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Poly(dicyclopentadiene) Coatings for the Mitigation of Surface Flashover in Gas Switch Housings

CEIDP 2022

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High Voltage Gas Switches

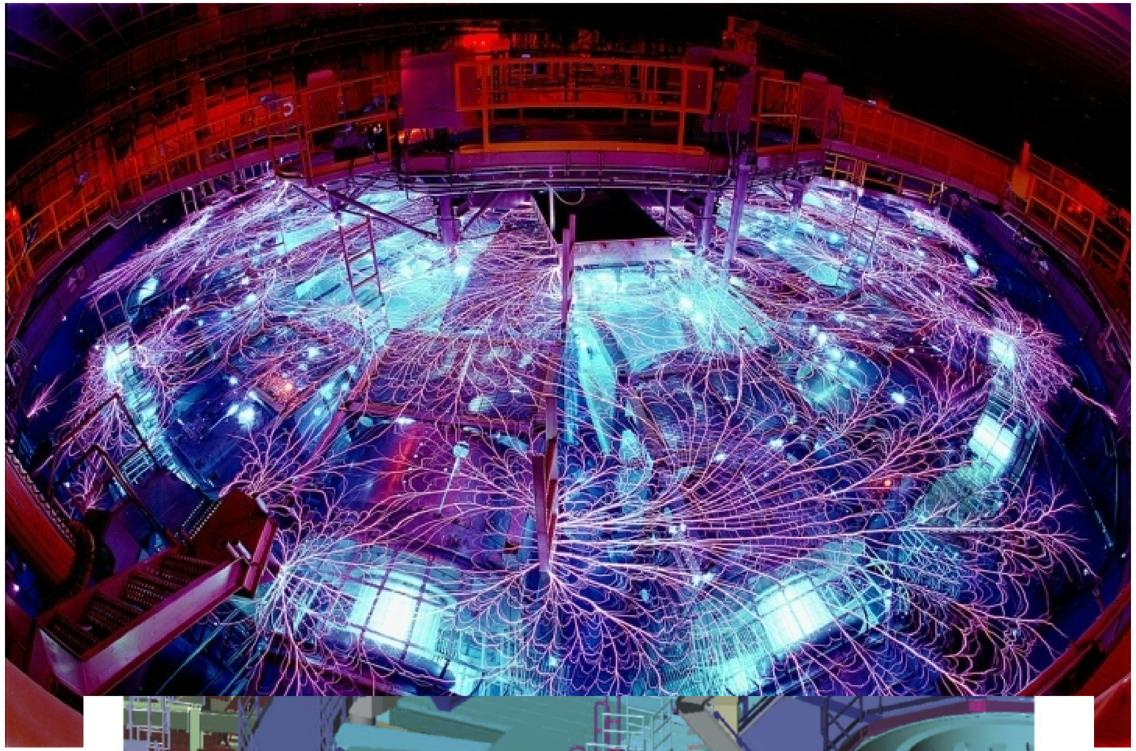
<u>Challenge:</u> Improve the reliability of high voltage gas switches

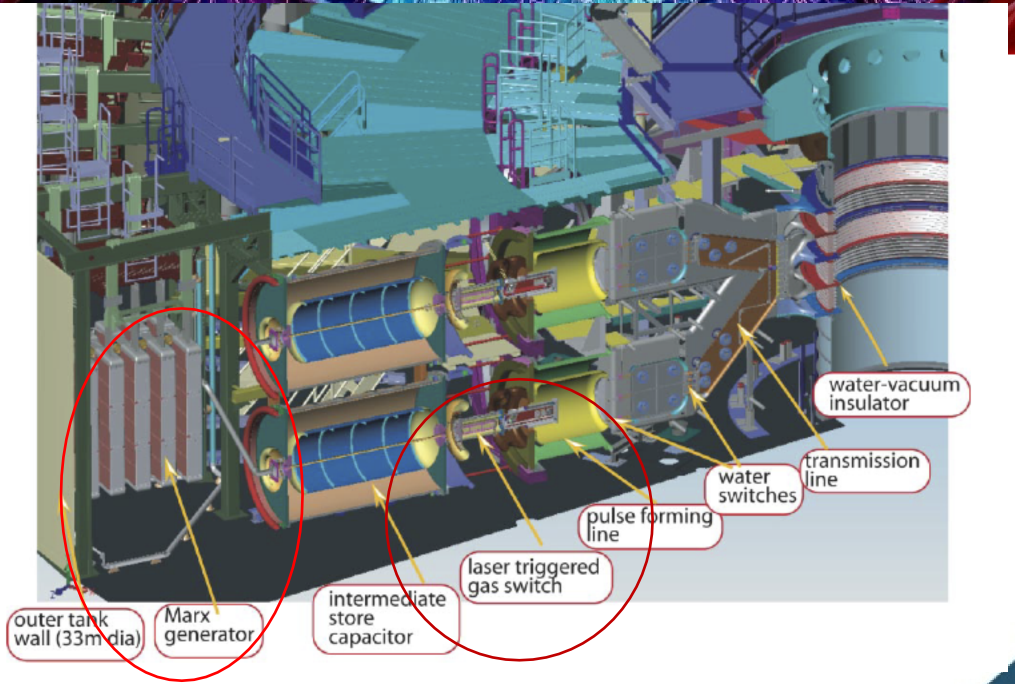
- Flashover of the housing is one of the leading causes of switch failure

<u>Goal:</u> Develop a novel polymer coating for gas switch housings that reduce flashover occurrences

<u>Hypotheses:</u>

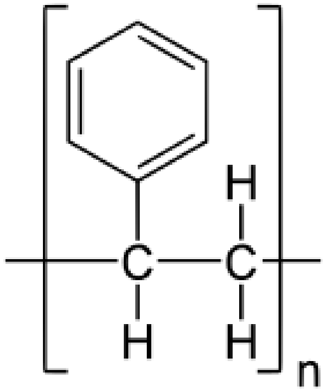
- Higher oxygen content acts as trap sites for free electrons
- Self-clearing can be achieved by increasing the oxygen/hydrogen-to-carbon ratio preferentially creating CO_2 or CH_4 rather than graphitic carbon after a flashover event



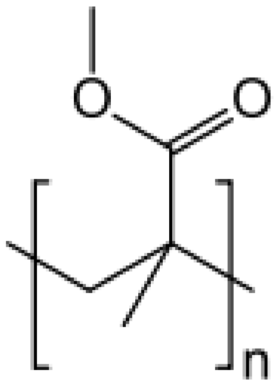


Materials Used

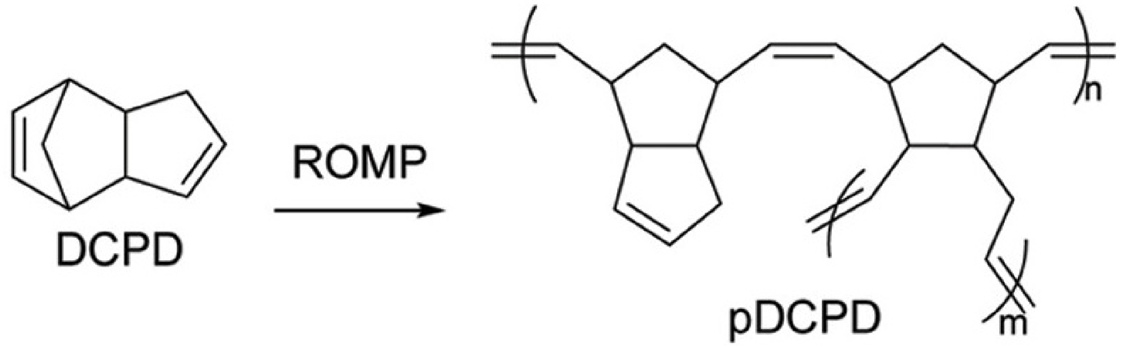
- Rexolite (cross-linked polystyrene)
  - Currently used as insulator in water-insulator-vacuum section
- PMMA (poly(methyl methacrylate))
  - Currently used as insulator in most gas switch housings
  - Two types tested: extruded and cast
- pDCPD (poly(dicyclopentadiene))
  - Novel polymer under investigation
  - In-house and Proxima* formulations used
  - Thermal treatment accelerates oxidation process



Rexolite (polystyrene)



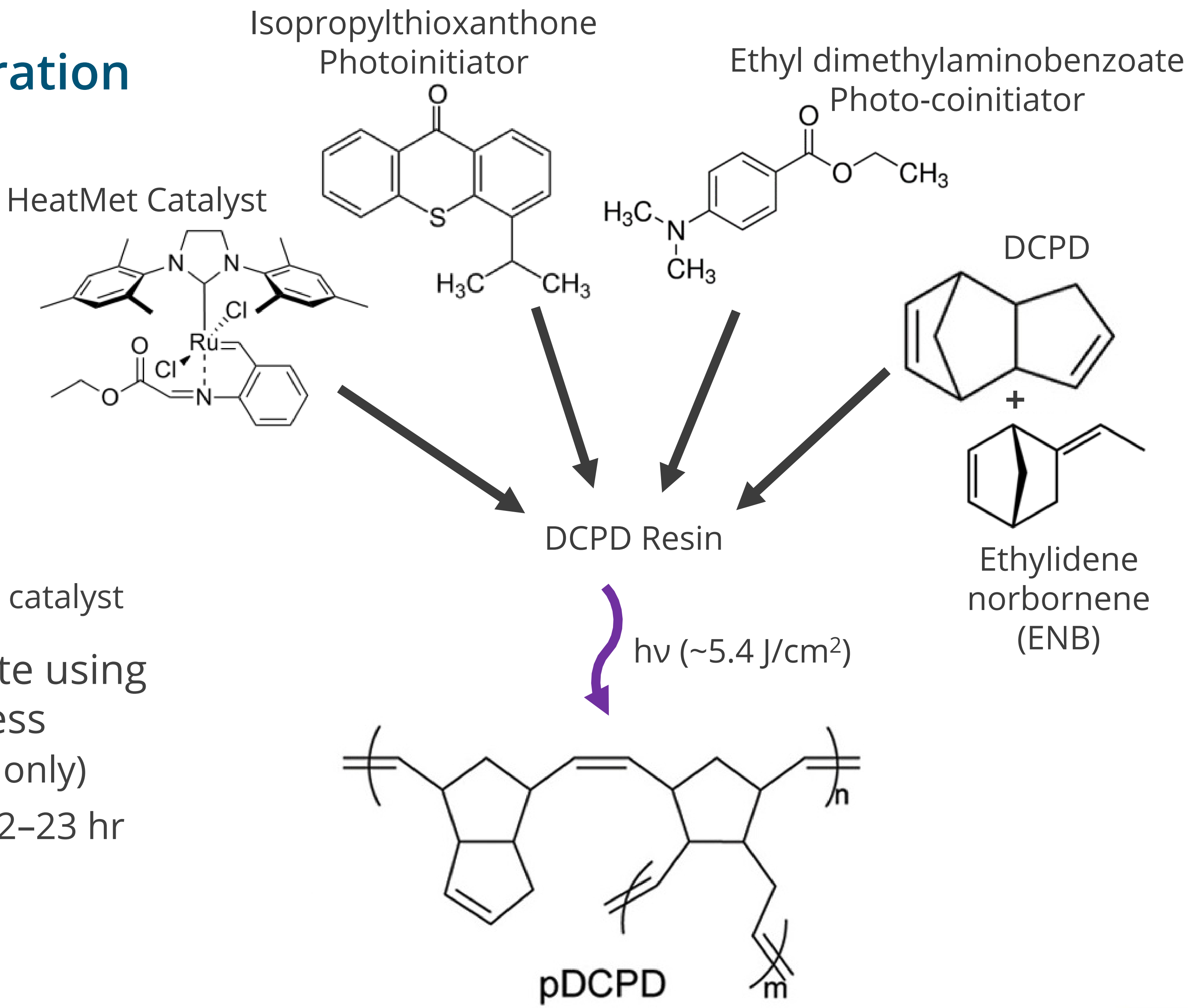
PMMA



*Proxima® HPR-2102/CT-762 from Materia, Inc.

pDCPD Sample Preparation

- DCPD resin preparation
  - In-house resin
    - Catalyst
    - Photoinitiator
    - Photo-coinitiator
    - 95:5 (wt%) DCPD and ENB
  - Proxima
    - Proprietary DCPD-based resin and catalyst
- Coated onto cast PMMA substrate using doctor blade for uniform thickness
  - UV cured for 90–270 s (in-house only)
  - Thermal treatment at 100°C for 2–23 hr



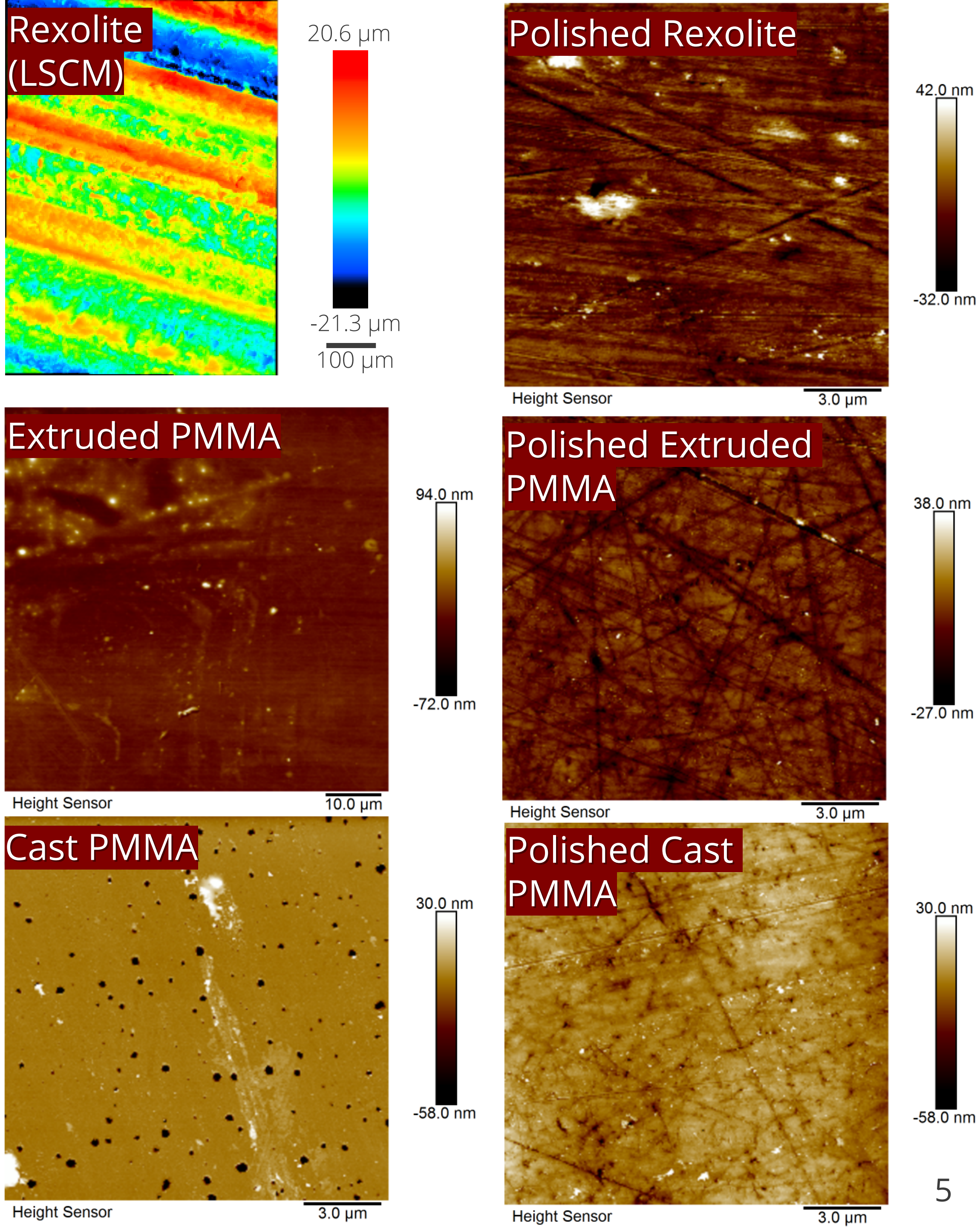
Atomic Force Microscopy

- Rexolite, extruded & cast PMMA, and pDCPD-coated PMMA were characterized for surface roughness
  - Polished samples of the purchased materials were also prepared to have similar surface roughness values

Surface Roughness (Sa values)

	As Received (nm)	Polished (nm)
Rexolite	1,910±760*	5.3±1.0
Extruded PMMA	7.6±5.5	4.7±1.2
Cast PMMA	3.2±1.2	4.8±1.3
In-house pDCPD	6.2±7.2	--
Proxima pDCPD	17.6±7.3	--

* Values from Laser Scanning Confocal Microscopy



Atomic Force Microscopy

- Rexolite, extruded & cast PMMA, and pDCPD-coated PMMA were characterized for surface roughness
  - In-house pDCPD showed two types of surfaces, a more common fairly flat surface and a honeycomb surface

Surface Roughness (Sa values)

