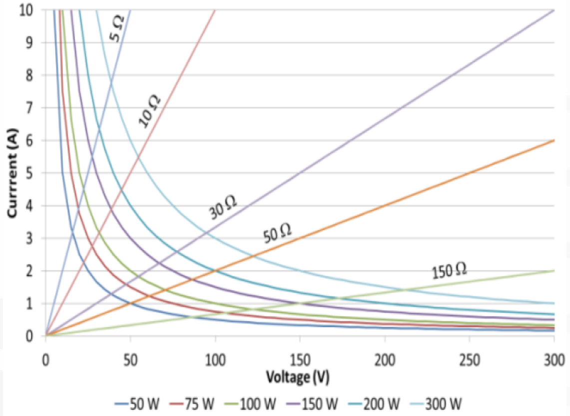
Experimental Low-Voltage (≤600V) Capabilities
Distributed Energy Technologies Lab (DETL)

- Customized PV Simulator provided power to a developed Arc-Fault Generator.
- PV DC & AC Simulators to evaluate varying power system configurations.

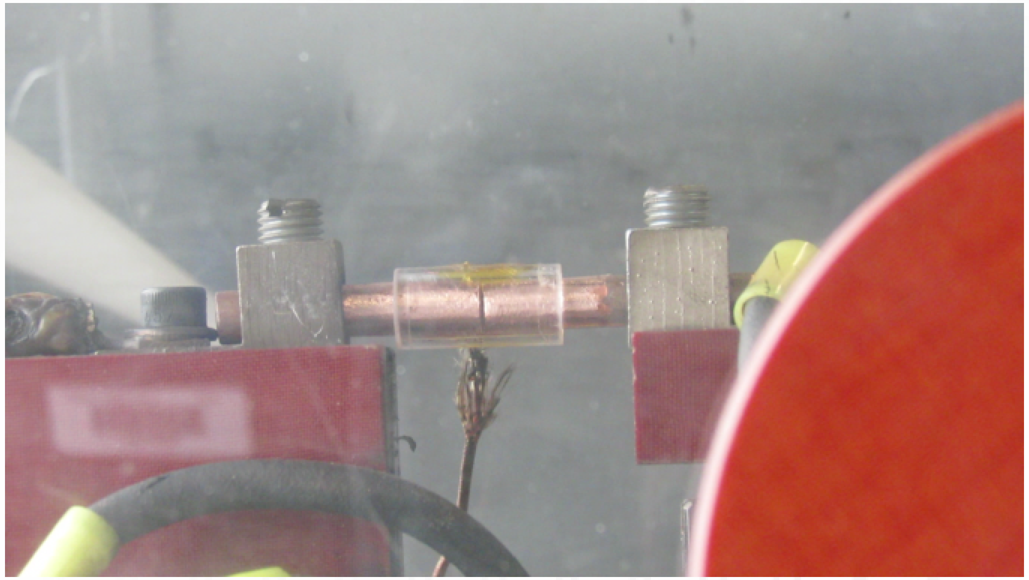


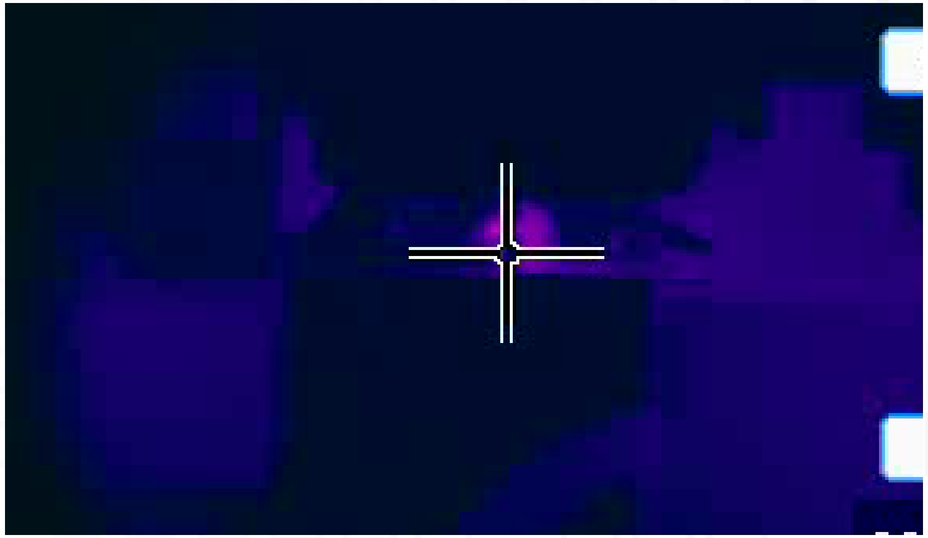




Schindelholz, E.J., Armijo, K.M., Johnson, J., Harrison, R.K. and Yang, B.B.Y., National Technology and Engineering Solutions of Sandia LLC, 2019. *Arc plasma-generating systems and methods thereof*. U.S. Patent 10,261,120.

Arc-Fault Characterization/Detection





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

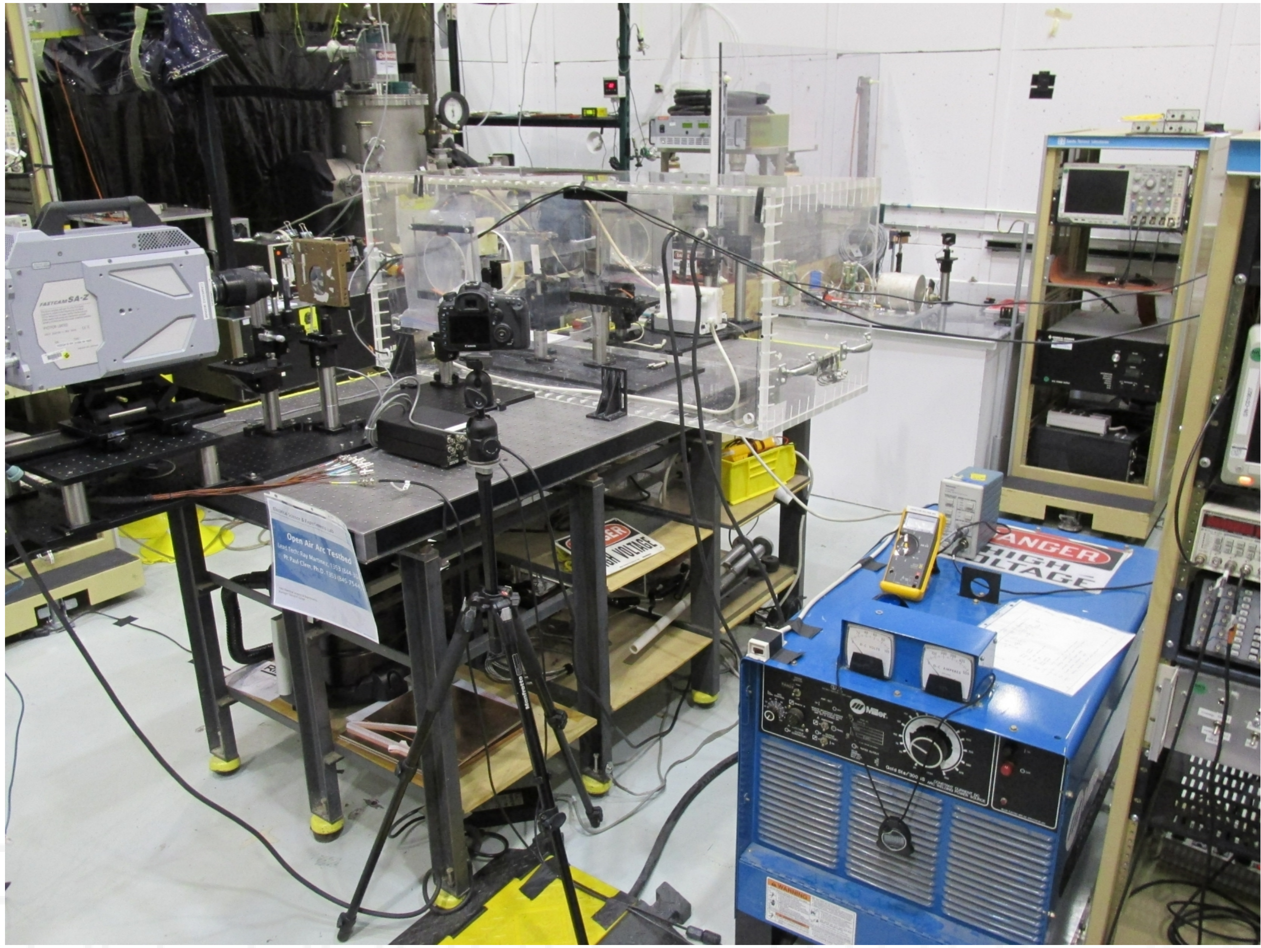
2014, Armijo, K.M., Hibbs, M., Johnson, J. and Fresquez, A, "Characterizing fire danger from low power PV arc-faults", *40th PVSC Conference*, Denver, CO.

Experimental Development for High-Voltage Validation SNL Lightening Simulator Facility

- Experimental testbeds developed for two capabilities:

  1. Capacitive discharge system produces a stored energy 1-50 kJ, to support arcs at 1 - 160 kA,
  2. RC dump using a ~810 µF capacitor & ~900 J.
  3. Long-duration, arc-triggering constant current source, follow-on supply

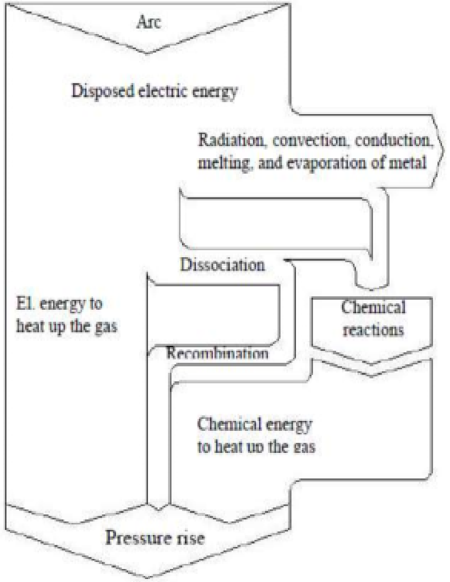
- Reproducible 30 s arc tests have been performed with the constant current system

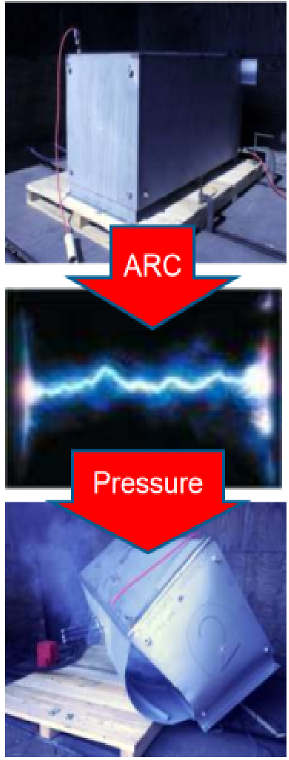


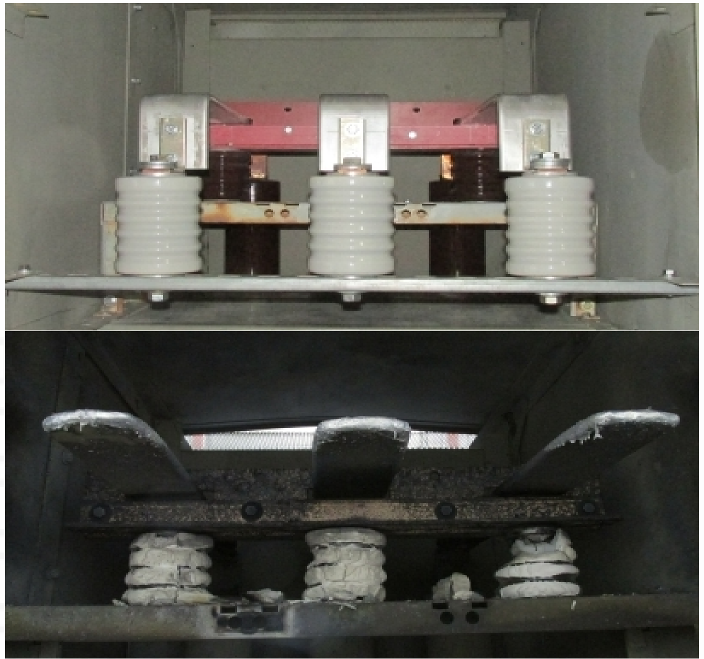
2014, Armijo, K.M et al., "Characterizing fire danger from low power PV arc-faults", *40th PVSC Conference*, Denver, CO.

AC High-Voltage R&D

- 480V, 4160V, 6900V and 10,000V AC tests
- Arcing despite Zero-pt. crossing extinguishment not occurring
- 3-Phase AC tests performed btw SNL, NRC & NIST

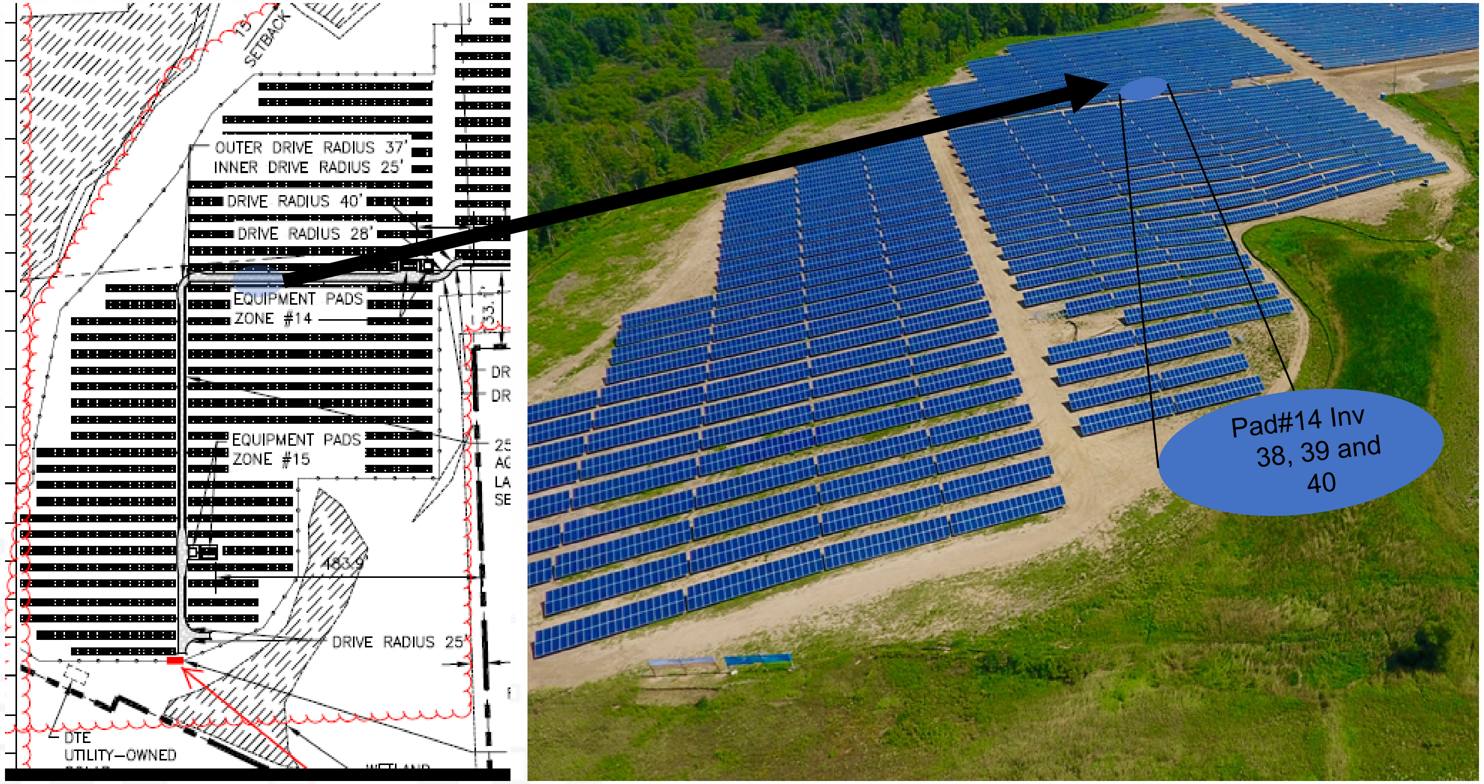






2018, Muna, A., C. LaFluer, KM Armijo, Clem, P., Tanbakuchi, A., "Aluminum High-Energy Arc-Fault (HEAF) Particle Size Characterization", NUREG/CR, U.S. Nuclear Regulatory Commission.

SNL Capabilities – Form the Lab to Field Experimental Faults R&D



Completed: 16 Arc-in-a-box tests 27 Equipment Failure tests

DTE Solar Park, Lapeer, MI

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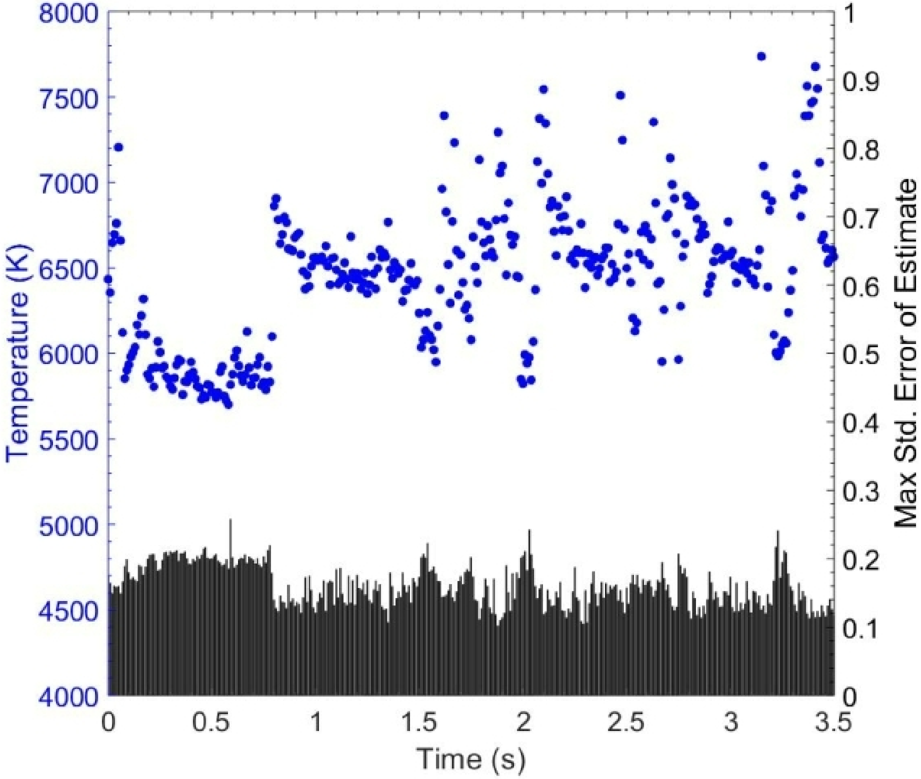
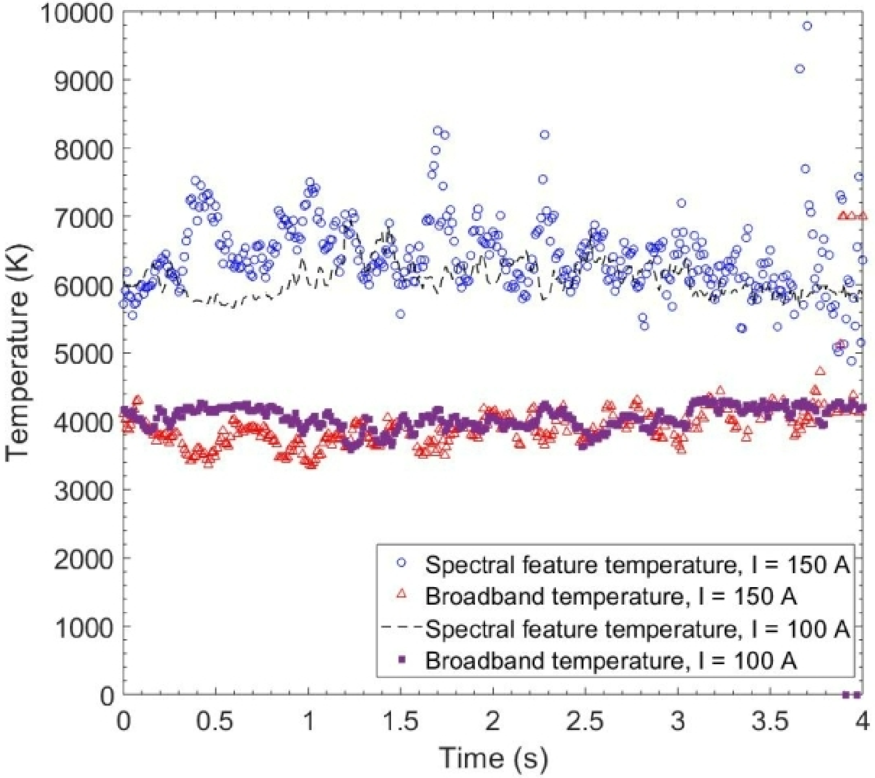
Paudyal, B., Bolen, M., Short, T. and Woodard, J., 2019, June. Measured dc Arc-flash Risk in a Photovoltaic System. In *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)* (pp. 3140-3143). IEEE.

