Progresses in Developing Micro-Multilayer Multifunctional Electrical Insulation (MMEI) System for High Voltage Applications

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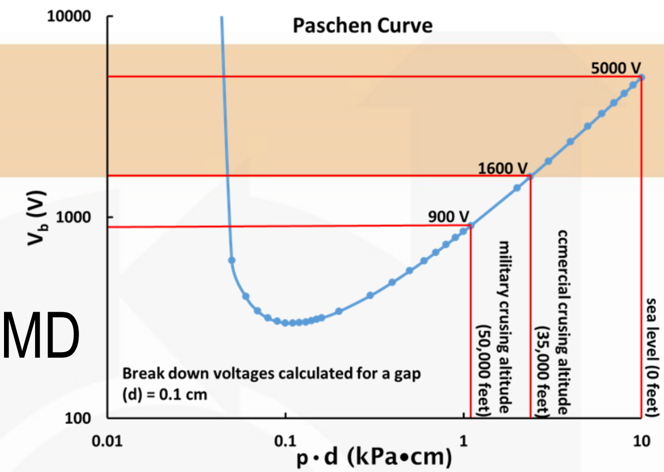
Background



- Development of electrified aircraft at NASA ARMD

<u>Potential Benefits</u>

– fewer emissions, improved fuel economy, quieter flight, improved efficiency and maneuverability, reduced maintenance costs, and improved reliability

<u>Challenges (Materials)</u>

– High power demand; 0.5 (for 9 seat) to <u>60 MW (for 300 seat) total propulsive power</u>, or 0.25 to <u>30 MW electric machines</u>

– Use high voltage for reasonable weight management, up to <u>20 - 40 kV</u> or higher → require <u>~ 1 mm (40 mil) thick SOA Teflon-Kapton-Teflon (TKT)</u> for proper insulation → huge weight gain from lots of power transmission lines (bus bar, wiring, & inter-connects) and electric equipment

– Current HV cable technologies, mostly designed for sea-level to low altitude, not suitable for such high-altitude airplane operations, particularly due to <u>corona PD susceptibility</u>

– Also, other specs to meet, e.g., 400 – 4000 Hz, 50 – 500 amps or higher, and 180 – 240 ºC or higher

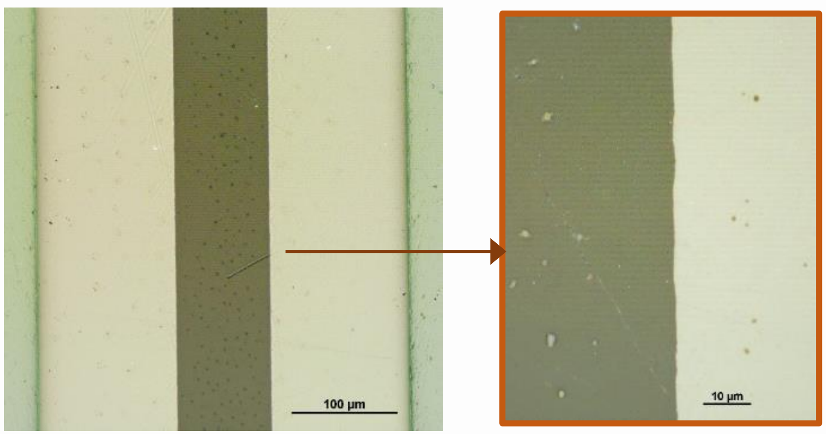
→ Thus, lightweight, high voltage, durable, high temperature, and PD resistant insulations critically needed

Background

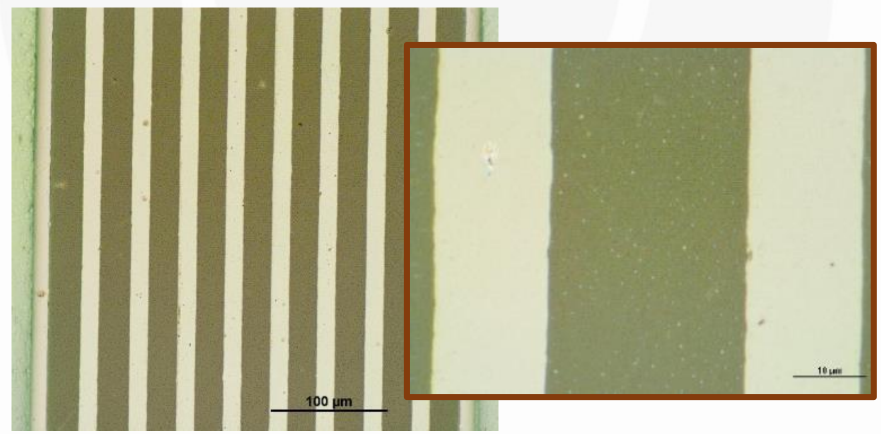
- Multilayered structures of well-known polymer insulation films, e.g., Kapton PI and PFA as bond layer, significantly improved dielectric breakdown voltage (V_B), <u>if well-bonded</u>;
  → <u>Micro-multilayer Multifunctional Electrical Insulation (MMEI)</u> system discovered, 2017*

- Kapton® PI film alone, 0.38 mm thick, V_B = ~30 kV (extrapolated)
- PFA film alone, 0.38 mm thick, V_B = 29 kV

5*KBF/5*PFA/5*KBF: 3-layers/0.38 mm th, V_B=38 kV

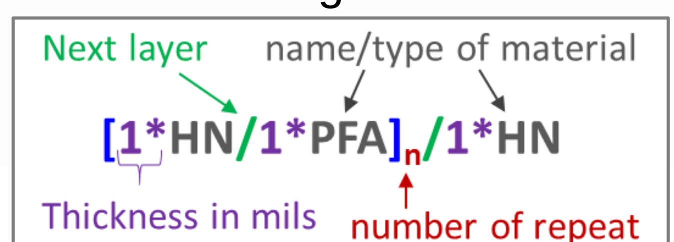


$[0.5*HPP/1*PFA]_9$ /0.5*HPP: 19-layers/0.38 mm th, V_B=46 kV



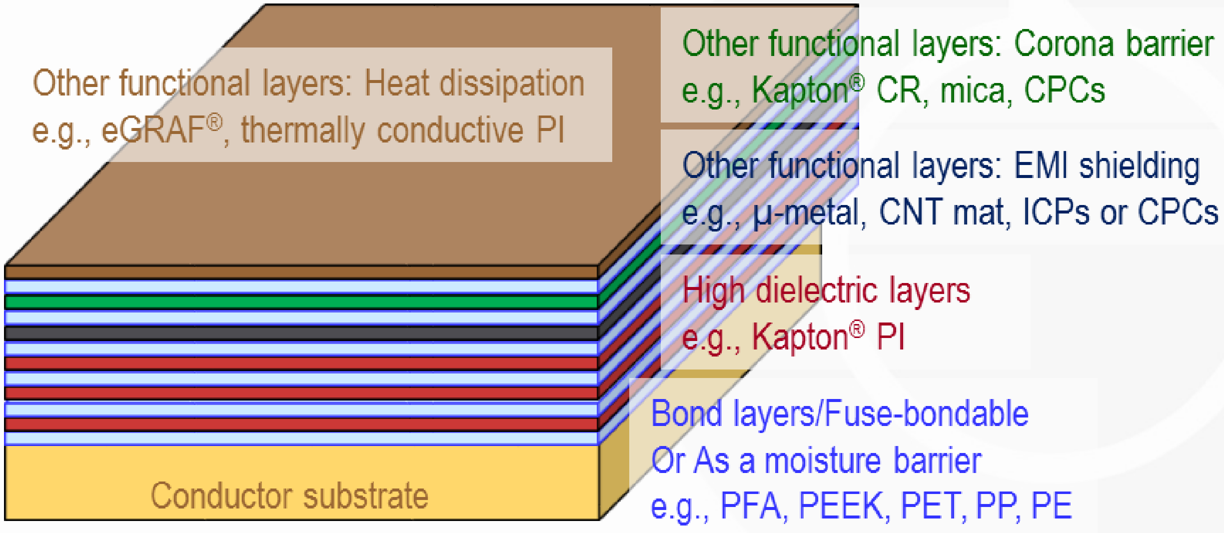
Excellent boding integrity from Heat Fuse-Bonding of PFA

* E. Eugene Shin, "High Performance Multilayer Insulation Composite For High Voltage Applications," United States Patent (U.S. Pat.) No. 10,546,666, January 28, 2020



Background

Typical MMEI design concept



- MMEI system can incorporate multifunctionalities naturally by its design capabilities, such as Corona PD resistance, EMI shielding, thermal management, and mechanical durability, etc.
- However, it will require extensive and systematic material-design-process optimizations, not by just simply adding some functional materials.

Objectives

Under the NASA’s Transformational Tools and Technology (TTT) program (Oct 2017 -   )

- To maximize dielectric performance of the new MMEI structures via material-design-process optimizations at minimum thickness
- To incorporate multifunctionalities, such as PD resistance, moisture barrier, EMI shielding, heat dissipation, and improved durability
- To demonstrate scale-up, manufacturability, and commercial applicability of MMEI system via prototype development

Experimental: Materials

<u>Initial Candidate Materials, all commercially available</u>

- Thermalimide Kapton® bagging film (KBF) (Airtech), 1, 2, & 5 mil: Thermally stable film
- Kapton® Polyimide (PI) high temperature high dielectric strength films (DuPont)
  - HN, 0.3, 1, & 5 mil: A general tough aromatic film, the baseline PI
  - HPP-ST or FPC, 0.5 & 1 mil: Superior dimensional stability and adhesion
  - CRC or CR, 1 mil: Corona resistant nano-composite film
  - HN, 05 & 1 mil, but Si adhesive, 1 & 1.5 mil, backed film
- Perfluoroalkoxy (PFA), 0.5, 1, 2, 5, 10, 20 mil: Semi-crystalline polymer as bond layer
- Polyethylene terephthalate (PET), 2 mil: Semi-crystalline polymer as bond layer
- Polyetheretherketone (PEEK), 0.5, 2, 5 mil: Semi-crystalline/bond layer or Moisture barrier
- Teflon® PTFE, 1, 2, 3, 5, 10, 15, 20, 40, 62.5 mil: Moisture barrier
- Flexible Electrical-Insulating Mica (FEIM), 4 mil: Corona barrier

<u>Alternative Candidates:</u>

- CIRLEX® Kapton® sheet, 10 & 20 mil (Fralock): Proprietary adhesiveless PI laminates, available thickness, 4 mil to 125 mil or thicker