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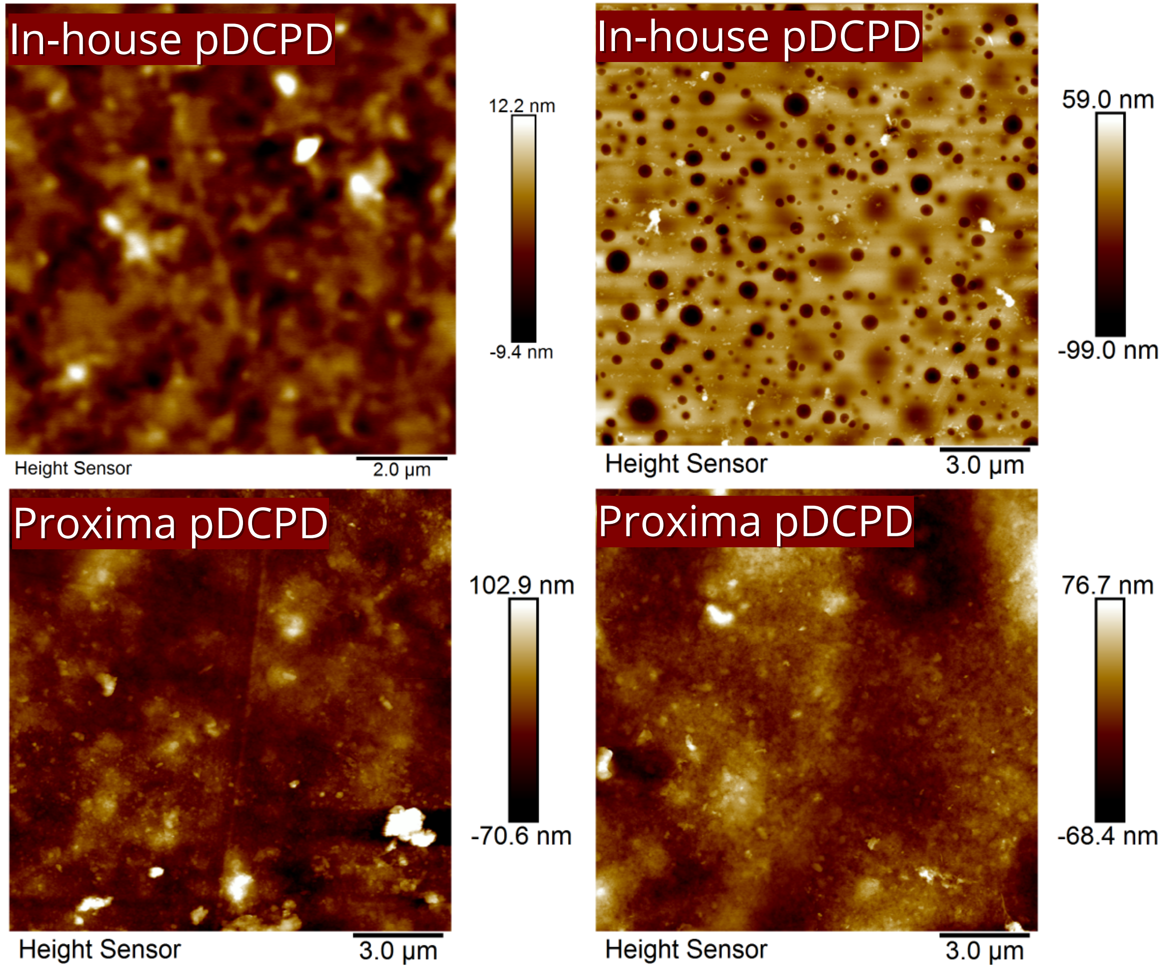
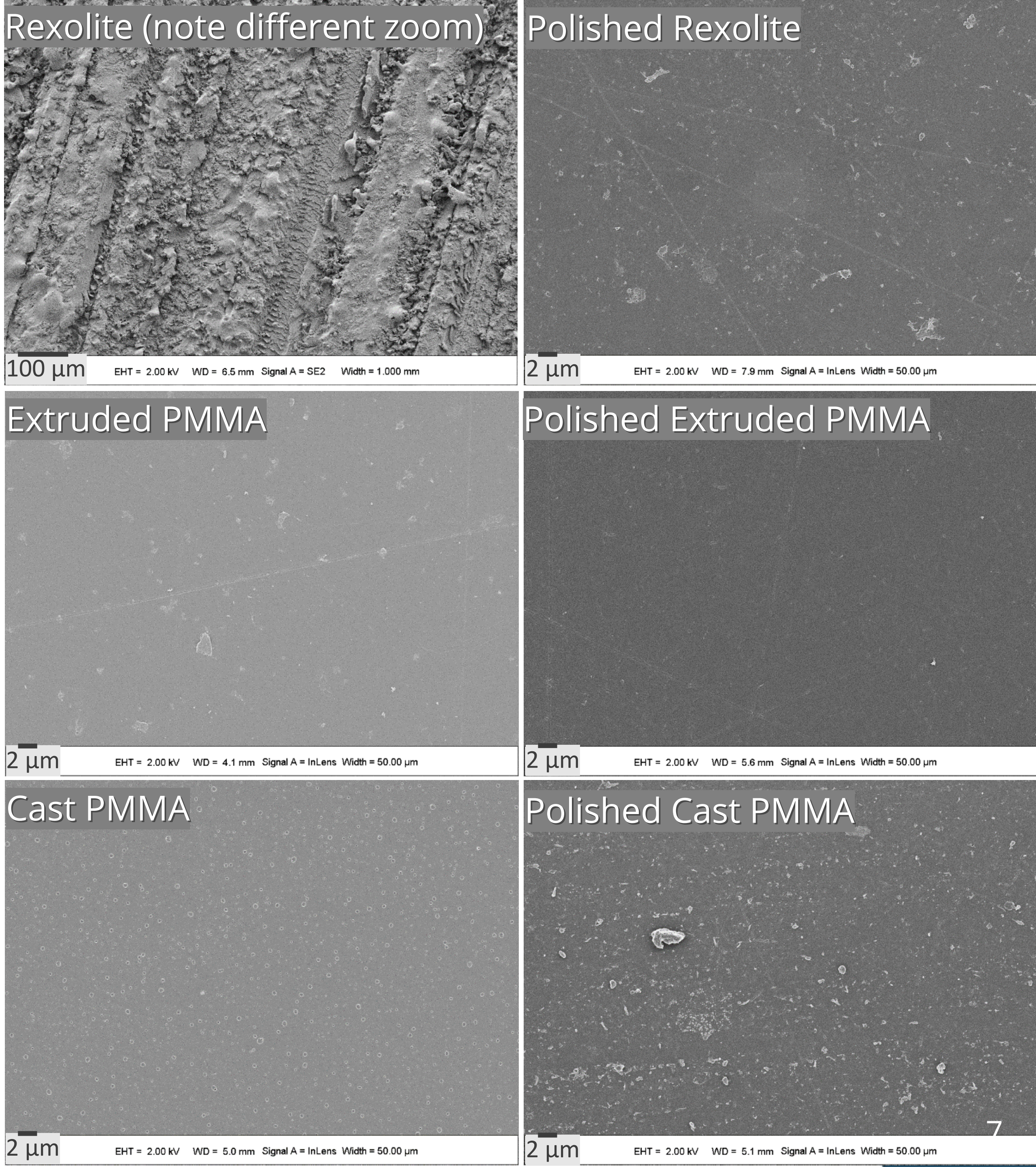


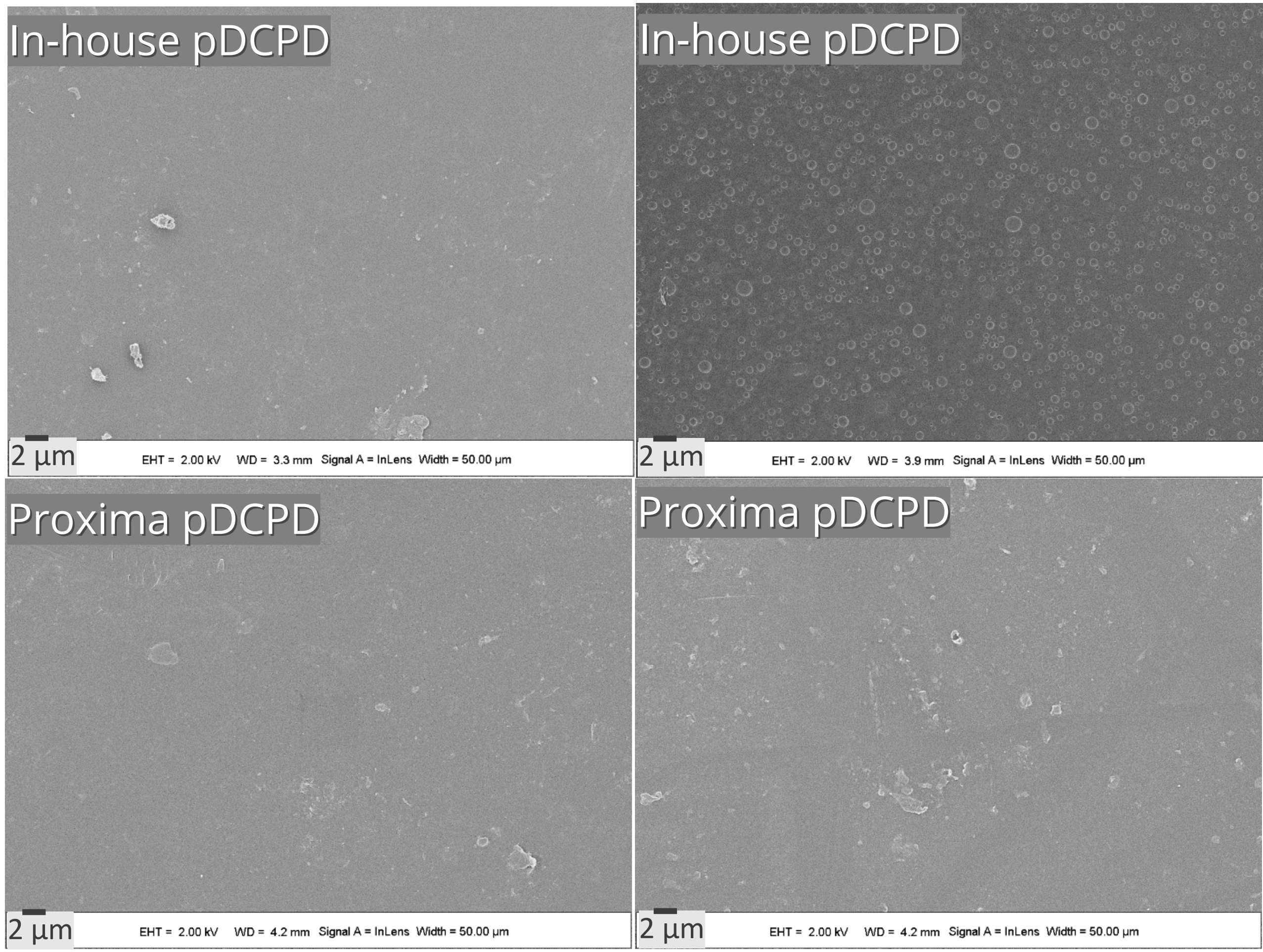
Scanning Electron Microscopy

- Images were also taken to observe the variation in the polymer surfaces
- As-received Rexolite was substantially rougher than others
- A number of small asperities are noted on the surfaces
  - Polished samples are generally smooth with some polishing marks



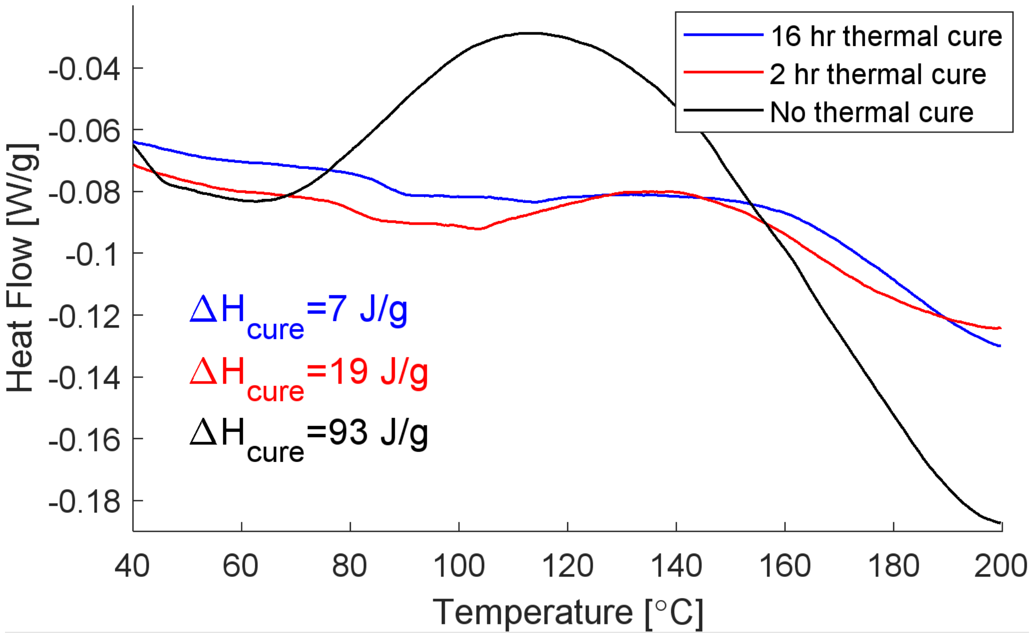
Scanning Electron Microscopy

- Images were also taken to observe the variation in the polymer surfaces
- A number of small asperities are noted on the surfaces
  - Some areas on the in-house pDCPD show the honeycomb structures noted in AFM

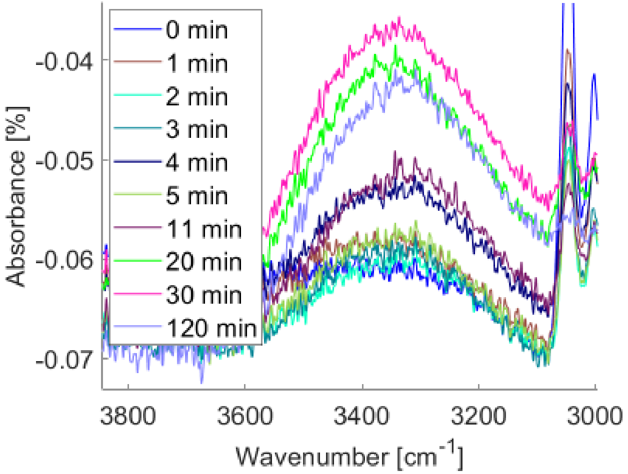


In-house pDCPD Characterization

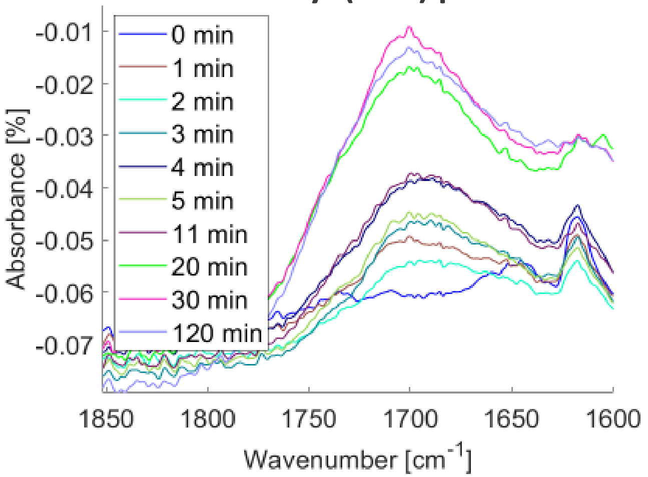
- Differential Scanning Calorimetry (DSC) was used to characterize the extent of cure
  - Residual cure found by integrating the area under the thermogram
- Fourier-Transform Infrared Spectroscopy (FTIR) was used to characterize the extent of oxidation
  - An increase in the C=O (carbonyl) and OH bonds show increasing extent of oxidation with increasing time at 100°C
  - Initial oxidation takes < 5 min
  - Appears fully oxidized after 20 min



Hydroxyl (OH) peak



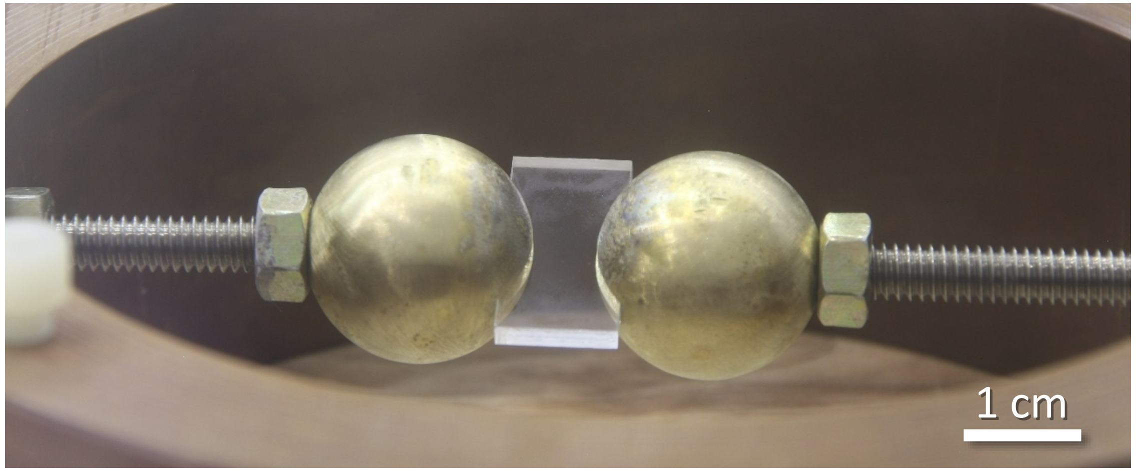
Carbonyl (C=O) peak

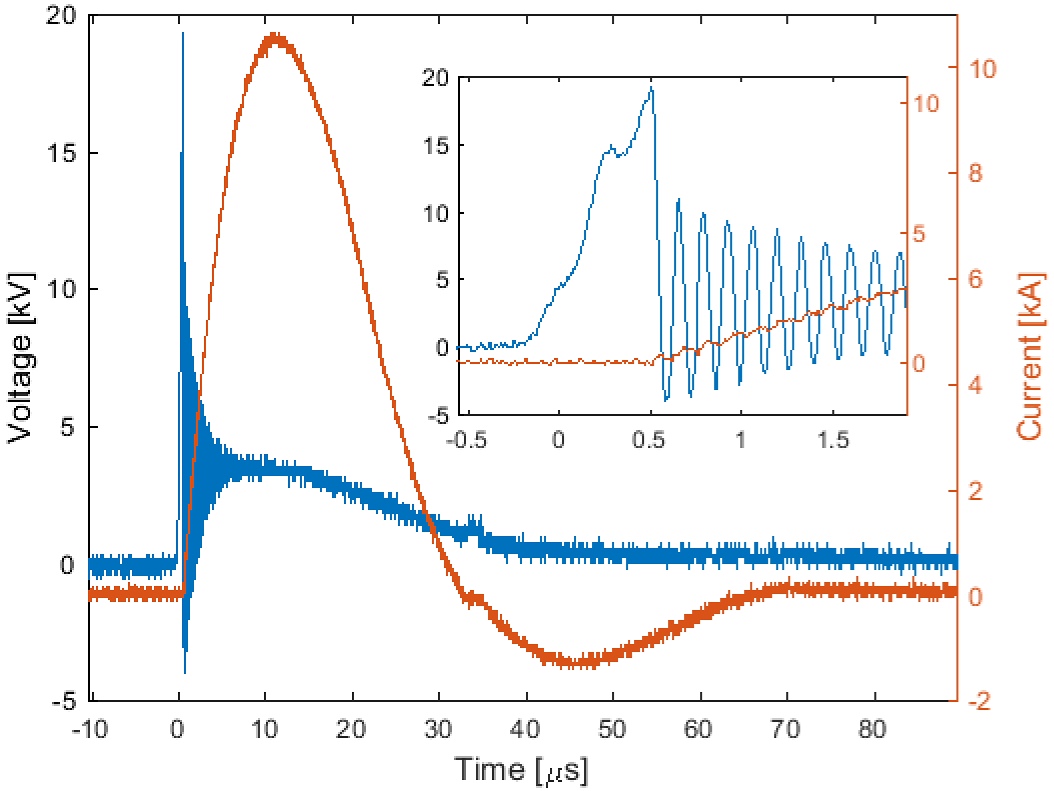


90s UV treatment for all samples at 60 mW/cm^2 (5.4 J/cm^2)

Electrical Characterization

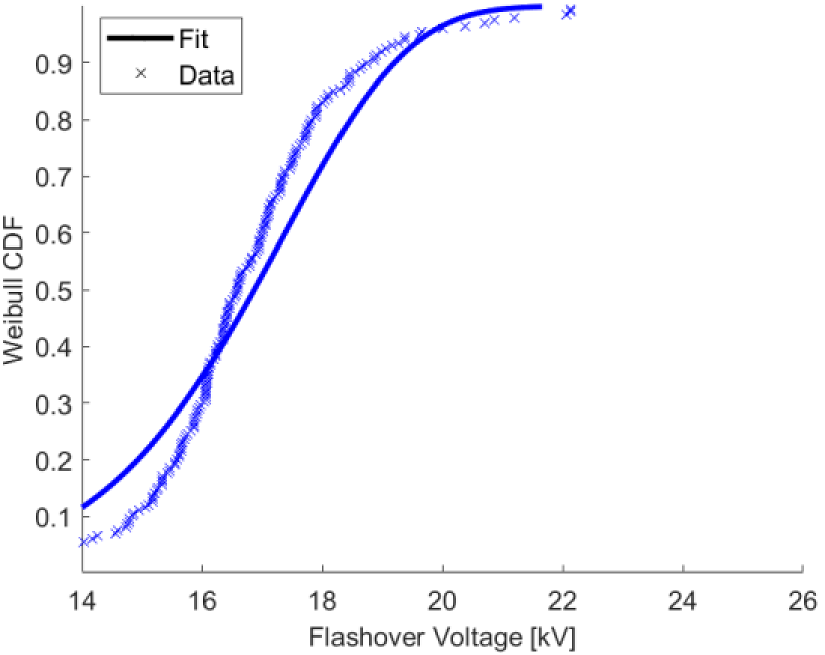
- Polymer sample slotted in a machined groove between two spherical electrodes
  - Environmental conditions (humidity, temperature, etc.) were not well controlled—discharges conducted in ambient air
- PG 24–2500 surge test generator from HILO-Test GmbH
  - 24 kV max voltage
  - 1.2/50 μs standard impulse voltage
    - 1.2 μs front time, 50 μs time to half voltage
  - Voltage measurements taken using a Tektronix 6015 high voltage probe
  - Current measurements taken using a Pearson 110A current transformer
- Generally 20 discharges/sample
  - 2 Rexolite and 1 in-house pDCPD were tested for 40 shots without any noticeable trend deviations
  - Top or bottom surface can flash