Spectral & Inferred Temperatures from Metal Vapor

Spectral feature temperatures & associated errors

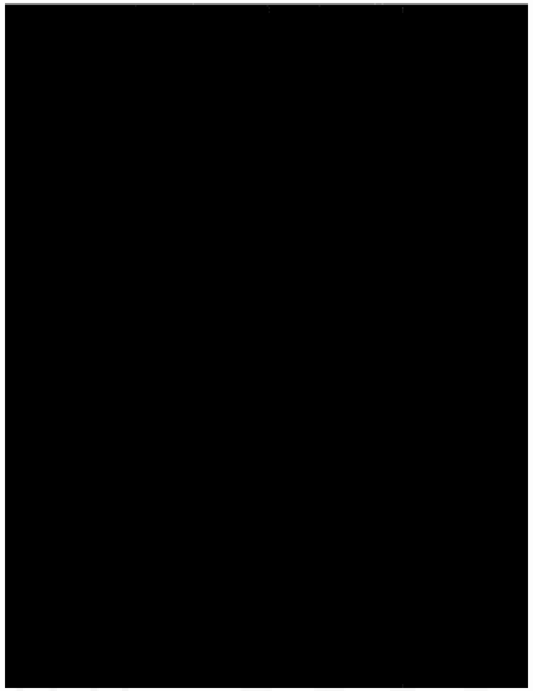


Comparing methods



Al arc emission

Time is -0.066734 s



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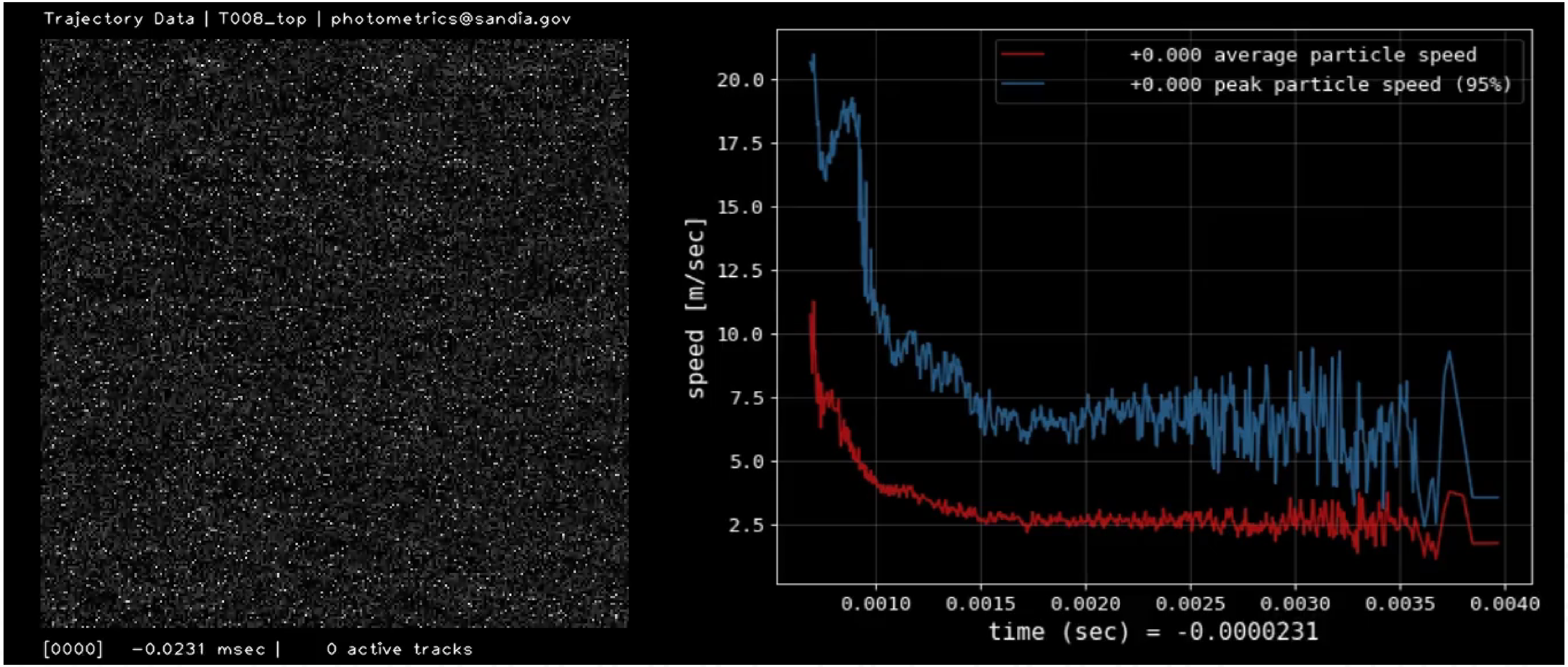
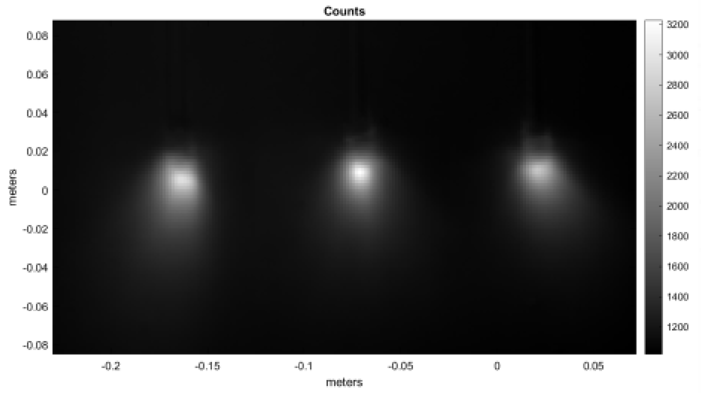
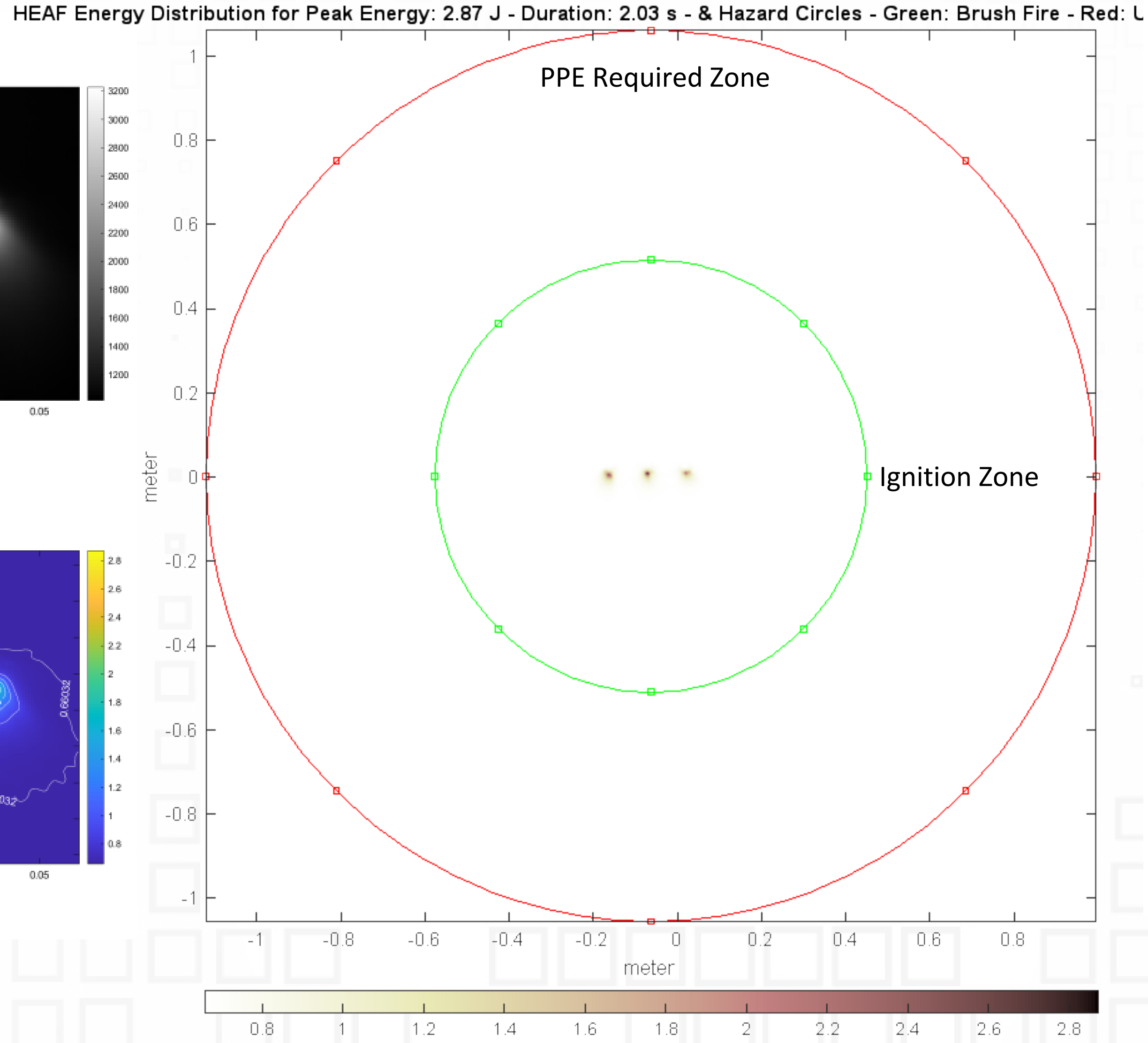
2020, Winters, C., Cruz-Cabrera, A., Armijo, K.M., "Characterization of DC Arc-Plasmas Generated by High-Voltage Photovoltaic Power Systems," *47th Photovoltaics Specialist Conference (PVSC)*, Calgary, Canada.

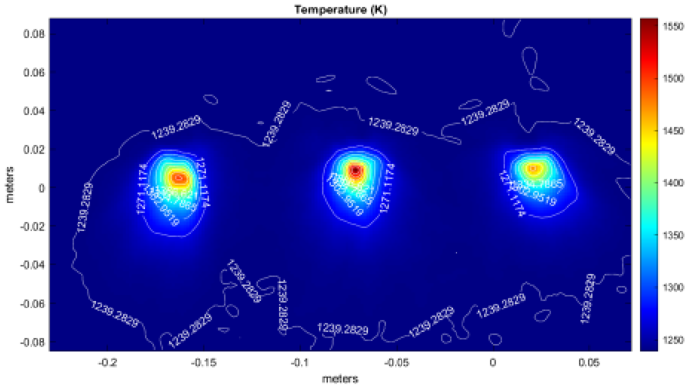
Arc-Blast Particle Collection & Analysis

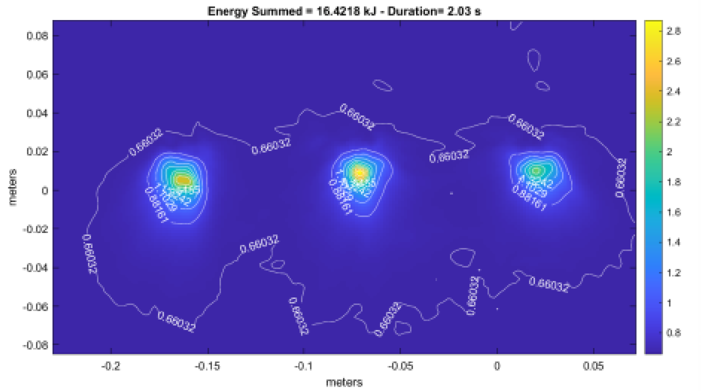


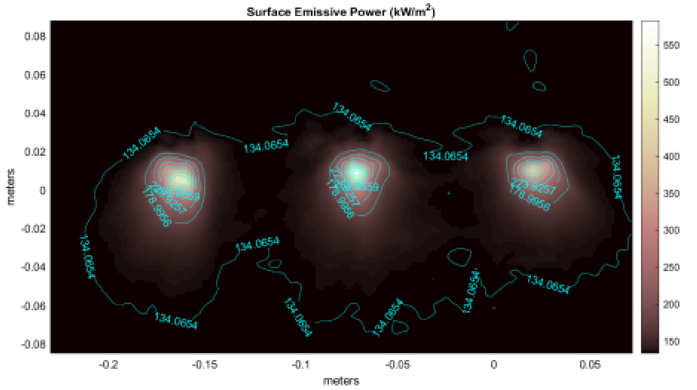
IR Zone of Influence (ZOI) Calcs for Codes & Standards











2020, Winters, C., Cruz-Cabrera, A., Armijo, K.M., "Characterization of DC Arc-Plasmas Generated by High-Voltage Photovoltaic Power Systems," *47th Photovoltaics Specialist Conference (PVSC)*, Calgary, Canada.

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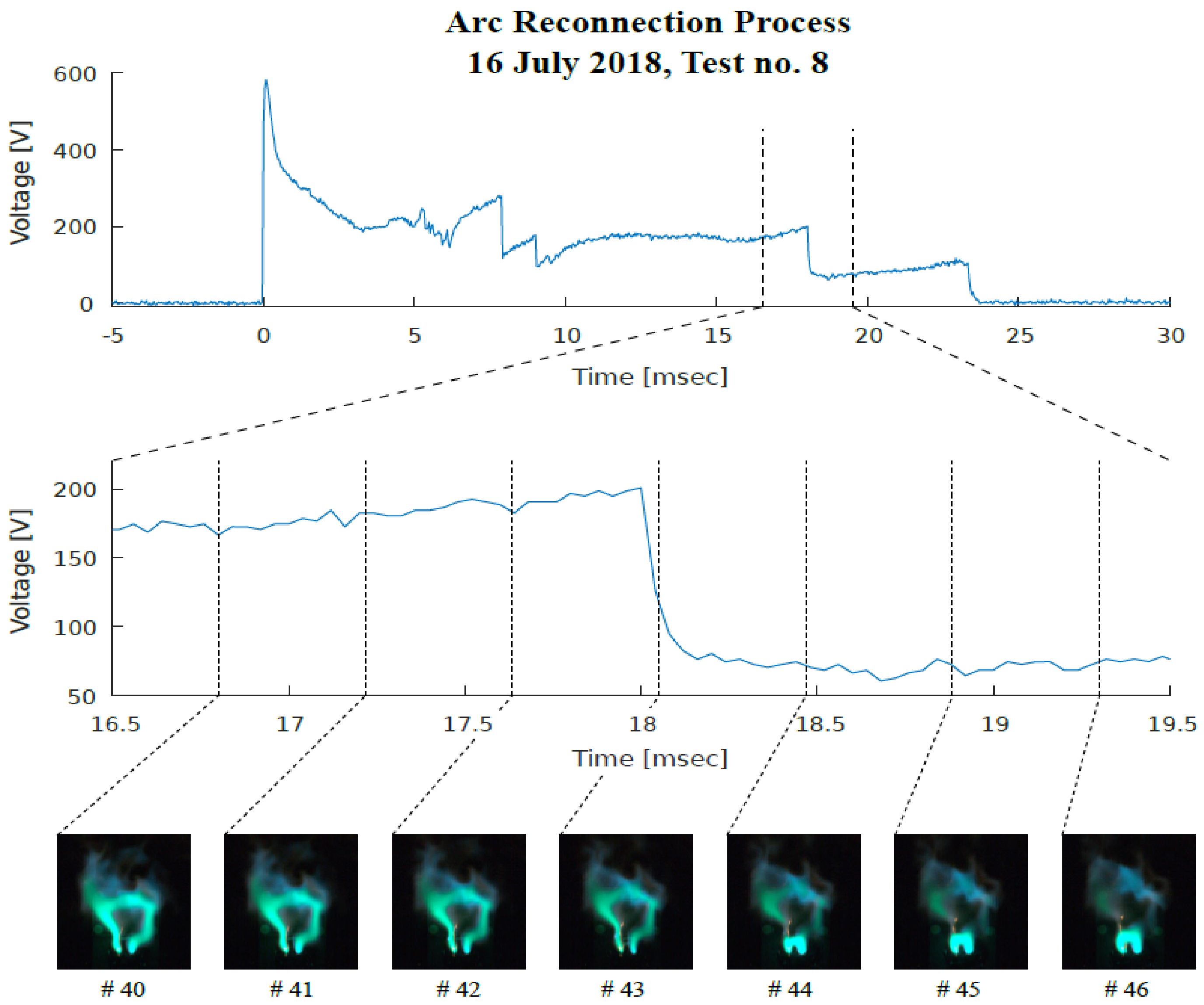
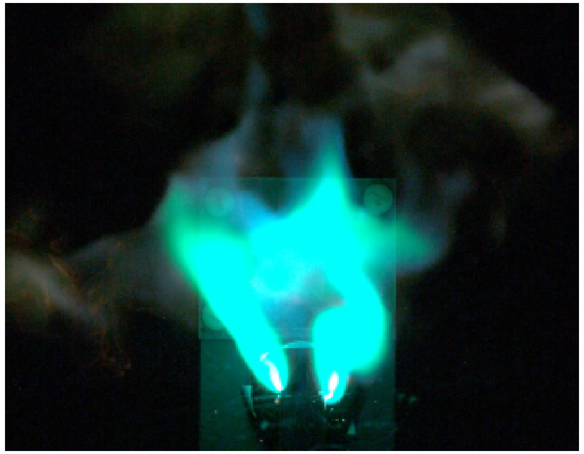
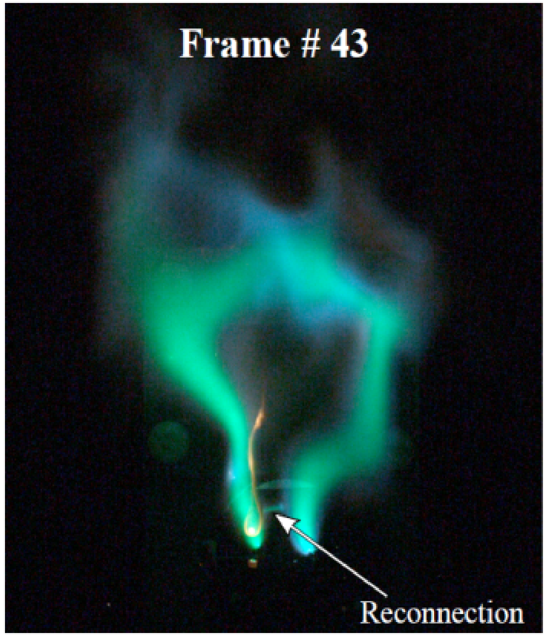
Dynamic arc restrike measurements







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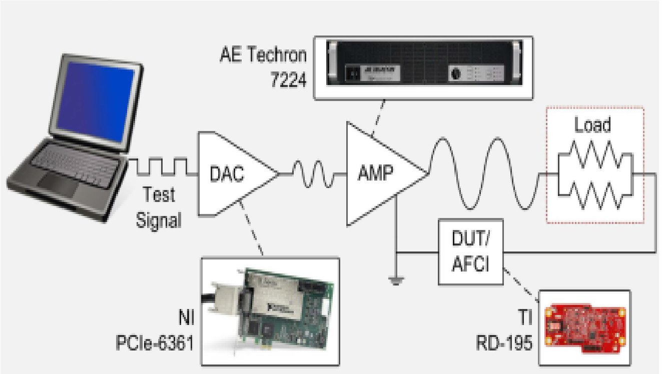
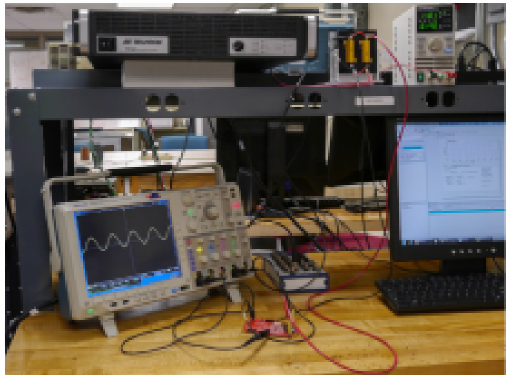
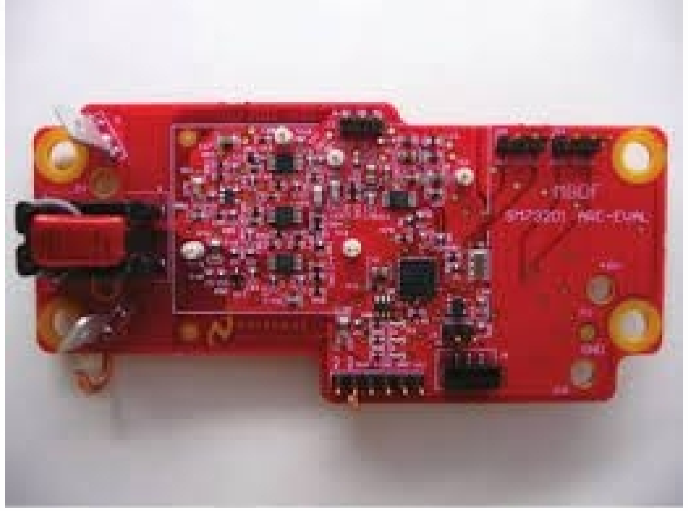
Arc-Fault Circuit Interrupter (AFCI) Development

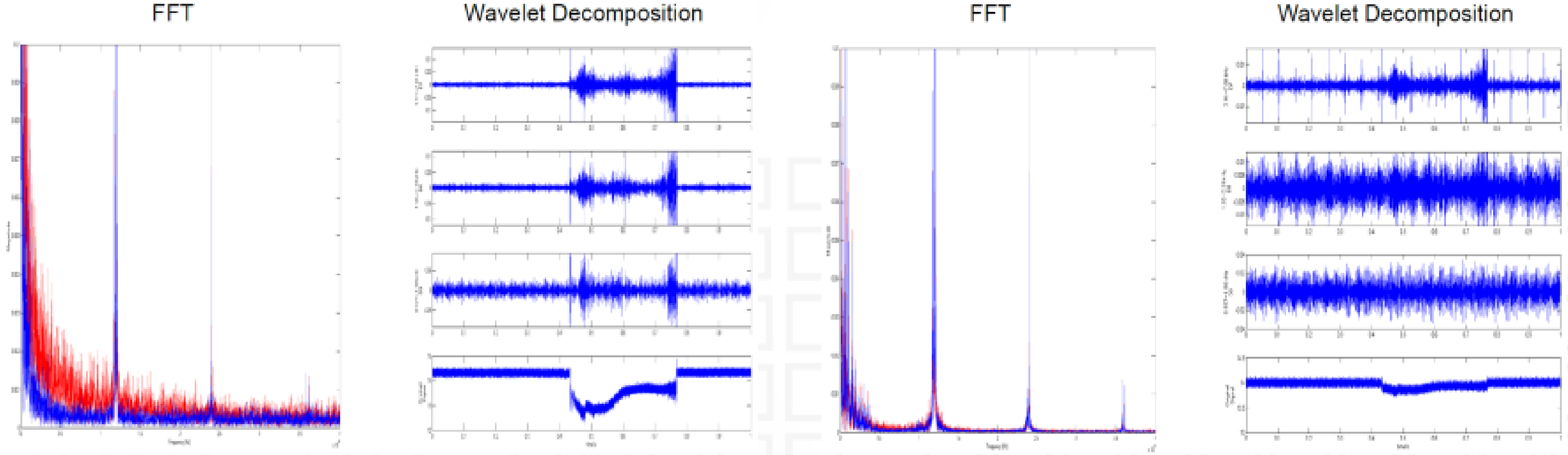
Wavelet Model work has the potential for providing capabilities for accurate arc-fault detection, which would reduce nuisance tripping issues

Novel Wavelet Model method for arc fault detection algorithm.









McConnell, S., Wang, Z., Balog, R.S. and Johnson, J., 2014, June. Evaluation method for arc fault detection algorithms. In *2014 IEEE 40th Photovoltaic Specialist Conference (PVSC)* (pp. 3201-3206). IEEE.