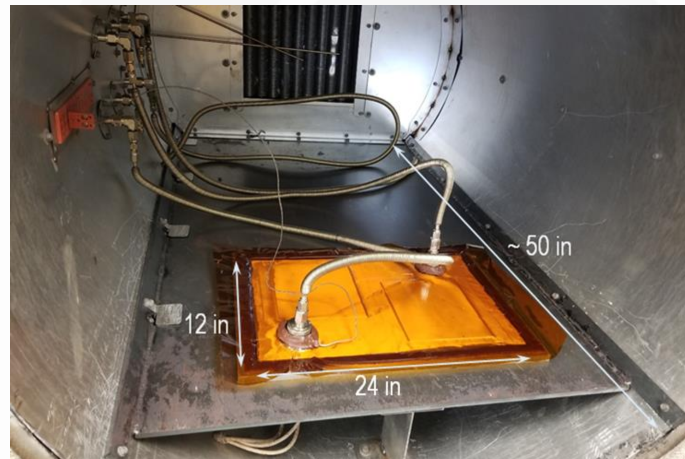
Experimental: Fabrication of Dielectric Test Samples

Simple Compression Molding

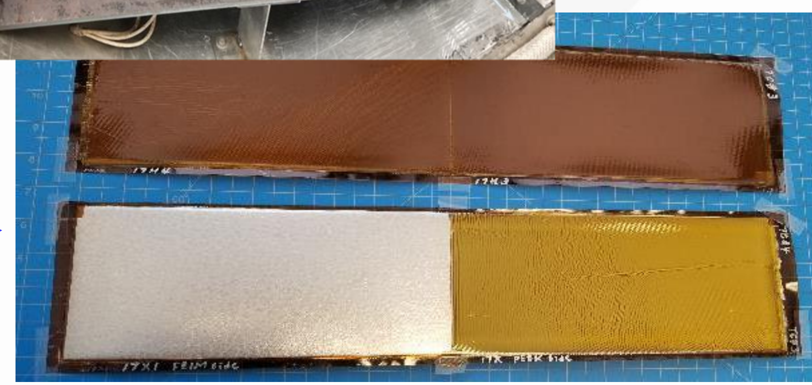
- Small samples, ~ 1.25" × 3.0"
- Controlled Temperature and Pressure

Autoclave Process

- Large samples, >> 4.5" × 19"
- Controlled Vacuum, T, P via Vacuum-bagging
- Ideal for complex 3-D structures, prototypes



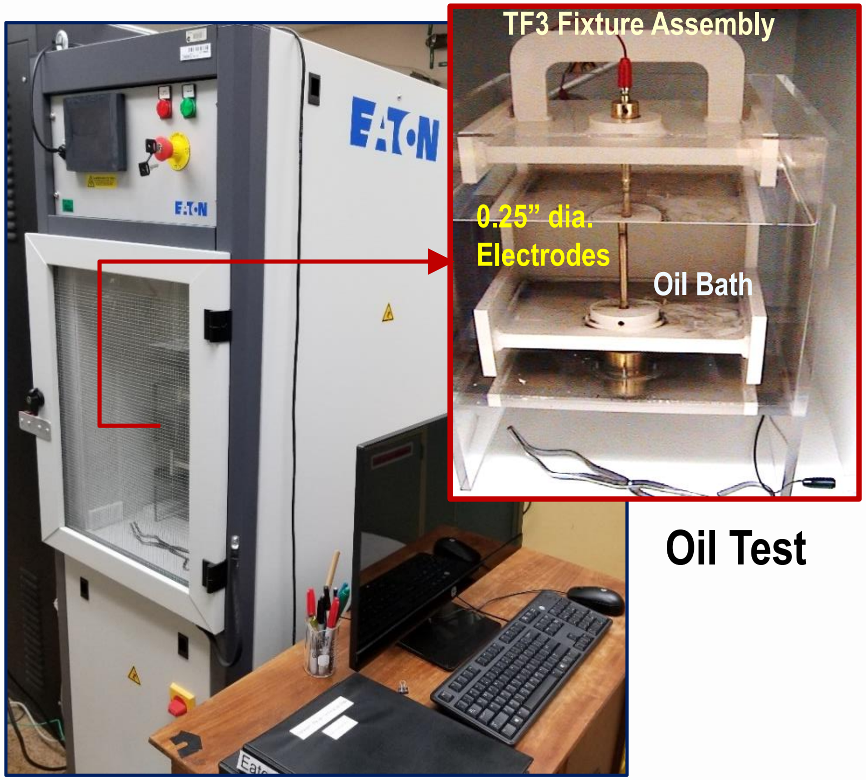
- Demanding optimization of processing conditions



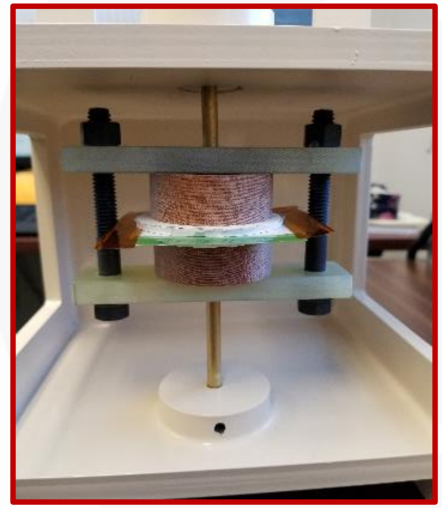
➢ Batch processes for feasibility demonstrations, but continuous processes to be developed

Experimental: Dielectric Breakdown Testing

Commercial test rig, Model DT2-60-20-SR-P-C by Sefelec Eaton, France; *V_B and leakage current (LC*)* used for material screening (ASTM D149)



Oil Test



Air Test

Pressure Gasket Fixture (2.5" OD - 1.5" ID):

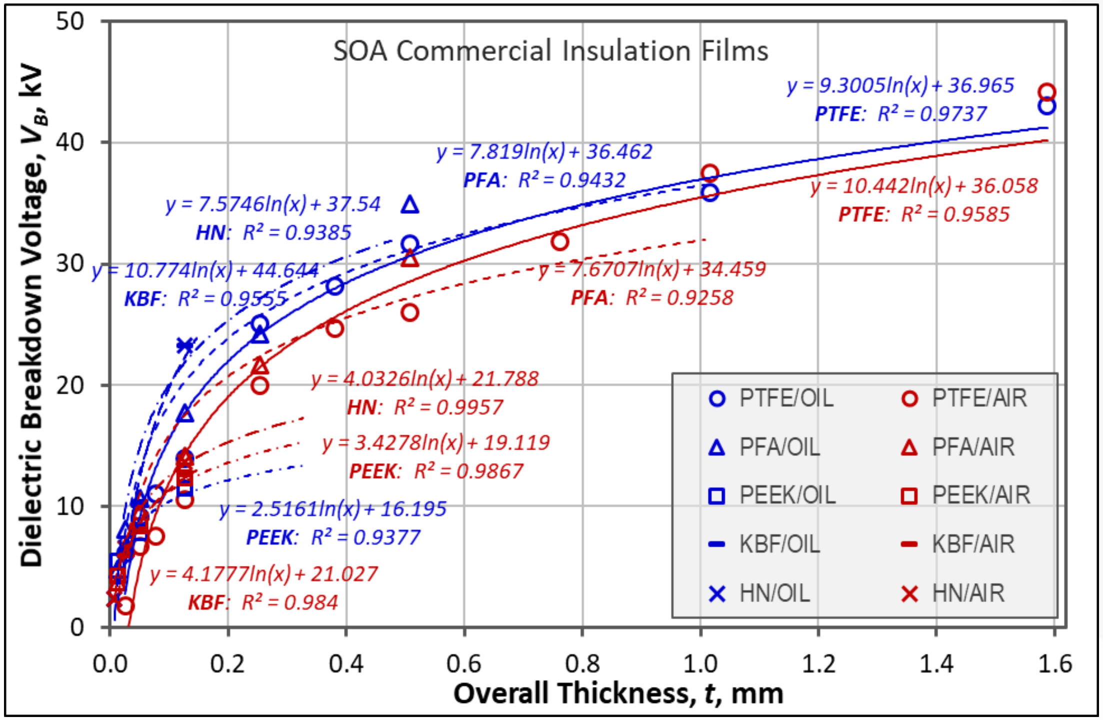
- to prevent HV flashover or arcing around the sample in air, thus, to minimize sample size (2.5" vs. >9")
- experimentally verified, V_B of the samples measured with the fixture was typically ~ 17% higher than that without it

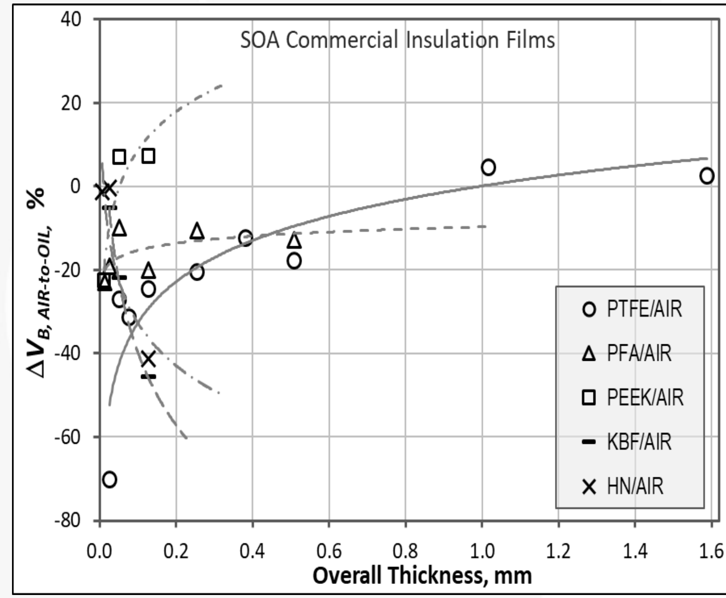
- Tested under either OIL or AIR at 0.6 kV/s ramp (or isovoltaic mode) up to 60 kV (AC) or 84 kV (DC)

*LC: a small pass-through current under applied voltage due to imperfection of dielectric material, relatable to PD potentials