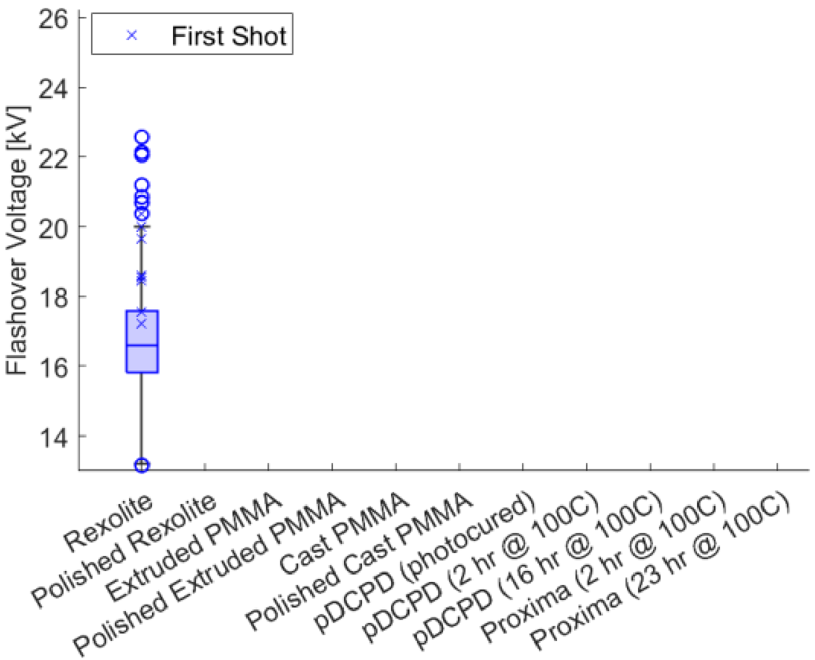


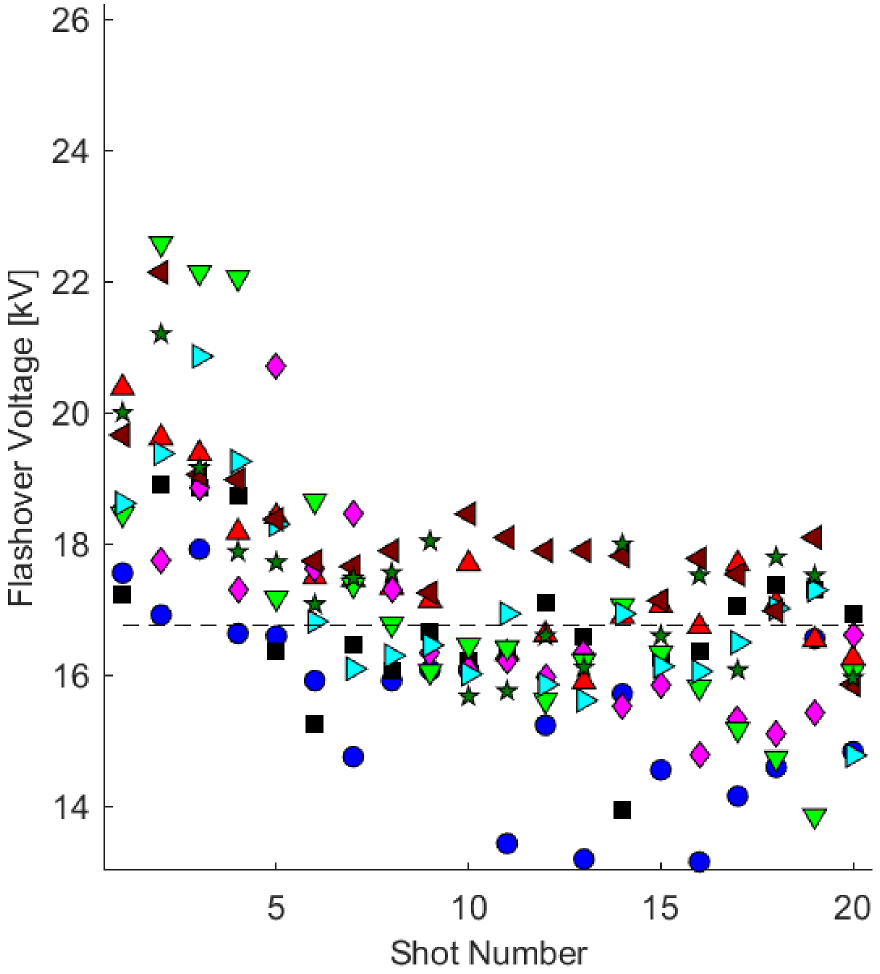


Electrical Characterization—As-Received Rexolite

- Rexolite shows clear decrease after initial few flashover events
  - Appears fairly constant after initial flashover events



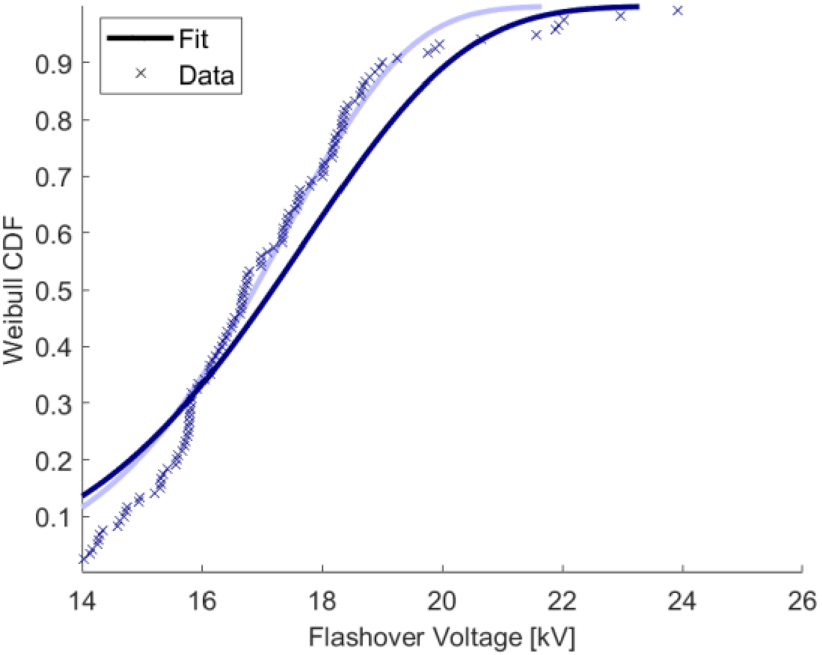


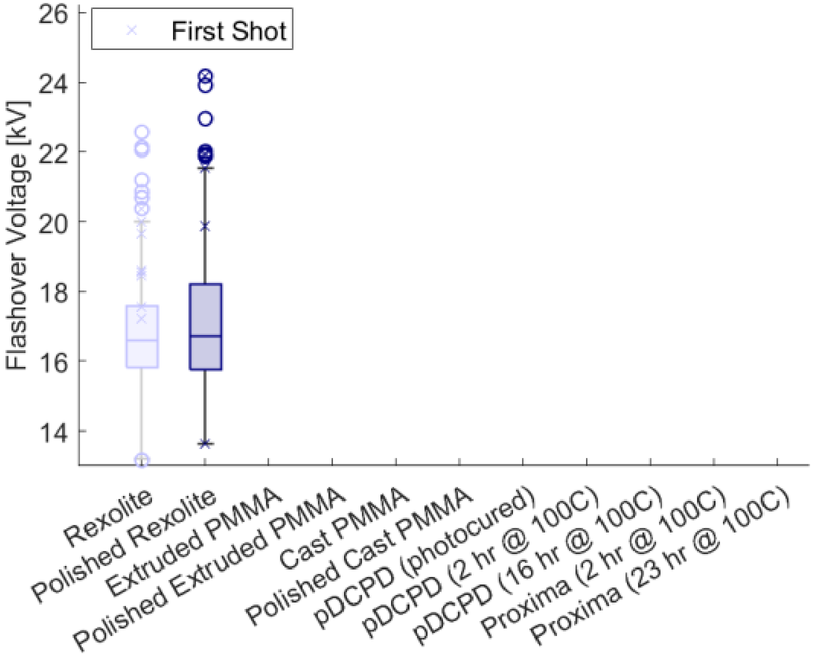


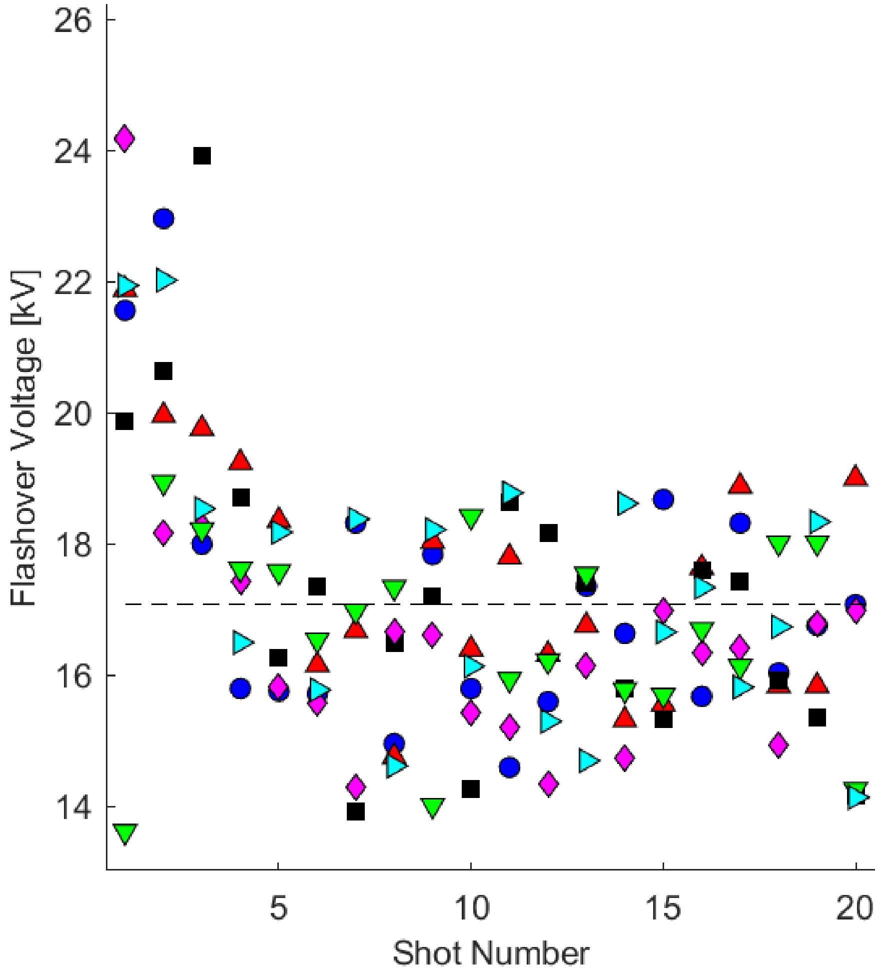
Mean V_F (kV, $\mu \pm \sigma$)	16.8 ± 1.7
Weibull Scale, α (kV)	17.6
Weibull Shape, β	9.28
# Samples (# Shots)	8 (199)

Electrical Characterization—Polished Rexolite

- Polished Rexolite shows clear decrease after initial few flashover events
  - Appears fairly constant after initial flashover events
- Polishing appears to have no effect
  - Behavior is not surface roughness dependent



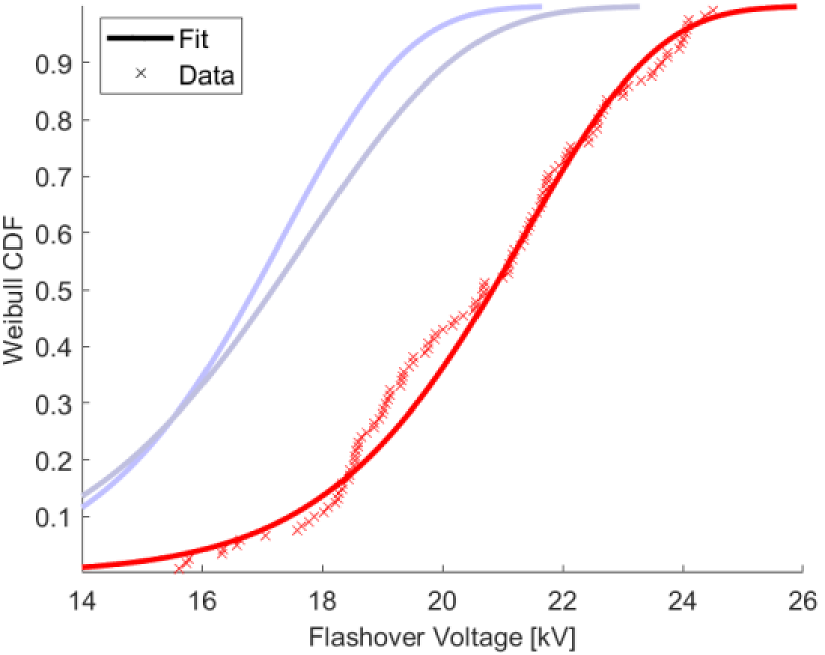


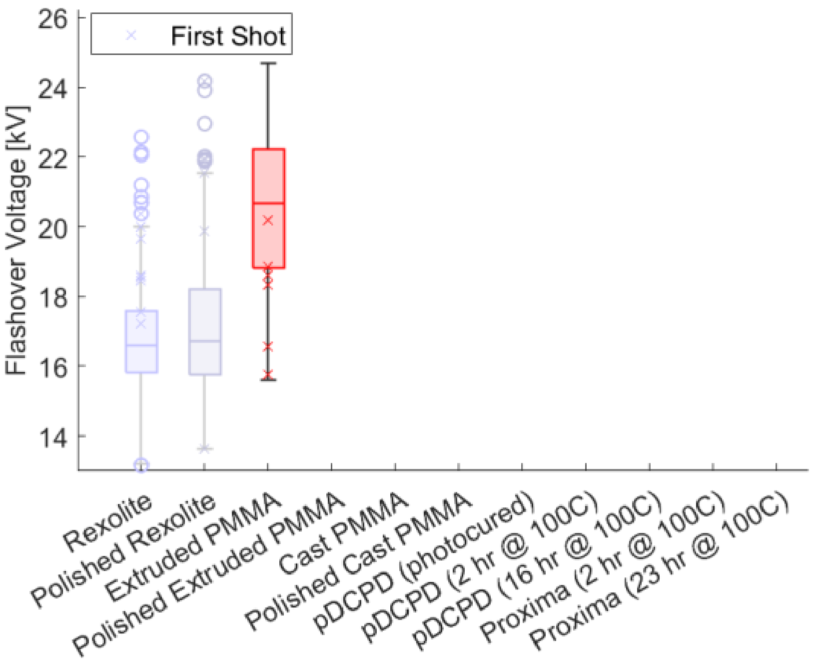


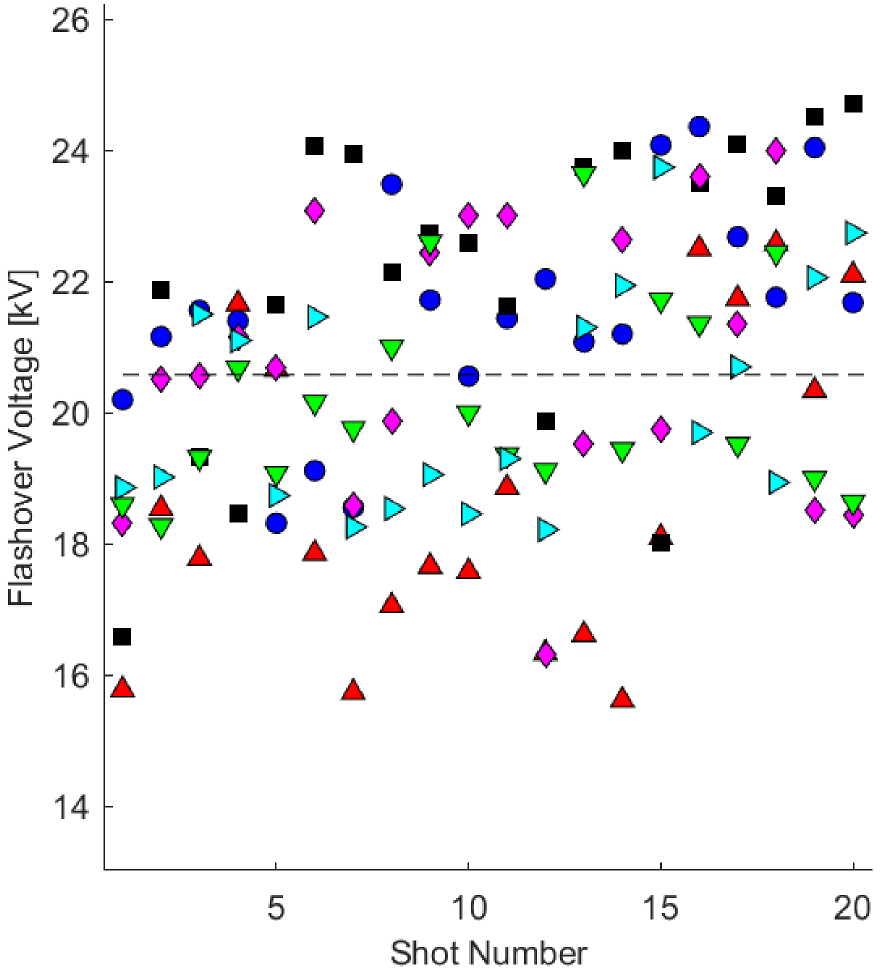
Mean V_F (kV, $\mu \pm \sigma$)	17.1 ± 2.0
Weibull Scale, α (kV)	18.0
Weibull Shape, β	7.62
# Samples (# Shots)	6 (120)

Electrical Characterization—As-Received Extruded PMMA

- Extruded PMMA does not show any clear trend with the number of flashover events
- Flashover voltage is higher than Rexolite