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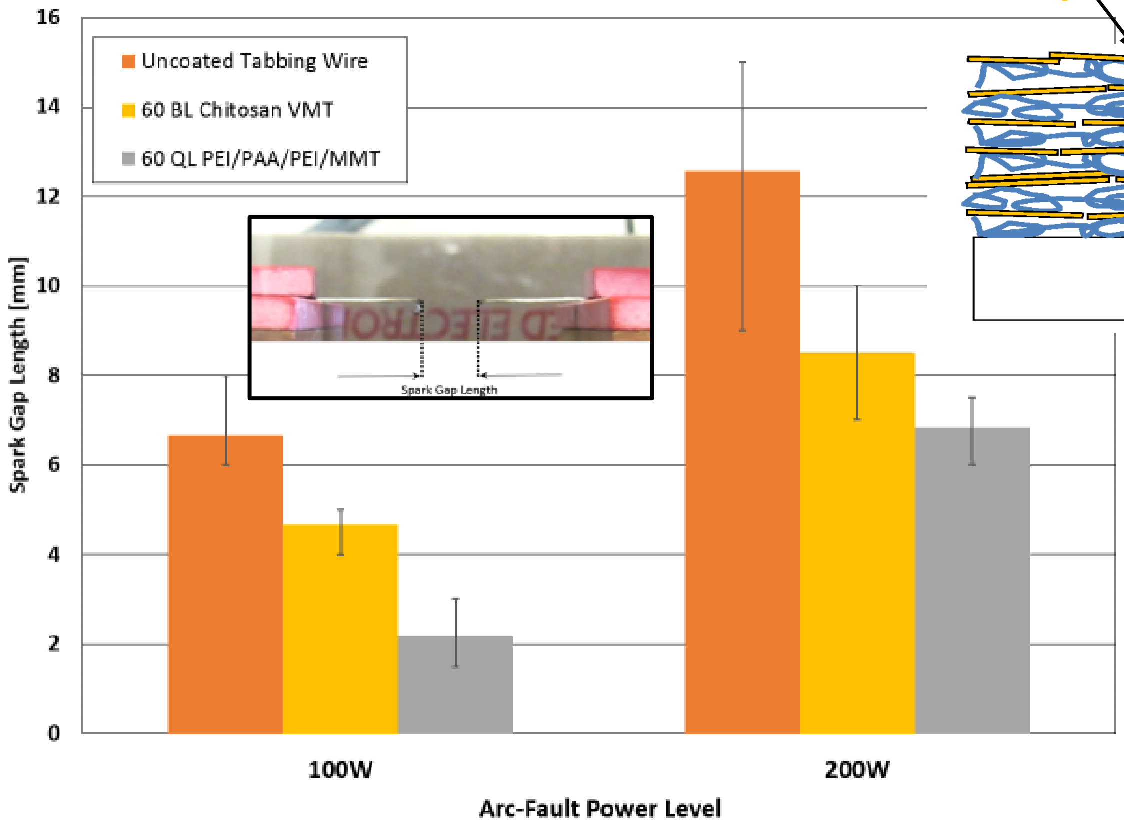
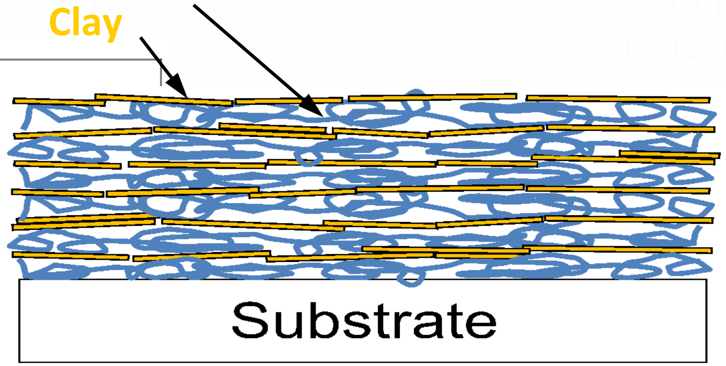
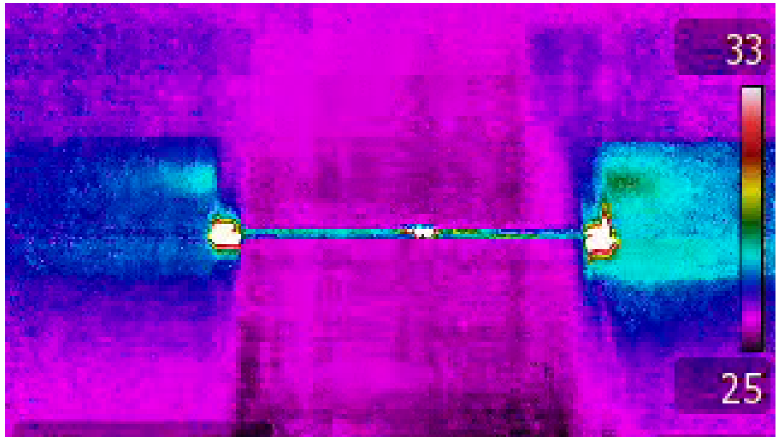
Self-Extinguishing Materials Research

- Layer by Layer Nano-Composites Self-Extinguishing Materials (Sandia LDRD)

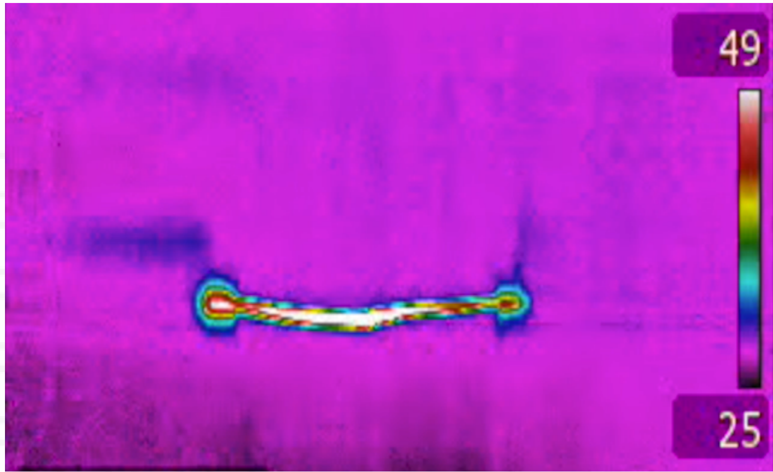




Uncoated Tabbing Wire



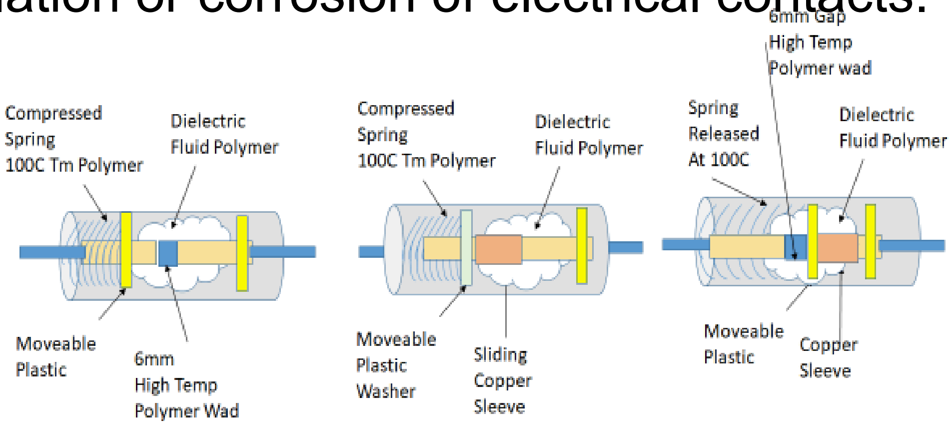
6QL PEI/PAA/PEI/MMT

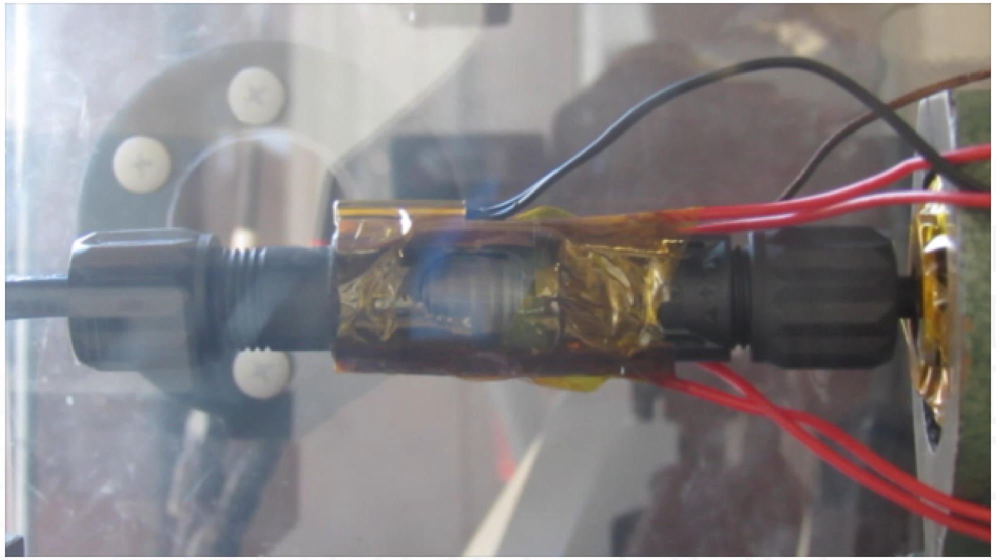


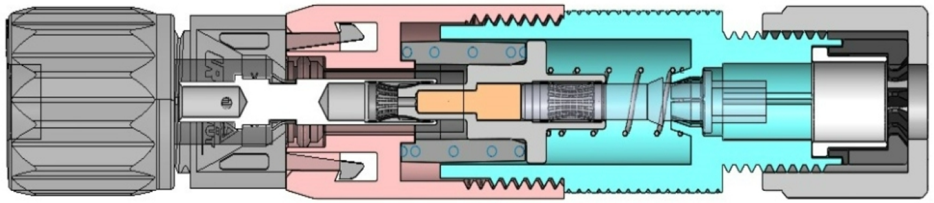
2017 Non-Provisional US Patent, 10,002,983 B1, "Nanocomposite Barrier Films for Photovoltaic Applications", E.D. Spoerke, M.E. Gordon, E. Schindelholz, K.M. Armijo, N.R. Sorensen, A. Martino and J. Grunlan.

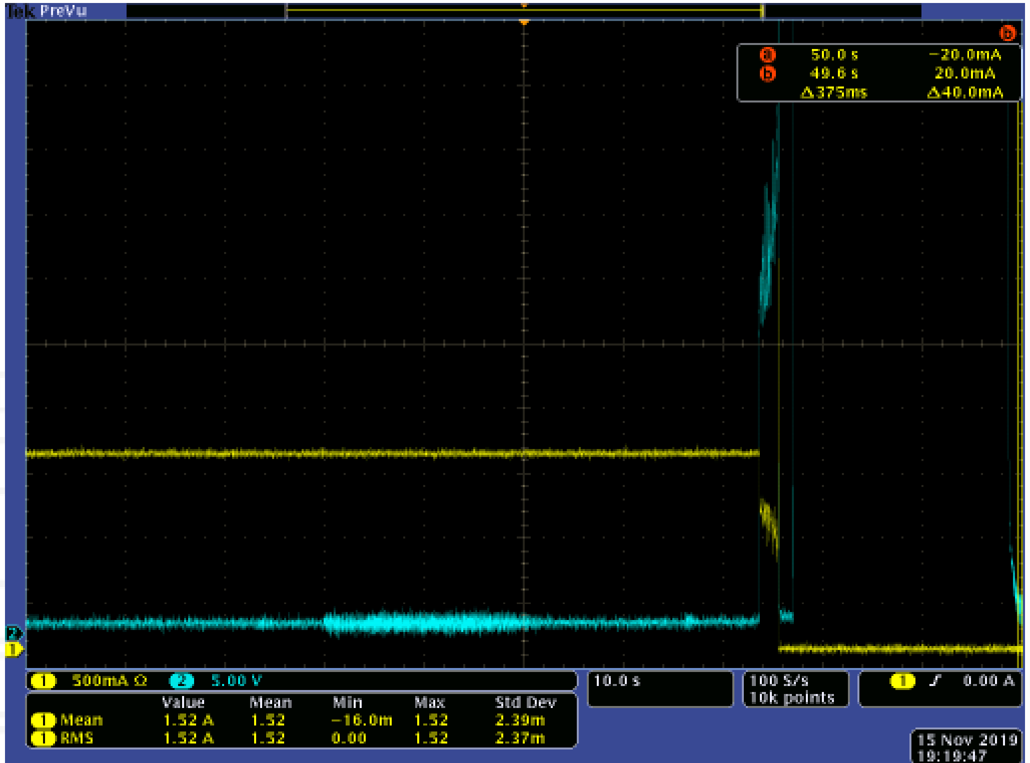
Self-Extinguishing PV Connectors

- Self-extinguishing connectors designed to detect / respond to Ohmic heating created from improper installation or corrosion of electrical contacts.





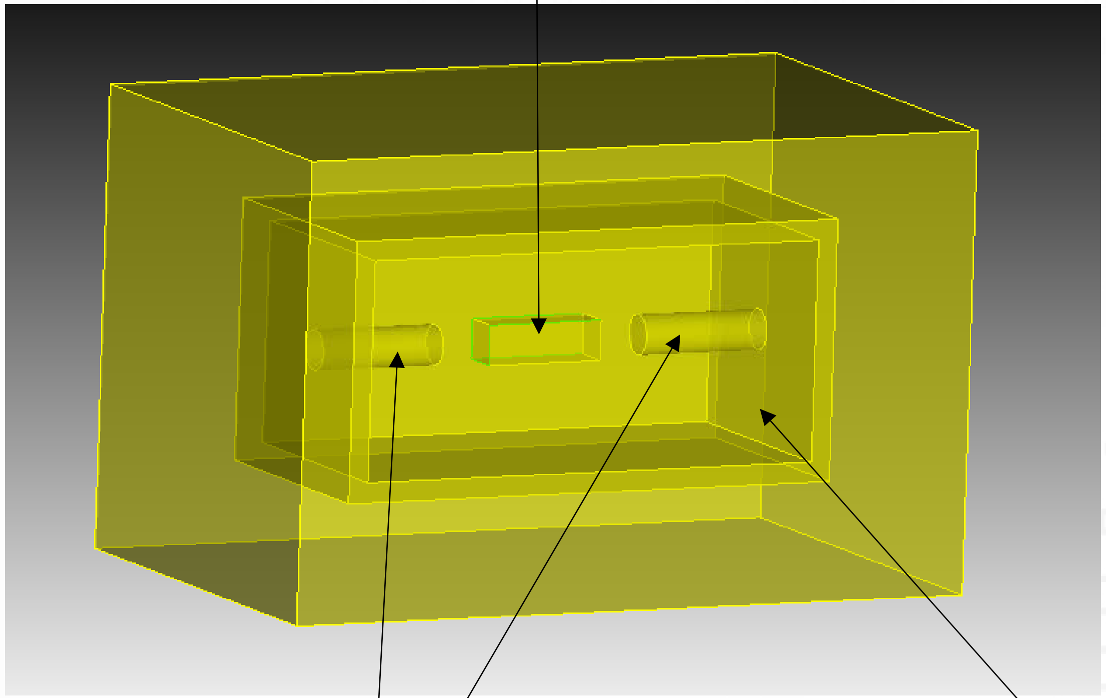




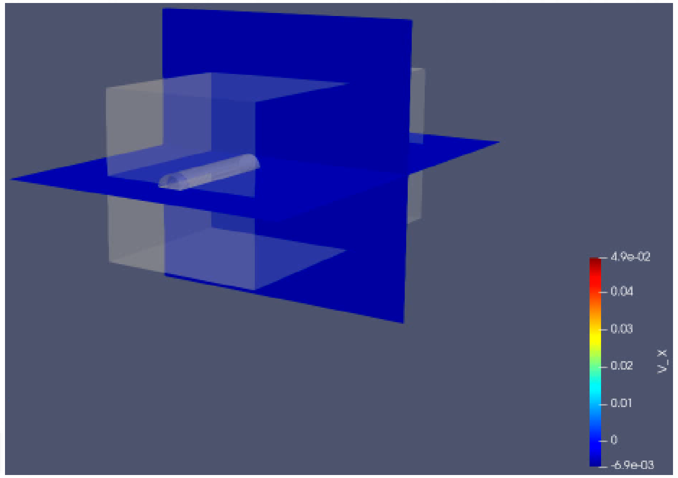
2020, Armijo, K.M. et al., "American Made Solar Challenge Guardian Sensors, Self Extinguishing Connectors", Final Report, NMSBA, SAND-0156.

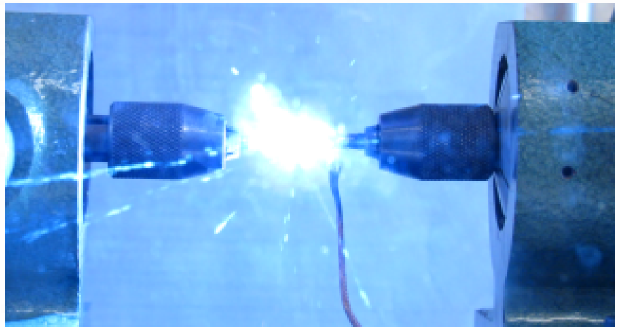
Sandia Arc-Fault Advanced Modelling for Codes & Standards

Energy source region, P = 4 x 10^8 W/m^3 (approximately 100 V, 10 A Arc)

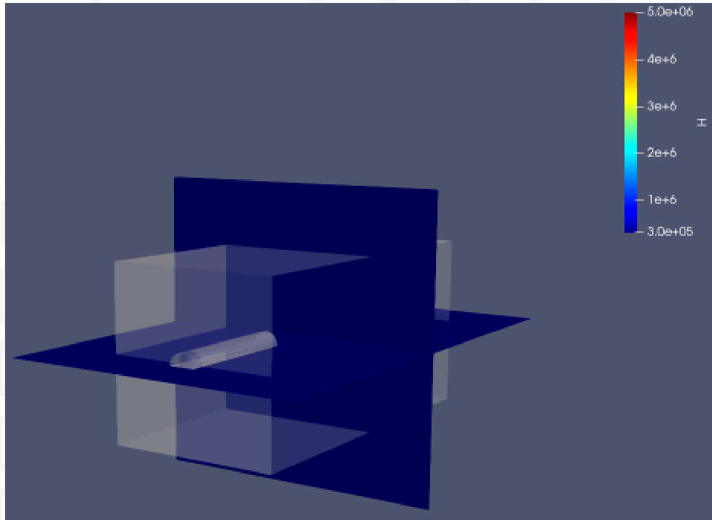


Velocity





Enthalpy



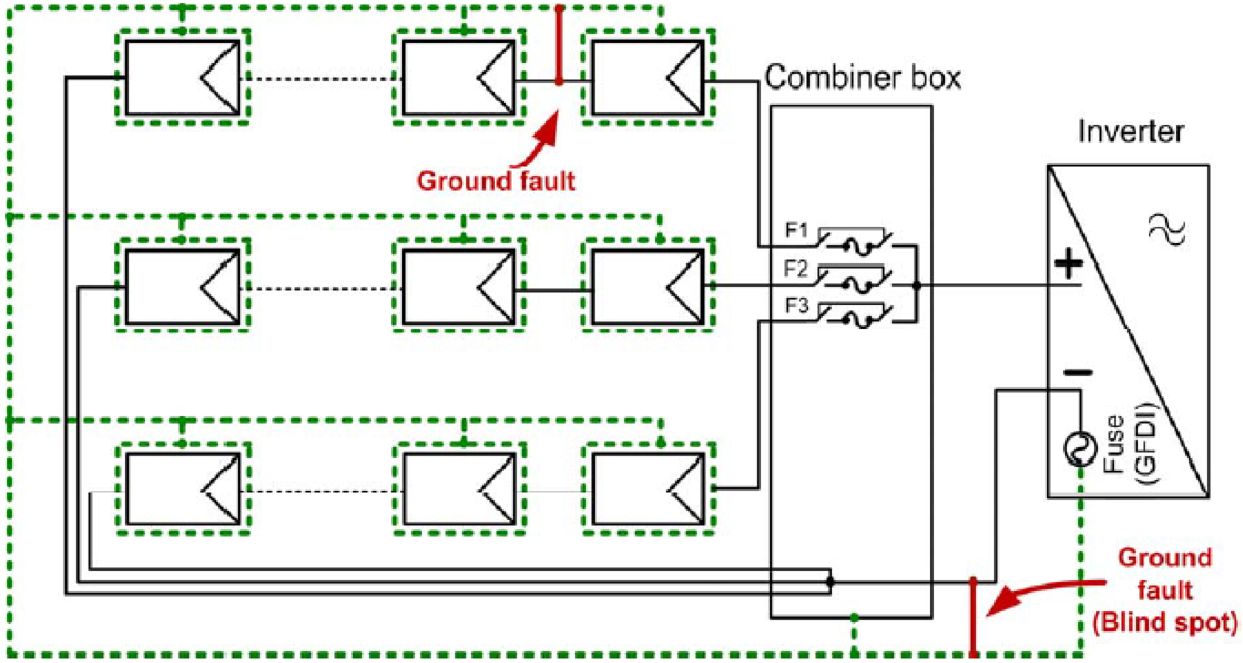
Electrodes, r = 0.5 cm, l = 4 cm

Open boundary – "open-box" like test

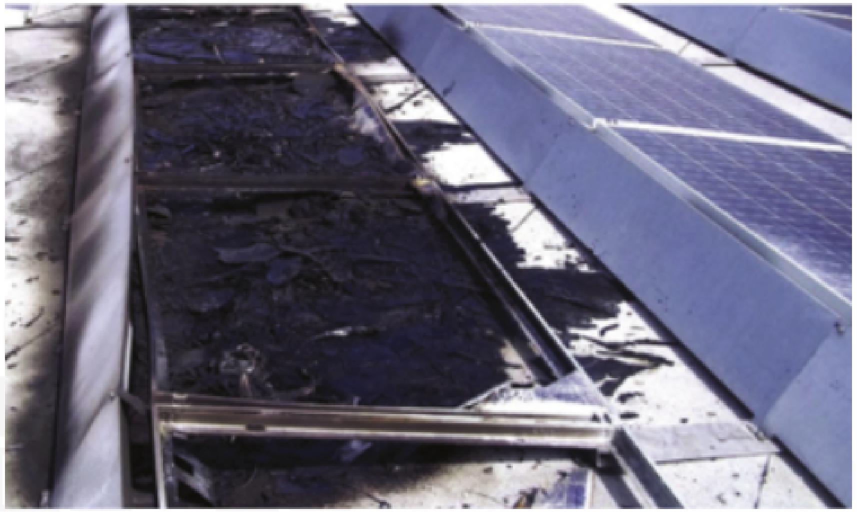
Ground Fault Research & Development

- Exposed unintentional non-current carrying metals/conducting parts of PV systems connected through conducting wire to reference ground.

- Fuse-based GFDI (Ground Fault Detector/Interrupter) designs vulnerable to faults to the grounded current-carrying conductor.



Blind spot in a listed inverter's fuse-based ground-fault protection scheme which resulted in a fire.



J. Flicker, J. Johnson, Solar Energy, 140 (2016) 34-50

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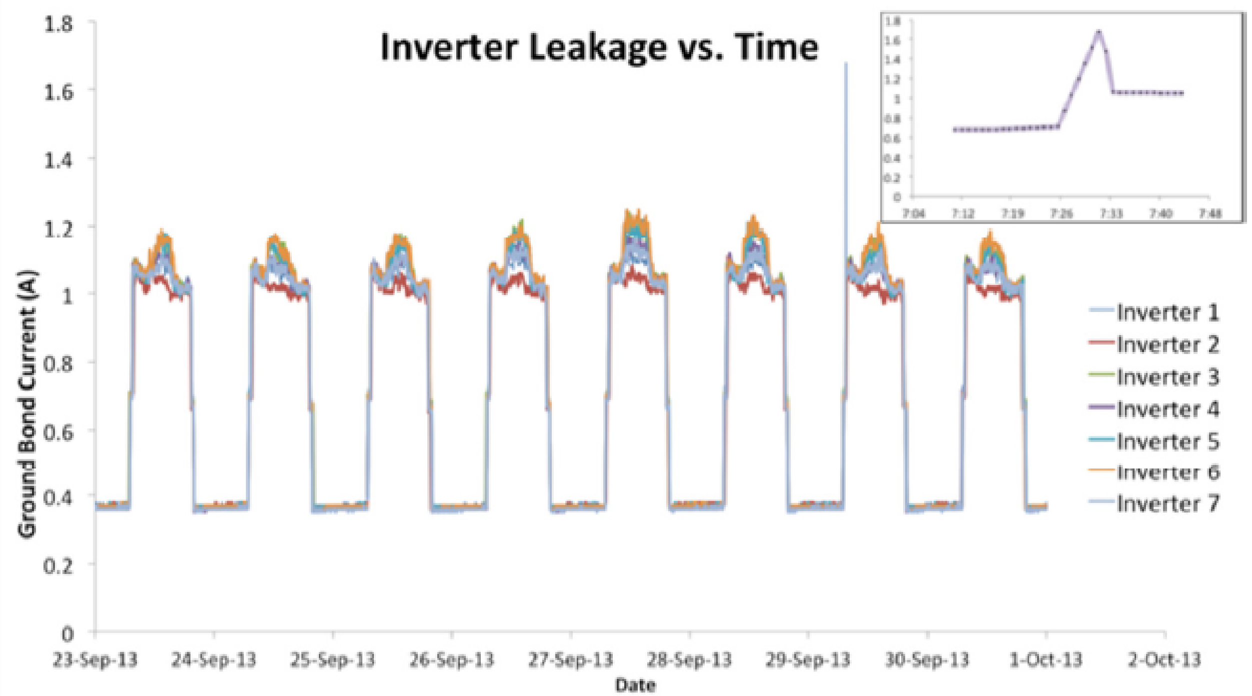
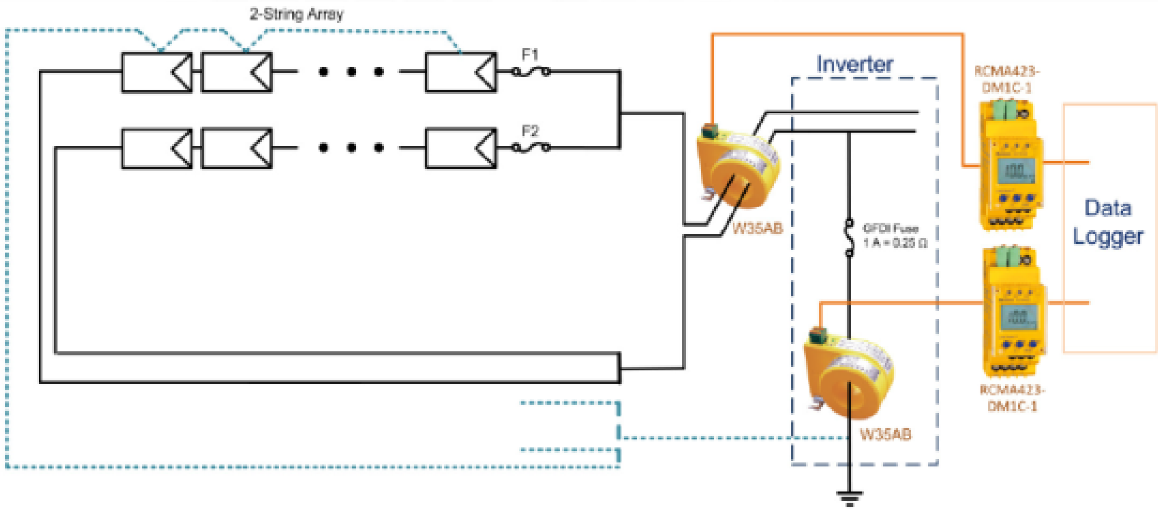
Ground Fault Sandia Research & Development

- Fuse-based GFDI (Ground Fault Detector/Interrupter) designs vulnerable to faults to grounded current-carrying conductor.
- SPICE simulations & field measurements to determine thresholds for Residual Current Detectors (RCDs), isolation resistance periodic checkers (Riso), and Current Sense Relays (CSRs).