Results & Discussions: The SOA Materials

Overall Dielectric Performance as a function of Thickness

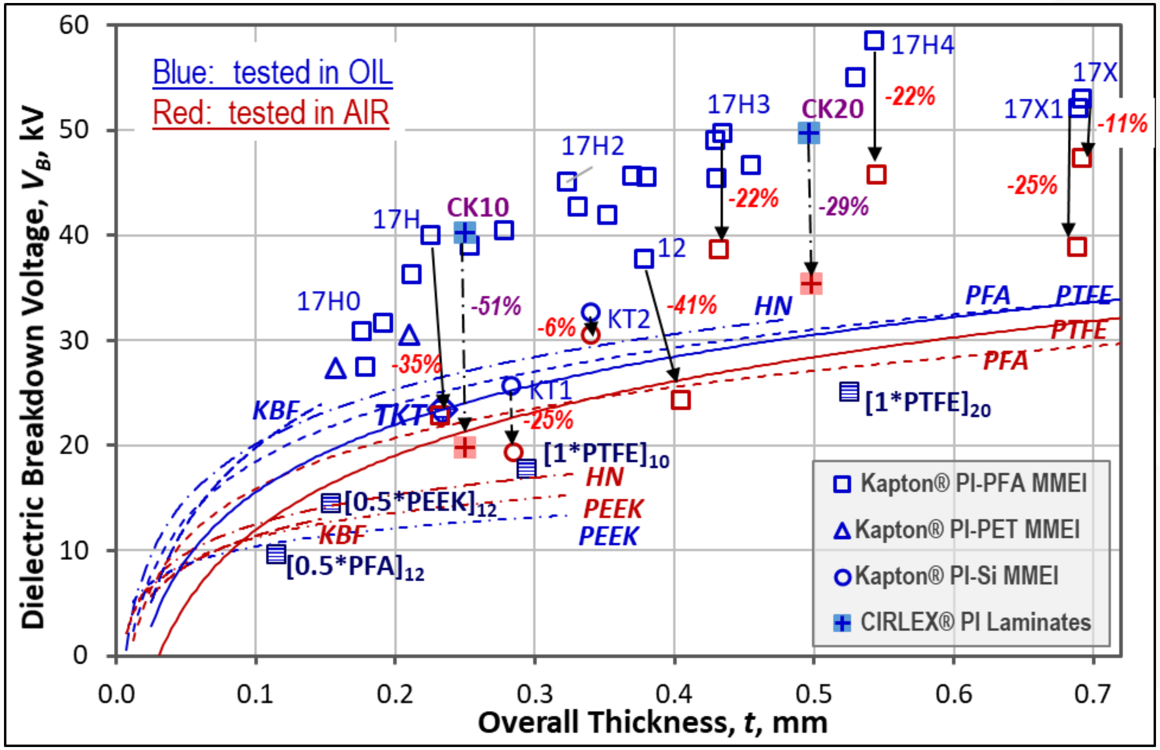


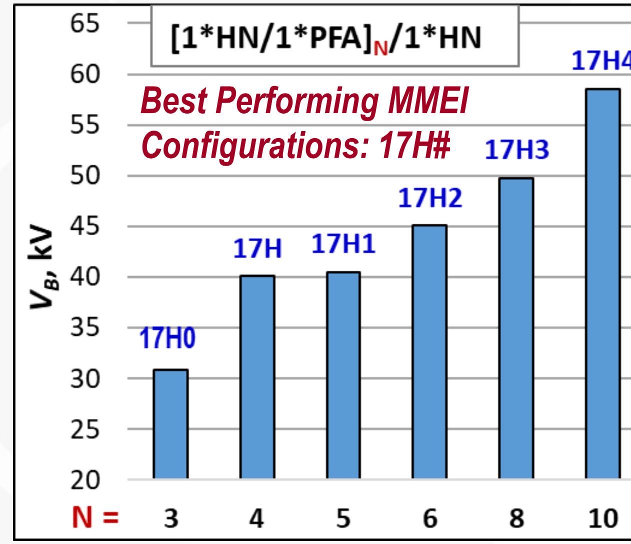


- V_B-*t*, best curve fitting followed logarithmic trendlines regardless of material type or test medium
- Opposite behavior in $\Delta V_{B,\,AIR\text{-}to\text{-}OIL}$ –t relation between Kapton® PI materials and semi-crystalline bond-layer materials, i.e., the former increasing negative % change with thickness but the latter decreasing it; The least changes from PFA

Results & Discussions: Current Status of MMEI Development

Overall Dielectric Performance of MMEI Structures To Date



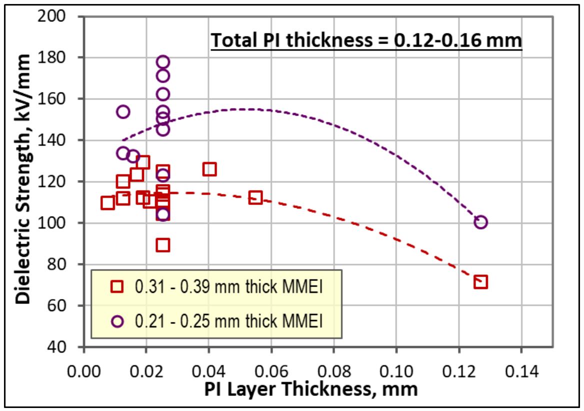


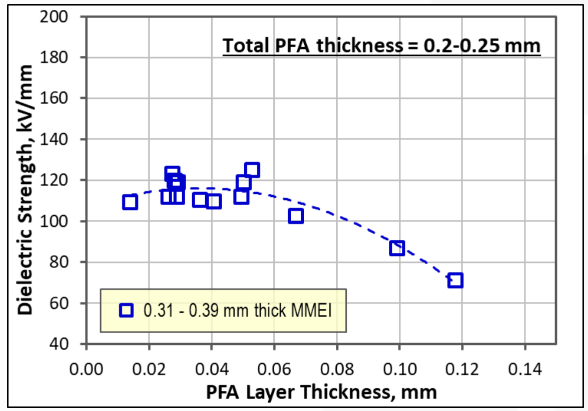
KT1 [1*HN/1.5*Si]$_4$/1*HN
KT2 [0.5*HN/1*Si]$_8$/1*HN
CK10 [?*HN]$_?$ from Fralock
CK20 [?*HN]$_?$ from Fralock

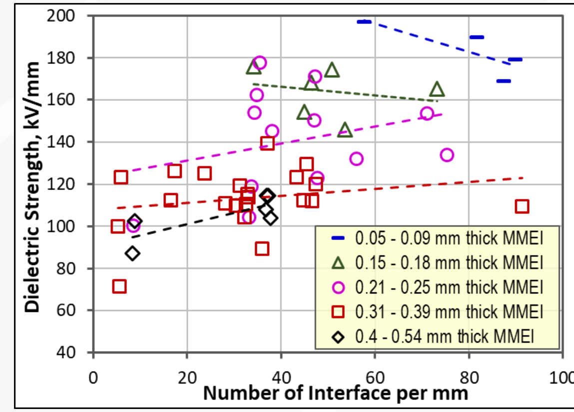
- MMEI structures, esp. 17H#, outperformed all of SOA materials and TKT → The highest increase, ~91% by 17H4 against the projected V_B of Kapton® HN PI (or ~98% thickness reduction, i.e., 0.54 vs. 24.6 mm, respectively)
- Cirlex® HN laminates performed reasonably well, but laminates of PEEK, PTFE, or PFA did poorly
- For $\Delta V_{B,\,AIR\text{-}to\text{-}OIL}$, PFA, PTFE, PEEK < PI-Si MMEI < PI-PFA MMEI < CIRLEX PI Laminates < Kapton® PI
- 17X and 17X1 configurations w/ additional multifunctionalities for full-scale prototypes, to be discussed later

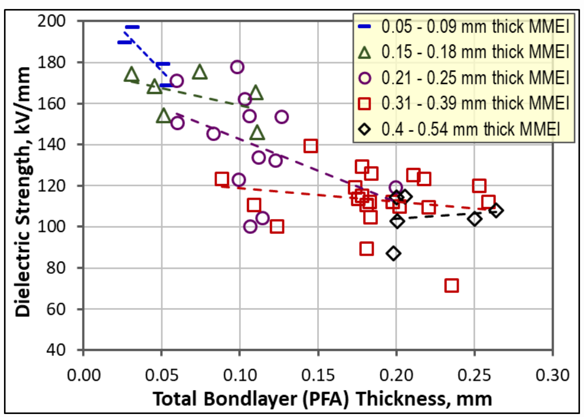
Results & Discussions: Current Status of MMEI Development

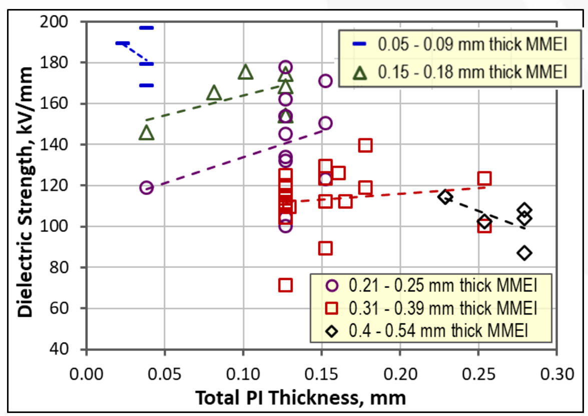
Systematic Parametric Analyses of MMEI Structures