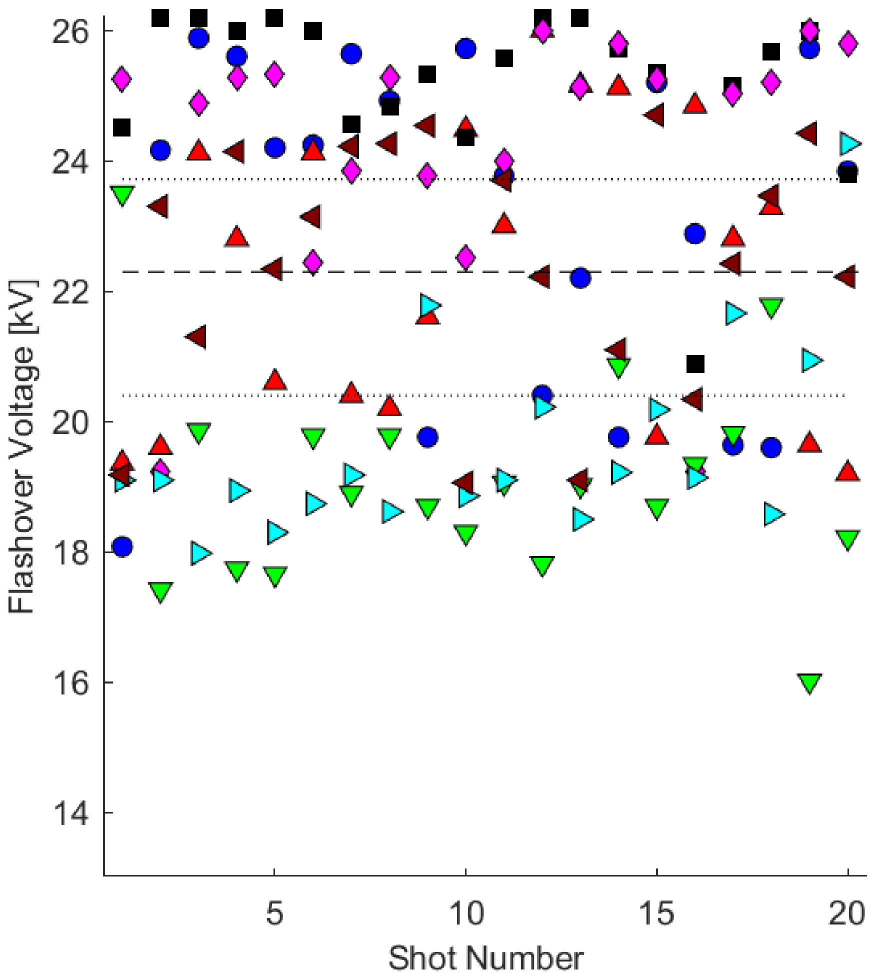


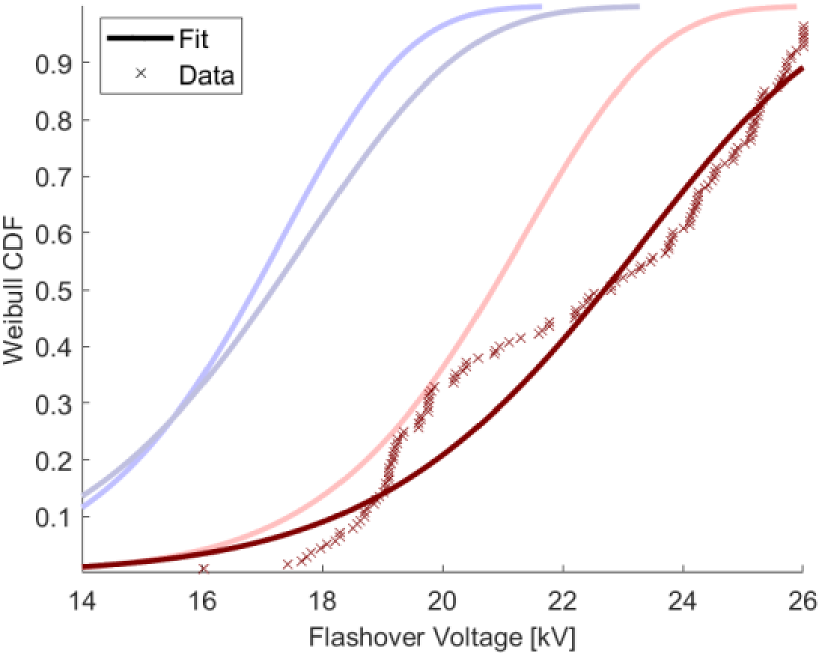


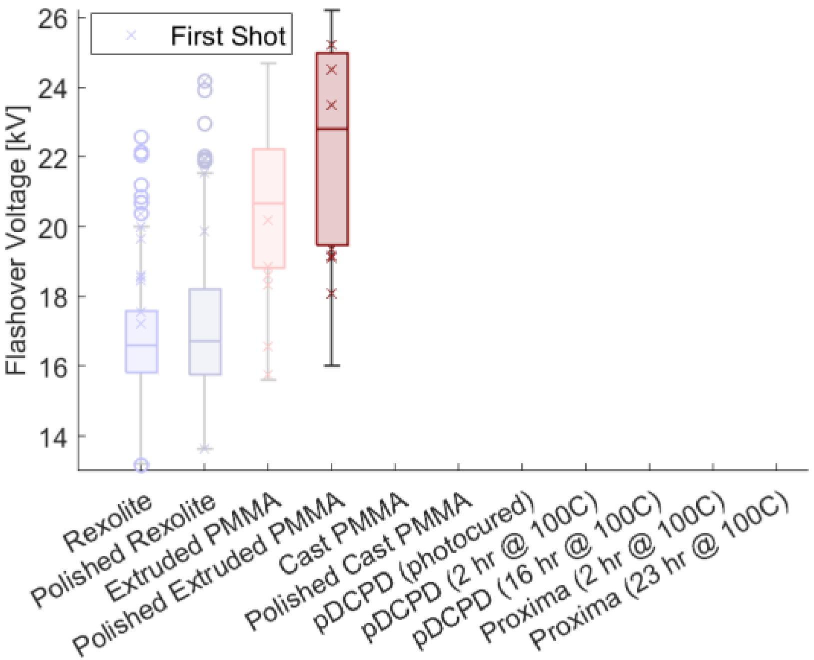
Mean V_F (kV, $\mu \pm \sigma$)	20.6 ± 2.2
Weibull Scale, α (kV)	21.6
Weibull Shape, β	10.66
# Samples (# Shots)	6 (121)

Electrical Characterization—Polished Extruded PMMA

- Polished sample have higher flashover voltage compared to unpolished samples
- Polished extruded PMMA had batch-to-batch variation
  - Initial batch had higher flashover voltage
  - Many did not flash at maximum power supply voltage
  - Weibull analysis includes these as censored data



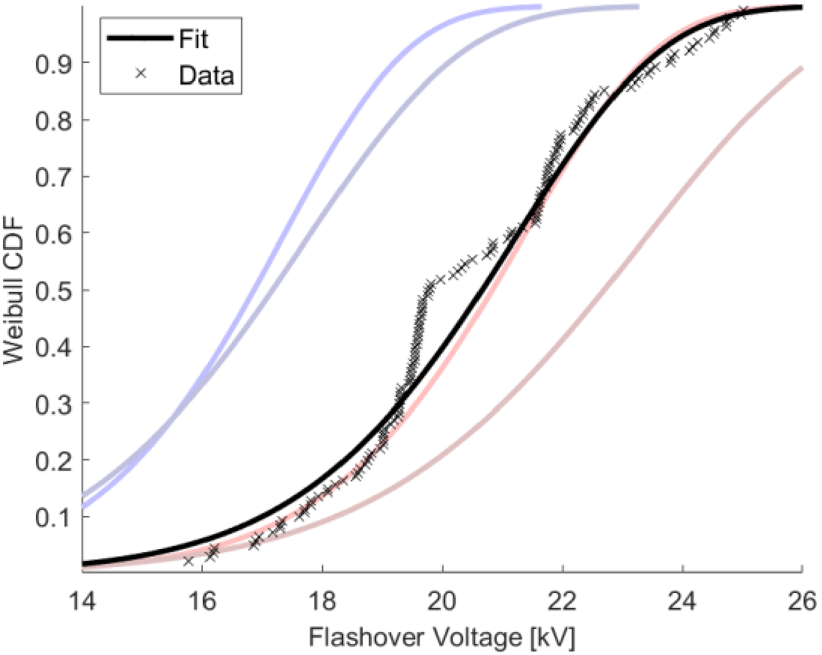


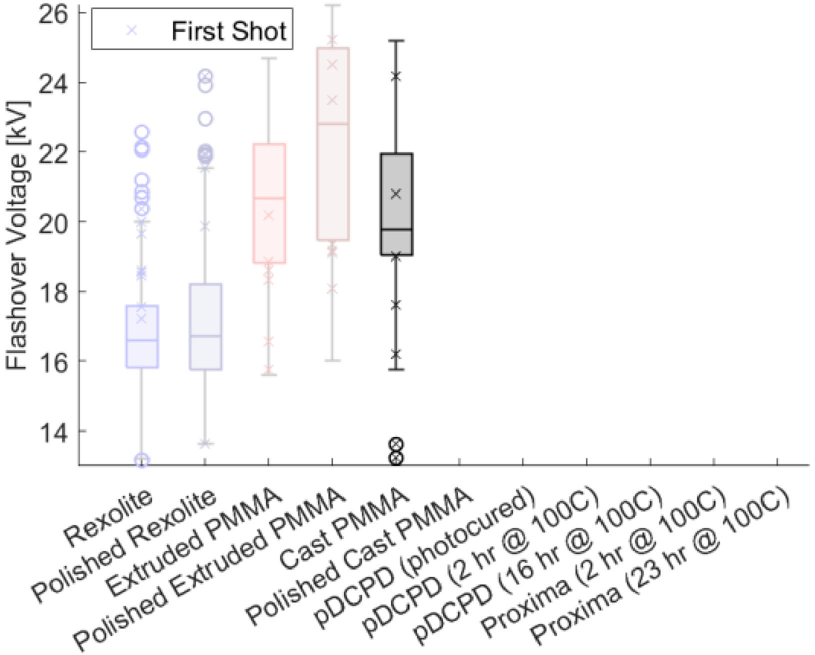


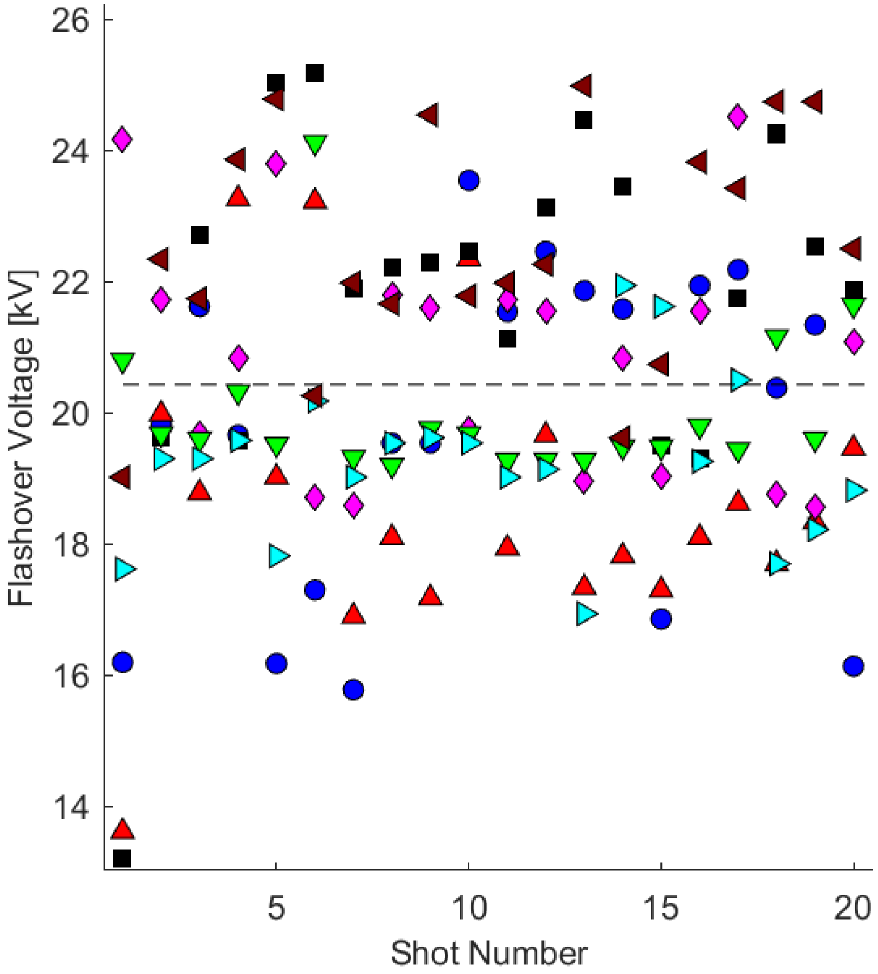
Mean V_F (kV, $\mu \pm \sigma$)	22.3 ± 2.8
Weibull Scale, α (kV)	23.7
Weibull Shape, β	8.59
# Samples (# Shots)	7 (140)

Electrical Characterization—As-Received Cast PMMA

- Cast PMMA is comparable to extruded PMMA
  - Similar flashover voltage
  - Similar standard deviation in flashover voltage



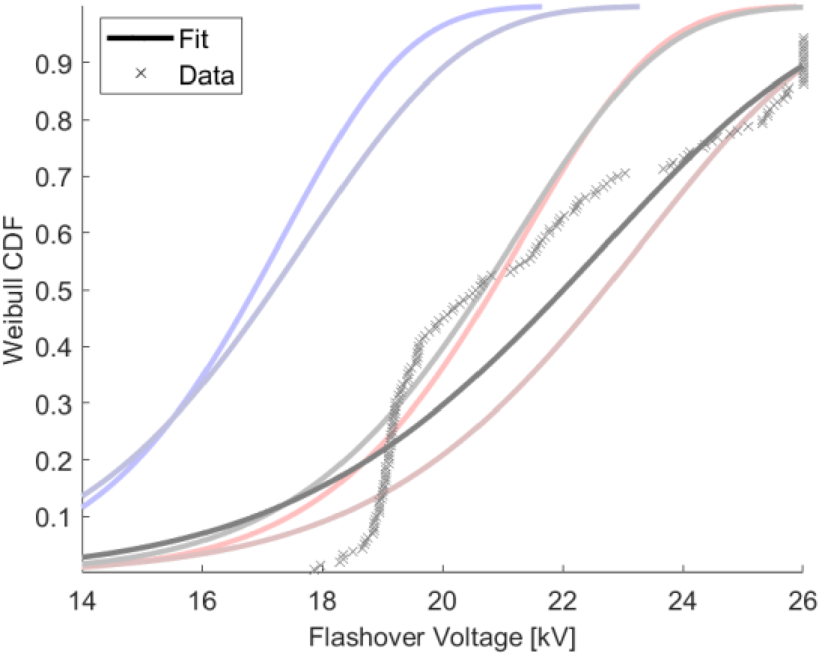


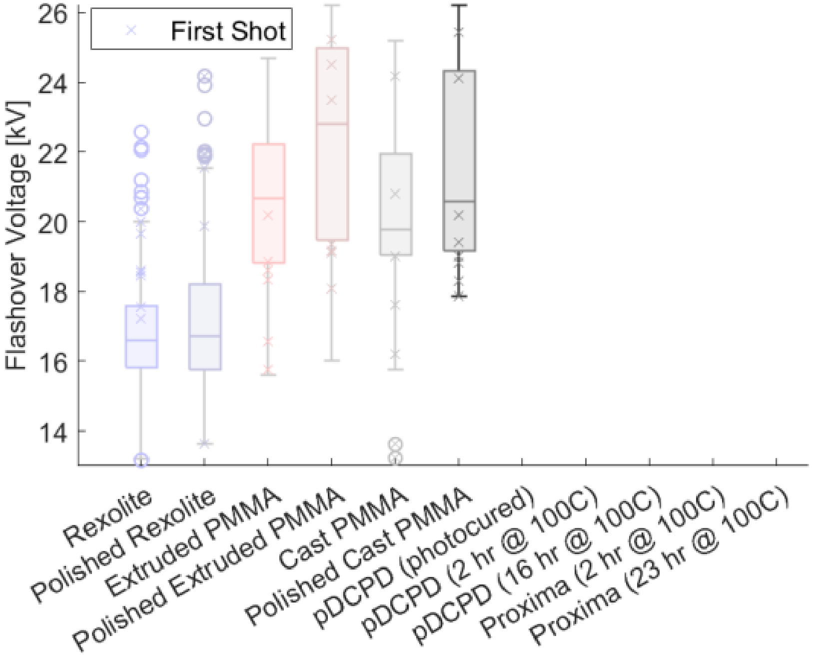


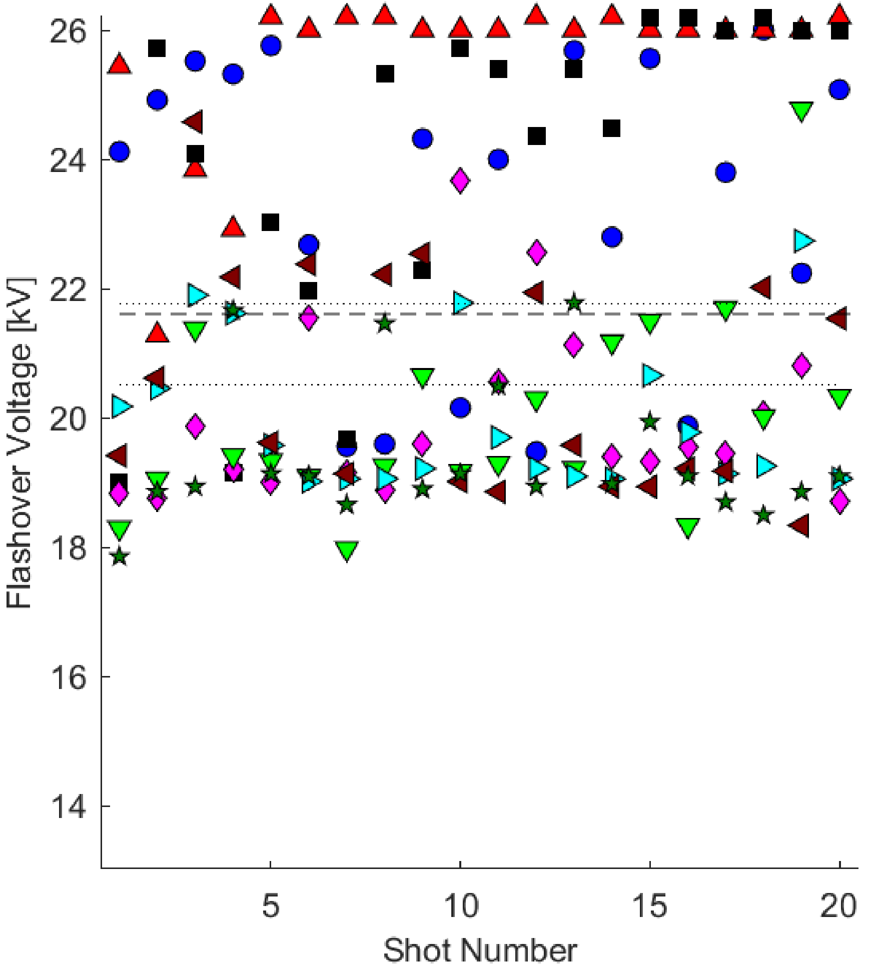
Mean V_F (kV, $\mu \pm \sigma$)	20.4 ± 2.3
Weibull Scale, α (kV)	21.5
Weibull Shape, β	9.68
# Samples (# Shots)	7 (141)

Electrical Characterization—Polished Cast PMMA

- Polished sample have higher flashover voltage compared to unpolished samples
- Polished cast PMMA seems comparable to polished extruded PMMA
  - Similar batch-to-batch variation with initial batch having higher flashover voltage
  - Many did not flash at maximum power supply voltage