"IEEE PVSC on the "Recommendations for RCD and Riso Ground Fault Detector Trip Thresholds"



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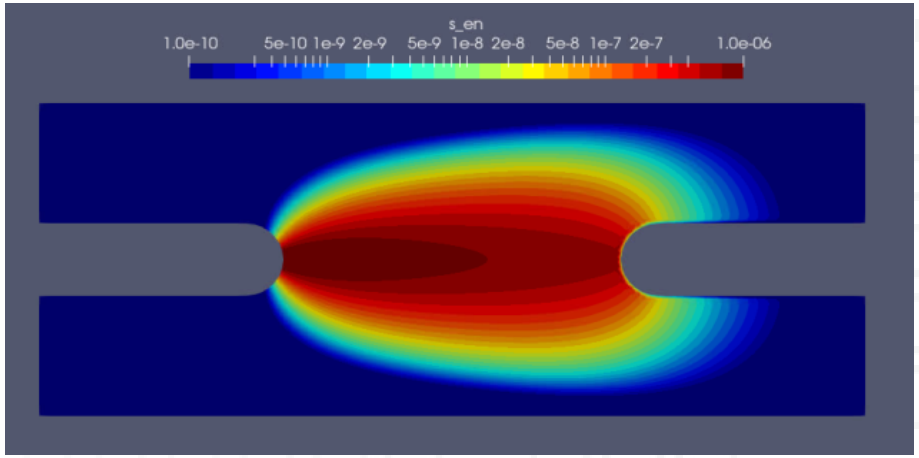
Arc ARIA Simulation Validation of DOE EERE DTE Experiments

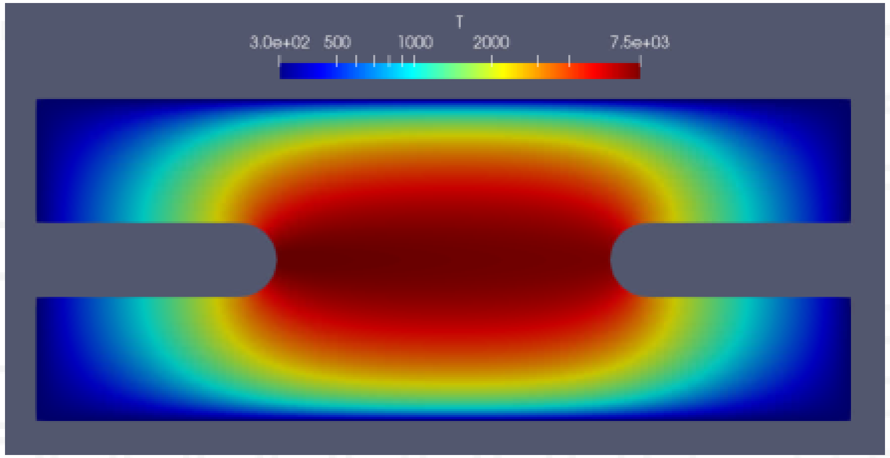
- Results of electric arc simulation only after t = 22 microseconds. Near-steady state conditions.
- Simple electron energy equation

Test #	Test System	Reference Field Test Data (DTE-Test)			
		Gap (inches)	Varc (V)	Iarc (A)	IE (cal/cm2)
1	Arc-in-a-Box: HEFEO	0.5	363	1101	11.66 (9.8s)
2	Arc-in-a-Box: HEFEO	6	341	1189	1.94 (1.85s)
3	Arc-in-a-Box: VEFEO	0.5	71	537	0.01 (2s)
4	Arc-in-a-Box: VEFEO	2	109	256	NA
5	Arc-in-a-Box: VEP	0.5*	71	537	0.01 (2s)
6	Arc-in-a-Box: VEP	0.5	109	256	NA
7	SolarBox Combiner Box #1 (W/ added Wiring)	Lug to Lug	194	777	4.61 (9.9s)
8	SolarBox Combiner Box #1 (W/ added Wiring)	Lug to BackPanel	159	554	0.36 (1.85s)
9	Solectria Inverter	Lug to Lug (Inverter Cabinet)	224	424	0.85 (1.85s)
10	Solectria Inverter	Lug to Lug (Combiner Box cabinet)	201	779	6.34(9.9s)

Electron density



Temperature



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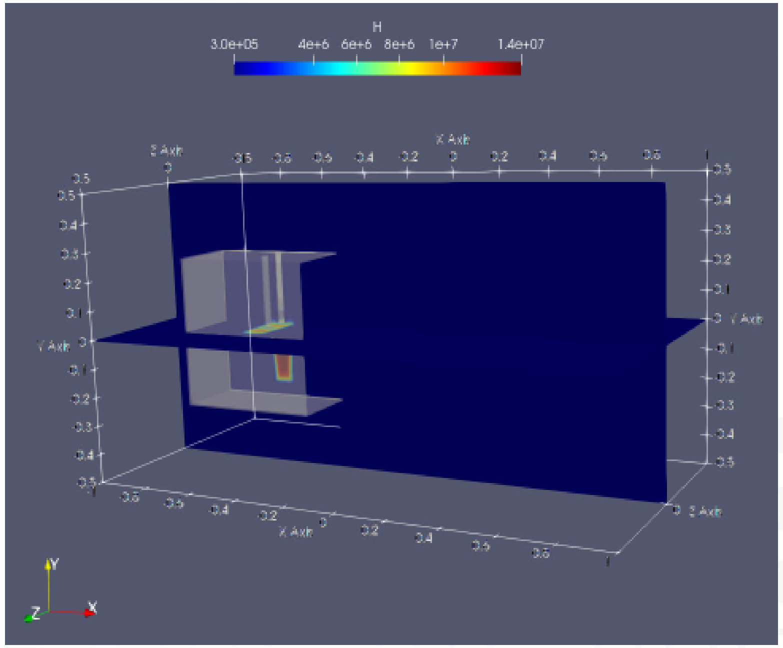
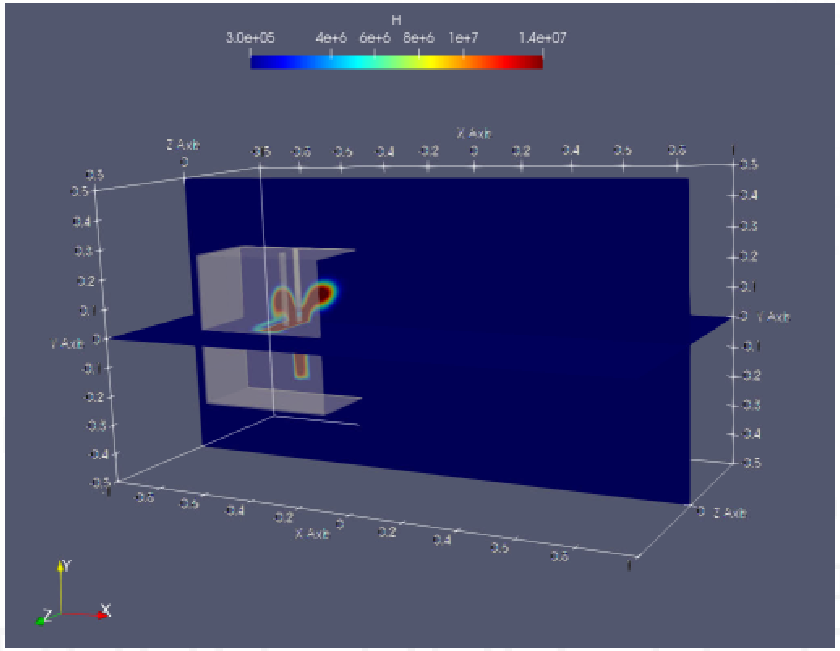
3D Aria Simulations

Evolution of Enthalpy

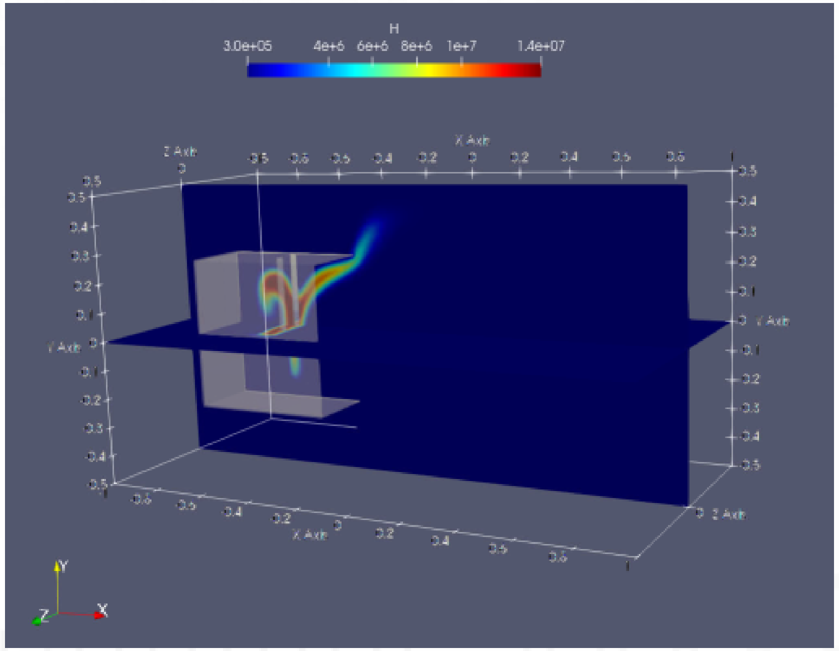
t = 0.33 s



t = 1.08 s



t = 1.83 s



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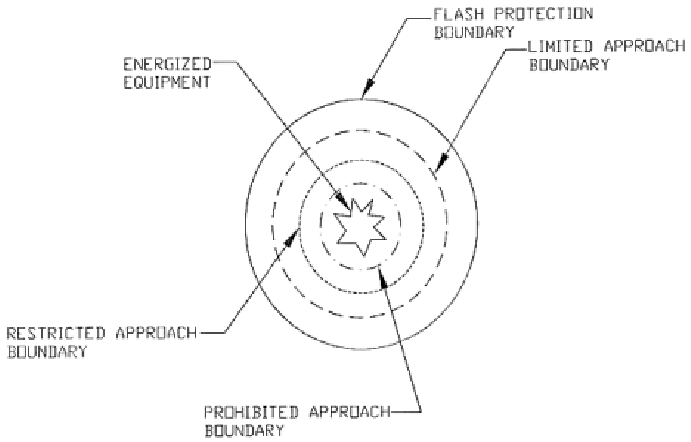
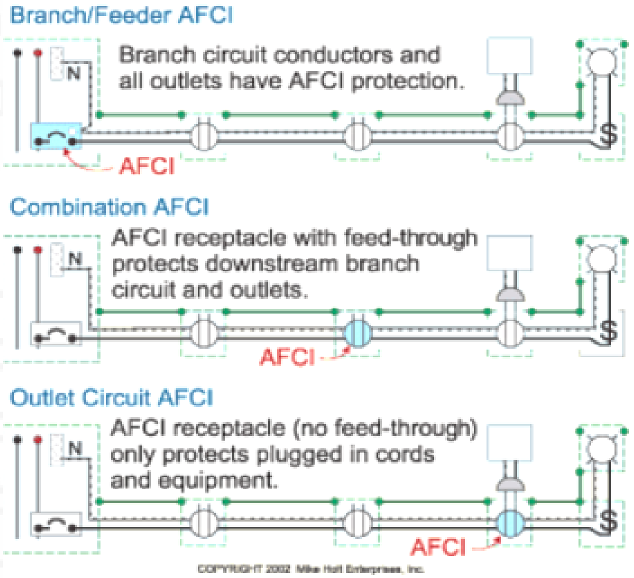
Back-Up Slides

Types of Arc-Faults

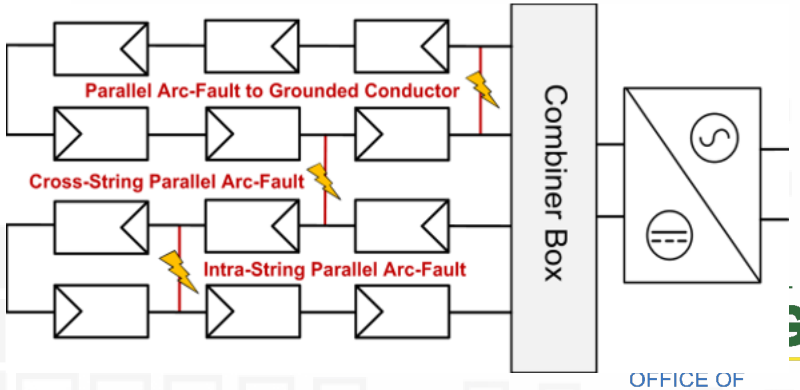
- **Series** – Occurs with pulled connections while PV is producing current. Connections include soldered joints, compression wire connections, or actual connectors used on wire leads attached to PV panels.
- **Parallel** – Parallel arcs occur when an insulation system suffers a breakdown. Two conductors of opposite polarity in same DC circuit are often in close proximity to each other. Insulation between the two wires can become ineffective due to animals chewing on them, UV breakdown, embrittlement, cracking, moisture ingress and freeze/thaw cycles.
- **To ground** – Fault requires failure of one insulation system. While GFDI (Ground Fault Detector & Interrupter) provides some measure of protection against this fault, there have been cases of faults to ground that failed to trip the GFDI protection yet created an arc.

Areas of Arc-Faults: J-Box, Inverter wiring, interconnections, etc.





Parallel Faults



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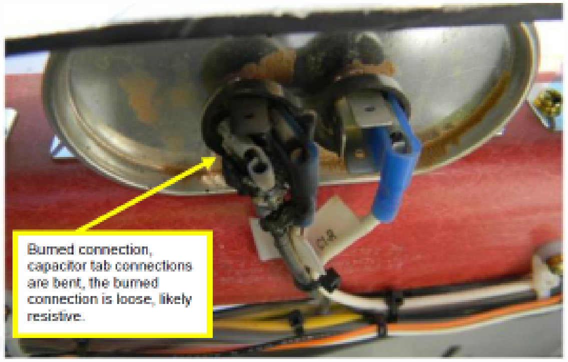
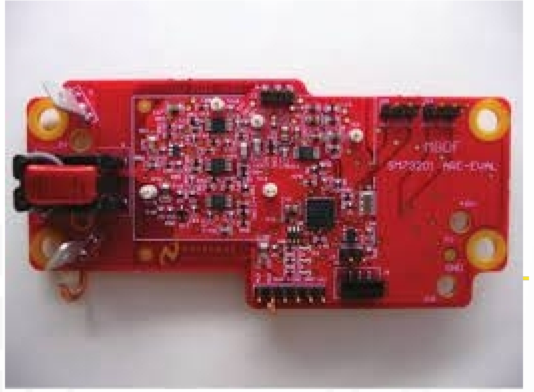
Arc-Fault Codes and Standards

- *National Electrical Code® (NEC) 2020 &* 690.11
  - 2011 *NEC* requires arc-fault mitigation for PV systems on/penetrating a building
  - 2014-Present *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*"
  - Arc-fault testing parameters (e.g., inclusion of ballast resistors, capacitors, etc.)
  - DC power supplies for PV simulation
  - Unwanted tripping tests
  - **Arc generation methods**
- IEEE1584 provides:
  - Guidance for specification & performance of arc-flash hazard calculations in accordance with process defined in IEEE Std 1584(TM)
  - Outlines minimum recommended requirements to enable PV owners to specify arc-flash hazard study, including scope of work and associated deliverables.
- NFPA 70E:
  - Standard for determining Incident Energy, Max Power and Zone of Influence (ZOI) for determining PPE and Approachable distance.





Arc-Fault Circuit Interruption Protection

- For compliance, devices must undergo a sequence of tests to verify its safety, performance of detecting arc-faults, and ensure a basic level of unwanted tripping.
- Independent laboratory tests performed with listed, recognized and prototype AFCIs/AFDs to demonstrate limitations with state-of-the-art arc-fault detection products.

ARC-FAULT CIRCUIT INTERRUPTER AND ARC-FAULT DETECTOR ARCING, MASKING, AND UNWANTED TRIPPING RESULTS

			Arc Detection Tests		Masking Tests		Unwanted Tripping Tests											
			1. Arc-fault Generation at Different Power Levels		2. Masking with Inductance/Capacitance		3. Unwanted Tripping with Inductance/Capacitance in Circuit		4. Loading Condition I									
AFCI Product	UL 1699B Compliance	Product Specs	100-200 W[^]	300 W[^]	L[*]	C[*]	L[*]	C[*]	Power Supply[ǂ]	Tigo Optimizers[$]	Inverter E[$]	Inverter F[$]	Inverter G[$]	Inverter H[$]	Inverter I[$]	Charge Controller J[$]
A	Unrecognized	Stand-Alone AFD Product	✓	✓	Masked 234 W arc with 994 μH, ran indefinitely	Masked continuous arc with 1.5 μF	✓	✓	✓	✓	Trip on startup period	Trip on startup and normal operation	Trip on inrush and startup period	Trip on inrush	Trip on startup and operation	✓
B	Unrecognized	Stand-Alone AFD Product	✓	✓	Masked 234 W arc with 994 μH, ran indefinitely	Masked continuous arc with 1.5 μF	✓	✓	✓	✓	Trip on startup period	Trip on startup period	Trip on inrush and startup period	Trips when using power supply	Trip on startup and operation	✓
C	Recognized	Stand-Alone AFD Product	169 W (36 V, 4.7 A), 30+ seconds, pull apart	✓	Masked 234 W arc with 994 μH, ran indefinitely	Masked continuous arc with 1.5 μF	✓	✓	✓	✓	✓	✓	✓	✓	Trip (only once)	✓
D	Unlisted	8-string Combiner Box with AFCI	169 W (36 V, 4.7 A), 30+ seconds, pull apart	298 W (42 V, 7.1 A), 20 sec, steel wool, Inv. I	Masked 234 W arc with 994 μH, ran indefinitely	Masked continuous arc with 1.5 μF	✓	✓	✓	✓	✓	✓	✓	✓	Trip (only once)	✓
E**	Listed	3.8 kVA, 1ϕ, inverter with transformer	102 W (16 V, 6.4 A), 20+ seconds, pull apart	328 W (40 V, 8.2 A), 20 seconds, pull apart	Masked arc with 994 μH	Masked continuous arc with 1.5 μF	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
F**	Listed	8.2 kVA, 1ϕ, TL inverter	✓	324 W (38.6 V, 8.4 A), 7 sec, steel wool	✓	✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
G	Listed	3.0 kVA, 1ϕ, inverter with transformer	✓	✓	Masked arc with 994 and 127 μH	Masked continuous arc with 1.5 μF	✓	✓	Would run only with inductors	✓	N/A	N/A	N/A	N/A	N/A	N/A
H	Listed	4.2 kVA, 1ϕ, TL inverter	✓	✓	Tripped when inductor installed	Tripped when capacitor installed	Tripped with 994, 127, and 82 μH	Tripped with 1.5 μF	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
I	Listed	5.5 kVA, 1ϕ, TL inverter	169 W (36 V, 4.7 A), 30+ seconds, pull apart	298 W (42 V, 7.1A), 20 sec, steel wool	N/A	N/A	N/A	N/A	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
J	Unlisted	14.4 kVA, 1ϕ charge controller	✓	N/A	N/A	N/A	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
Recommended for Manufacture Testing			✓	✓	✓	✓	✓	✓	✓	✓	Test using as many inverters, converters, and charge controllers as possible for stand-alone devices.					
Recommended for UL 1699B Inclusion			✓	✓	Test with 1 mH unless otherwise specified by the mfr.	Test with 3 mF unless otherwise specified by the mfr.	Test with 1 mH unless otherwise specified by the mfr.	Test with 3 mF unless otherwise specified by the mfr.	✓	✓	Test using 1 single phase inverter, 1 three-phase inverter, 1 converter, and 1 charge controller for all stand-alone devices going to be UL 1699B recognition.					

^ Test currently in the UL 1699B Outline of Investigation.
* Tests added to the UL 1699B Outline of Investigation in November, 2014.
ǂ Tests not included in the UL 1699B Outline of Investigation.
$ Only a single 1-phase or 3-phase inverter, converter, or charge controller is used as the load in the current version of Loading Condition I.
** These products are from the same manufacturer.

J. Johnson, K.M. Armijo, M. Avrutsky (Tigo Energy), D. Eizips (Tigo Energy), S. Kondrashov (Tigo Energy), Arc-Fault Unwanted Tripping Survey with UL 1699B -Listed Products, IEEE Photovoltaics Specialists Conference, June 2015.

Arc-Fault Circuit Interruption Protection

- Testing inverter-integral AFCIs, combiner box AFCIs, and stand-alone AFDs through realistic tests beyond UL 1699B, all products were found to either cause unwanted tripping or were ineffective at detecting detrimental arc-fault events.
- Based on findings, AFD/AFCI manufacturers are encouraged to adopt these experiments in their design process to improve their respective products.
- Results suggest similar tests be added to the certification standard to improve products entering the market.