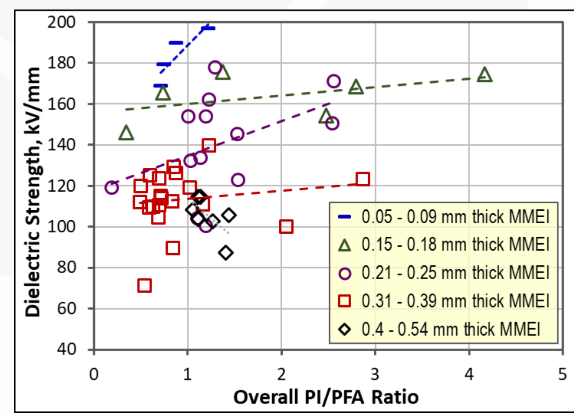








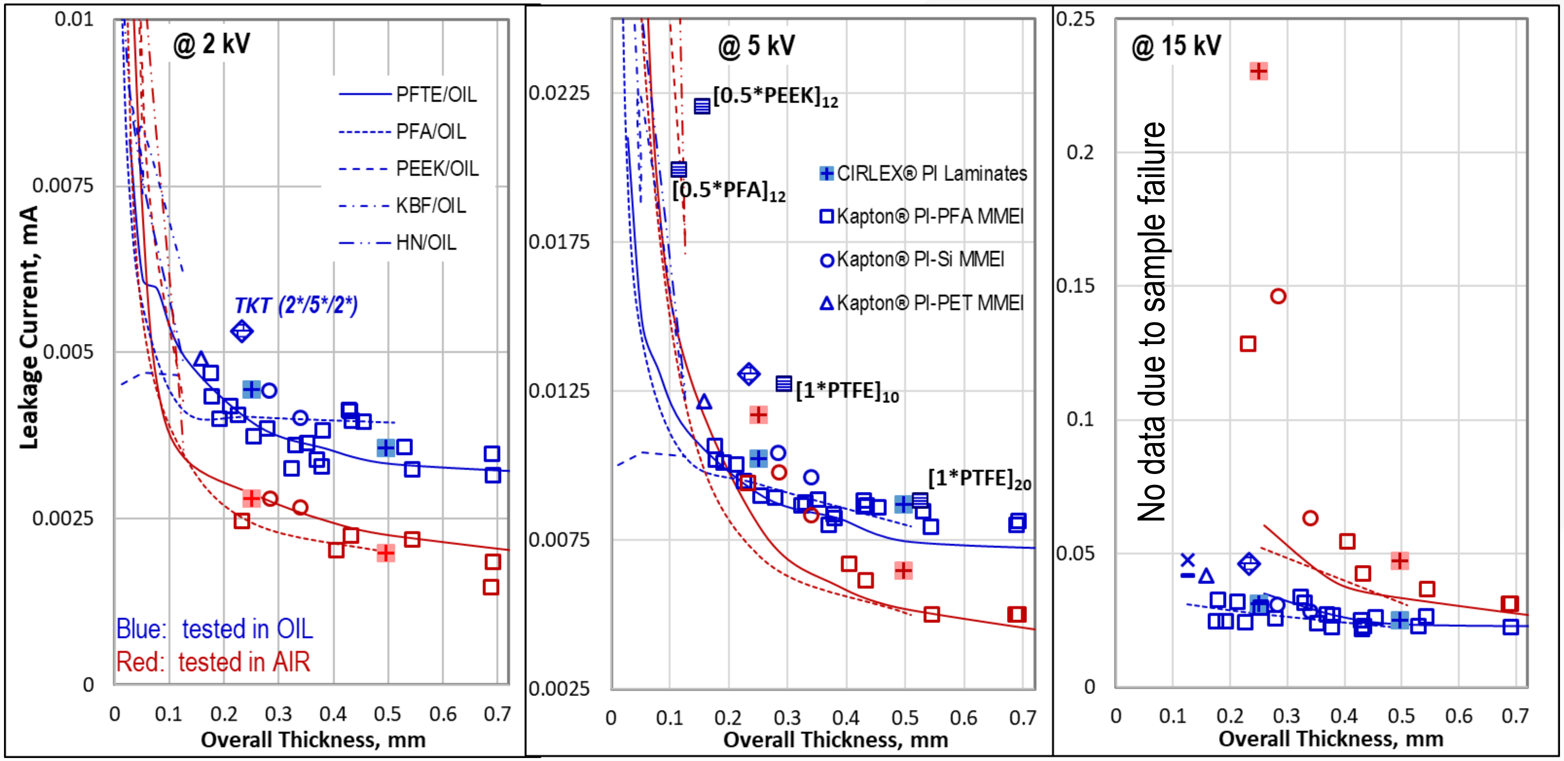




- Added new data points from more batches of the improved/optimized MMEI structures
- Consistent with the initial analysis → used for further optimization of MMEI structures

Results & Discussions: Current Status of MMEI Development

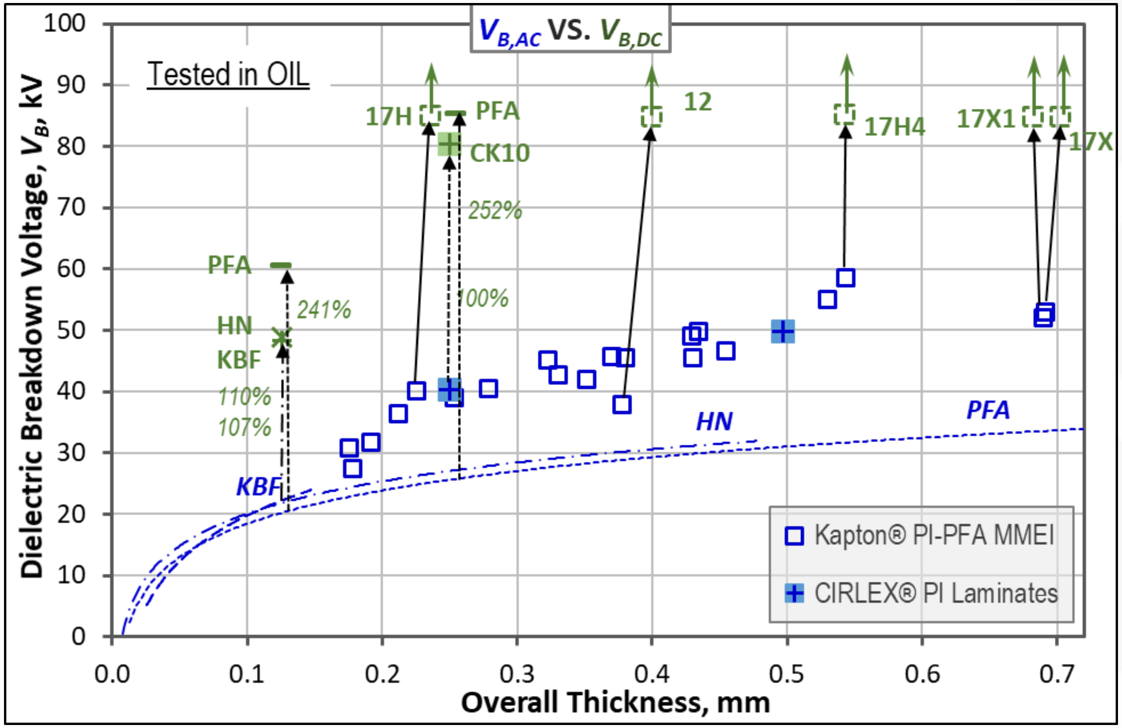
Overall Dielectric Performance of MMEI Structures To Date



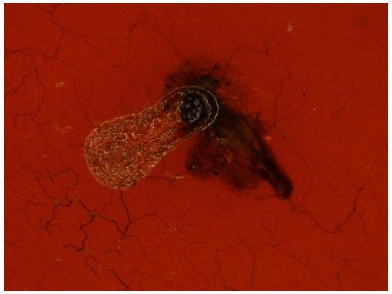
- Overall, the leakage current as a gauge of structural imperfection:
  - in OIL, Laminates of PEEK, PTFE, PFA > TKT > Cirlex® PI laminates ≥ MMEI structures ≅ SOA materials
  - in AIR, Cirlex® PI laminates >> MMEI structures > SOA materials
- After exposure to 350 ºC, LC of 5*PFA ↑, but no changes in Kapton® PI, i.e., good thermal stability

Results & Discussions: Current Status of MMEI Development

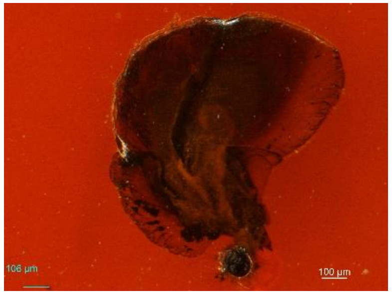
Overall Dielectric Performance of MMEI Structures To Date



5*HN under AC, OIL



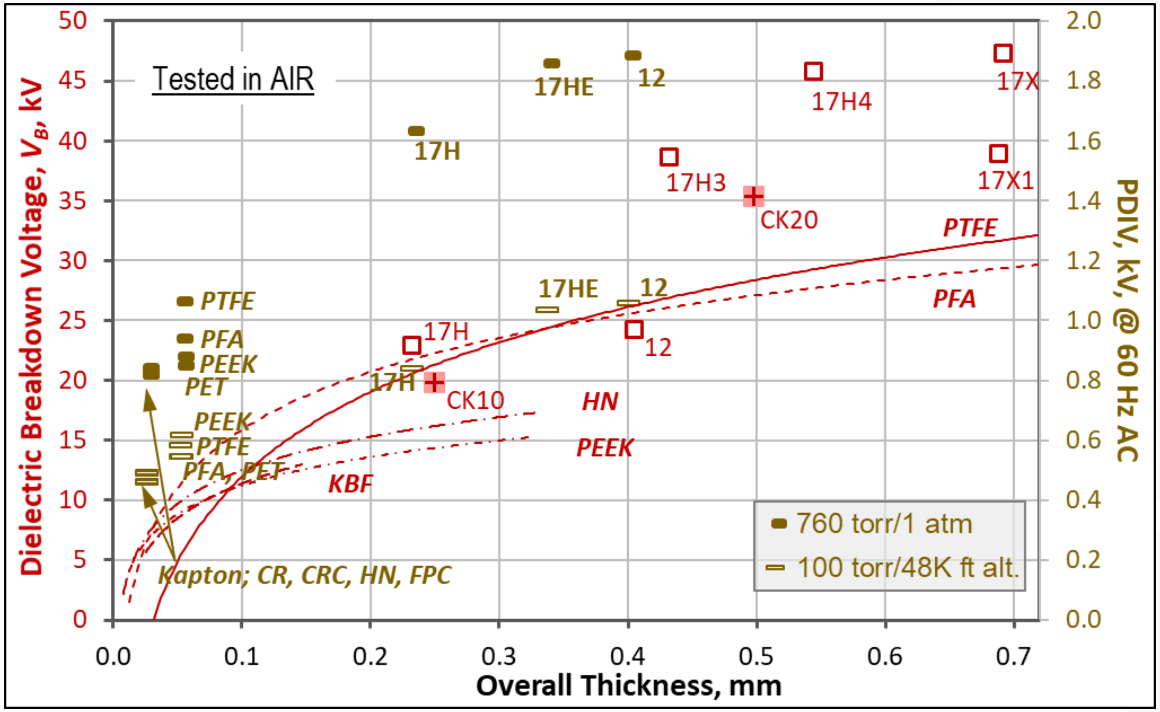
5*HN under DC, OIL

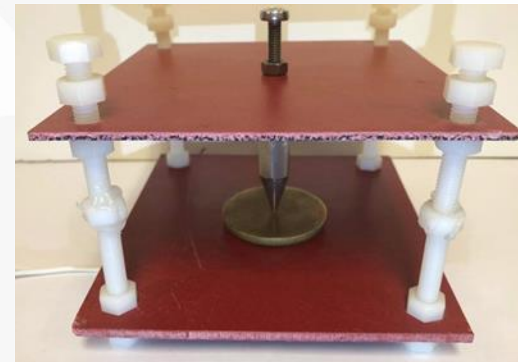


- In all cases, $V_{B,DC} >> V_{B,AC}$
- Under DC, PFA outperformed Kapton® or Cirlex®
- MMEI structures showed higher increases in $V_{B,DC}$ than typical SOA materials or Cirlex® PI laminates
  - None of MMEI structures failed up to the Vmax, 84 kV, of the test system
  - MMEI outperformed Cirlex® under DC, more than under AC, by comparing 17H and CK10 at the similar overall thickness
- Under DC, all Kapton® and MMEI samples showed no pre-failure damages, such as micro-crack, crack, or cavitation, even in oil medium unlike under AC