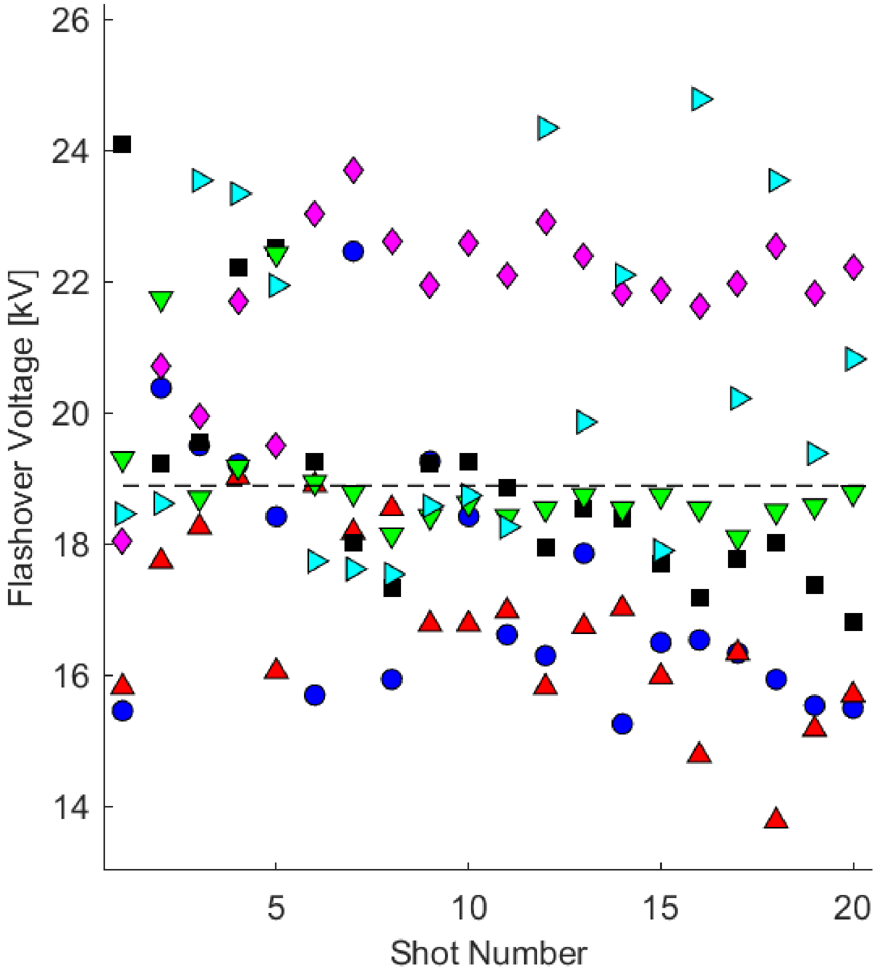


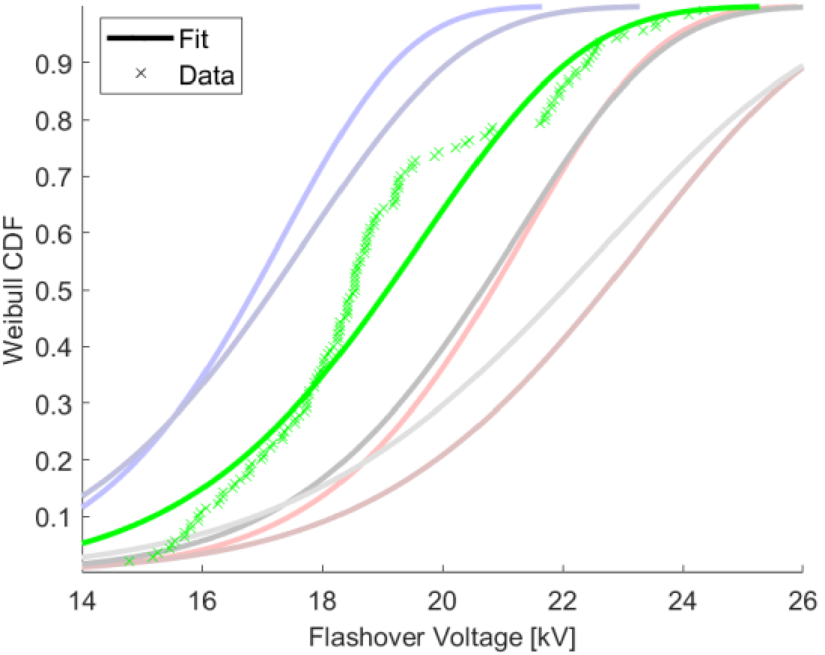


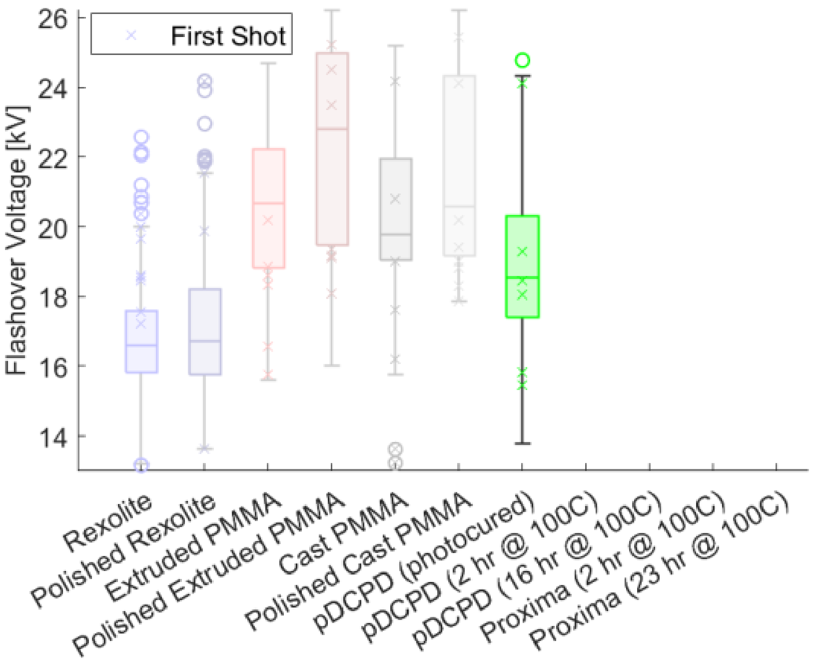
Mean V_F (kV, μ ± σ)	21.6 ± 2.8
Weibull Scale, α (kV)	23.2
Weibull Shape, β	7.09
# Samples (# Shots)	8 (160)

Electrical Characterization—In-house pDCPD (photocure only)

- Flashover voltage is higher than Rexolite but lower than PMMA
- In-house pDCPD does not show any clear trend with the number of flashover events



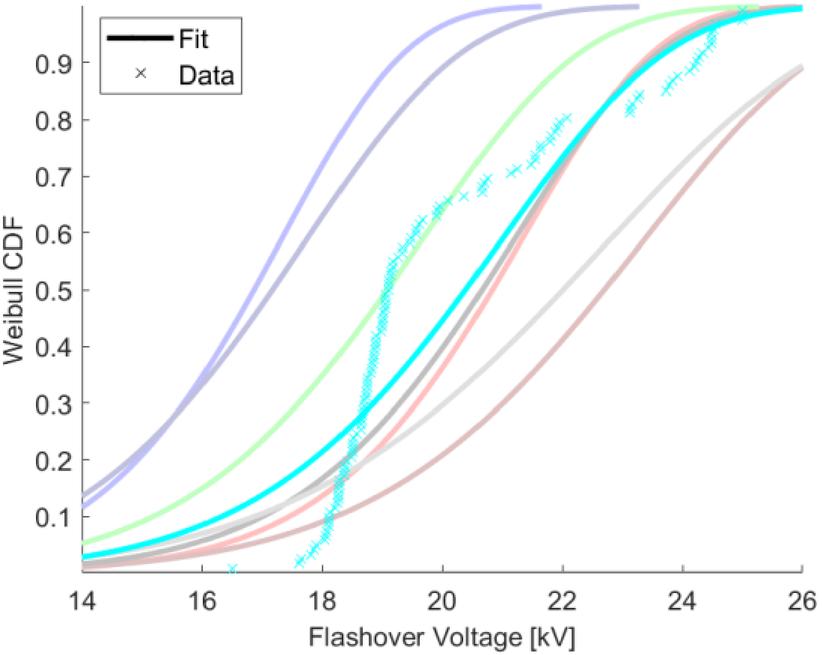


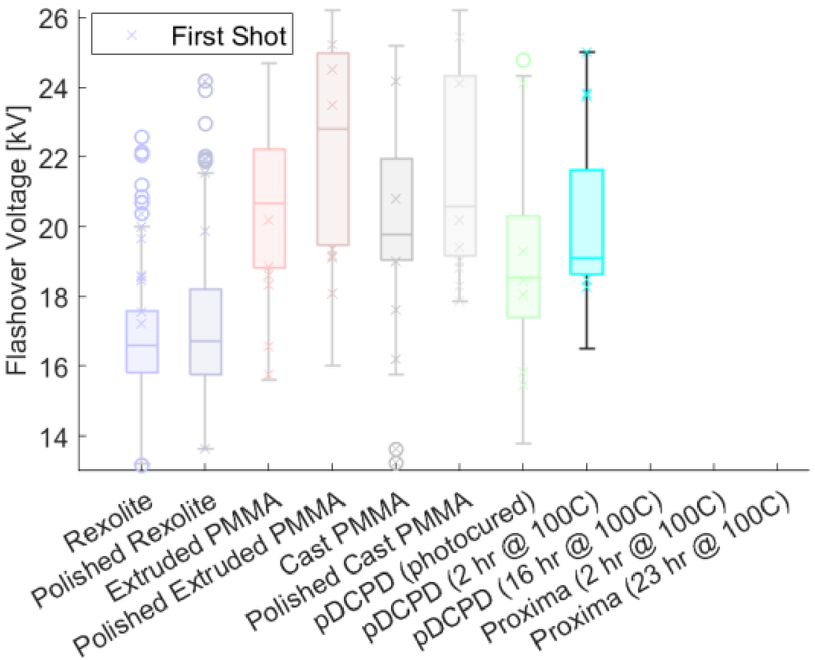


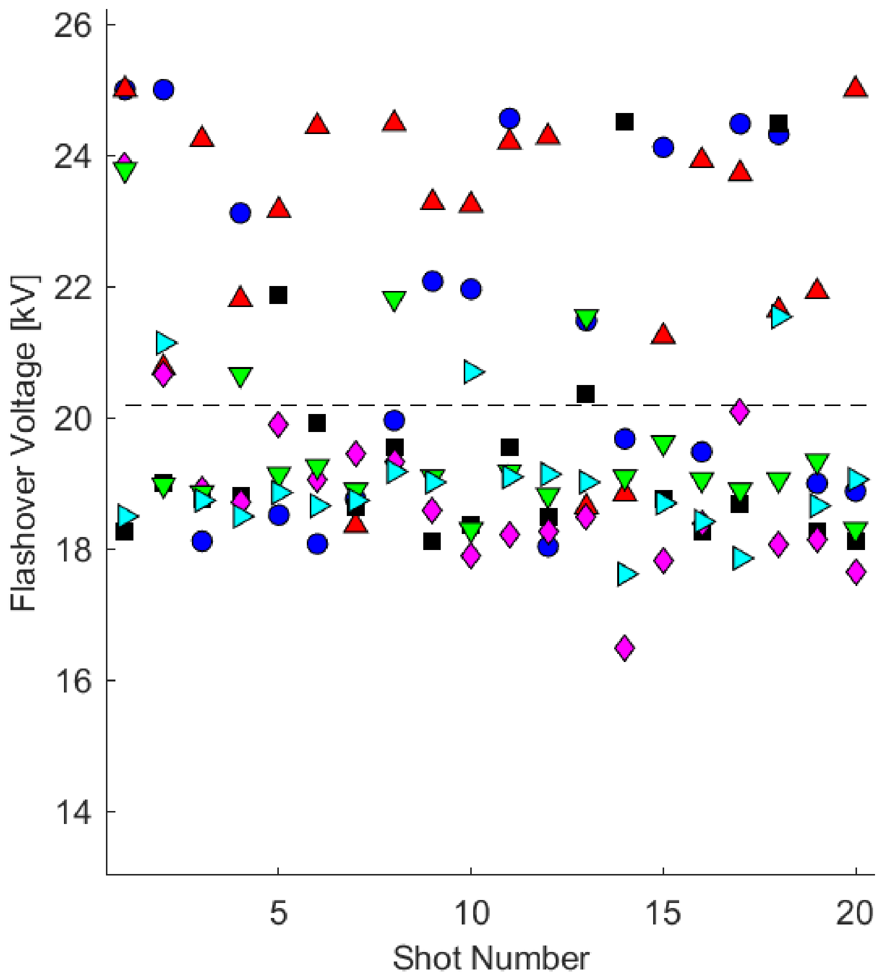
Mean V_F (kV, μ ± σ)	18.9 ± 2.4
Weibull Scale, α (kV)	20.0
Weibull Shape, β	8.26
# Samples (# Shots)	6 (140)

Electrical Characterization—In-house pDCPD (2 hr @ 100°C)

- Thermally treated in-house pDCDP is similar to only photocured in-house pDCPD
  - No clear trend with the number of flashover events
  - Flashover voltage is slightly higher compared to photocured only samples
  - Unclear if oxidation or further thermal curing is having an effect



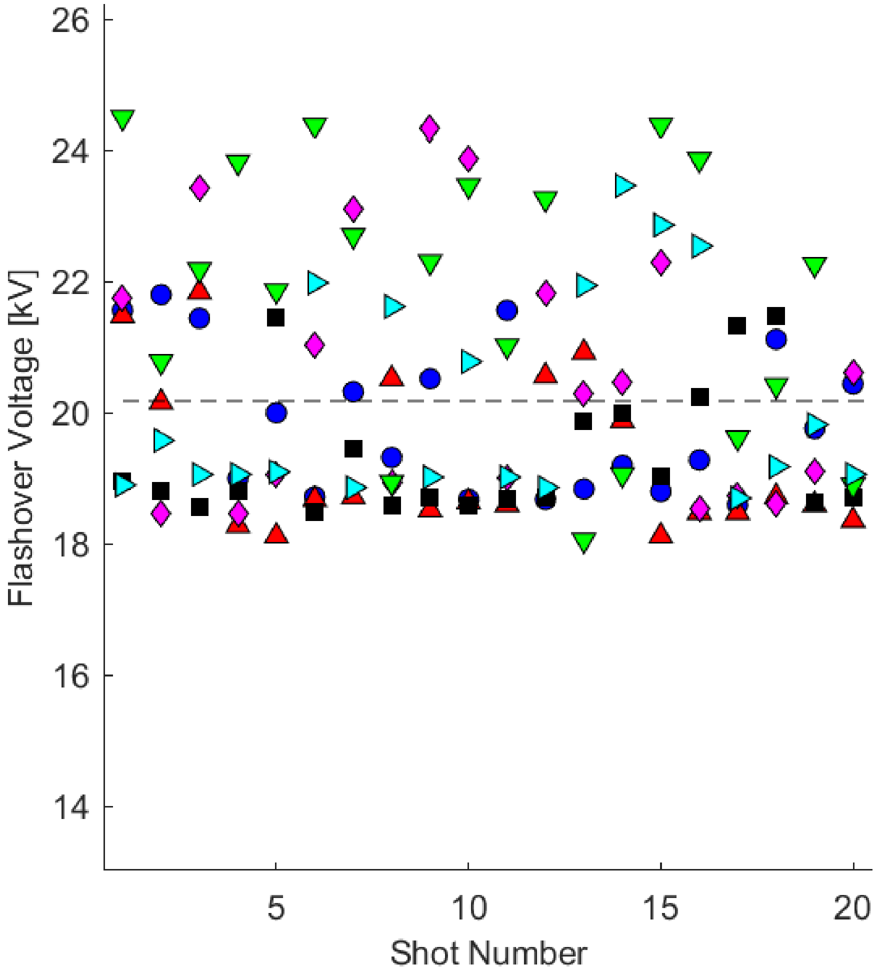


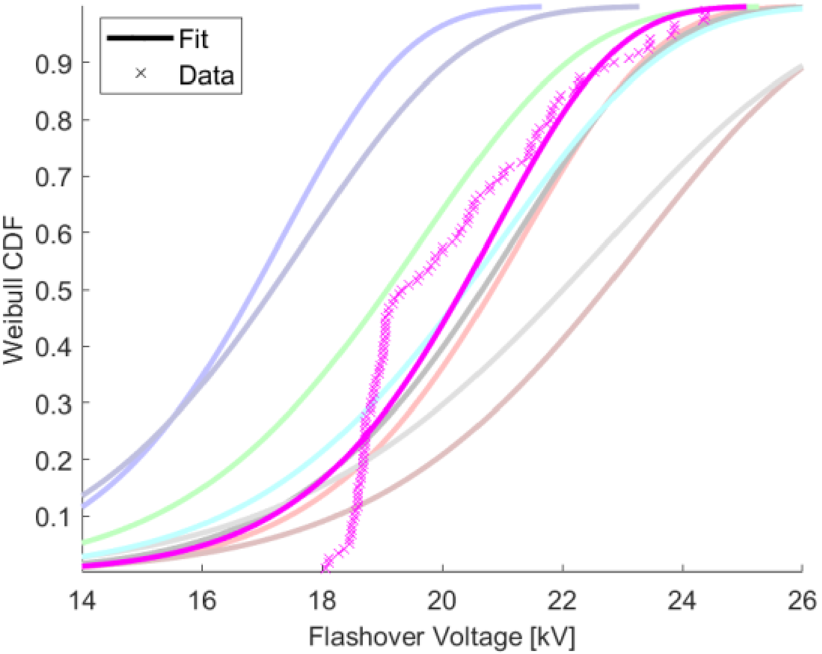


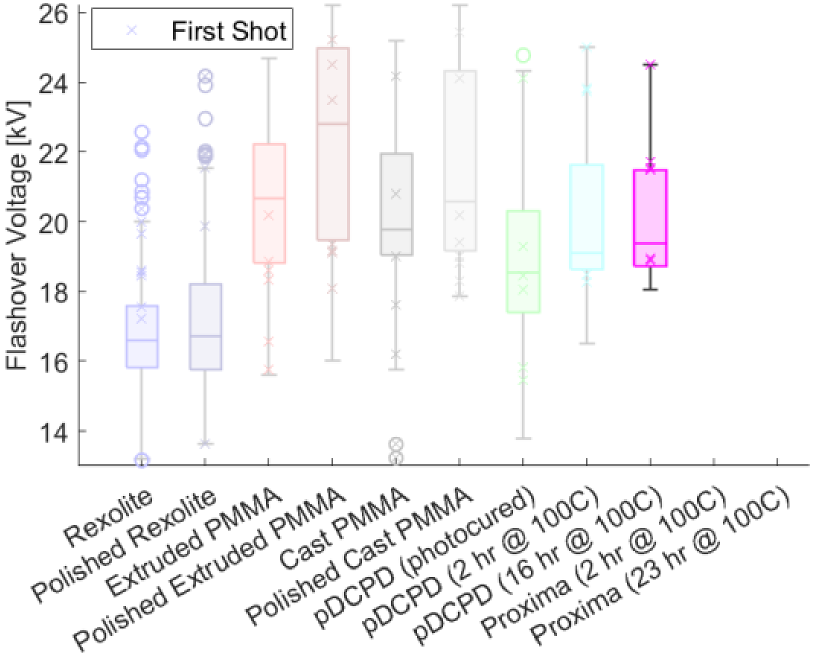
Mean V_F (kV, μ ± σ)	20.2 ± 2.2
Weibull Scale, α (kV)	21.3
Weibull Shape, β	8.49
# Samples (# Shots)	6 (122)

Electrical Characterization—In-house pDCPD (16 hr @ 100°C)

- Thermally treated in-house pDCDP is similar to only photocured in-house pDCPD
  - Longer thermal treatment does not appear to have any effect
  - Additional oxidation did not appear to have any effect



