Feasibility of Micro-Multilayer Multifunctional Electrical Insulation (MMEI) System for High Voltage Applications

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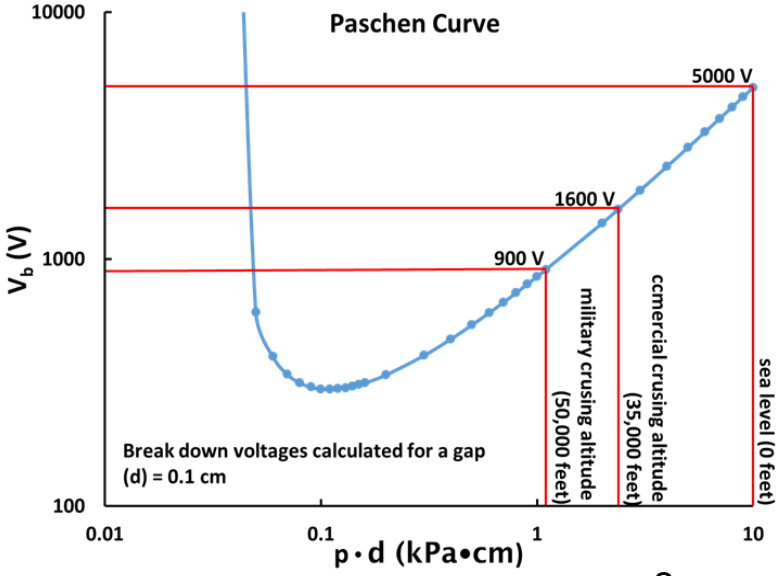
Background

Supporting development of Electrified Aircrafts at NASA & Industries

- **Potential Benefits**
  - fewer emissions, improved fuel economy, quieter flight, improved efficiency and maneuverability, reduced maintenance costs, and improved reliability
- Challenges (Materials)
  - High power demand, e.g., 0.5 (9 seat) to 60 MW (300 seat) total propulsive power→ larger currents, thus larger conductors→ huge weight/volume gain
  - High voltage (HV), high frequency (HF) Option, up to 20 - 40 kV or higher → ~ 1 mm thick SOA electrical insulation→ still significant weight gain
  - Current HV cable technologies, mostly designed for sea-level to low altitude, not suitable for high-altitude airplane operations due to corona PD
  - Also, other specs to meet, e.g., up to 4 kHz, 50 – 500 amps, 180 – 240 ºC+

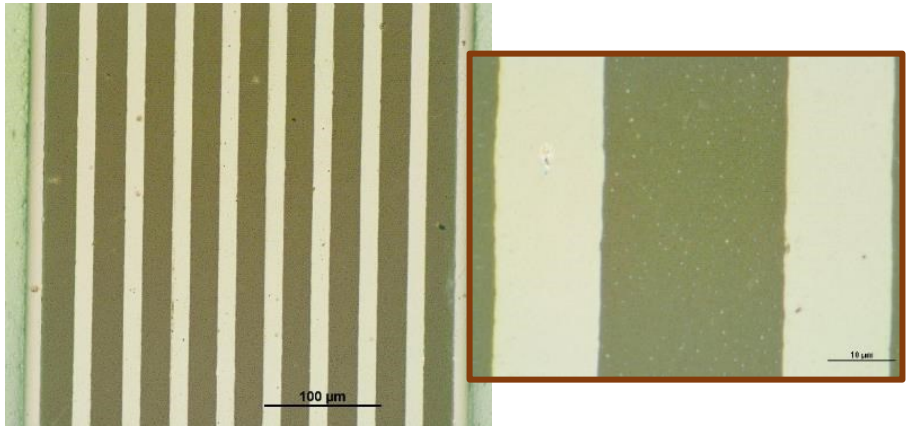
→ Critical need for lightweight, HV, HF, high temperature, and PD resistant electrical insulation system



Background

- Multilayered structures of thin polymer insulation films, e.g., Kapton PI and PFA or PEEK as bond layer, significantly improved dielectric breakdown voltage (V_B), <u>if well-bonded,</u> regardless of test conditions, Oil vs Air or AC vs DC