ARC-FAULT CIRCUIT INTERRUPTER AND ARC-FAULT DETECTOR ARCING, MASKING, AND UNWANTED TRIPPING RESULTS (CONTINUED)

			Unwanted Tripping Tests																
			5. Loading Condition II – DC Disconnect ^	6. Loading Condition III – Irradiance Change*	7. Frequency Sweep with Coupling Transformer†	8. Inductive Coupling between Arrays				9. AC-DC Coupling				10. Broadband Noise Injection			11. Injected Inverter Signatures with Coupling Transformer		
AFCI Product	UL 1699B Compliance	Product Spec				Inverters F, G, H*	Inverters F, G, I*	Inverters F, G, Charge Controller J*	Inverters E, G, H*	Paper Shredder *	Shop Vacuum *	Bench Grinder *	Relay on AC load†	50 m²	100 m²	150 m²	Noise A†	Noise B†	Noise C†
A	Unrecognized	Stand-Alone AFD Product	✓	Tripped when 1/2 PV array is connected	Square wave tripped at 100 kHz, 133 kHz, 1-10 kHz, 73 & 78 kHz Trip with Inv. F			On J DC system		✓	✓	✓	Tripped with Power Supply	N/A	N/A	N/A	N/A	N/A	N/A
B	Unrecognized	Stand-Alone AFD Product	✓	✓	Square wave tripped at 1 and 2 kHz for many Inv.; Sine wave tripped 3-10 kHz			✓ On J DC system		✓	✓	✓	Tripped with Power Supply	N/A	N/A	N/A	N/A	N/A	N/A
C	Recognized	Stand-Alone AFD Product	✓	✓	Square wave tripped at 2kHz with Inv. E, 12-14 kHz trip with Inv. H			✓ On J DC system		✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
D	Unlisted	8-string Combiner Box with AFCI	✓	✓	✓			✓ On J DC system		✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
E**	Listed	3.8 kVA, 1ϕ, inverter with transformer	✓	Tripped when 1/2 PV array is disconnected or resistance added	✓				✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
F**	Listed	8.2 kVA, 1ϕ, TL inverter	✓	Tripped when 1/2 PV array is disconnected or resistance added	✓	✓	✓	✓		✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
G	Listed	3.0 kVA, 1ϕ, inverter with transformer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
H	Listed	4.2 kVA, 1ϕ, TL inverter	✓	✓	✓	✓			✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
I	Listed	5.5 kVA, 1ϕ, TL inverter	✓	✓	N/A		✓			✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
J	Unlisted	14.4 kVA, 1ϕ charge controller	✓	✓	Square wave tripped at 1-2 kHz and 4 kHz			✓		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Recommended for Manufacturer Testing			✓	✓	✓	✓	✓	✓	✓	Test as many devices as possible.			✓	✓	✓	✓	✓	✓	✓
Recommended for UL 1699B Inclusion			✓	✓	✓ (With sine wave injection)	Test with same devices from Loading Condition I							✓	✓					

^ Test currently in the UL 1699B Outline of Investigation.
* Tests added to the UL 1699B Outline of Investigation in November, 2014.
† Tests not included in the UL 1699B Outline of Investigation.
** These products are from the same manufacturer.

J. Johnson, K.M. Armijo, M. Avrutsky (Tigo Energy), D. Eizips (Tigo Energy), S. Kondrashov (Tigo Energy), Arc-Fault Unwanted Tripping Survey with UL 1699B-Listed Products, IEEE Photovoltaics Specialists Conference, June 2015.

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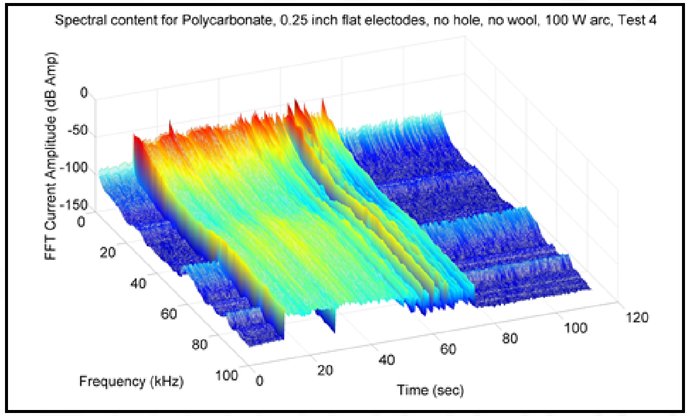
Arc-fault Noise Signatures

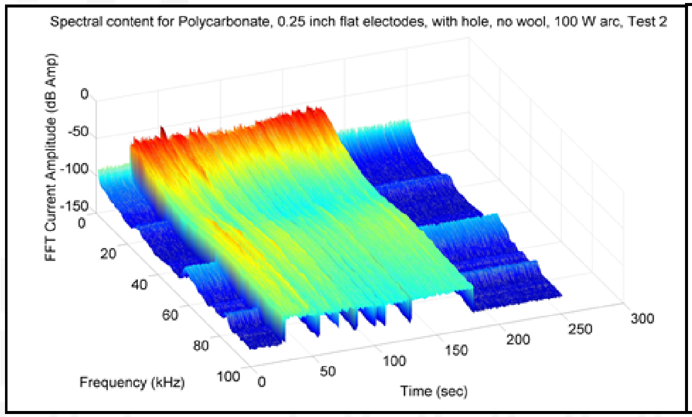
- Discrete Fourier Transforms (DFTs) of the DC current during the arc-fault tests were saved at a rate of ~0.28 DFTs/sec.
- Arc stability and polymer pyrolyzation determine arc-fault noise patterns
  - If liquid polymer, steel wool, or copper dust from electrode enter plasma stream the arc can flicker 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

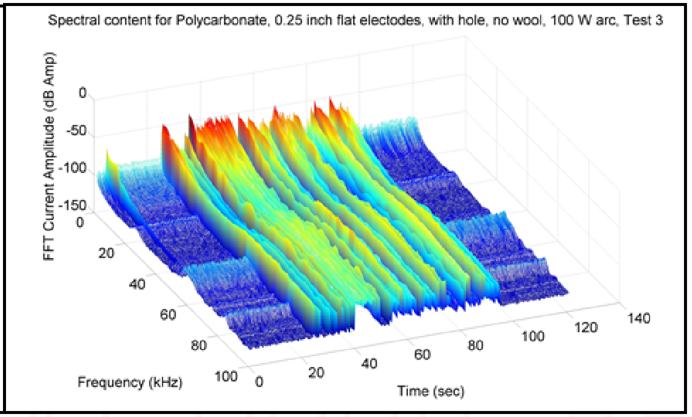
Identical Tests with Hole



Stable Arc-Fault until t = ~60 s



Stable Arc-Fault



Less Stable Arc-Fault

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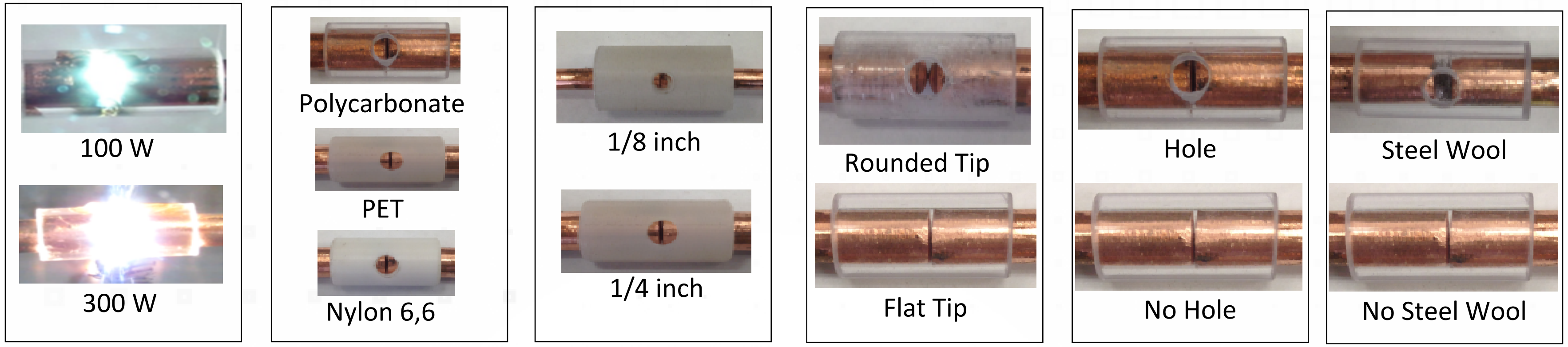
Alternative arc-fault generation methods

Parametric Materials Analysis:



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

Armijo, K.M., Hibbs, M., Johnson, J. and Fresquez, A, "Characterizing fire danger from low power PV arc-faults", *40th PVSC Conference*, Denver, CO.

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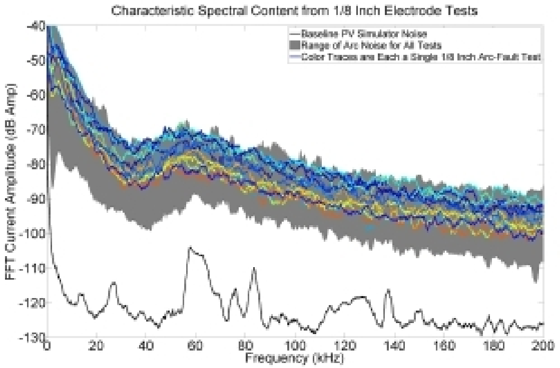
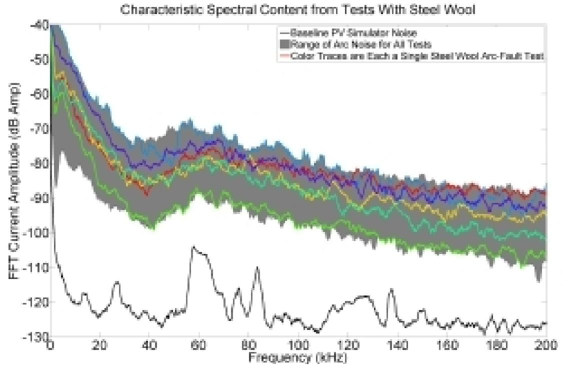
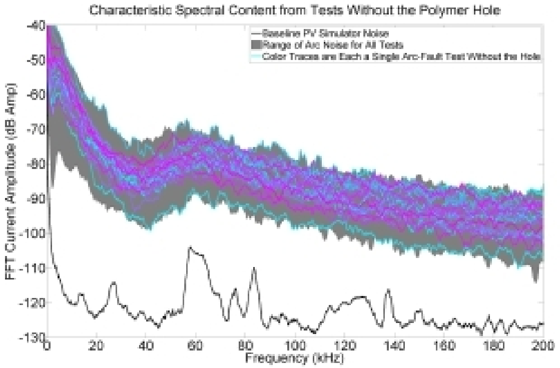
Factors for Noise Generation



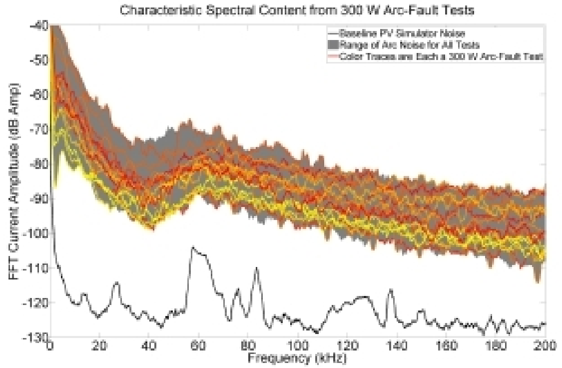
Smaller electrodes produce high noise signatures due to increased off-gassing rates and oxygen depletion.



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

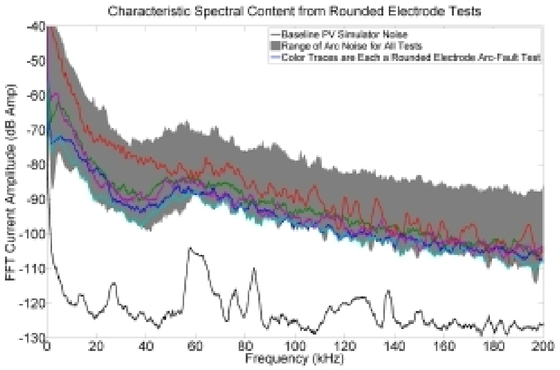


Holes produced slightly cleaner burning arc-faults, possibly because of the increased presence of oxygen.

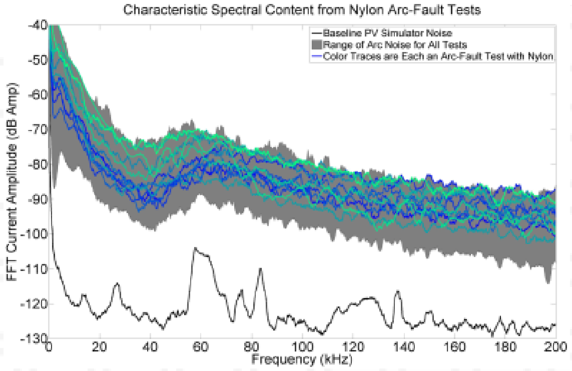


Higher power arc-faults tend to create more stable, cleaner burning, *slightly* less noisy arcs.

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.



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.

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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 impa $t_{trip} = min\left(2, \frac{750}{i_{arc} \cdot V_{arc}}\right)$ e scales, which requires rapid and accurate AFCI responses.
- UL 1699B defines the maximum AFCI trip time according to:

Arc Duration Time [sec.]

Arc Power [W]	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
$T_{melt} = 155^oC$
$T_{ignition} = 450^oC$

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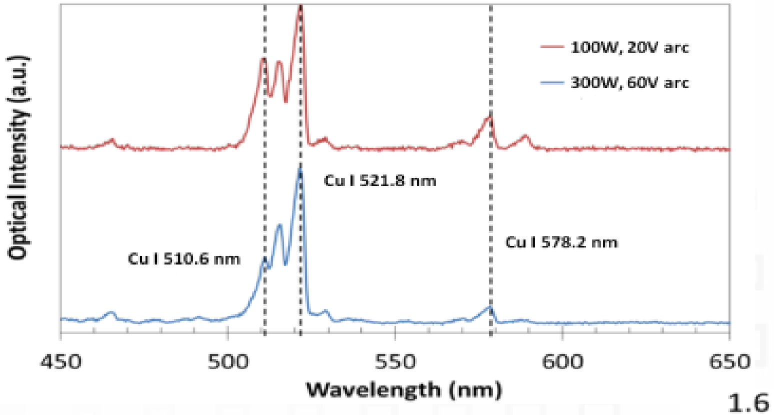
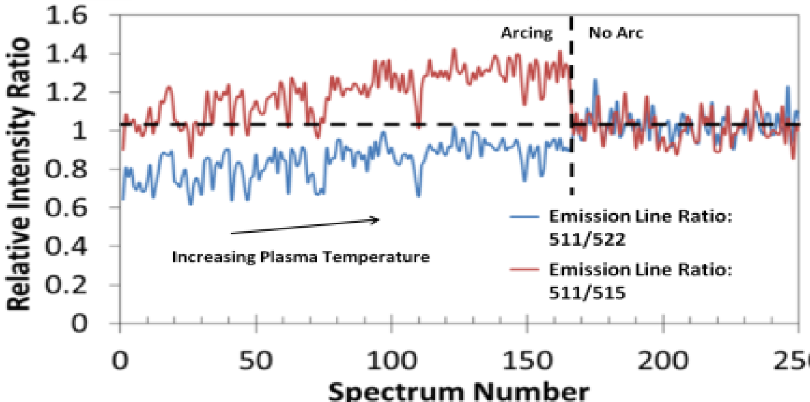
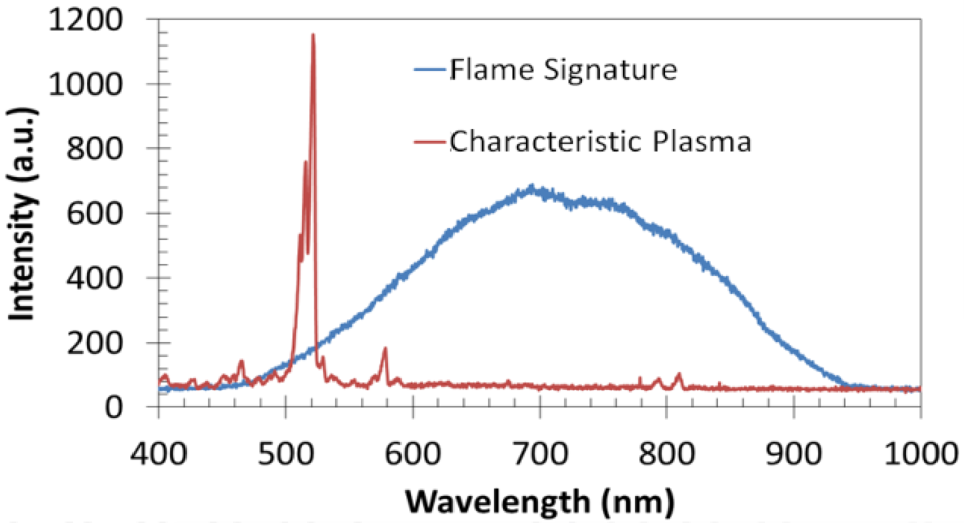
Optical Emission Spectrum Analysis

- 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 300 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.







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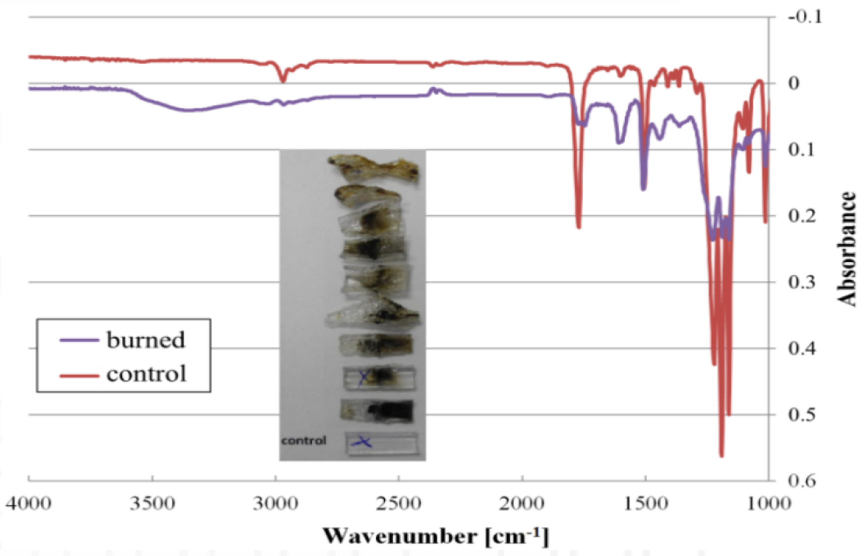
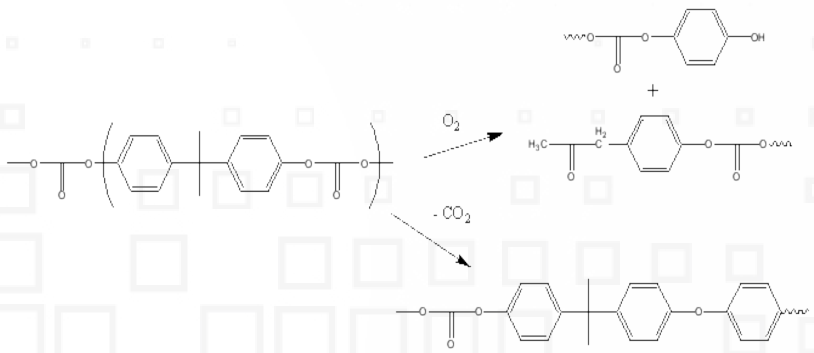
Chemical Degradation Mechanisms

- 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.

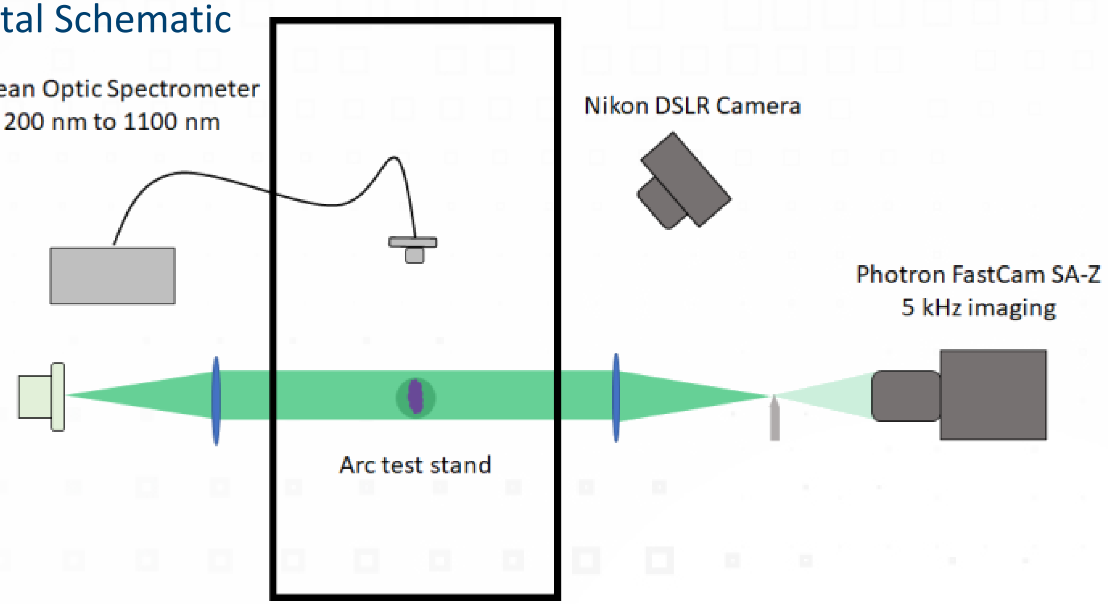




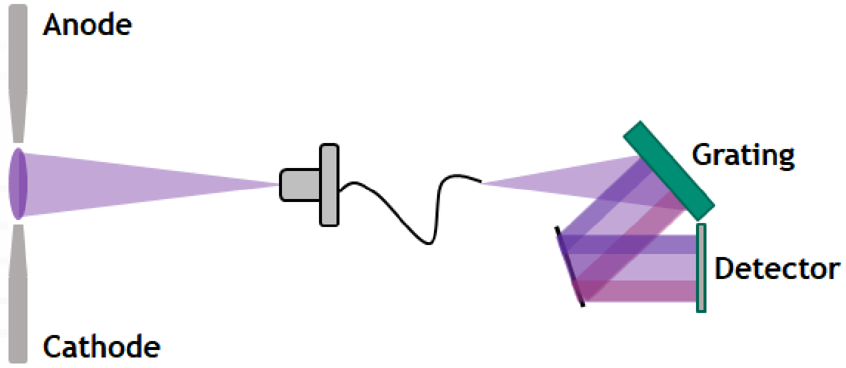
Armijo, K.M., Johnson, J., Hibbs, M. and Fresquez, A., **2014**, "Quantifying Photovoltaic Fire Danger Reduction with Arc-Fault Circuit Interrupters", *29th EUPVSEC Conference*, Amsterdam, The Netherlands