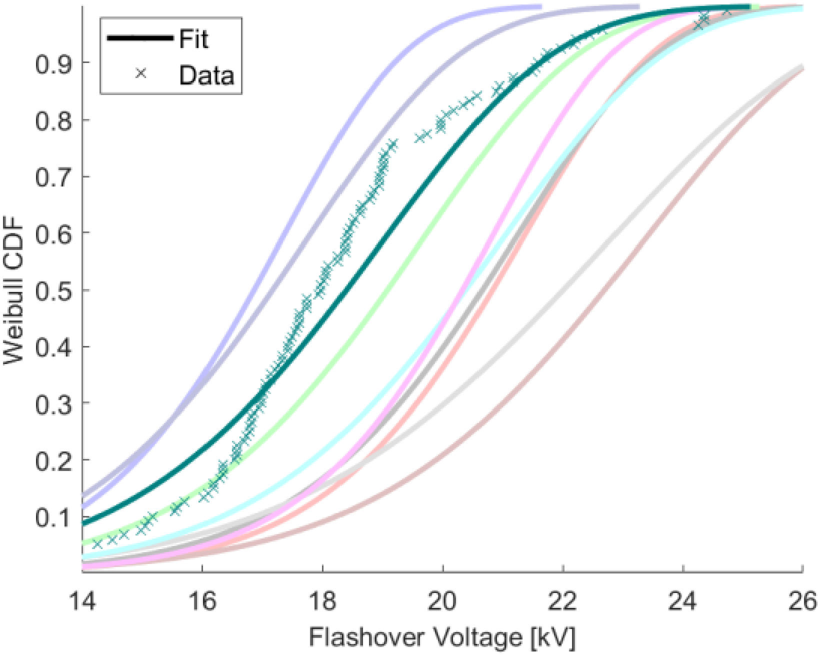


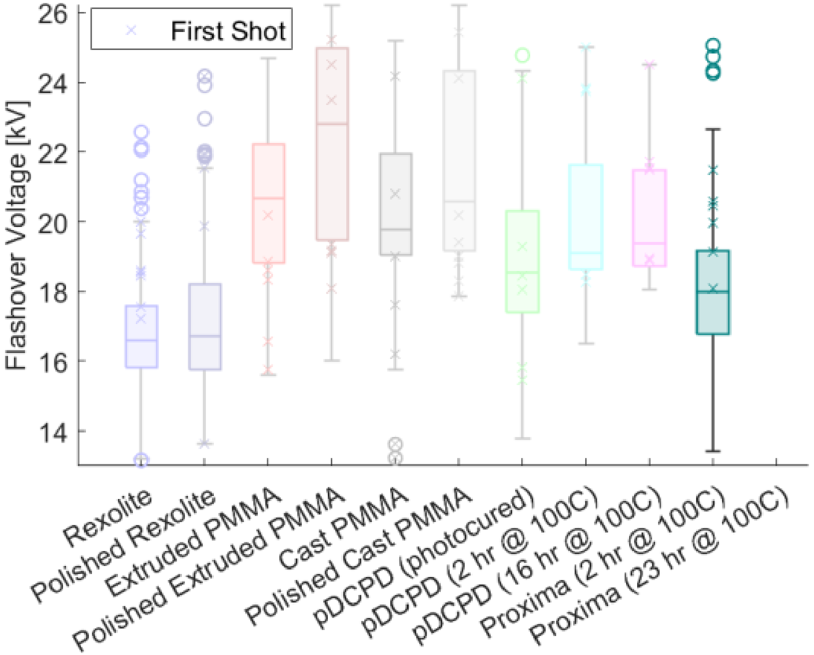


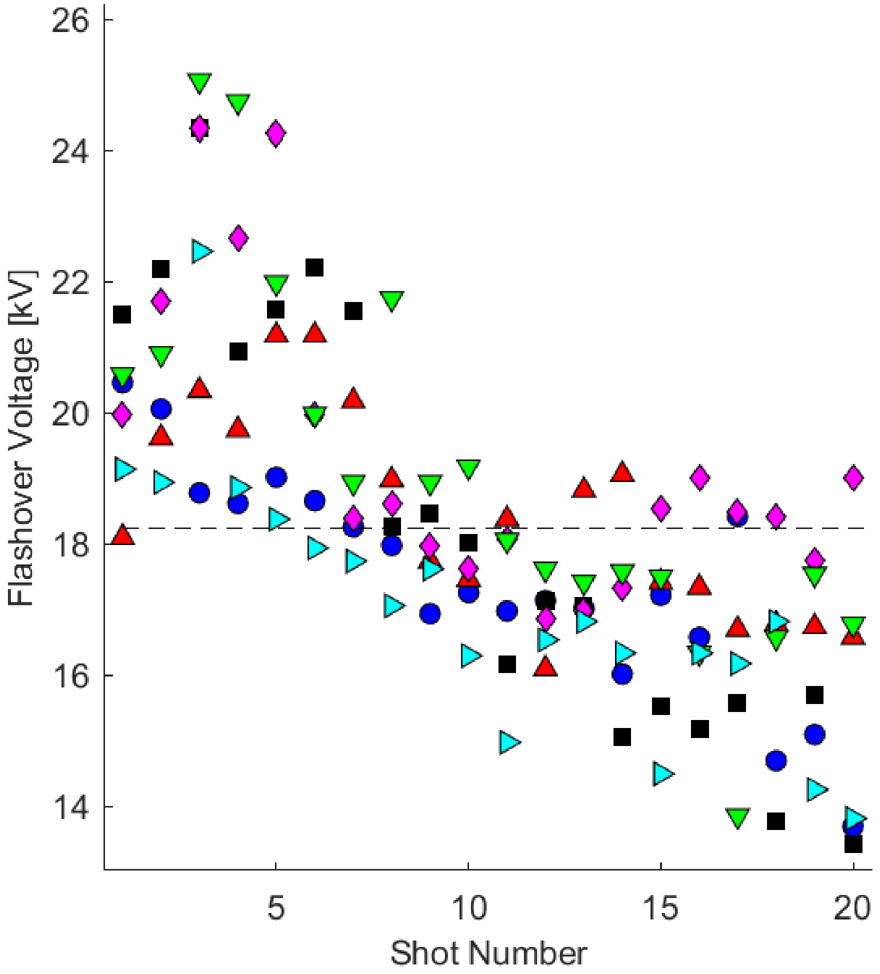
Mean V_F (kV, $\mu \pm \sigma$)	20.2 ± 1.7
Weibull Scale, α (kV)	21.0
Weibull Shape, β	11.08
# Samples (# Shots)	6 (120)

Electrical Characterization—Proxima pDCPD (2 hr @ 100°C)

- Proxima pDCPD shows increase and then a substantial decrease in flashover voltage with further flashover events
  - Initial flashover voltage is comparable to in-house pDCPD



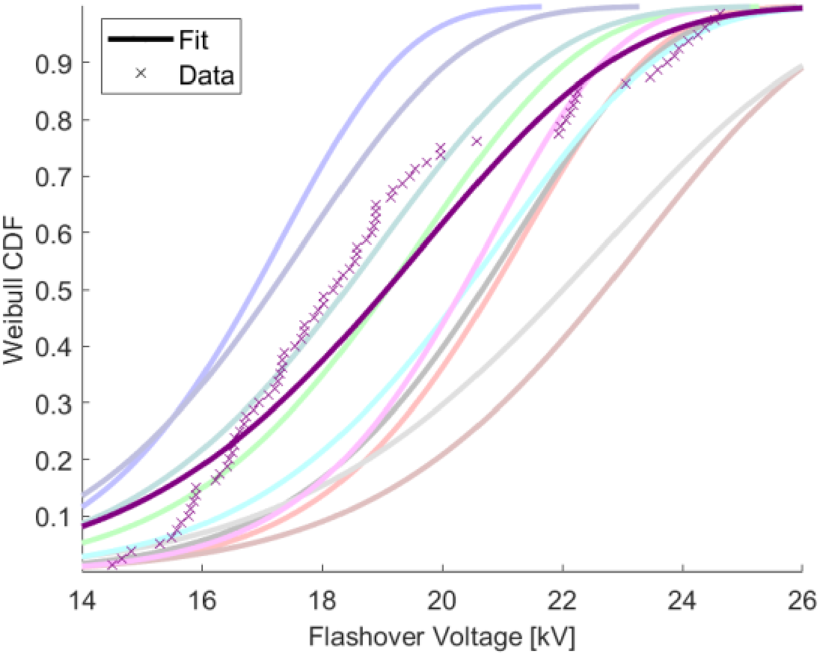


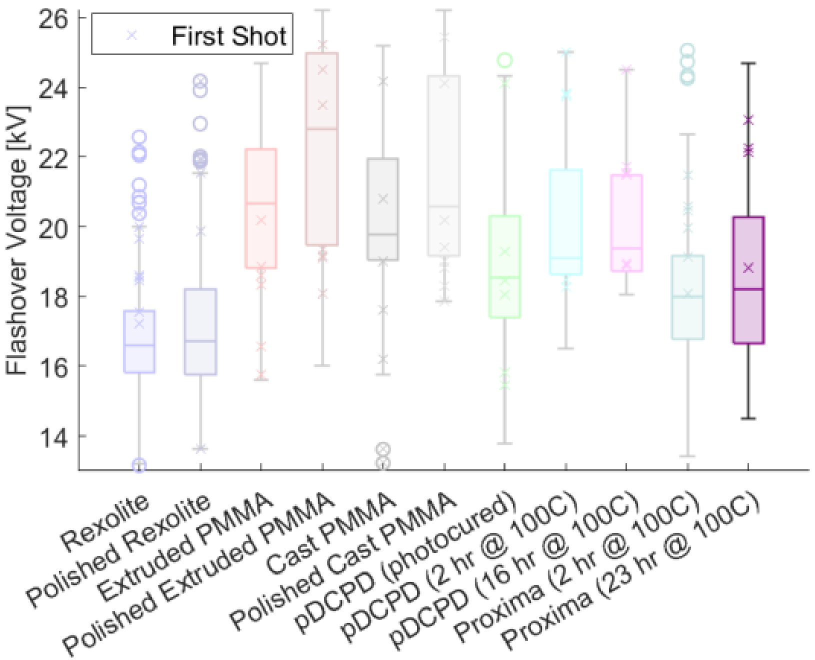


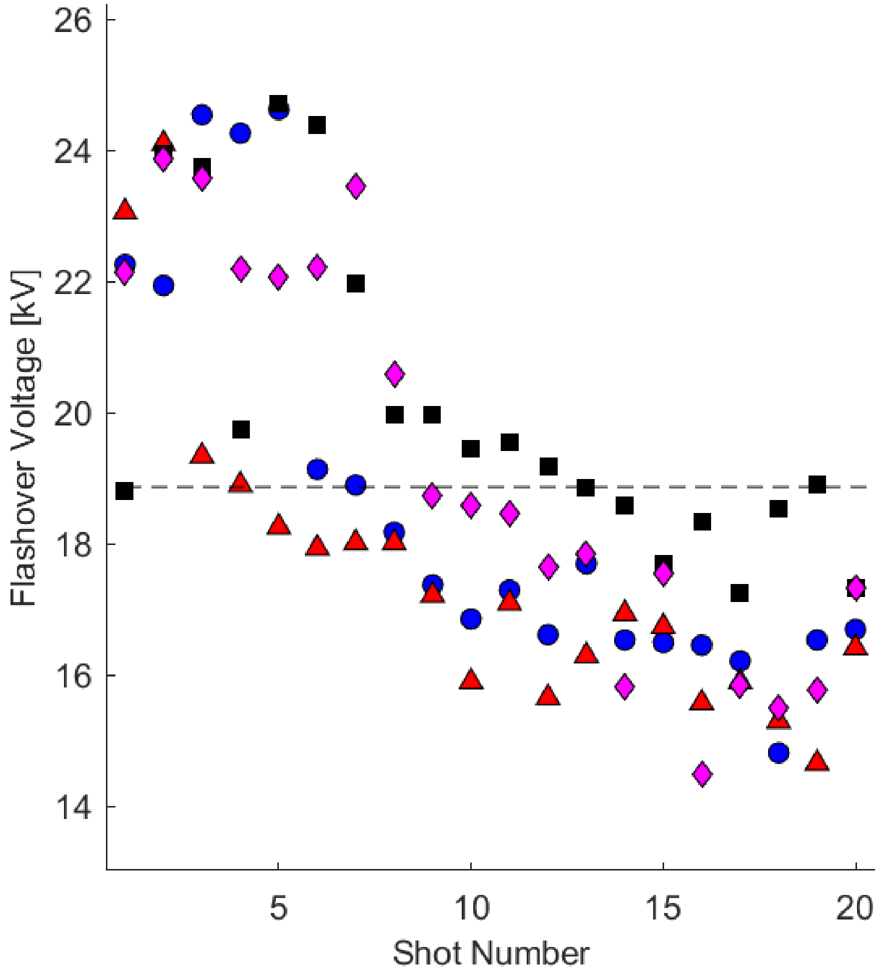
Mean V_F (kV, $\mu \pm \sigma$)	18.2 ± 2.4
Weibull Scale, α (kV)	19.3
Weibull Shape, β	7.44
# Samples (# Shots)	6 (120)

Electrical Characterization—Proxima pDCPD (23 hr @ 100°C)

- Proxima pDCPD shows increase and then a substantial decrease in flashover voltage with further flashover events
  - Longer thermal treatment does not appear to have any effect
  - Additional oxidation did not appear to have any effect



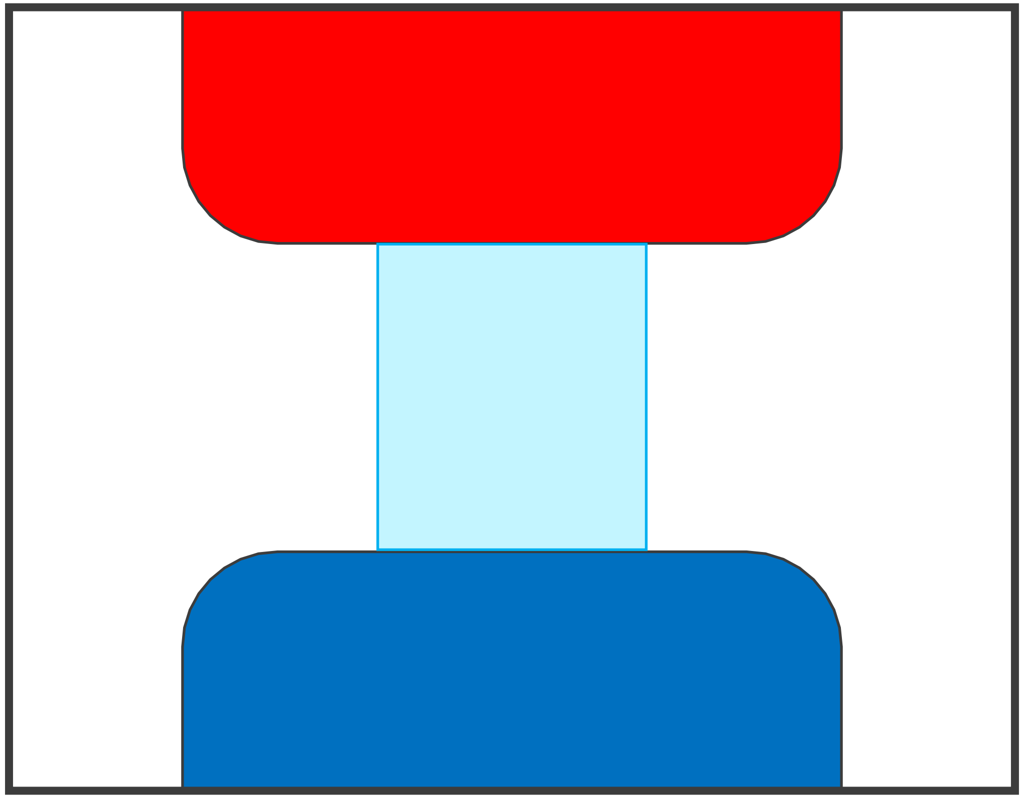




Mean V_F (kV, μ ± σ)	18.9 ± 2.8
Weibull Scale, α (kV)	20.1
Weibull Shape, β	6.79
# Samples (# Shots)	4 (80)

Conclusions

- pDCPD is not superior to PMMA in flashover voltage withstand
  - Thermal treatment to increase the oxidation of pDCPD does not have a substantial effect
- Rexolite and Proxima pDCPD have degraded flashover voltage withstand after initial flashover events
  - No degradation observed for PMMA or in-house pDCPD
- Future work
  - Transition to a cylindrical electrode configuration
    - Allows for more consistent contact with electrodes
  - Enclosed environment for better control over environmental factors
  - Investigate differences between in-house and Proxima pDCPD resins in flashover performance
  - Incorporate semiconductor trap particles in resin coating

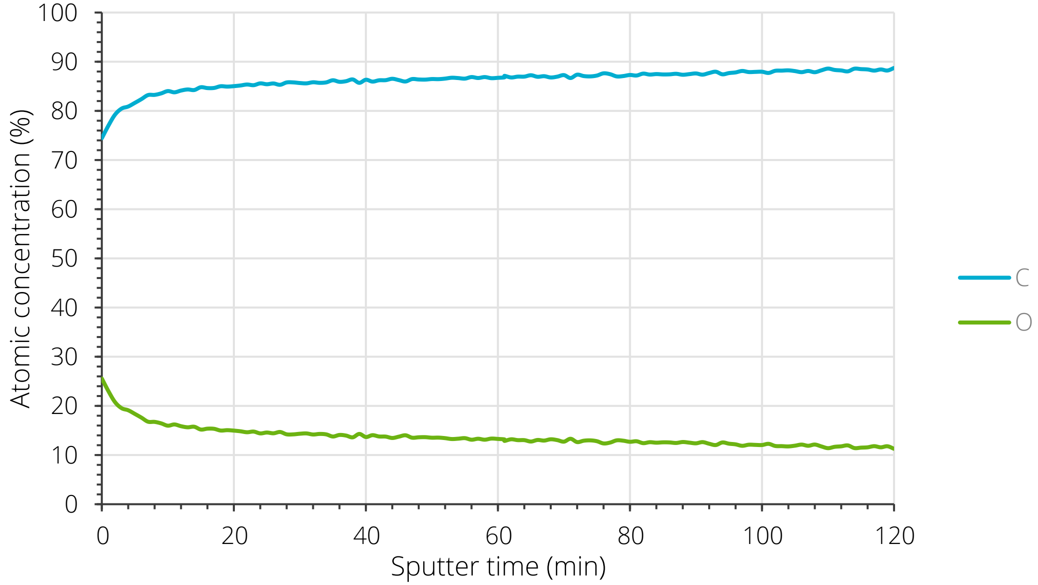


Cylindrical electrical testing setup schematic

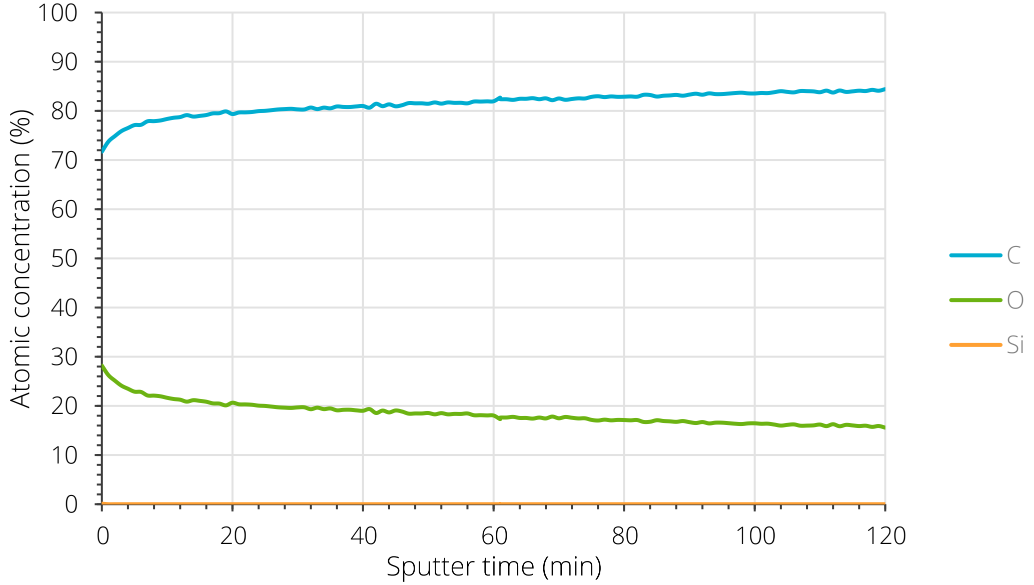
Backup Slides

XPS

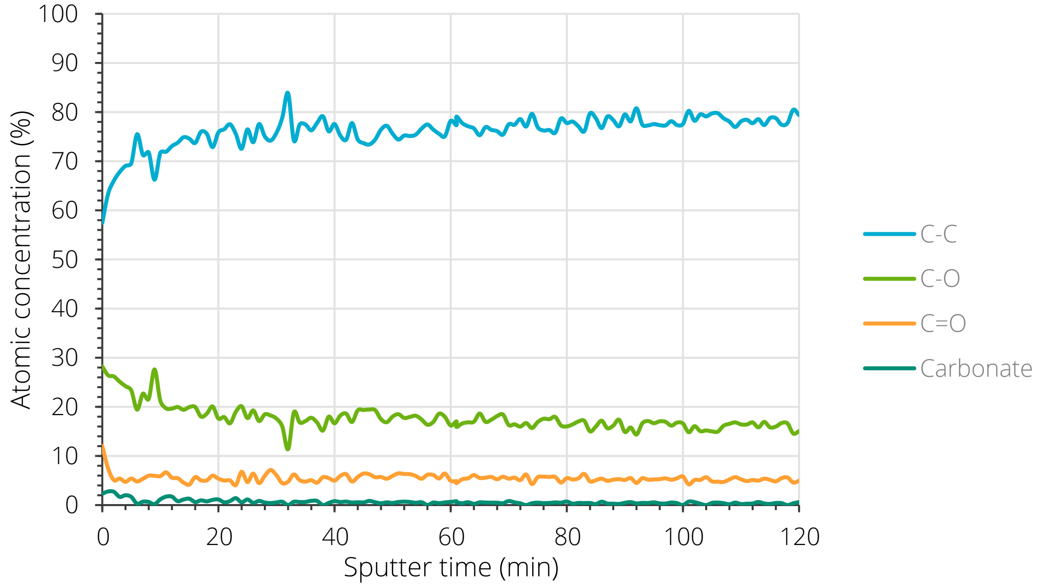
Survey on pDPC (2 hr) sample



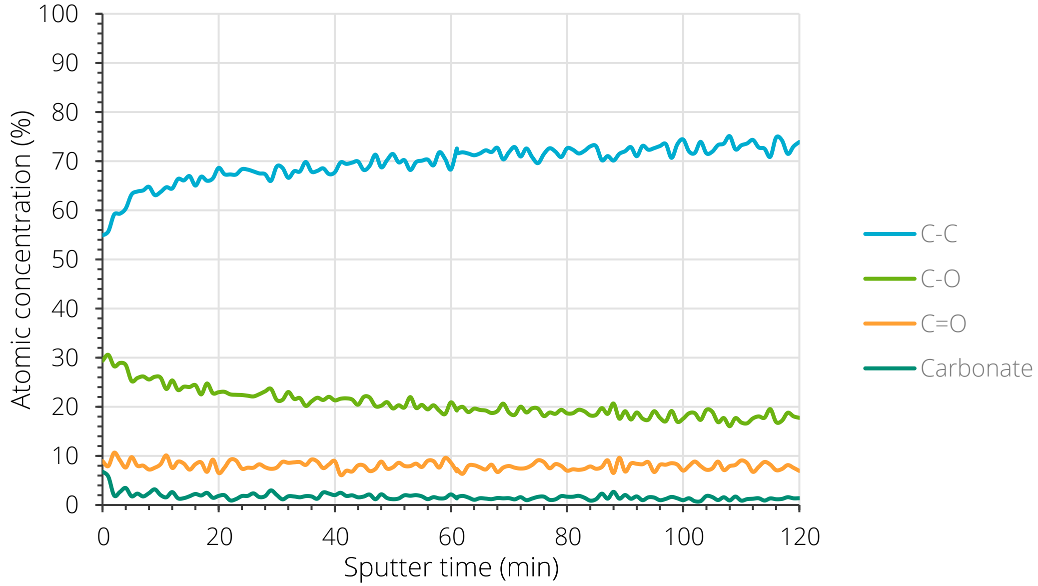
Survey on pDPC (17 hr) sample



Carbon components on pDCPD (2 hr cure) sample



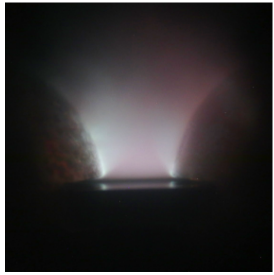
Carbon components on pDCPD (17 hr) sample