  → <u>Micro-multilayer Multifunctional Electrical Insulation (MMEI)</u> system*

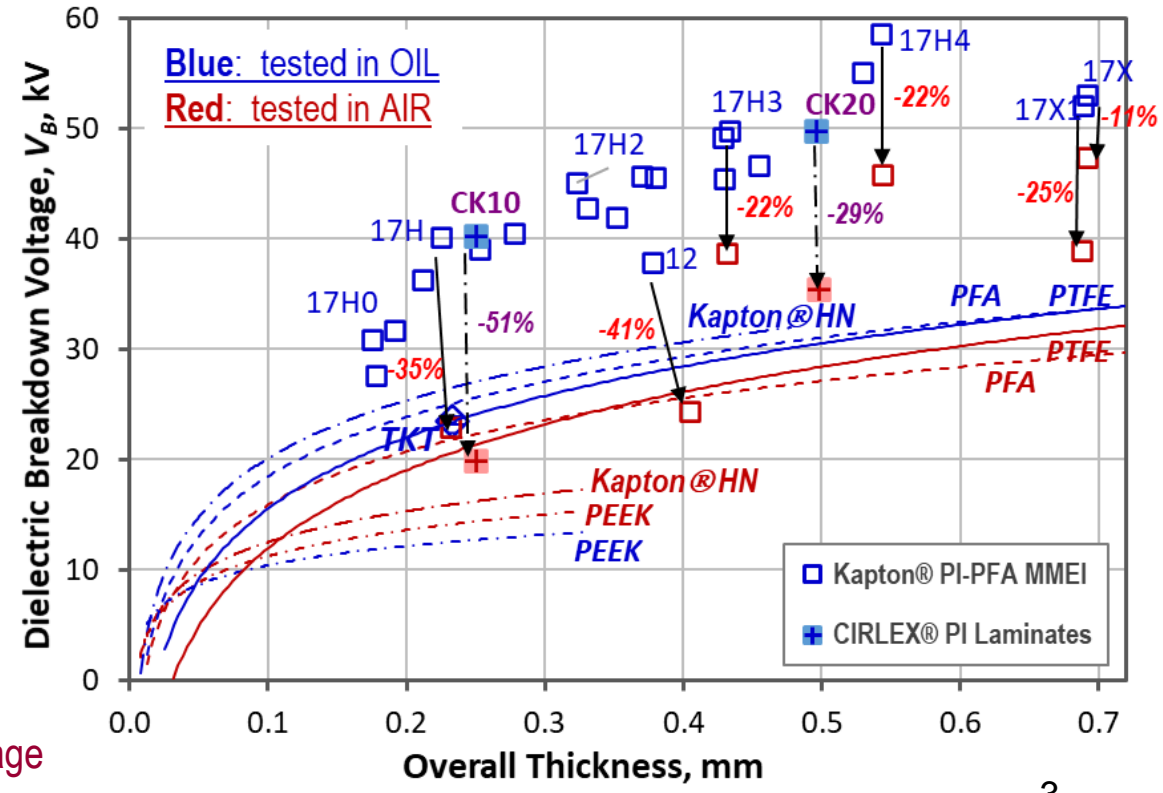


Cross-section of a 19-layer MMEI, $[0.5*HN/1*PFA]_9/0.5*HN$; Overall thickness of 0.38 mm