Optical Diagnostics Setup

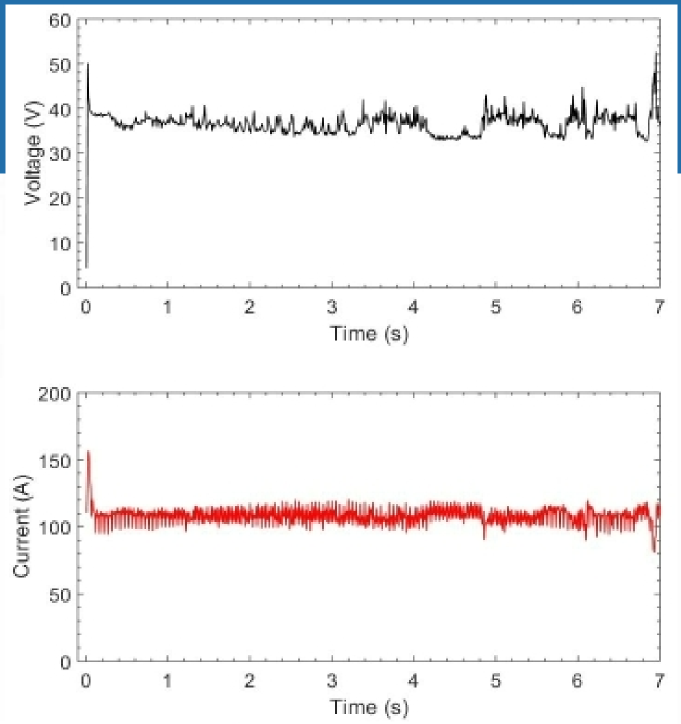
Experimental Schematic



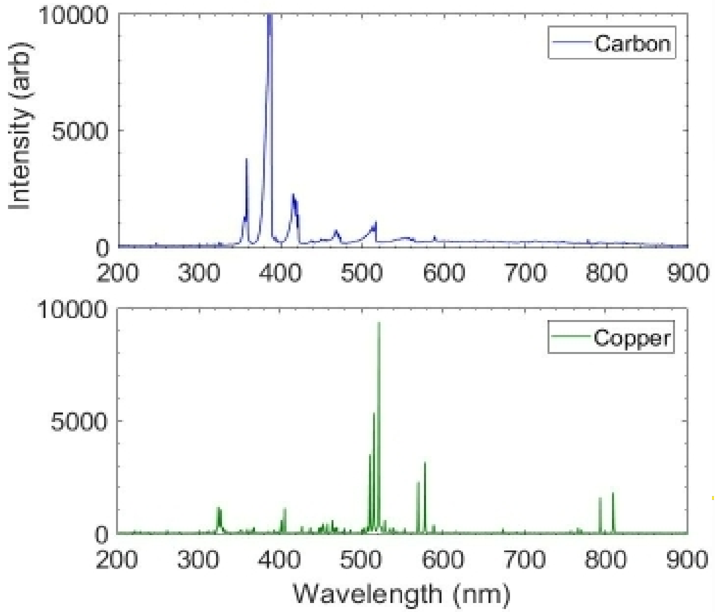
Optical emission spectroscopy



Traces from DC power supply

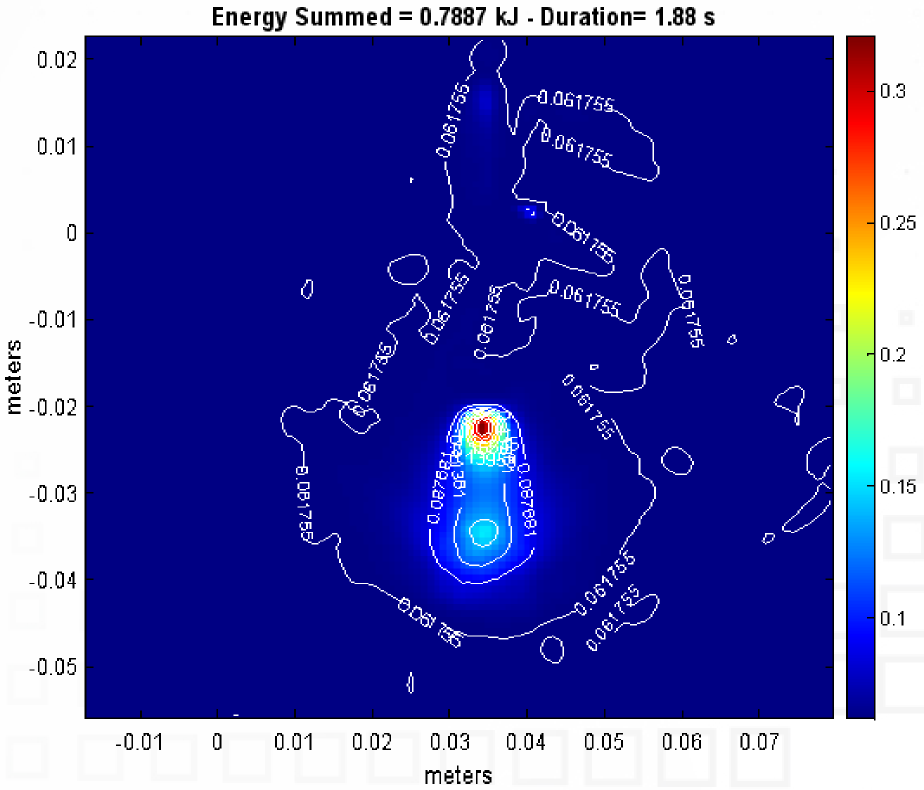


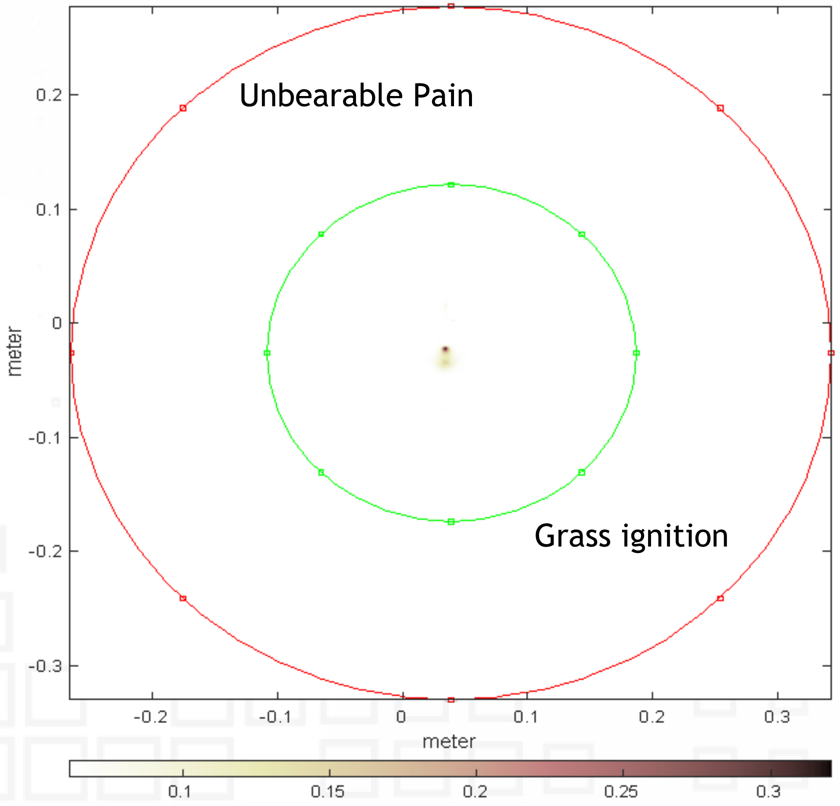
OES spectra:



IR ZOI Calculations of Lab and DTE Data

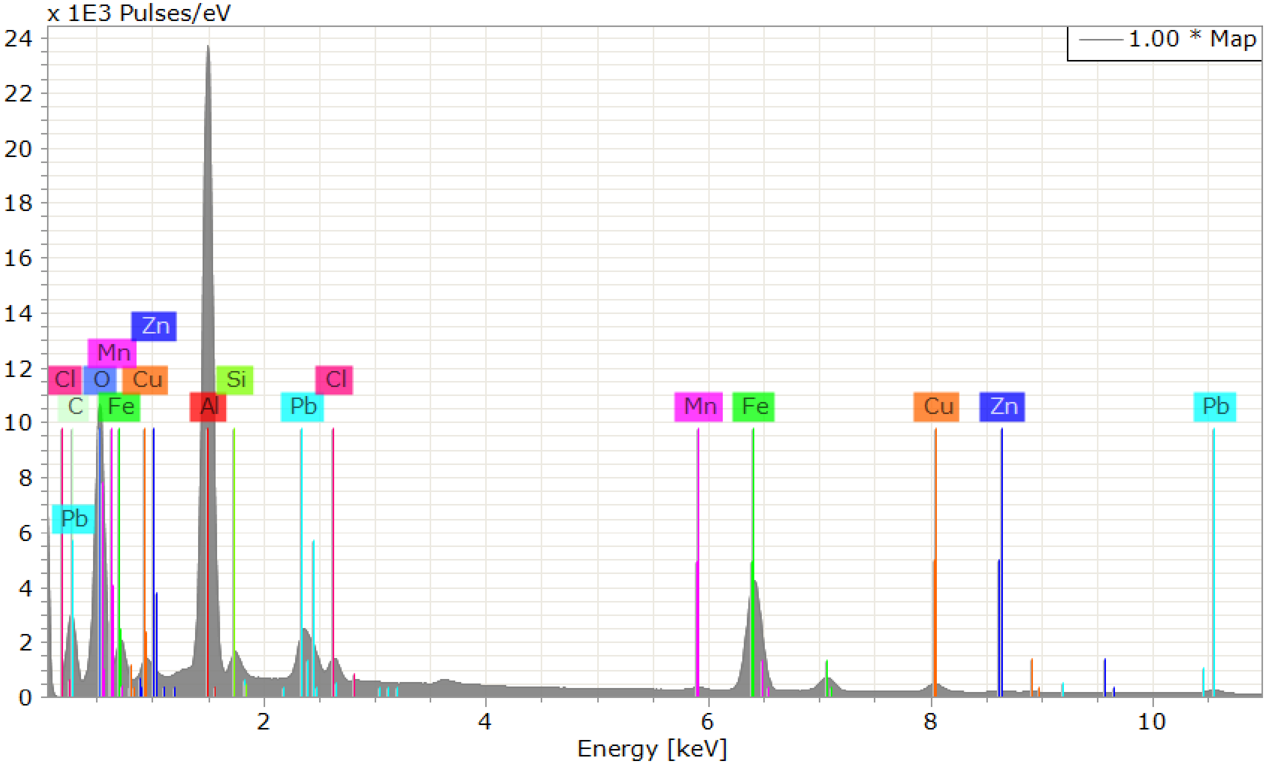
- Research on-going to convolve IR spectra with lower wavelength spectral data for more accurate results for ZOI.
- Spectra in the visible indicates that the arc plasma extends from the UV to 0.9 µm, but cameras collected arc related data in the infrared.

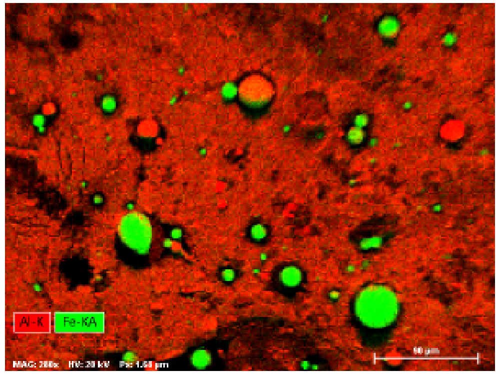




KEMA test oxidation vs. distance from switchgear

- Particles collected for 7kV, 32 kA, 4s test 4: racks 2-3 and back wall show Al, Fe, Pb





HEAF analysis in progress:

1) X-ray fluorescence total metal vs. oxygen quantification
2) comparison of oxidation vs. arc duration (2s vs. 4s) and current level (24 kA vs. 32 kA)
3) carbon thermometry of October 2018 KEMA testing

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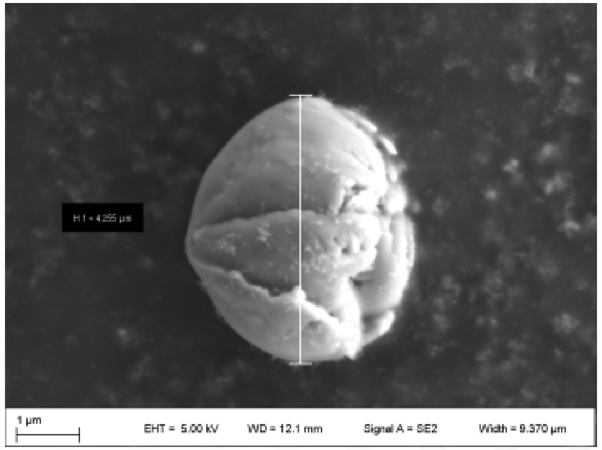
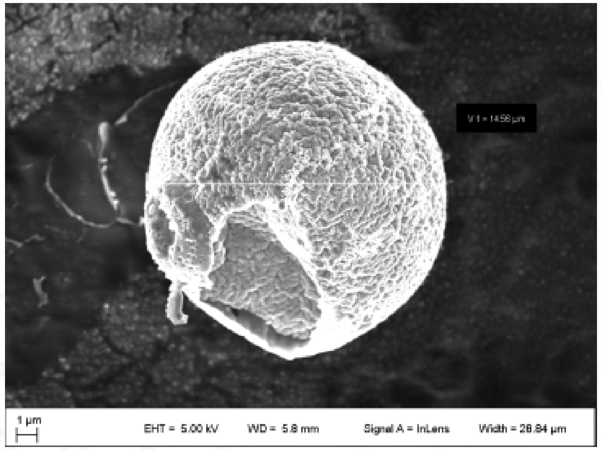
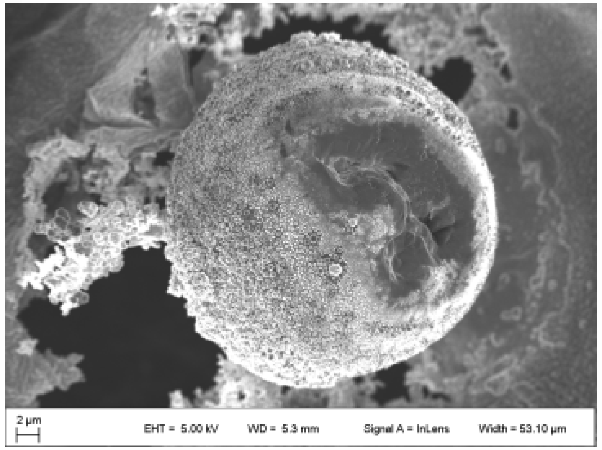
Electron Microscopy of Small Scale Arc-Generated Al Particles (Sandia tests)

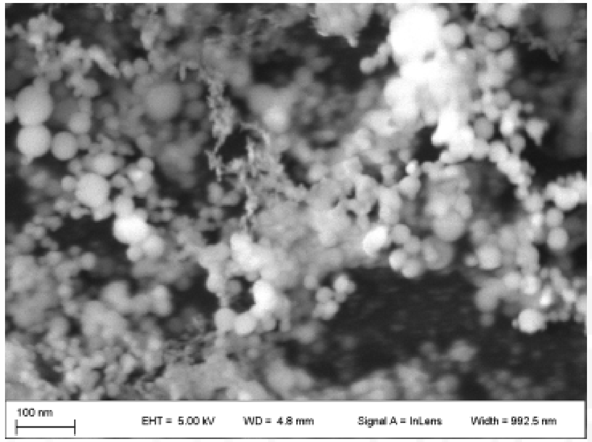
- 6.9 kV arc-generated particles (2.5-14 μm) were collected on aerogel substrates and carbon microscopy tape

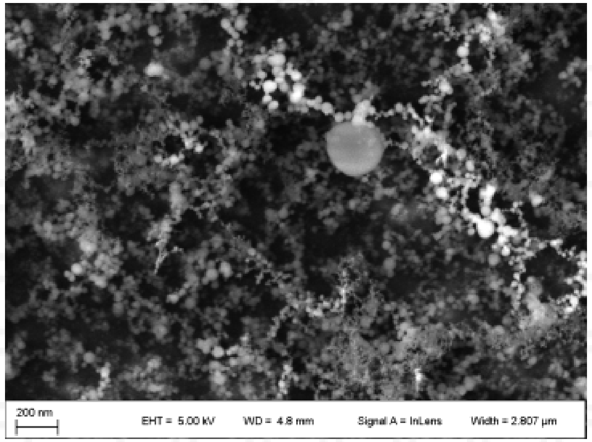


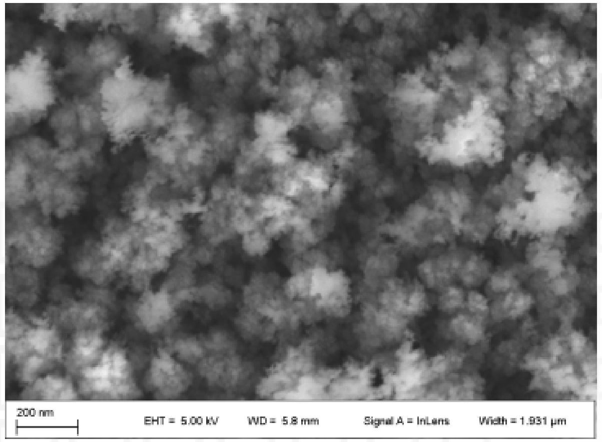




Nanoscale particles: appear fully oxidized to Al_2O_3







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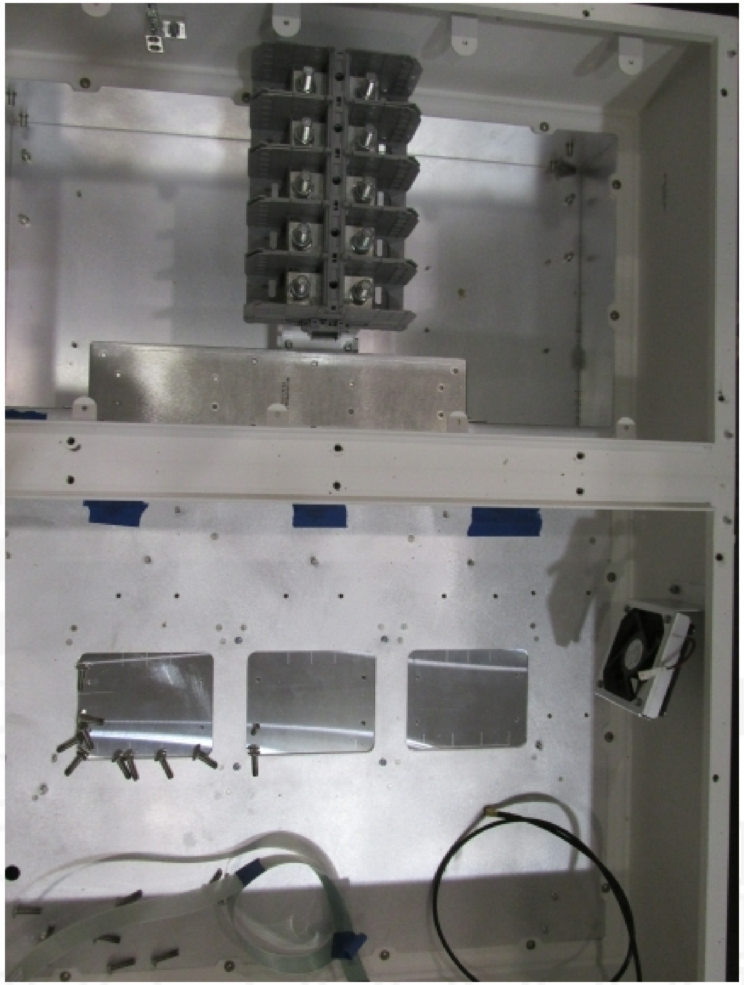
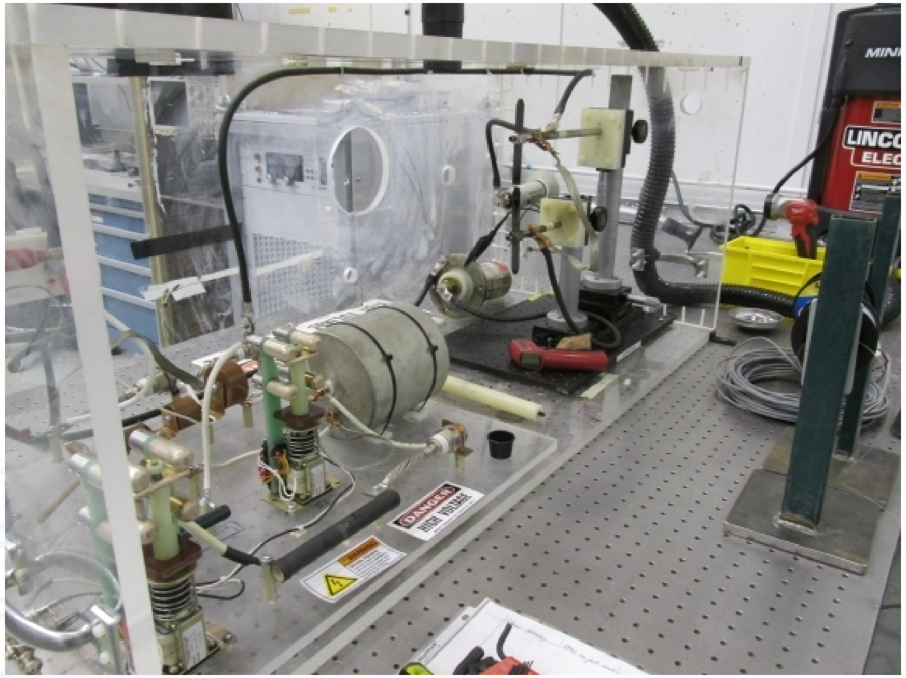
Sandia HEAF Component Tests

SolarBOS and Arc-in-a-Box Setup

Mock-Up Solectria Inverter



Arc-in-a-Box



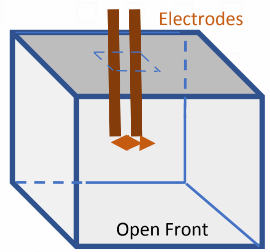
High-Voltage Setup

Arc-in-A-Box Experiments

20x20x20-inch box

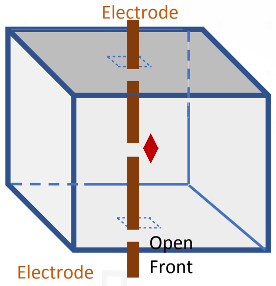
Calibration test (Vertical Electrodes, similar to NG experiment)			
Electrode Gap	**Source (Nameplate, kW)**	**Inverter Status**	**# of Strings**
0.5 in	838	off	140
2 in	838	off	140

Vertical parallel



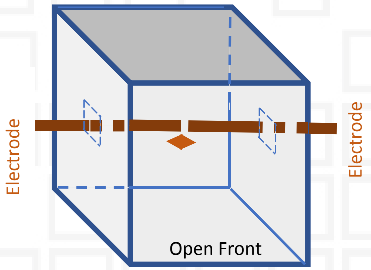
Vertical Electrodes, facing each other (Sandia National Lab will provide electrodes, 0.5 in dia.)			
Electrode Gap	**Source (Nameplate, kW)**	**Inverter Status**	**# of Strings**
0.5 in	144	off	24
0.5 in	275	off	46

Vertical pin-to-pin



Horizontal Electrodes, facing each other (Sandia National Lab will provide electrodes, 0.5 in dia.)			
Electrode Gap	**Source (Nameplate, kW)**	**Inverter Status**	**# of Strings**
0.5 in	144	off	24
0.5 in	275	off	46

Horizontal pin-to-pin



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DTE DC Testing Results

- Variations in electrode gaps: 0.5, 2, 4 and 6 in.
- Variation in Source: 312, 264, 527 and 1054 kWdc
- Targeted duration: 2 sec. (one test lasted 10 sec.)
- 16 Test shots

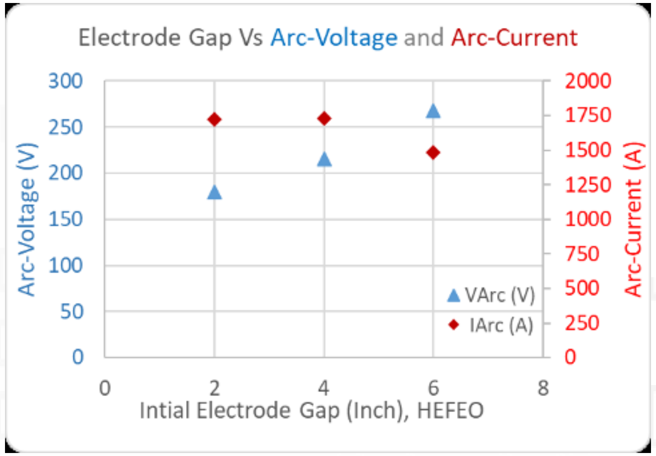
VEFEO	Vertical Electrode Facing Each Other
HEFEO	Horizontal Electrodes Facing Each Other
VEP	Vertical Electrodes, Parallel
NDR	No Data Recorded