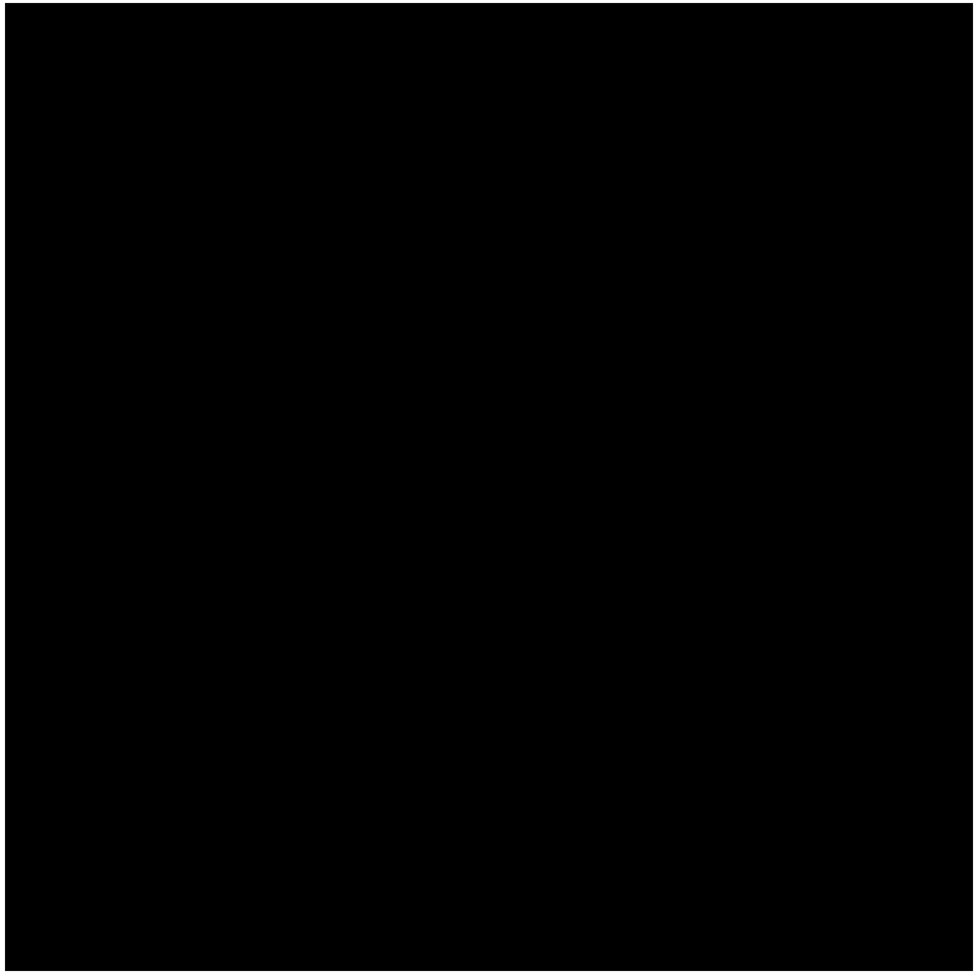
Electrical Testing—Discharge Imaging

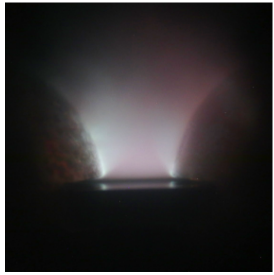
- High speed camera has ability to capture based on change in image intensity
- Have some videos
  - Generally only 2–3 frames with plasma
  - Looks qualitatively similar to Canon long-exposure image (right)

Electrical Testing—Discharge Imaging



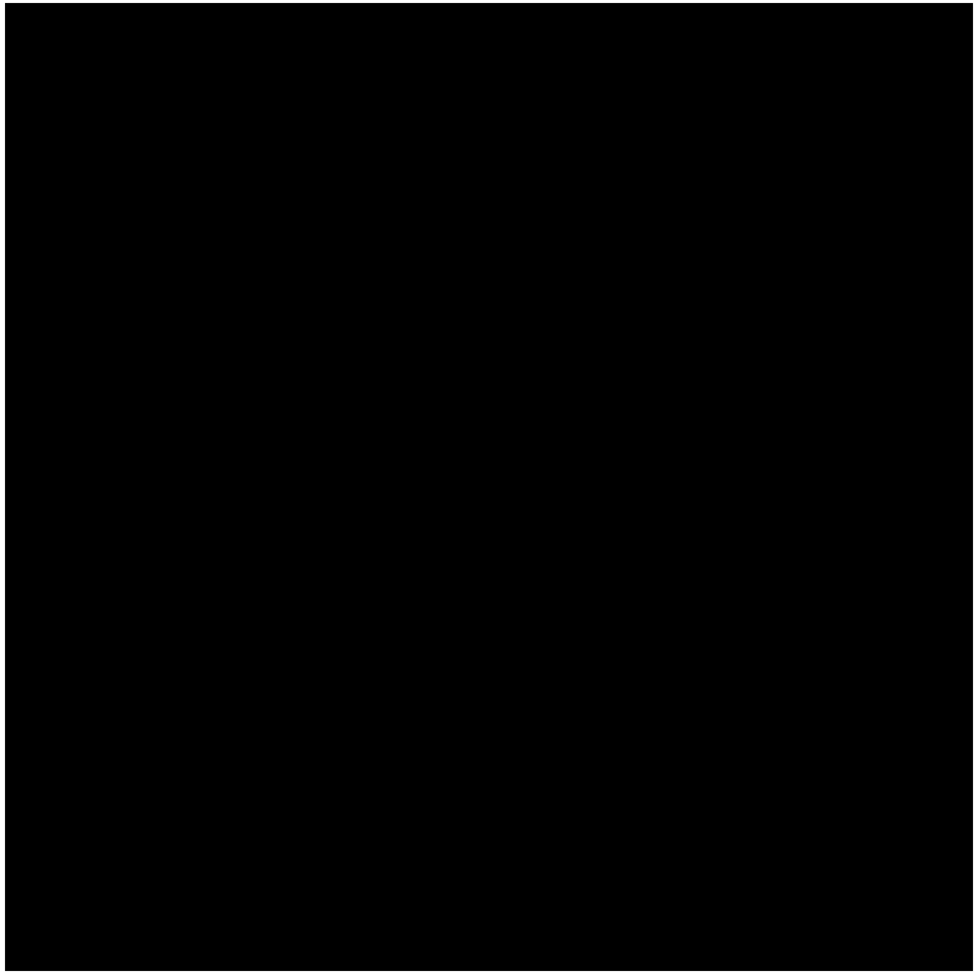
- Attempted to capture discharge with high speed camera
  - Phantom v711
    - 256 x 256 pixels; 79,000 fps; 12 μs exposure
  - All videos capture the same field of view
- Initially overexposed
  - Subsequent videos had a neutral density filter in front of the camera
  - This speed is too slow to adequately capture the discharge
  - A few shots however appear to have captured the beginning of the discharge