Next layer — name/type of material

$[1*HN/1*PFA]_n/1*HN$

Thickness in mils — number of repeat

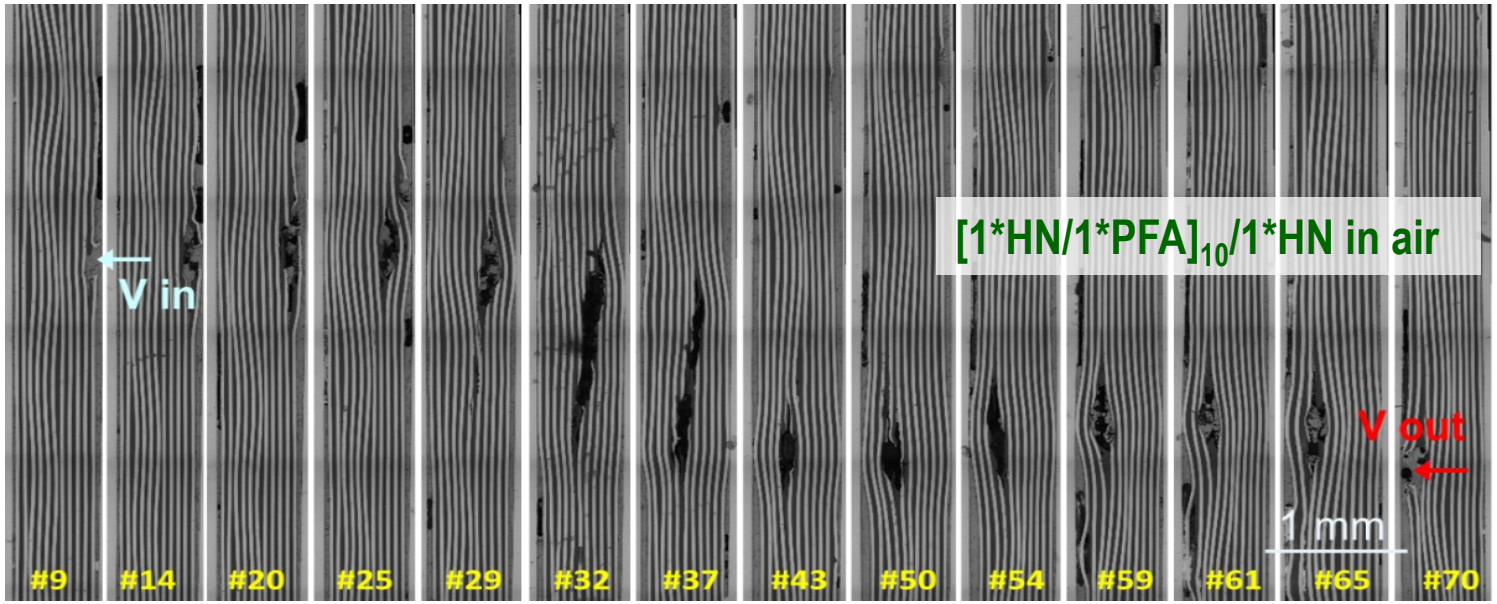


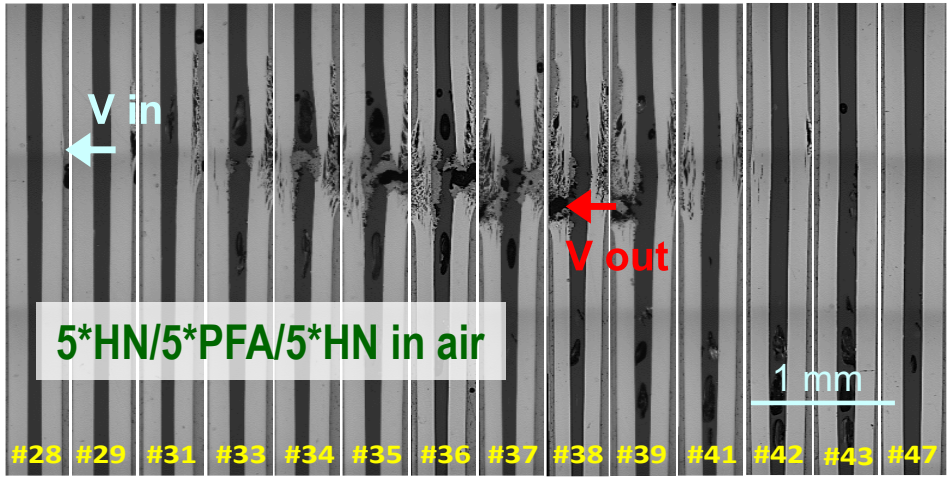
* E. Eugene Shin, "High Performance Multilayer Insulation Composite For High Voltage Applications," United States Patent (U.S. Pat.) No. 10,546,666, January 28, 2020

Background

Potential MMEI performance mechanisms

Sequence of representative cross-sectional micrographs of the damage and failure zone





- MMEI structures with higher V_B, typically consisted of thinner individual layers or more # of interfaces, induced a significantly more torturous path for HV current flow through the insulation layers.
- Formation or propagation of damage such as defects/voids in the MMEI structures was effectively suppressed with decreasing the individual layer thickness, typically less than 1 mil/25.4 μm.
- This 3-D DZ analysis confirmed that the size of DZ was directly proportional to V_B in general.

Experimental: Materials

Candidate Materials for MMEI, all commercial products

- Kapton® Polyimide (PI) high temperature high dielectric strength films (DuPont)
  - Thermalimide bagging film (KBF) (Airtech), 1, 2, & 5 mil: Thermally stable film
  - 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

Alternative Candidates:

- CIRLEX® Kapton® sheet, 10 & 20 mil (Fralock): Proprietary adhesiveless PI laminates, 4 mil to 125 mil + thick