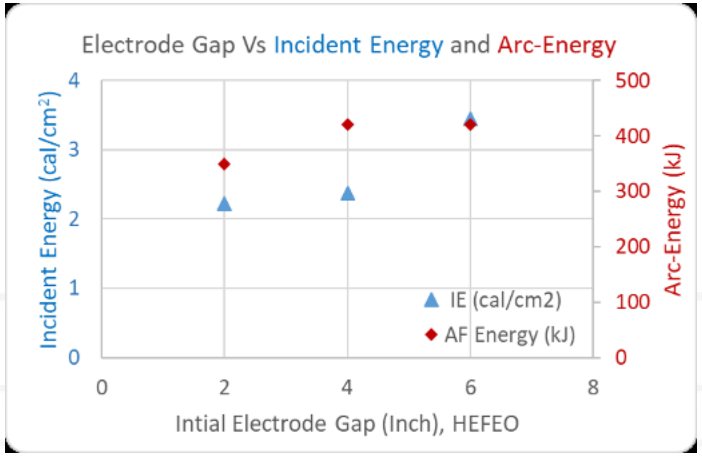
	Electrode	Electrode Gap	Source	Arc time	Voc	Irradiance	Tmodule	IE (cal/cm2)			NG PQ		EPRI PQ		Arc Energy (kJ)	
Test #	Orientation	(in)	(kWp, STC)	(s)	(V)	(W/m2)	(DegC)	Min	Max	Mean	Varc (V)	Iarc (A)	Varc (V)	Iarc (A)	EPRI-PQ	NG-PQ
2	(VEFEO)	0.5	264*	2	760	431	45	NDR	**NDR**	NDR	51	175	NDR	NDR	NDR	16
3	(VEFEO)	0.5	528	2	765	700	40.5	0.00	**0.01**	0.00	71	537	ND	ND	NDR	78
20	(VEFEO)	0.5	264	2	774	730	49	NDR	**NDR**	NDR	78	280	74	290	41	40
21	(VEFEO)	2	264	2	775	670	49.6	NDR	**NDR**	NDR	109	256	93	221	39	50
4	(HEFEO)	0.5	132	2	766	971	53.2	NDR	**NDR**	NDR	ND	ND	ND	ND	NDR	NDR
5	(HEFEO)	0.5	528	2	751	814	58.2	0.00	**0.30**	0.16	92	554	94	ND	NDR	103
6	(HEFEO)	2	1054	2 (1.8)	757	993	56.6	0.08	**1.82**	0.99	159	1361	171	1522	494	422
7	(HEFEO)	4	1054	2 (1.85)	757	980	55.1	0.23	**2.05**	1.07	215	1525	209	1520	604	577
8	(HEFEO)	6	1054	2 (1.85)	757	1088	53.5	0.08	**3.09**	1.63	268	1401	261	1387	685	613
9	(VEP)	0.5	1054	2 (1.85)	756	975	56.3	0.27	**1.96**	1.08	251	1648	240	1566	713	626
10	(VEP)	0.5	1054	2 (1.85)	758	1070	51.3	0.22	**2.07**	1.14	232	1405	220	1642	683	653
11	(VEP)	0.5	1054	2 (1.85)	754	960	54.3	NDR	**NDR**	NDR	NDR	NDR	NDR	NDR	NDR	NDR
12	(VEP)	2	1054	2 (1.9)	752	870	56.1	0.33	**2.47**	1.52	344	1305	326	1394	885	879
13	(VEP)	2	1054	2 (1.85)	749	740	52.7	0.24	**1.92**	1.08	330	1179	341	1189	768	705
14	(VEP)	2	1054	10 (9.8)	749	680	47.8	2.80	**11.54**	7.02	372	1095	363	1101	3937	4083

	PVSyst (modeled)					Calculated IE using Models					
Test #	Vmp (V)	Imp (A)	Voc (V)	Isc (A)	Pmax (kW)	Tom S (EPRI)	Tom S (EPRI) Simplified*	Stokes & Oppn	Doan (NFPA)	Paukert	Enrique
2	648	156	759	186	101	0.07	0.45	0.34	1.39	0.13	4.05
3	623	515	768	610	322	0.31	1.46	1.27	4.64	0.52	15.33
20	646	262	776	298	169	0.17	0.72	0.57	2.29	0.22	6.77
21	641	240	770	274	154	0.22	0.66	0.86	2.08	0.40	6.16
4	628	173	774	199	109		0.48	0.37	1.52	0.14	4.35
5	609	731	762	821	445	0.41	1.97	1.77	6.18	0.73	17.82
6	612	1450	765	1630	888	1.87	3.52	5.95	11.52	3.26	35.51
7	624	1415	770	1607	883	1.93	3.57	8.49	12.23	5.44	35.33
8	613	1540	767	1737	945	2.68	3.86	11.14	13.16	5.99	37.78
9	621	1407	766	1600	874	2.78	3.55	3.70	12.27	1.59	34.97
10	615	1514	769	1706	932	2.67	3.79	3.98	12.96	1.71	37.26
11	621	1392	766	1576	865		3.50	3.64	11.39	1.56	33.62
12	618	1264	762	1428	781	4.07	3.18	5.34	11.04	2.94	32.11
13	621	1070	756	1214	665	3.00	2.70	4.46	9.07	2.36	26.59
14	619	989	752	1116	612	15.67	15.89	21.30	43.93	11.28	129.78

Ratio (Calculated/Measured)						
Test #	Tom S (EPRI)	Tom S (EPRI) Simplified	Stokes & Oppn	Doan (NFPA)	Paukert	Enrique
5	1.36	6.51	5.9	20.4	2.4	58.9
6	1.03	1.94	3.3	6.3	1.8	19.6
7	0.94	1.74	4.1	6.0	2.7	17.3
8	0.87	1.25	3.6	4.3	1.9	12.2
9	1.42	1.81	1.9	6.3	0.8	17.8
10	1.29	1.83	1.9	6.2	0.8	18.0
12	1.65	1.29	2.2	4.5	1.2	13.0
13	1.56	1.40	2.3	4.7	1.2	13.8
14	1.36	1.38	1.8	3.8	1.0	11.2

* Varc = 300V and Iarc = Isc





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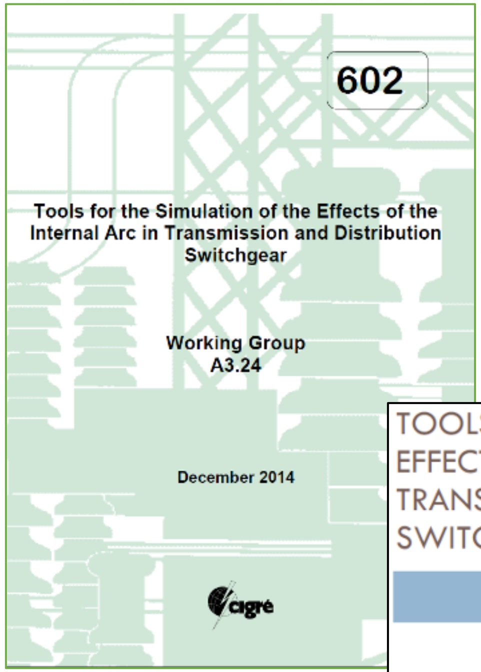
Opportunities in Arc Modeling

"Tools for the Simulation of the Effects of the Internal Arc in Transmission and Distribution Switchgear"

Working Group A3.24, December 2014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Tools for the Simulation of the Effects of the Internal Arc in Transmission and Distribution Switchgear
Working Group A3.24
December 2014
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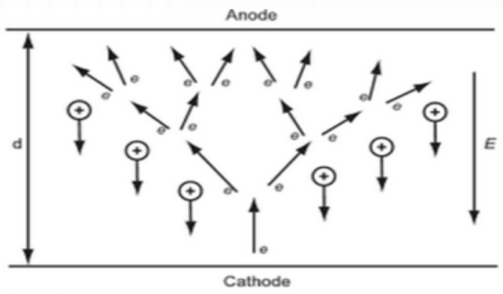

4.3.2 Arc and gas models in CFD, and other enhancements

The programming interface allows the implementation of user-defined algorithms. In the simplest approach, the arc is modeled by an energy input, which is homogeneously distributed in the arc compartment volume, using the thermal transfer coefficient k_p described in Chapter 2.

In a more detailed approach [Besnard2009], the arc heating power is confined to a small number of finite volumes in the vicinity of the arc initiation point. In order to balance the temperature rise in these finite volumes, a model of the radiation process is needed. As a result, the temperatures in the vicinity of the arc initiation point reach high values (11000 K in air typically), whereas the arc compartment still includes cold gas regions, as do the other compartments. This accounts for the high temperature gradients existing during the internal arc event, leading to high density gradients.

The most complete approaches, where the arc would be modeled using physical equations describing the arc roots, the arc plasma column, the effect of electro-magnetic fields on the motion of the arc, the transfer of energy from the arc plasma to the surrounding gas etc. have never been applied to internal arc to our knowledge.

TOOLS FOR THE SIMULATION OF THE EFFECTS OF THE INTERNAL ARC IN TRANSMISSION AND DISTRIBUTION SWITCHGEAR

WG A3.24

Members

N. Uzelac, **Convenor** (US) M. Glinkowski, **Secretary** (US), L. del Rio (ES), M. Kriegel, **Former Convenor** (CH), J. Douchin (FR), E. Dullni (DE), S. Feitoza Costa (BR), E. Fjeld (NO), H-K. Kim (KR), J. Lopez-Roldan (AU), R. Pater (CA), G. Pietsch (DE), T. Reiher (DE), G. Schoonenberg (NL), S. Singh (DE), R. Smeets (NL), T. Uchii (JP), L. Van der Sluis (NL), P. Vinson (FR), D. Yoshida (JP)

Aim: arc physical model, where current and electrode gap → radiation, convective and thermal energy transport

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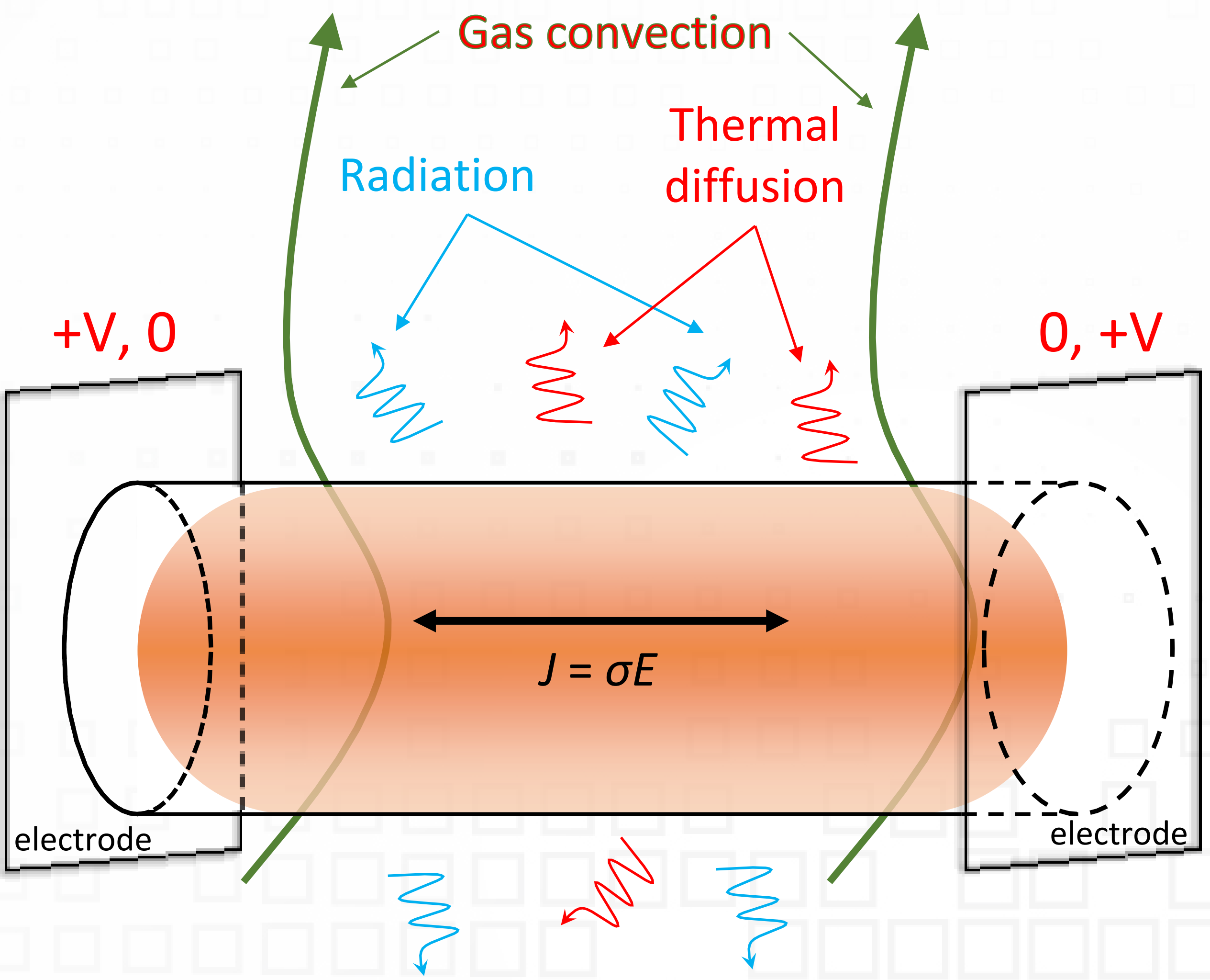
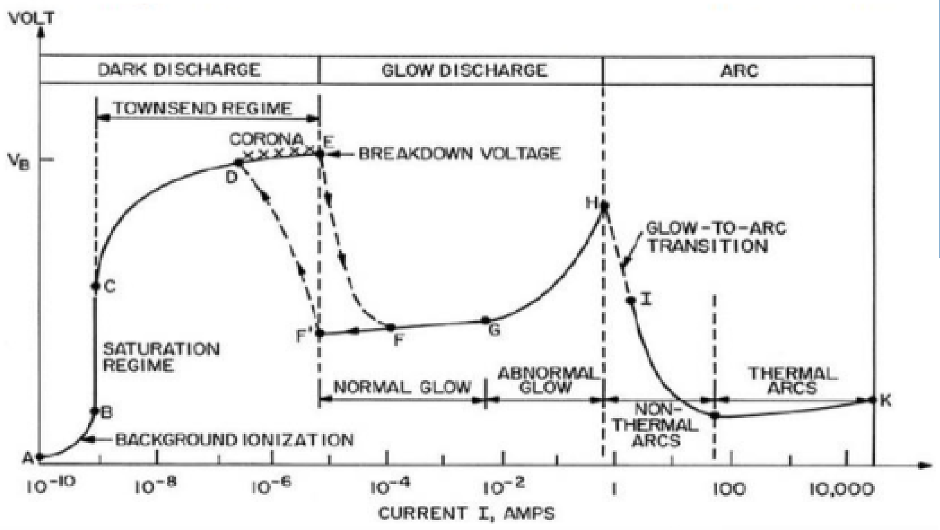
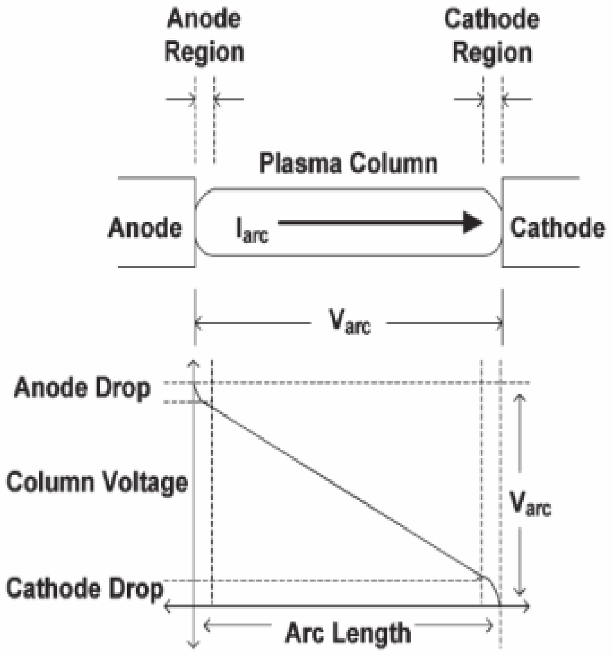
Modelling Overview



A free burning cylindrical arc





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ARIA: Set of equations for arc modeling

- Conservation of mass:

$$\underbrace{\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\, \mathbf{c_0})}_{} = 0$$

Convection

- Conservation of momentum:

$$\rho\left[\frac{\partial \mathbf{c_0}}{\partial t} + \mathbf{c_0} \cdot \nabla \mathbf{c_0}\right] = -\nabla p + \mu \left[\nabla^2 \mathbf{c_0} + \frac{1}{3}\nabla(\nabla \cdot \mathbf{c_0})\right] + \rho\, \mathbf{g} + \mathbf{J} \times \mathbf{B}$$

Advection | Hydrostatic pressure | Viscous pressure | Buoyancy | Magnetic pressure

- Conservation of energy:

$$\rho\, c_p\left[\frac{\partial T}{\partial t} + \mathbf{c_0} \cdot \nabla T\right] = \mathbf{J} \cdot \mathscr{E} + \lambda\, \nabla^2 T$$

Advection | Joule heating | Diffusion

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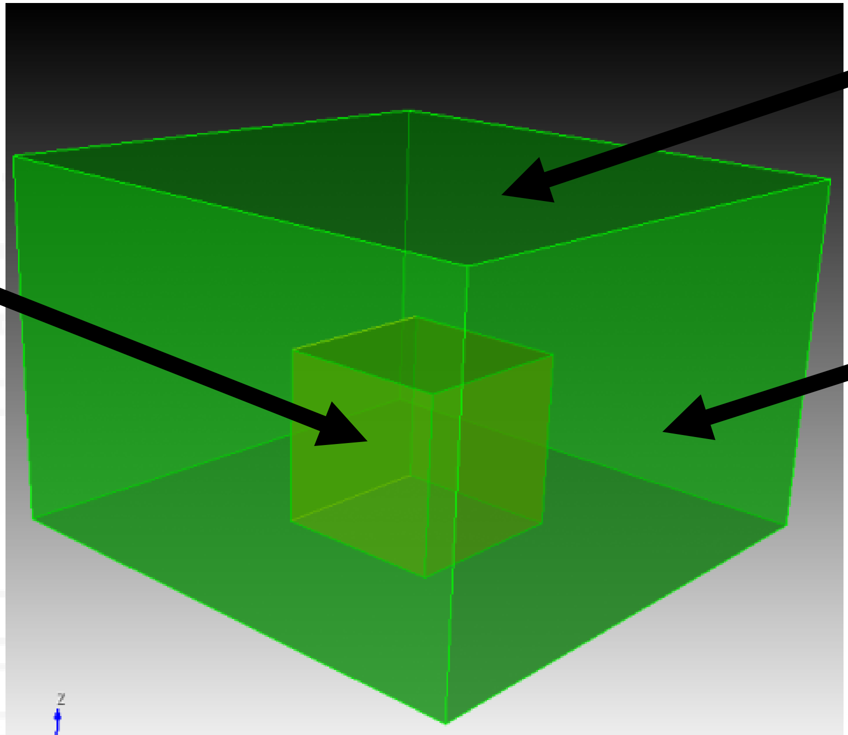
Continued Modelling Work

- From task schedule, we have engaged in Aria-Fuego model coupling for a radiant brick system. The first iteration of this was just thermal. The second iteration was thermal + fluid. And the third iteration, presented here, is thermal + turbulent fluid (with variable density).

1 cm^3 steel cube, 600 K. Conduction solved in Aria. This begins to mimic the thermal source term from the developing Aria arc model.

Coupling:
Aria applies thermal flux condition with Fuego information, and Fuego enforces a temperature directly from Aria.



3 cm x 3 cm x 2 cm

Gas domain solved in Fuego. We use a Cantera model for air (density, viscosity, etc.). 1-parameter turbulence model.

One side (+y) is open, other 5 are closed.

Future coupling will include thermal source term from Aria arc model going into Fuego.

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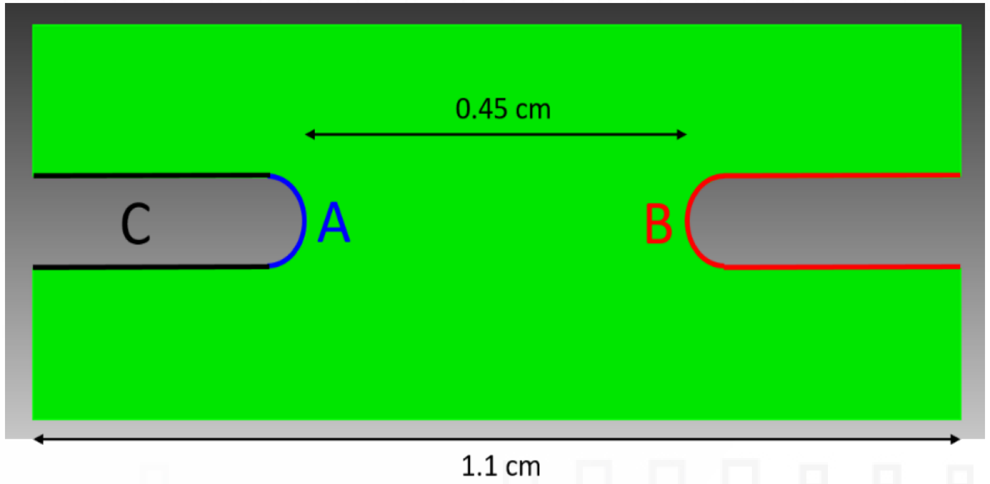
Electric arc simulation

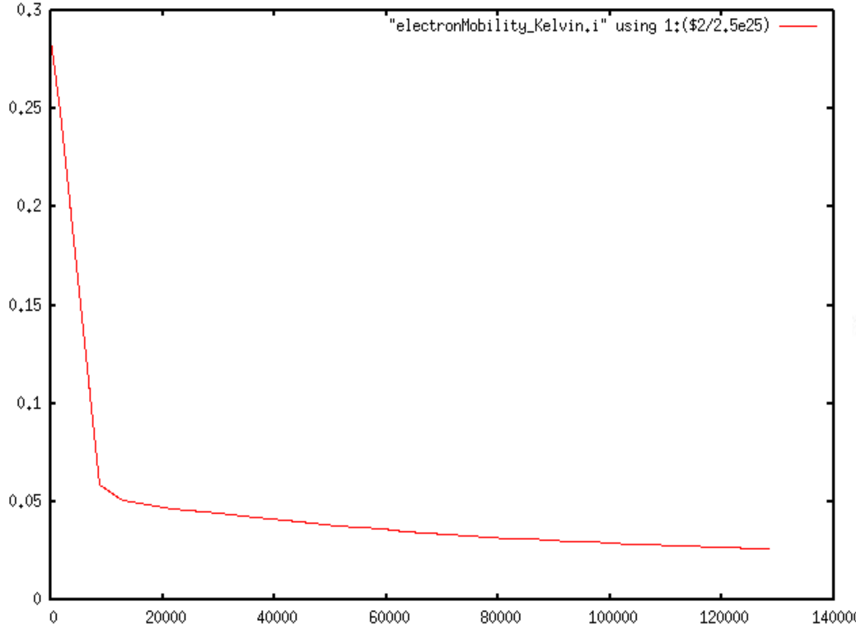
- Small model for equation verification. Two-dimensional simulation with cathode (A,C) and anode (B)