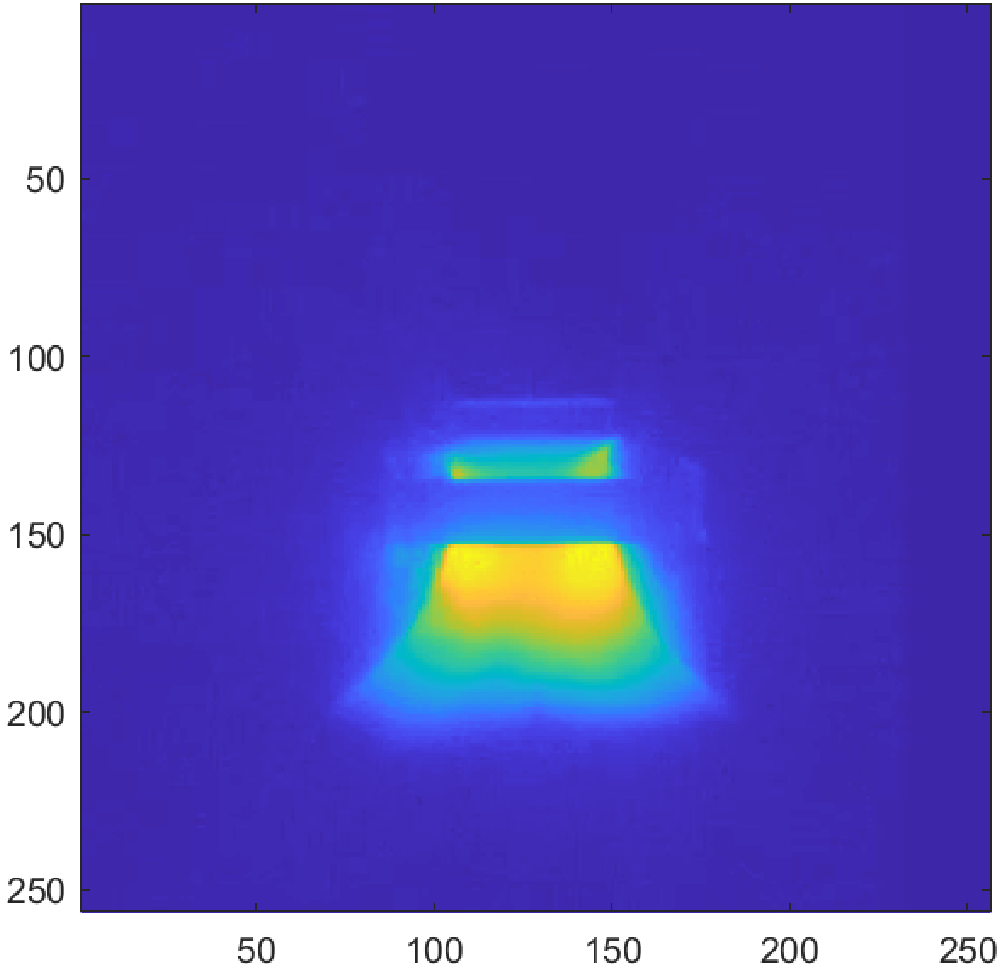


Electrical Testing—Discharge Imaging

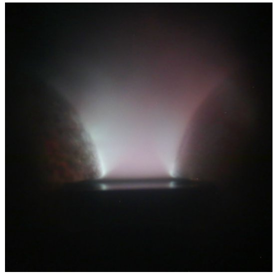
Color Video of Discharge



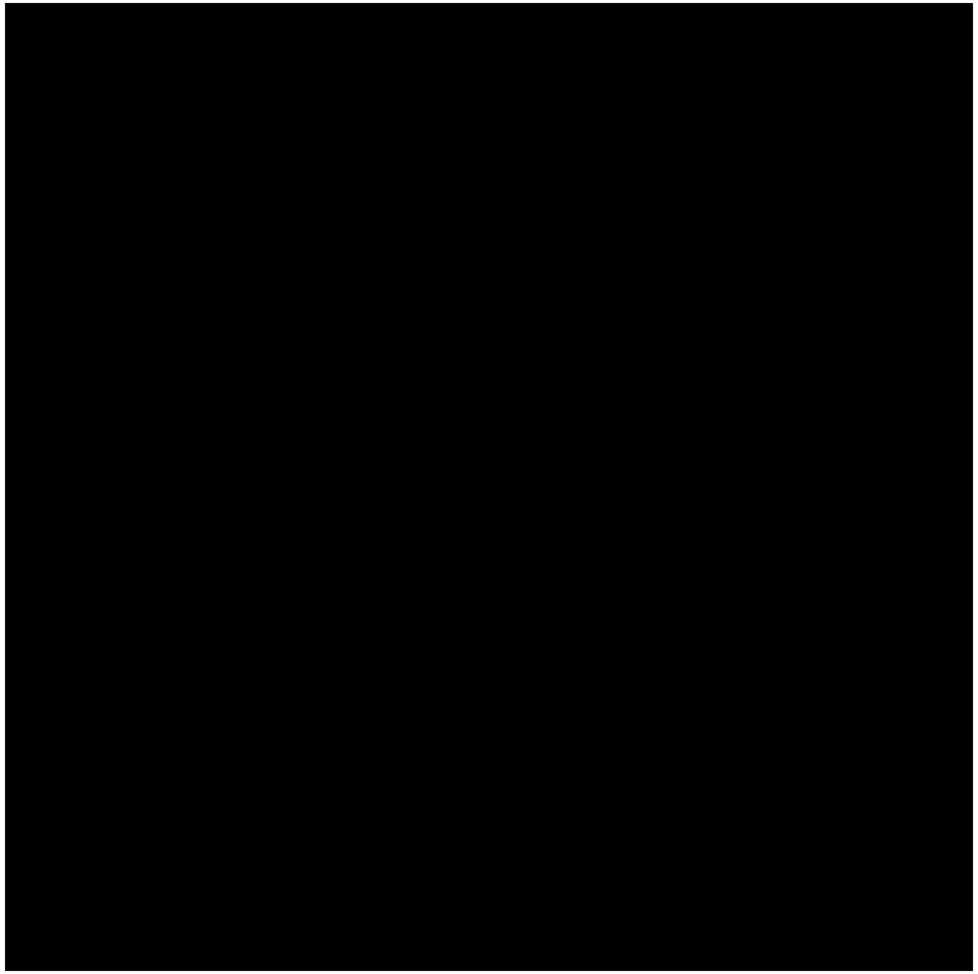
Intensity of first frame



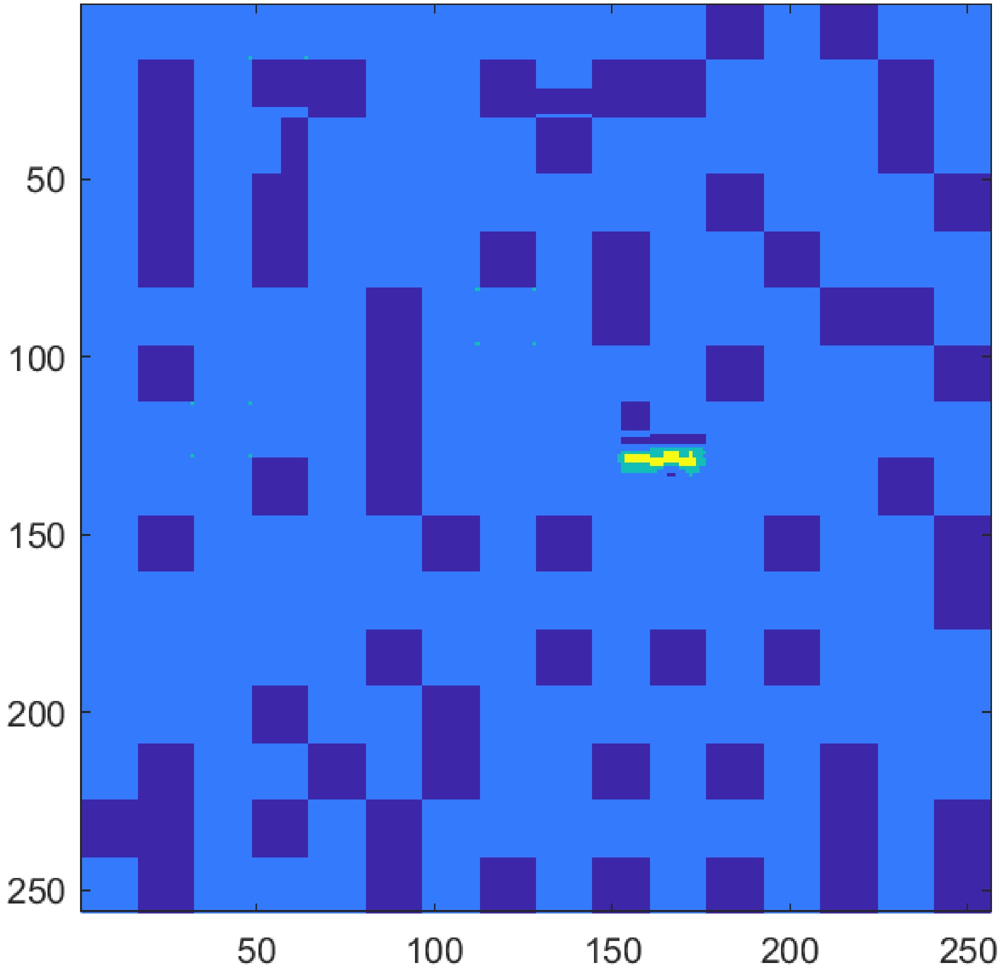
Electrical Testing—Discharge Imaging



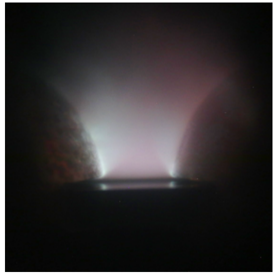
Color Video of Discharge



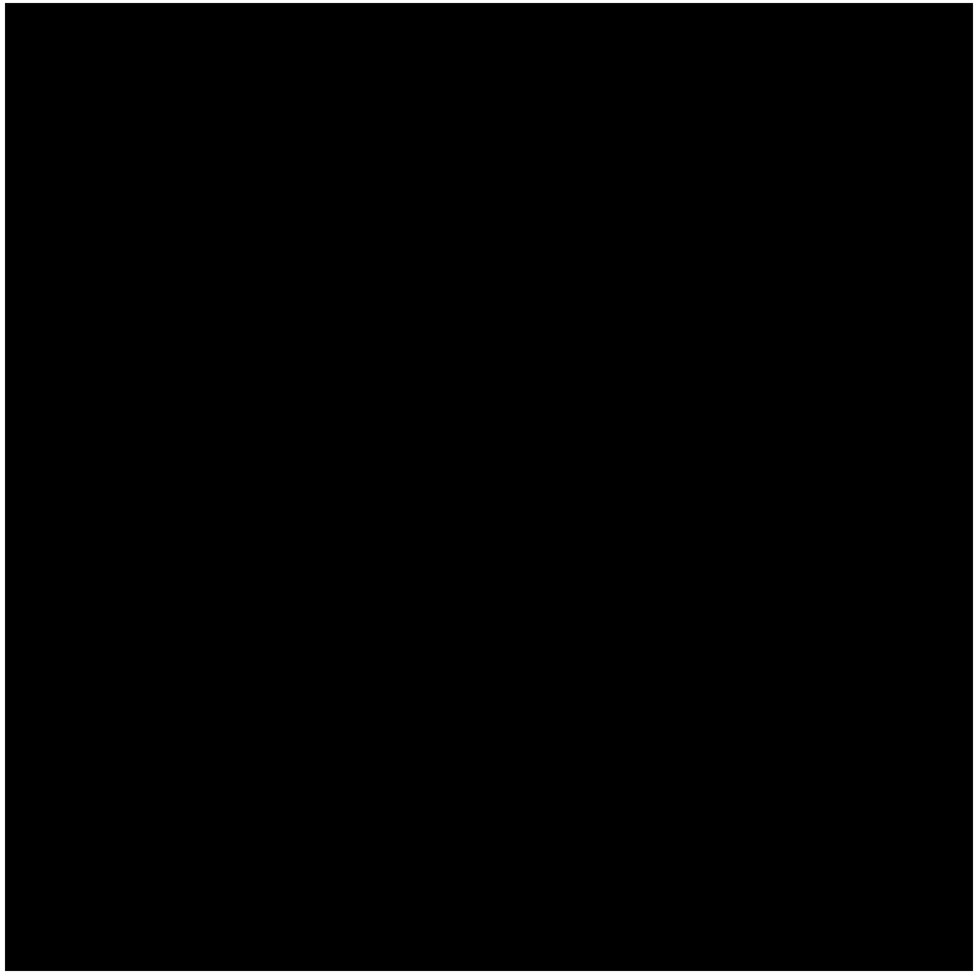
Intensity of first frame



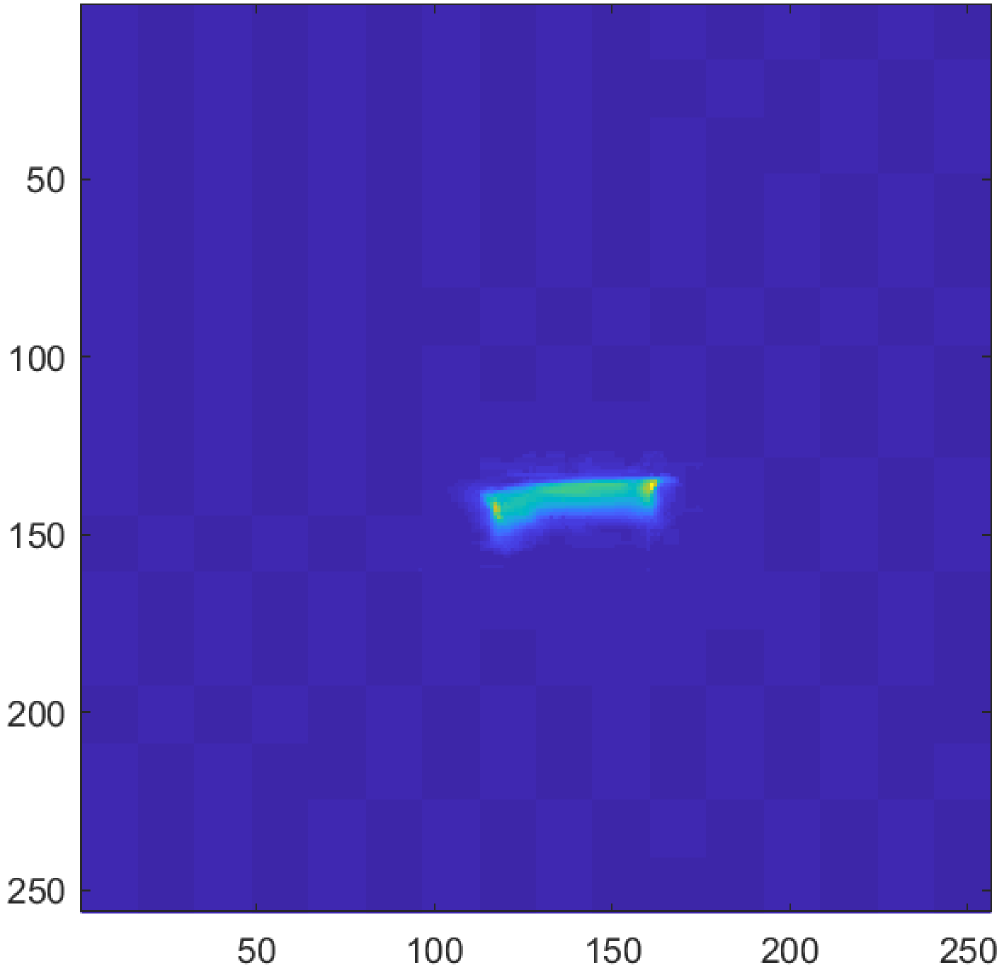
Electrical Testing—Discharge Imaging



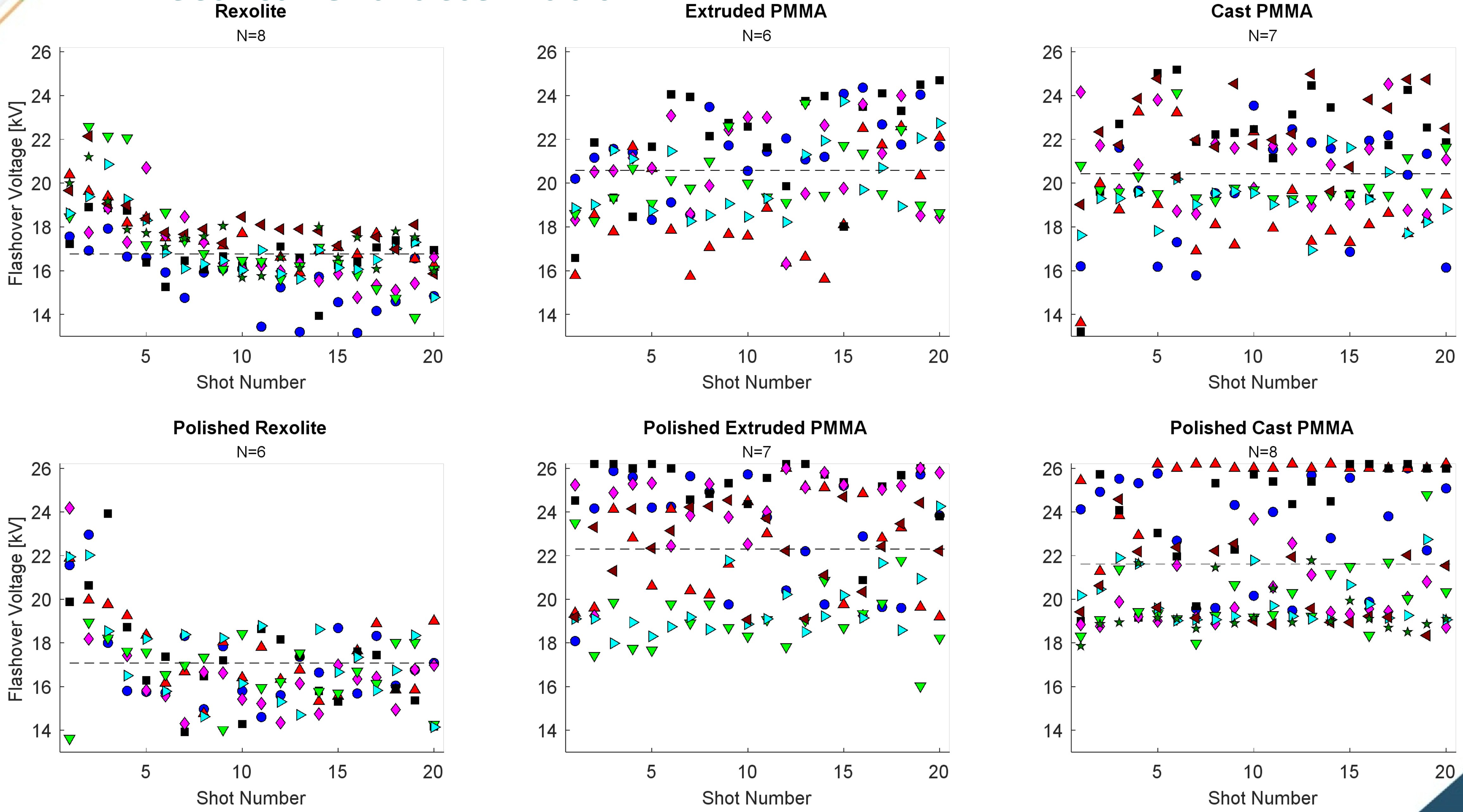
Color Video of Discharge



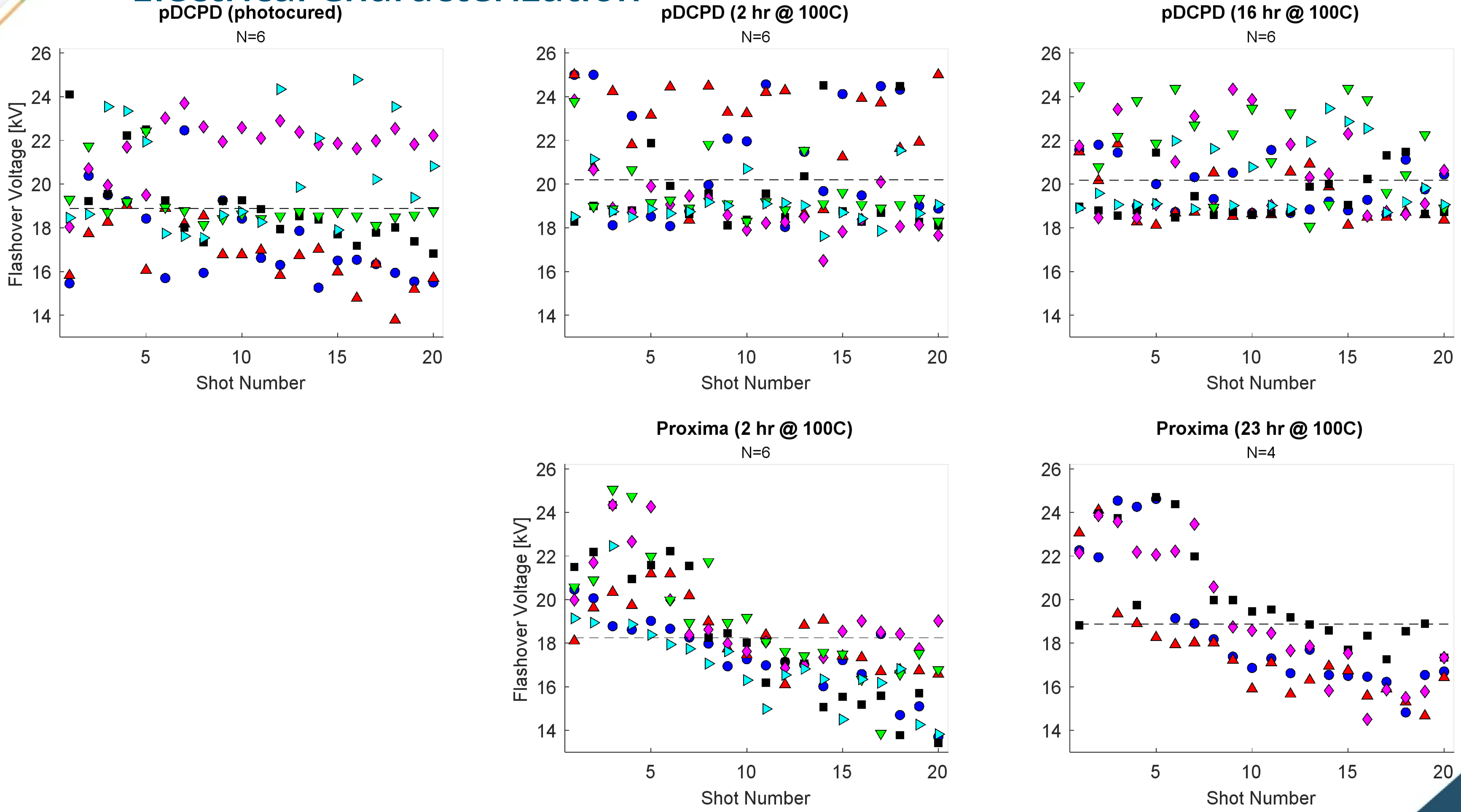
Intensity of first frame



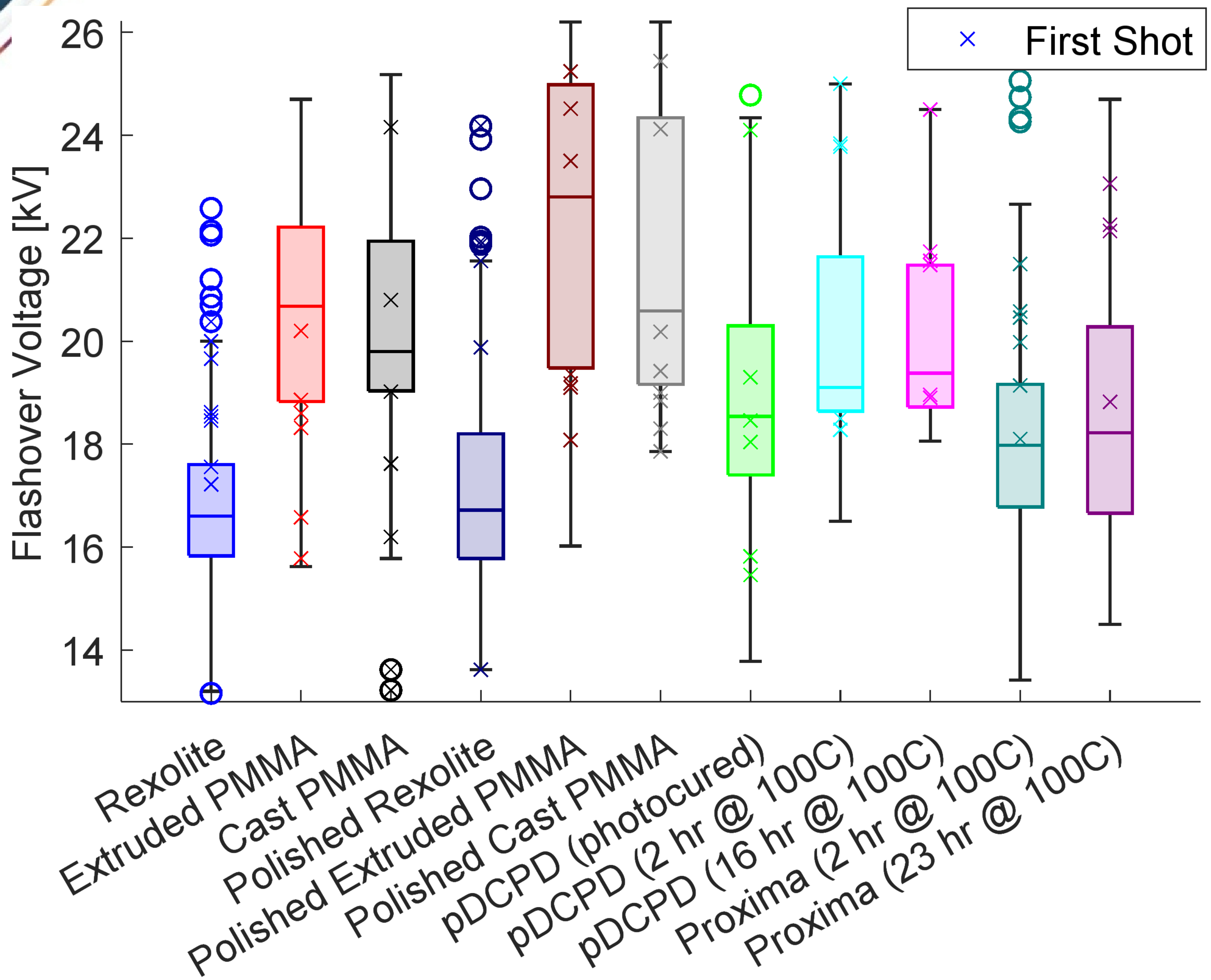
Electrical Characterization



Electrical Characterization



Electrical Characterization

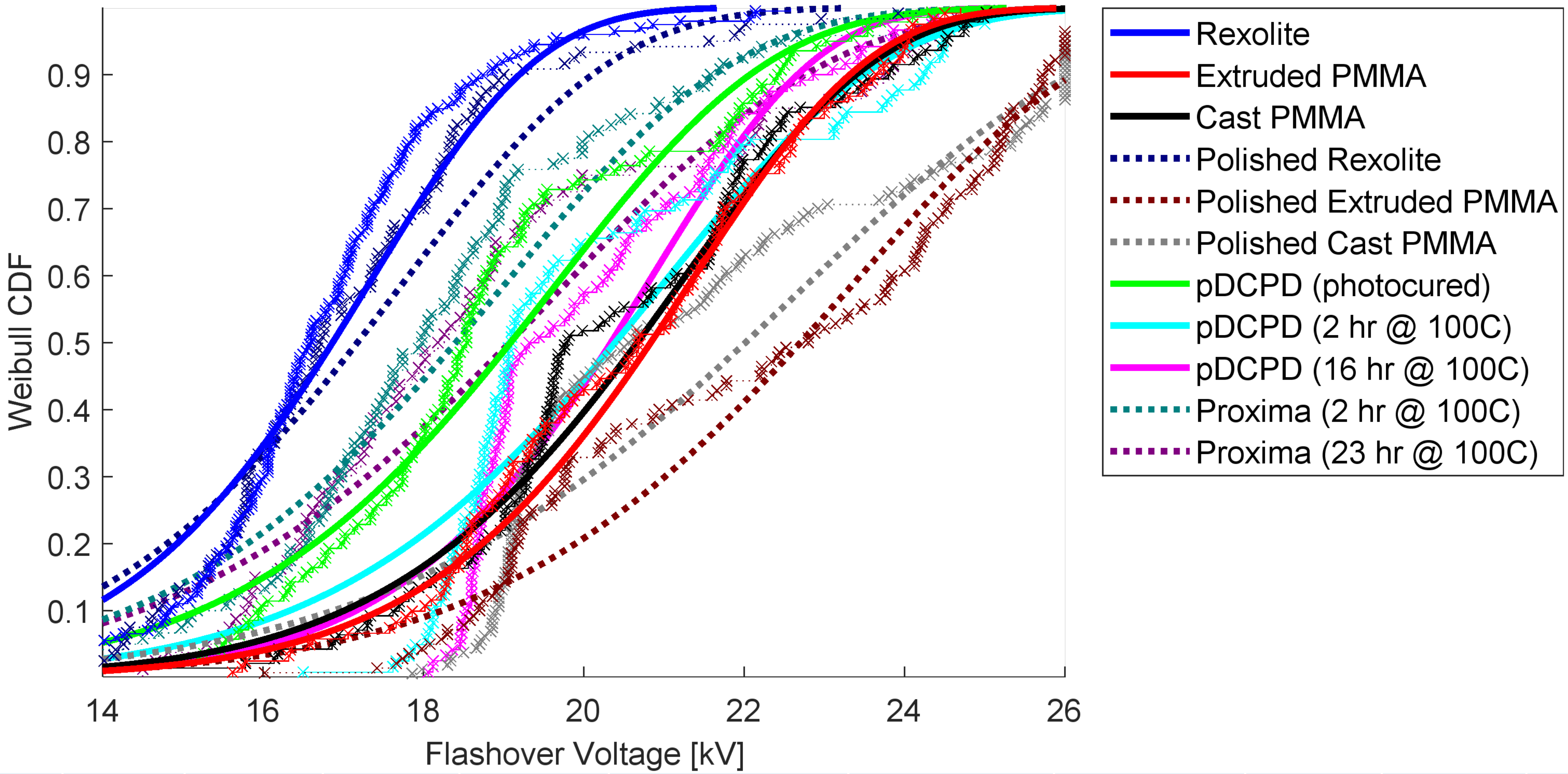


	# Shots	# Samples
Rexolite	199	8
Extruded PMMA	121	6
Cast PMMA	141	7
Polished Rexolite	120	6
Polished Extruded PMMA	140	7
Polished Cast PMMA	160	8
In-house pDCPD	140	6
In-house pDCPD (2 hr)	122	6
In-house pDCPD (16 hr)	120	6
Proxima pDCPD (2 hr)	120	6
Proxima pDCPD (16 hr)	80	4

Generally 20 shots/sample

2 Rexolite and 1 pDCPD samples were tested for 40 shots/sample

Electrical Characterization



	Rexolite	Extruded PMMA	Cast PMMA	Polished Rexolite	Polished Extruded PMMA	Polished Cast PMMA	pDCPD (photocured)	pDCPD (2 hr)	pDCPD (16 hr)	Proxima (2 hr)	Proxima (23 hr)
Mean Vbr (kV)	16.8±1.7	20.6±2.2	20.4±2.3	17.1±2.0	22.3±2.8	21.6±2.8	18.9±2.4	20.2±2.2	20.2±1.7	18.2±2.4	18.9±2.8
Weibull Scale (kV)	17.6	21.6	21.5	18.0	23.7	23.2	20.0	21.3	21.0	19.3	20.1