Results & Discussions: Current Status of MMEI Development

PD Performance of MMEI Structures To Date (OSU-CHPPE)





Cone (2 mm dia.)-to-Plate Electrode setup used in environmental chamber

12: 5*KBF/5*PFA/5*KBF

17HE: $[1*HN/1*PFA]_4/[1*_{\rightarrow}2x1*PFA/1*CRC]_2$

- Incomplete, but more extensive, systematic PDIV/PDEV testing under way with OSU team including:
  - SOA materials as a function of sample thickness material type vs. thickness dependency
  - Additional MMEI structures with better PD resistant materials and Cirlex® PI laminates
- Significant decrease in PDIV with decreasing pressure regardless of material type

Results & Discussions: Mechanisms

Potential Mechanisms responsible for MMEI performance

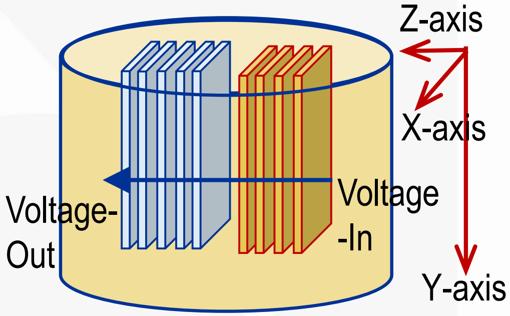
- molecular rearrangement-induced changes in capacitance or conductance
- formation of more torturous path for electron move by multilayered structures
- less or smaller void formation by heat fuse-bonding between layers resulting in less partial discharge
- increased space charge formation/storage capacity at interfaces resulting in lower voltage potentials

Efforts continued to identify/ascertain the controlling mechanisms experimentally via.

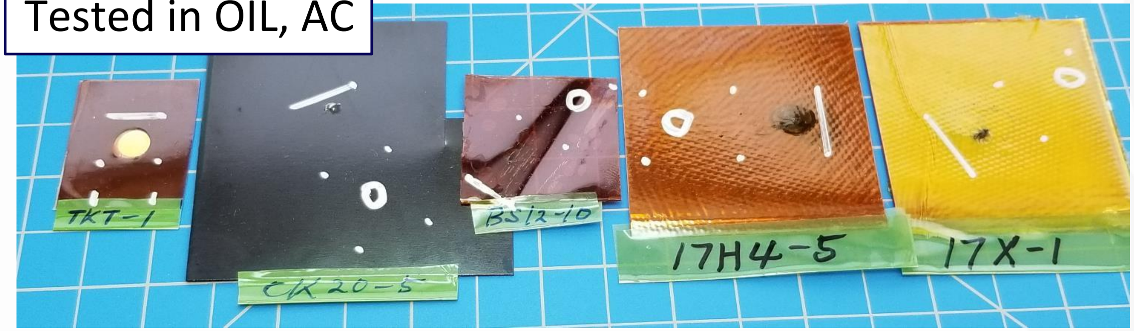
- Pulsed Electro-Acoustic (PEA) analysis
- 3-dimensional electromagnetic and electro-thermal modeling
- 3-dimensional dielectric breakdown damage and failure mode analysis

Results & Discussions: Mechanisms

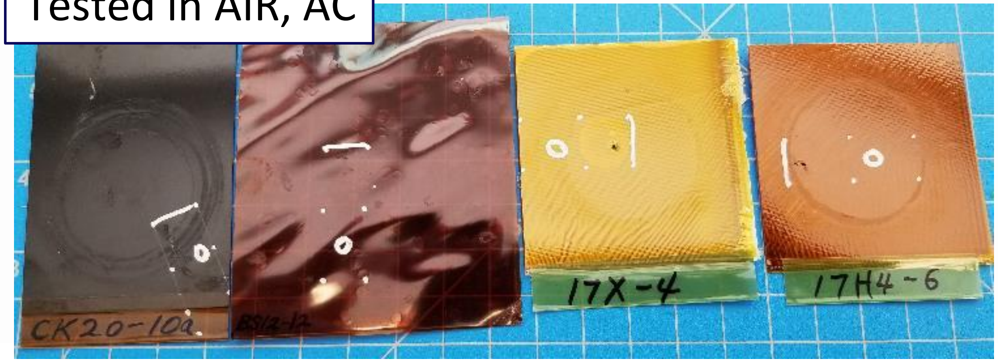
- 3-D Dielectric Failure Mode Analysis
  - Via RoboMet automatic serial polishing and micro-graphing process
  - Initially, obtained 97 high resolution cross-sectional micrographs (#0 to #96) with 50 -100 μm spacing, covered a total of ~ 8 mm in Y-axis
  - Accurate measurement of the spacings → overall DZ dimensions



Tested in OIL, AC



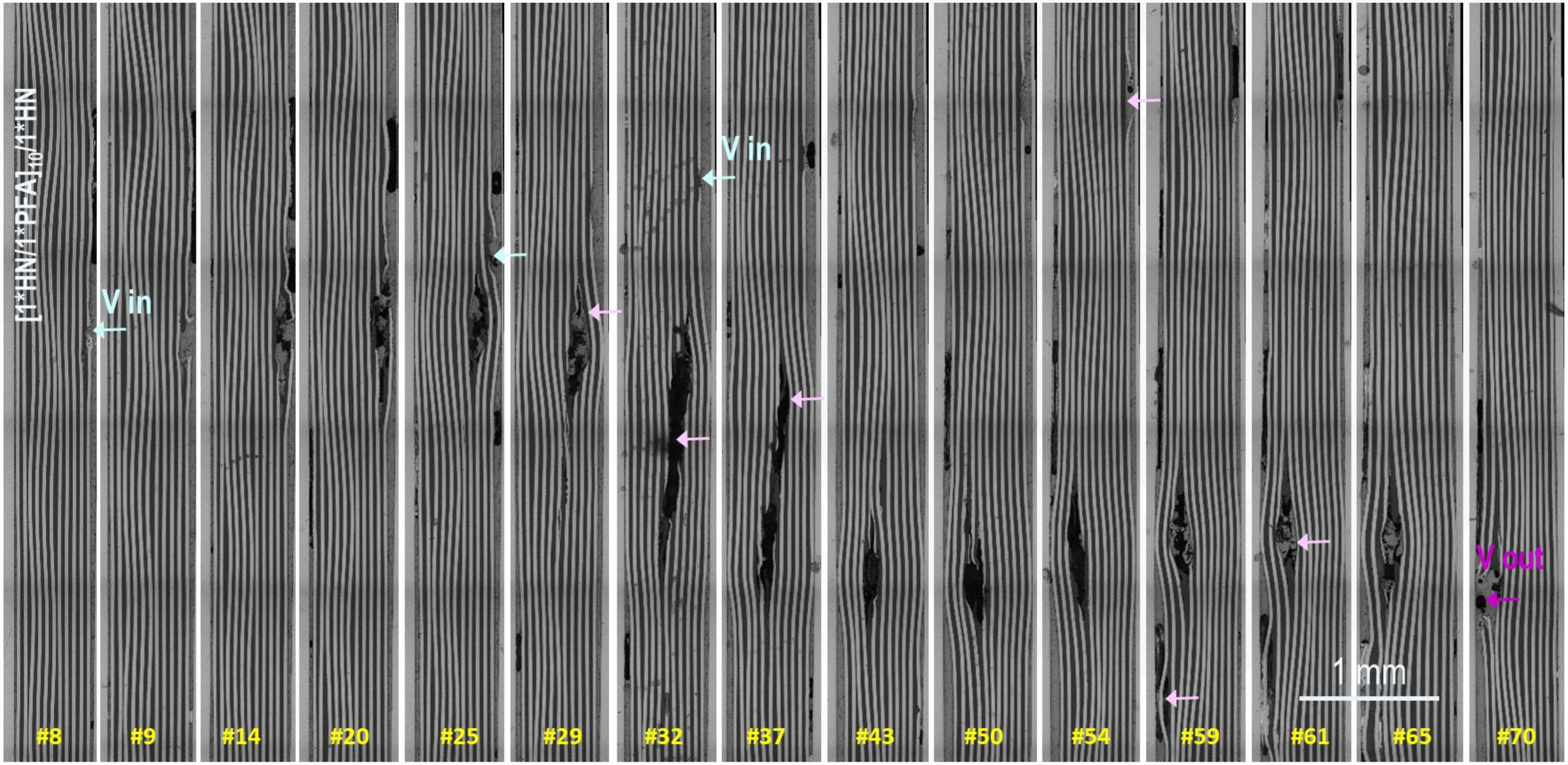
Tested in AIR, AC



- TKT: 2*PTFE/5*HN/2*PTFE
- CK20: 20*Cirlex Kapton laminate
- BS12: 5*KBF/5*PFA/5*KBF
- 17H4: $[1*HN/1*PFA]_{10}$/1*HN
- 17X: 0.3*HN/$[1*PFA/1*HN]_{10}$/$[1*PFA/1*CR]_{2}$ /2*PEEK/0.3*HN