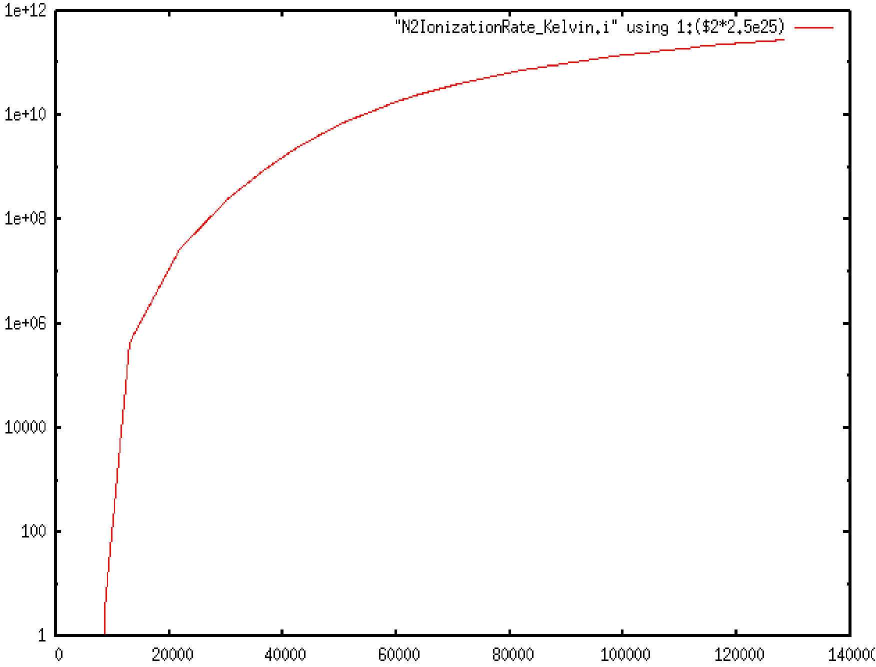


- Temperature dependent transport coefficients and collision rates (right images)

- Voltage of 1000 V applied to B, A and C boundaries set to V = 0

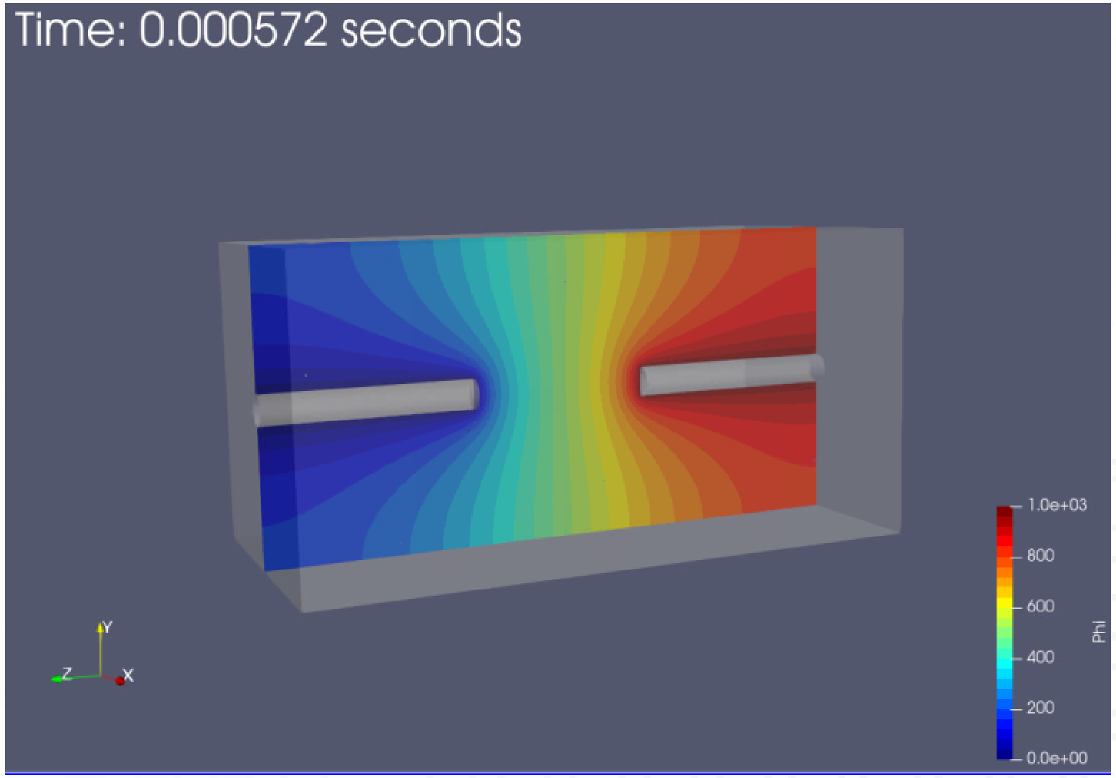
- Influx of electrons on surface A which is ramped over 1 microsecond



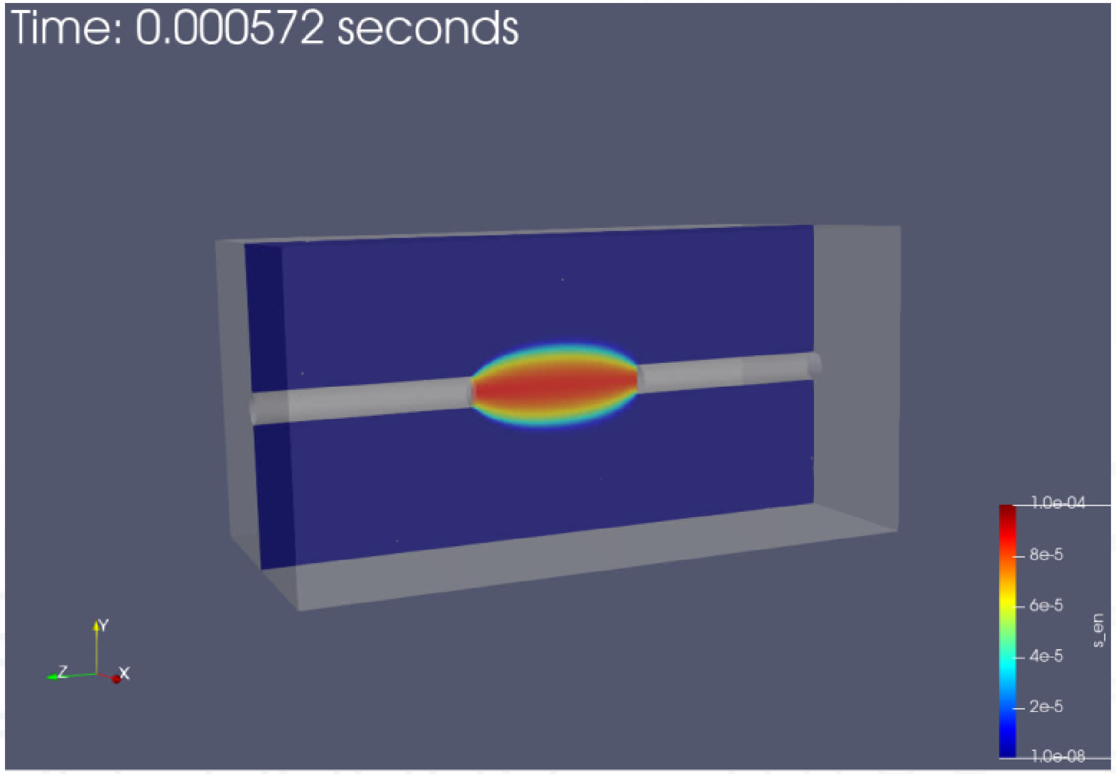


Towards larger arcs

Electrostatic potential (no space charge)



Electron density at 500 A, 1000 V.



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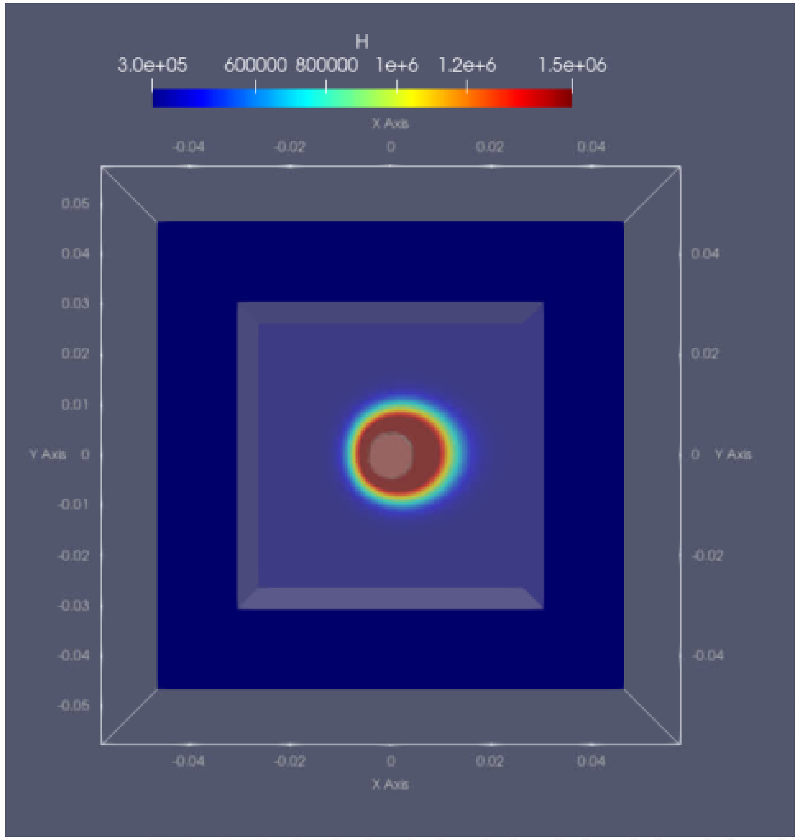
3D Aria Simulations

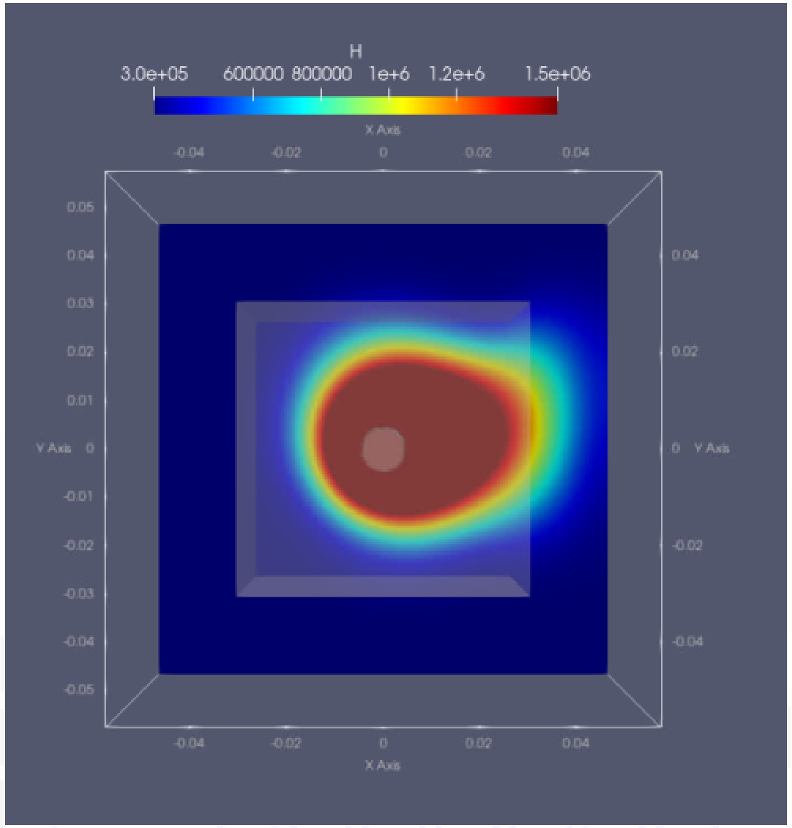
Enthalpy

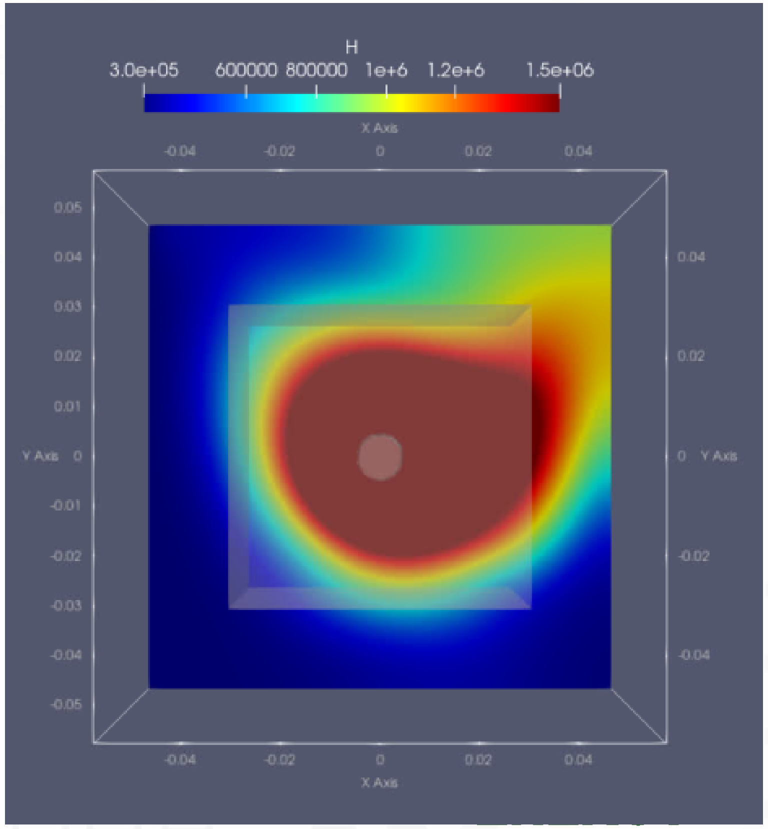
t = 0.45 s

t = 3.45 s

t = 10 s







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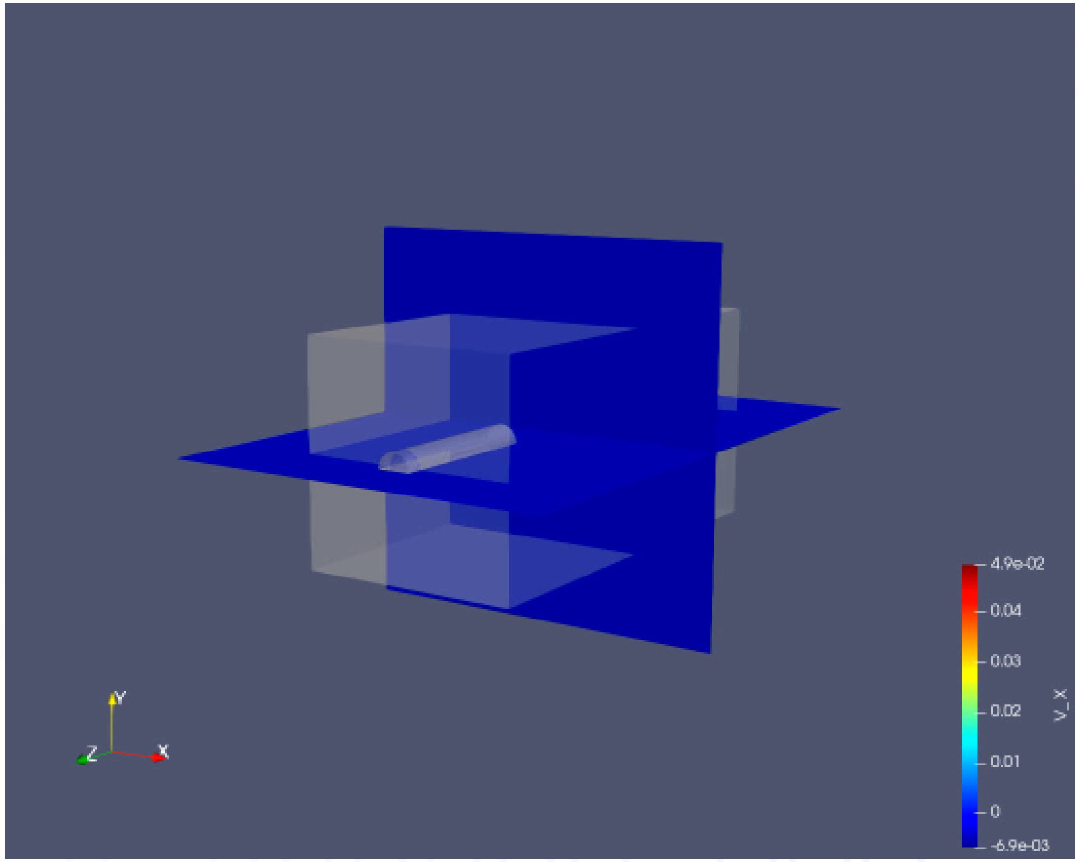
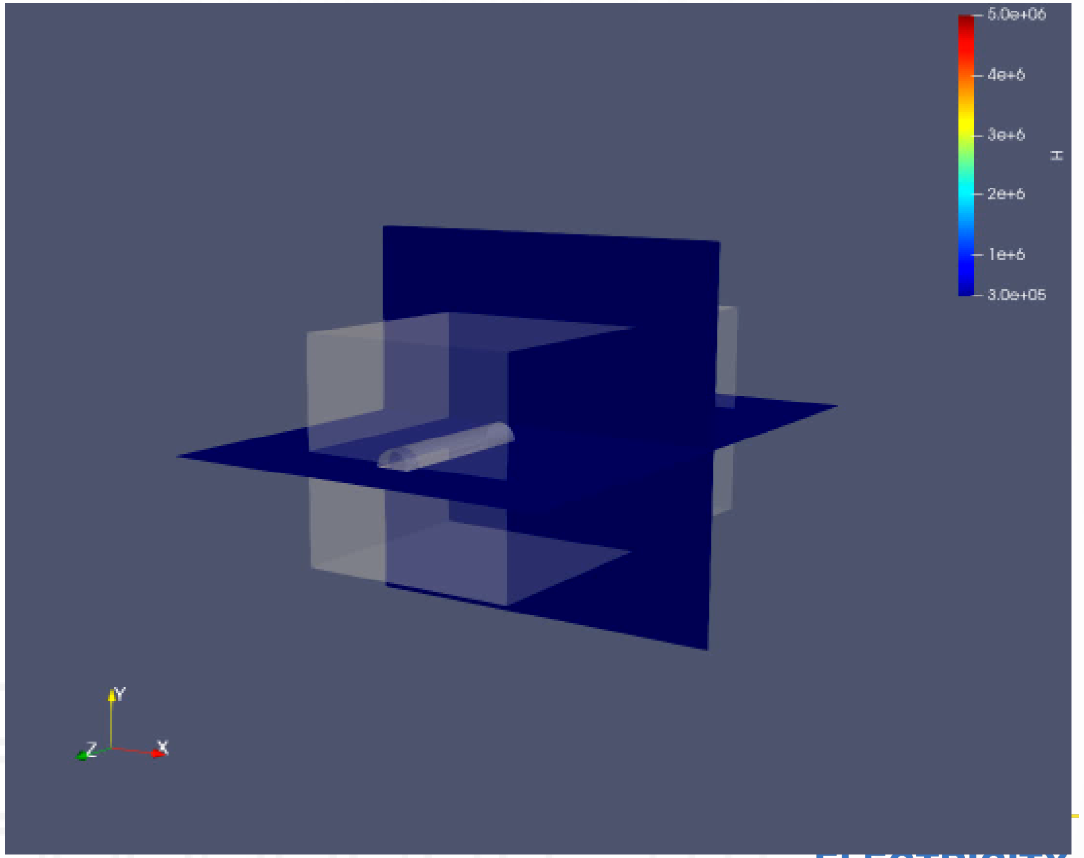
3D Aria Simulations

Evolution of Enthalpy and Velocity

Velocity

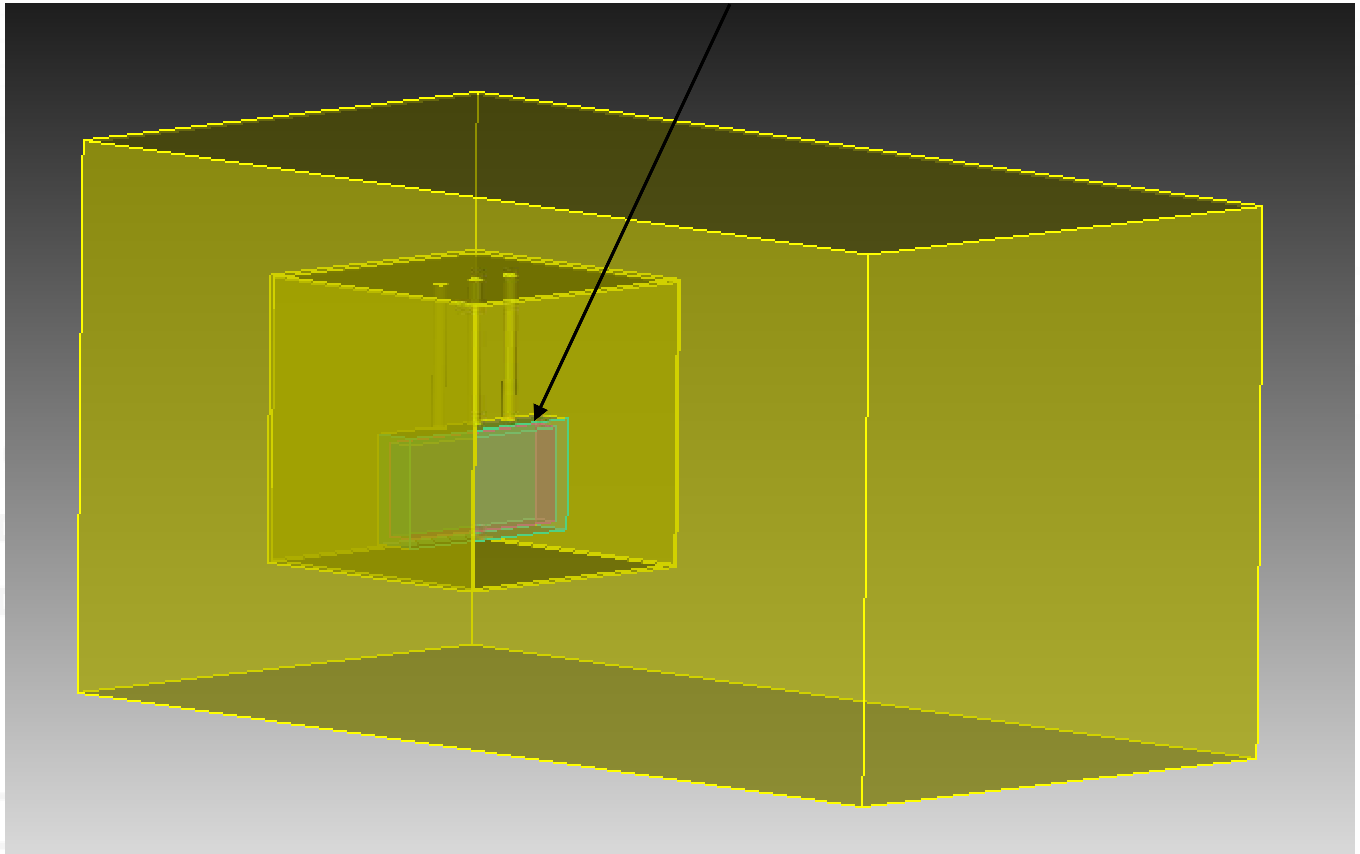


Enthalpy



3D Aria Simulations – Exemplar Type Geometry

Energy source region, P = 5 x 10^7 W/m^3 (Approximately 500 V, 500 A Arc)



Equations solved:

- Momentum
- Continuity
- Energy

40 million elements

Sources:

- Constant energy source between electrodes
- Boussinesq approximation for Buoyancy
  - Electrodes are vertical with respect to gravity

200 cm x 100 cm x 100 cm simulation domain

3 vertical electrode configuration in a 51 cm x 51 cm x 51 cm open box

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Conclusions

- SNL has arc-fault capabilities used for characterizing DC & AC applications.
- Photovoltaic (PV) electrical power systems have facilitated documented electrical system fires due to arc-faults within modules or balance of systems (BOS), impacting electrical safety and DC systems adoption.
- Determination of nominal and largest current leakage for “health” PV systems.
- 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.
- Development of novel self-extinguishing materials and components to arrest arc-faults.
- Knowledge of power radiated versus power convected by the arc is critical to understanding how high energy arc-faults will effect their surrounding

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