Results & Discussions: Mechanisms

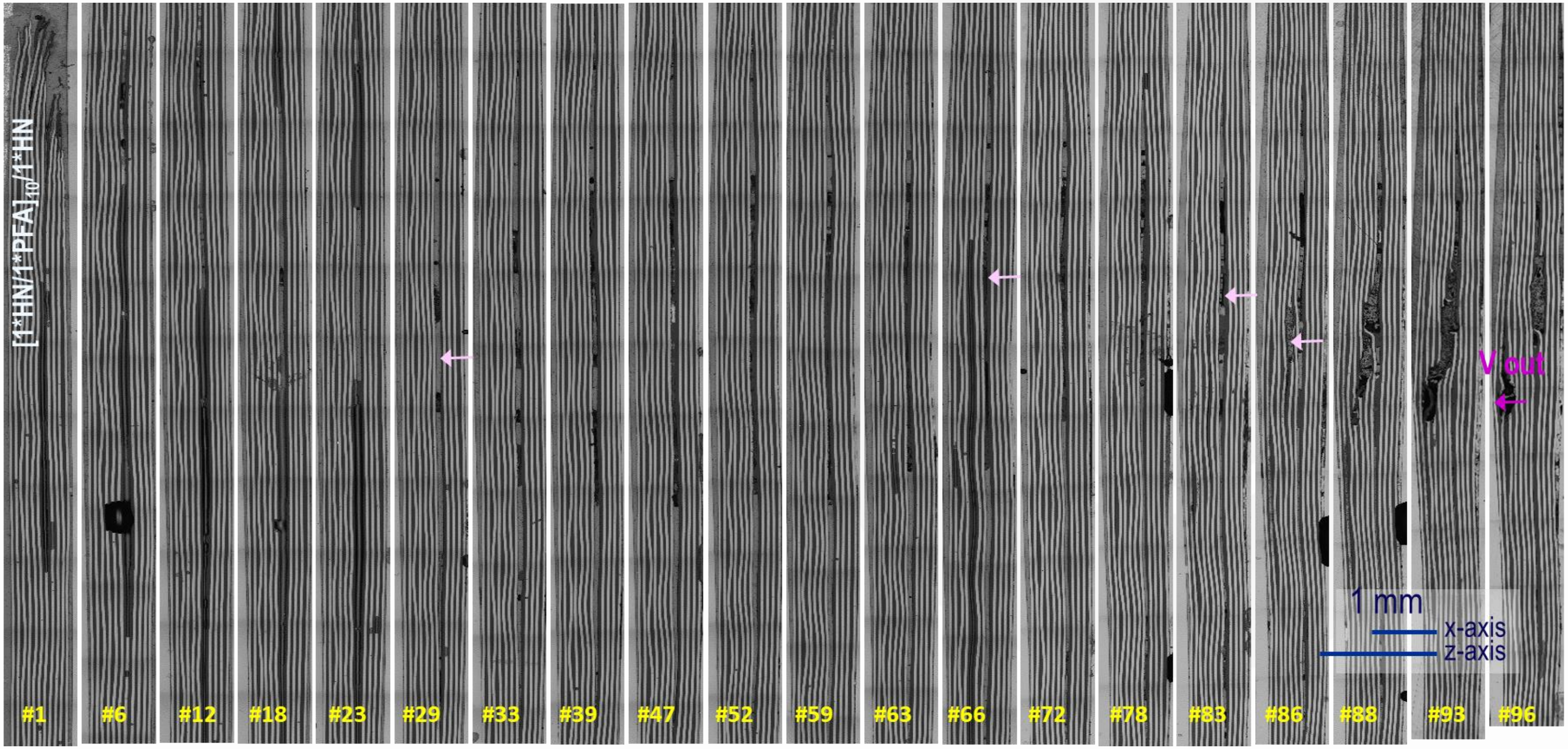
17H4-6 (21 layers, 0.545 mm Th) in AIR, V_B = 44.1 kV, Damage zone: X = 5.5 mm, Y (#8 - #80) = 5 mm



V_{Local} intensified at interfaces, released through repetitive sequence of interlayer debonding-propagation followed by thru-layer-perforation → lengthier, more torturous failure path: Similar path for 17X *(in-pane cracking, charring-disintegration of Kapton® layers*; interlayer debonding and propagation; cavitation in PFA layer if thicker than ~ 2 mil; melting and disintegration of PFA layer)

Results & Discussions: Mechanisms

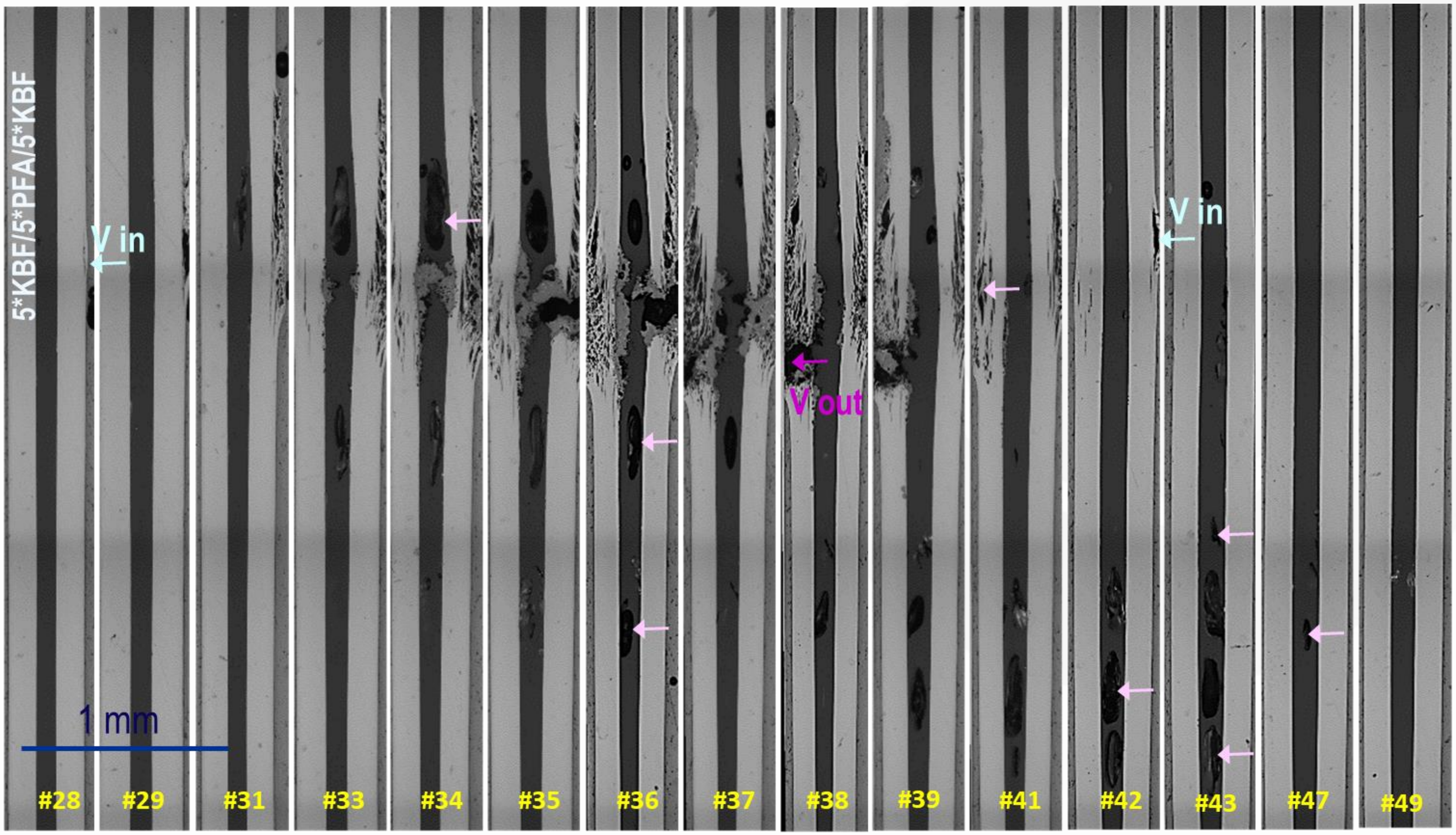
17H4-5 (21 layers, 0.545 mm Th) in OIL, V_B = 58.3 kV, Damage zone: X = 12 mm, Y (#0 - #96) = > 8 mm



V_{Local} intensified at interfaces, released through repetitive sequence of interlayer debonding-propagation followed by thru-layer-perforation → lengthier, more torturous failure path: Similar path for 17X (micro-cavitation & microcracking on outermost Kapton® layers; *cavitation, charring-disintegration of internal Kapton® layers*; interlayer debonding and propagation; melting & disintegration of PFA layers)

Results & Discussions: Mechanisms

BS12-12 (3 layers, 0.4 mm Th) **in AIR, V_B = 24.6 kV, Damage zone: X = 3.3 mm, Y** (#28 - #49) **= 1.2 mm**

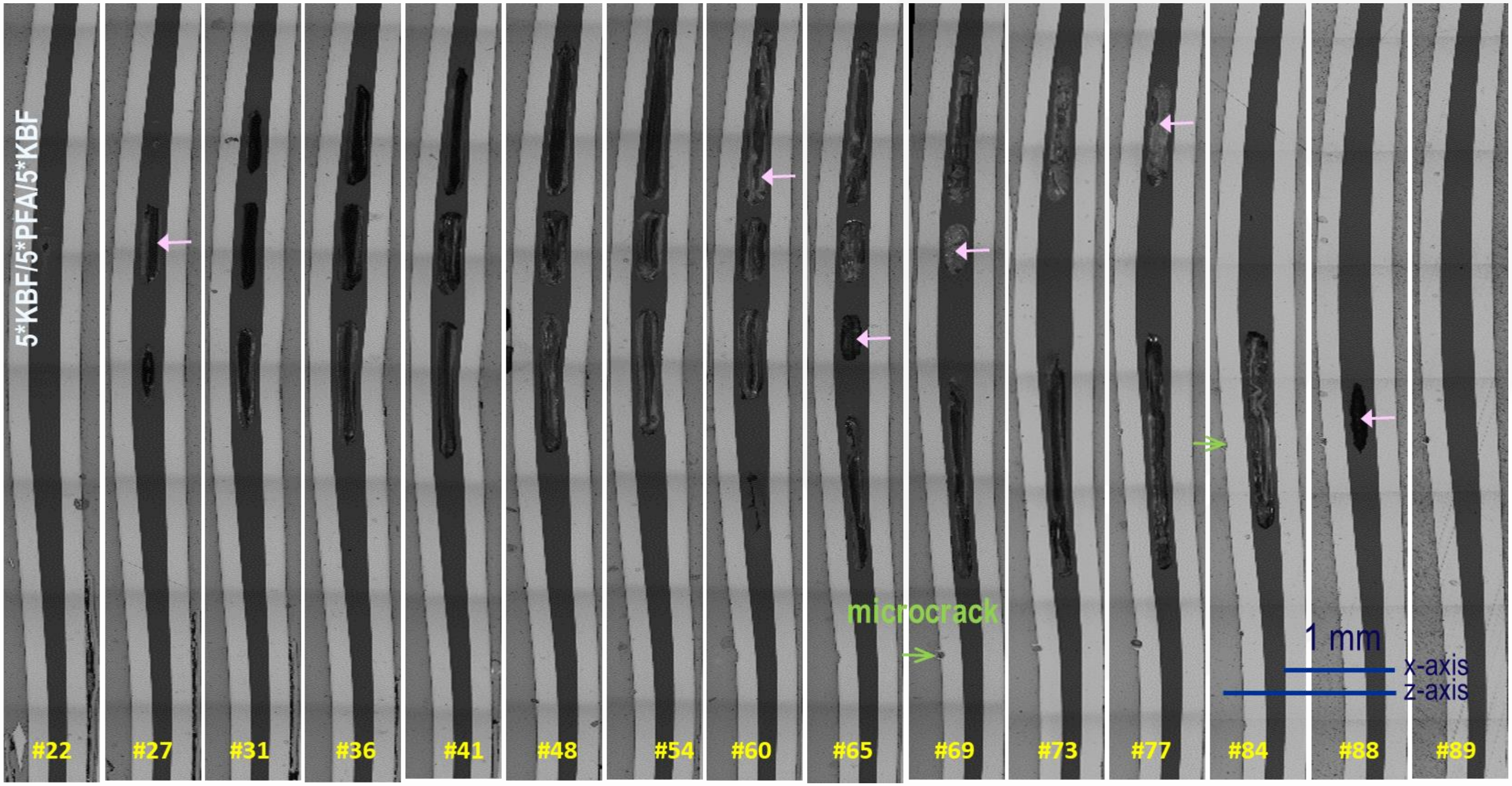


Simpler failure path via cavitation, cracking, and thru-layer-perforation

(in-pane cracking, charring-disintegration of Kapton® layers; extensive cavitation, melting and disintegration of PFA layer)

Results & Discussions: Mechanisms

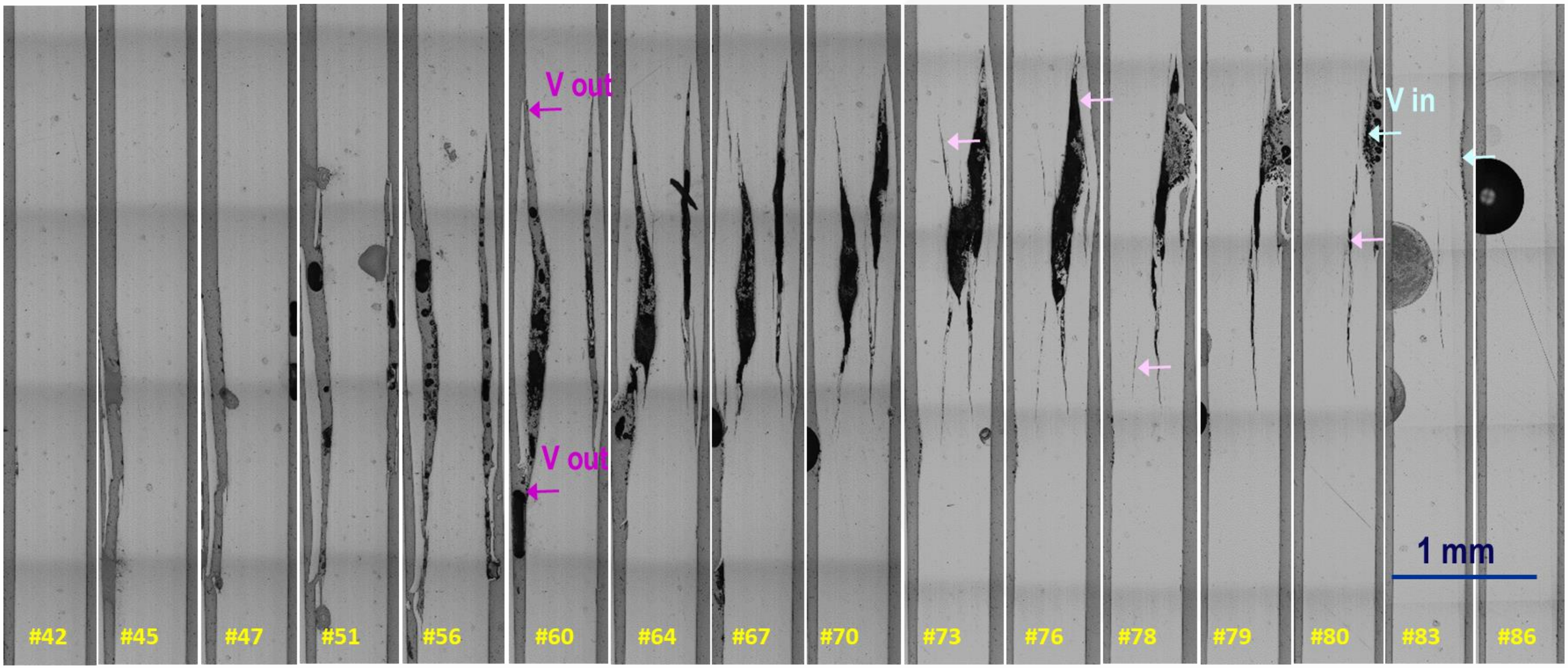
BS12-10 (3 layers, 0.42 mm Th) in OIL, V_B = 45.8 kV, Damage zone: X = 5.9 mm, Y (#22 - #89) = 5 mm



DZ not fully covered, but simpler failure path via cracking and cavitation: Similar path for TKT *(micro-cavitation, microcracking, charring, & disintegration of Kapton® layers*; excessive cavitation, melting and disintegration of PFA layer)

Results & Discussions: Mechanisms

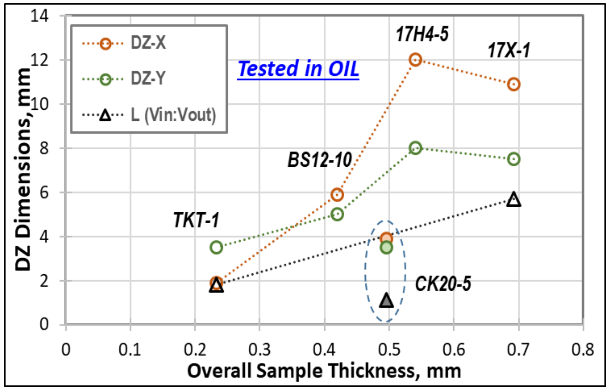
CK20-5 (? layers, 0.5 mm Th) in OIL, V_B = 53.8 kV, Damage zone: X = 3.9 mm, Y (#42 - #86) = 3.5 mm

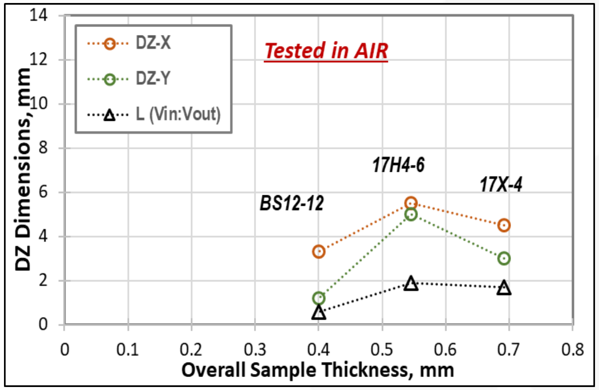


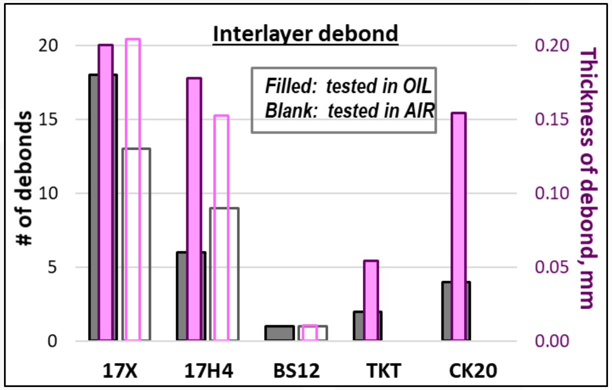
Voltage intensified & propagated via in-plane splitting/cracking, but not necessarily on interlayer interfaces due to stronger interface bonding? Intermediate failure mode between 17H4 and BS12 *(micro-cracking, in-plane cracking, cavitation, charring, and disintegration of Kapton®)*

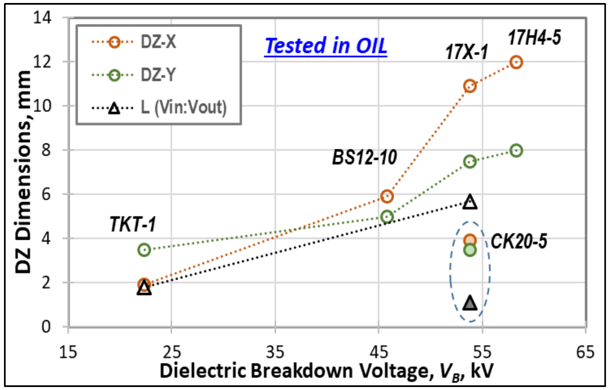
Results & Discussions: Mechanisms

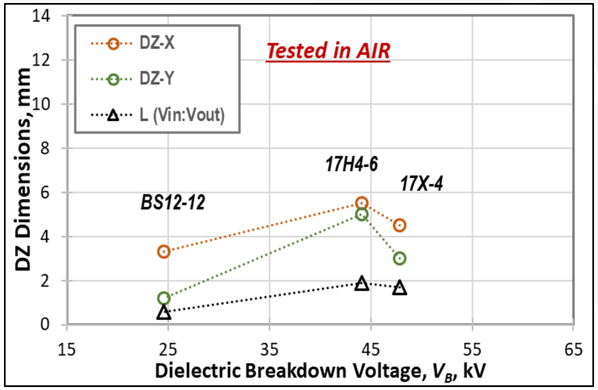
MMEI Structure - DZ – V_B Relations











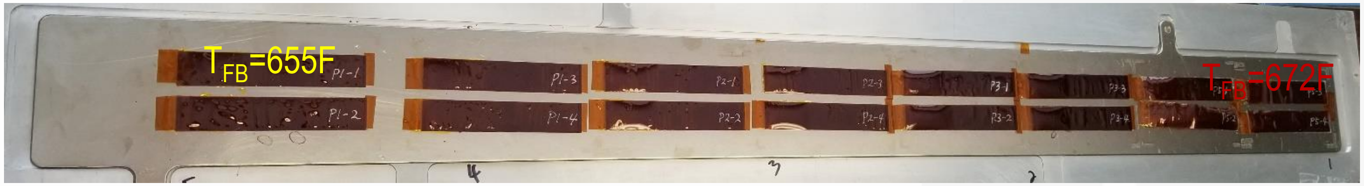
- Intensities of DZ presented by its dimensions, but also by thickness and number of interlayer debond
- DZ in OIL (mostly in-plane) > DZ in AIR (mostly localized, out-of-plane), probably due to different electric field distribution

- DZ type strongly dependent on layer thickness, e.g., (i) profuse and larger cavitation in thicker PFA layers in BS12, but no cavitation in thinner PFA layers of 17X or 17H4 (ii) cracking in internal Kapton® layers in OIL, only if layer thickness > 1 mil
  → suppression of damage with decreasing layer thickness or less PD with smaller defects/voids
- DZ ∝ V_B in general, i.e., proof of more torturous failure path by multilayered structures

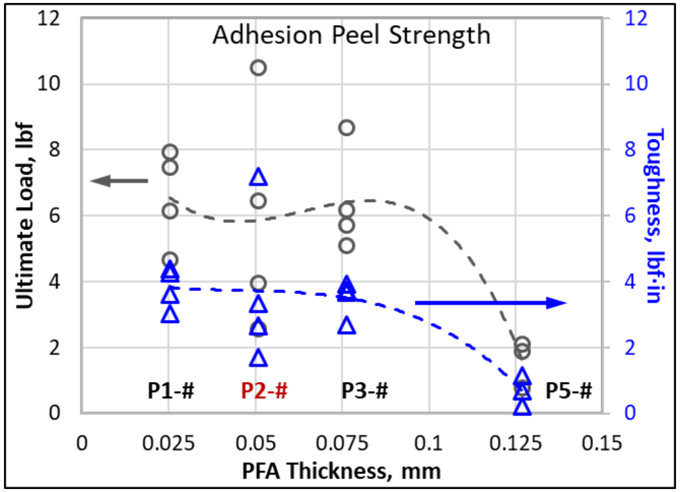
Results & Discussions: Scale-up & Commercial Applicability

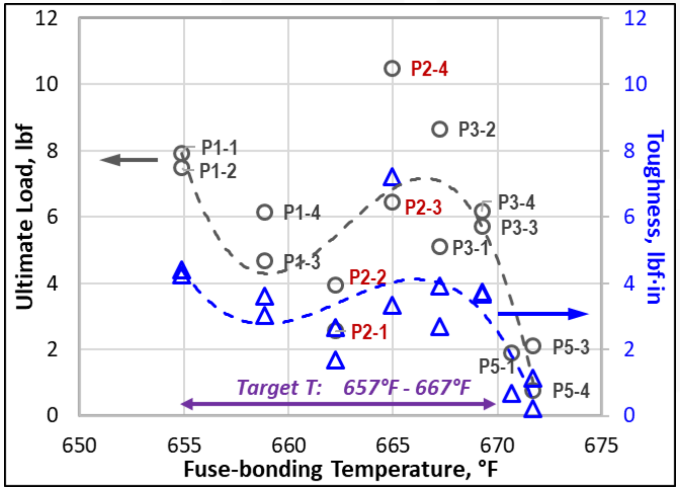
Optimization of the MMEI Candidate for Prototypes (40 kV rated)

17X: 0.3*HN/[1*PFA/1*HN]$_{10}$/[1*PFA/1*CR]$_2$/2*PEEK/0.3*HN with superior V_B and multifunctionalities of PD and moisture barrier → Optimum bondline thickness to Al conductor?



P1: 1*PFA/2*KBF/[1*→2×1*PFA/2*KBF]$_2$
P2: [1*PFA]$_2$/2*KBF/[1*PFA/2*KBF]$_2$
P3: [1*PFA]$_3$/2*KBF/[1*PFA/2*KBF]$_2$
P5: 5*PFA/2*KBF/1*PFA/2*KBF

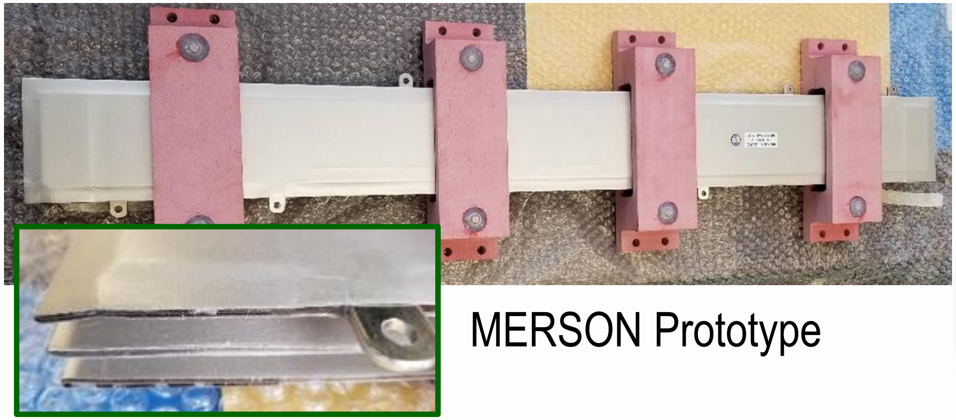




- Selected 2 mil PFA layer, i.e., Al conductor/1*PFA/[1*PFA/1*HN]$_{10}$/[1*PFA/1*CR]$_2$/2*PEEK/0.3*HN
- Targeted 655°F - 667°F (346°C - 353°C) for PFA fuse-bonding of 1-m long bus bar prototype

Results & Discussions: Scale-up & Commercial Applicability

Prototype Development: HV HF Bus Bar with MERSEN



MERSON Prototype

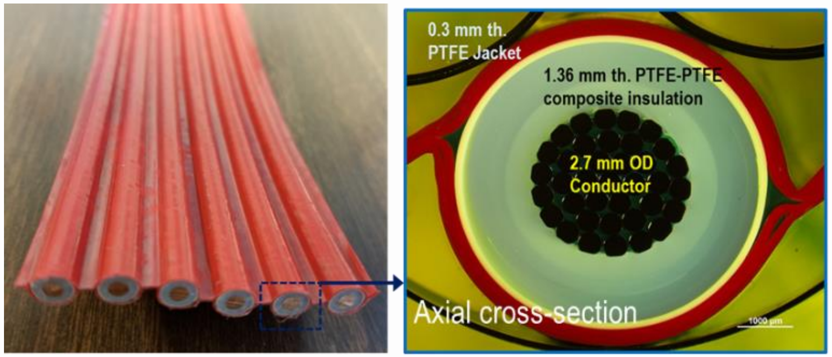
- 1 m long, 3-phase bus bar to carry up to 10 MW at 20 kV, 400 to 4000 Hz
- Applicable to vibration spec (8.0 G_{rms} random, Cat. V by Armstrong's test standard)
- Ni-plated Al conductor/Si/14*PTFE/Si/1*CR/Si/14*PTFE /Si /epoxy/5*Mica insulation, rated to -40 ºC ~ 180 ºC
- Experimentally validated up to 15 kV_{AC} for HiPot & PD

- Identical bus bar design, but with MMEI (17X) insulation
- Optimized fabrication conditions and procedures for "one-step lamination autoclave process"
- Conducting HiPot and PD at MERSEN, but synergistic-environmental PD and durability testing with the CHPPE/OSU using a newly built test chamber

GRC Prototype

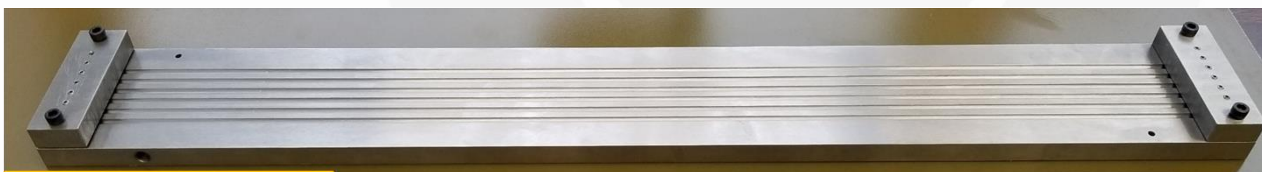
Results & Discussions: Scale-up & Commercial Applicability

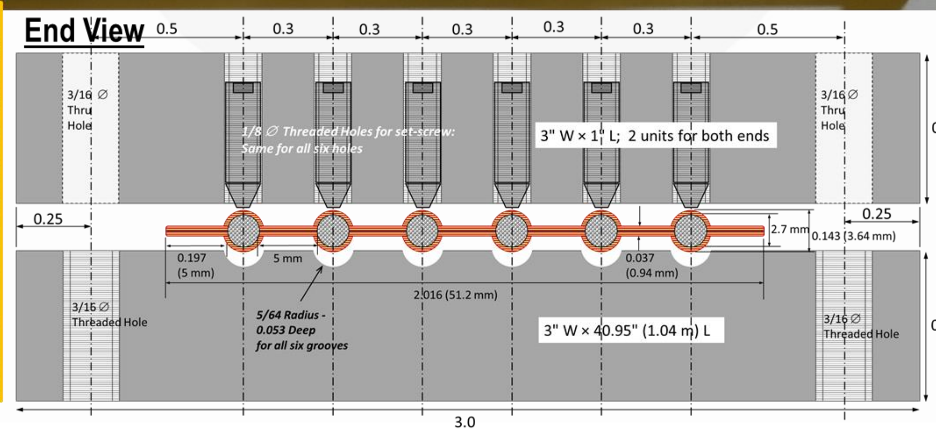
Prototype Development: HV HP Flat Pod Cable with GORE



- Unique design of six identical conductor pods to carry 0.25 MW at 15 kV or higher (rated to 40 kV)
- Insulated by the GORE's proprietary PTFE-PTFE composite and arranged horizontally by a corona resistant PTFE jacket, rated to -80 ºC ~ >260 ºC
- Experimentally validated up to 30 kV for HiPot

- Identical cable design with MMEI (17X): Optimized dimensions and fabrication conditions for <u>one-step lamination autoclave process</u>
- Designed and fabricated molding fixtures w/ A2 tool steel
- Conducting HiPot, PD, & durability testing in collaboration with the CHPPE/OSU





Summary and Conclusions

- The newly developed MMEI system was further optimized and improved:
  - MMEI structures outperformed most of the SOA insulation materials in terms of $V_{B,AC}$ or $V_{B,DC}$.
  - $[1*HN/1*PFA]_N/1*HN$ configurations performed best, and the highest improvement to date was 91% with N=10 (or ~98% reduction in insulation thickness) compared to the Kapton® HN, and outperformed Cirlex® PI laminates in terms of V_B, $\Delta V_{B,\ AIR\text{-}to\text{-}OIL}$, or leakage current.
  - In general, adding functional layers caused negative impact on the overall V_B of MMEI and it was not only material dependent but also structure dependent, thus, more systematic and careful design and optimizations required to incorporate multifunctionalities into MMEI.
  - Potential Mechanisms responsible for MMEI performance were suggested and some have been validated experimentally via 3-D dielectric damage and failure mode analyses.
- Significant progress was made in scaling up, assessing commercial applicability, and manufacturing full-scale prototypes of MMEI system:
  - The down-selected MMEI for the initial GRC prototypes of power cable and bus bar with superior V_B and anticipated multifunctionalities was further optimized for PFA-conductor bonding integrity; Al conductor/1*PFA/$[1*PFA/1*HN]_{10}$/$[1*PFA/1*CR]_2$/2*PEEK/0.3*HN and will be compared to the SOA commercial systems.

Future Work Plan

The following tasks are planned to continue for development and improvement of the MMEI system:

- Material-design-process optimizations, especially for additional multifunctionalities, such as EMI shielding, thermal management, or mechanicals, and development of new/modified constituent materials with improved performance
- Experimental validation of potential mechanisms on performance enhancement of MMEI structures
- Continuation of scale up, prototype developments, and commercialization
- More sophisticated performance evaluations of the MMEI structures/prototypes including synergistic durability assessment
- Thermal-mechanical-physical performance characterizations including interlayer adhesion integrity

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Thank You for your attention!

Any Questions?