Results & Discussions: Full-scale Demonstrations of MMEI

Developed 1 m long, 3-phase full-scale bus bar prototypes with MERSEN

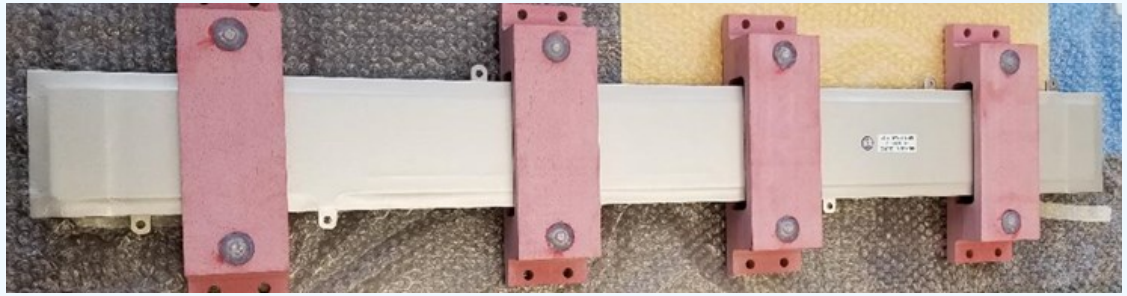
to demonstrate scalability, manufacturability, and commercial applicability

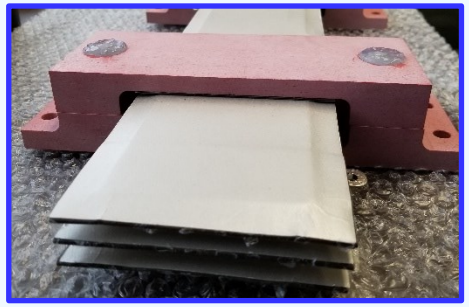
Prototype #1 w/ SOA insulation

Al/Si/14*PTFE/Si/1*CR/Si/14*PTFE /Si/epoxy/5*Mica

– Avg weight of insulation per conductor = 427 gram

– Avg thickness of insulation per side = ~ 0.81 mm (32 mils)



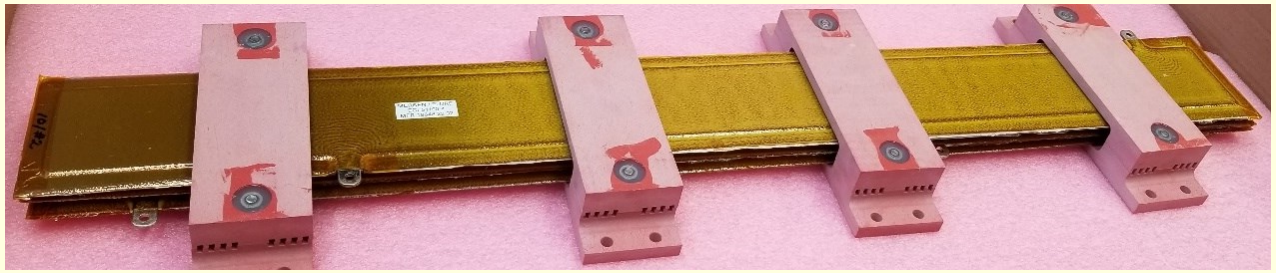


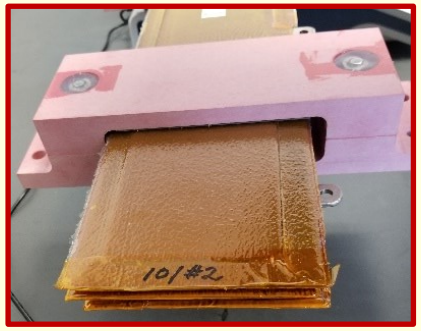
Prototype #2 w/ MMEI insulation

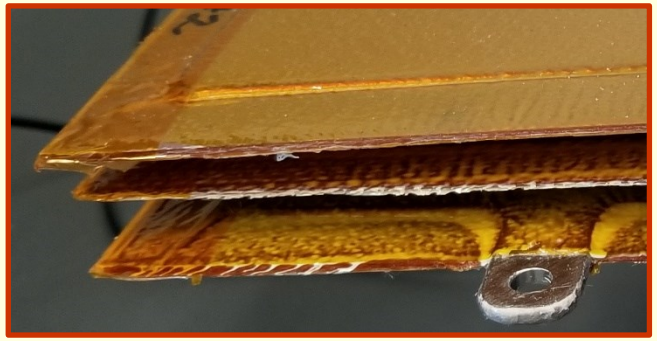
Al cond./1*PFA/[1*PFA/1*HN]$_{10}$/[1*PFA/1*CR]$_2$/2*PEEK/0.3*HN

– Avg weight of insulation per conductor = 363 gram → **~ 15% ↓**

– Avg thickness of insulation per side = ~ 0.71 mm (28 mils) → **~ 12% ↓**







Results & Discussions: Full-scale Demonstrations of MMEI

Evaluated prototypes by HiPot & PD testing (ASTM D149-20) at MERSEN

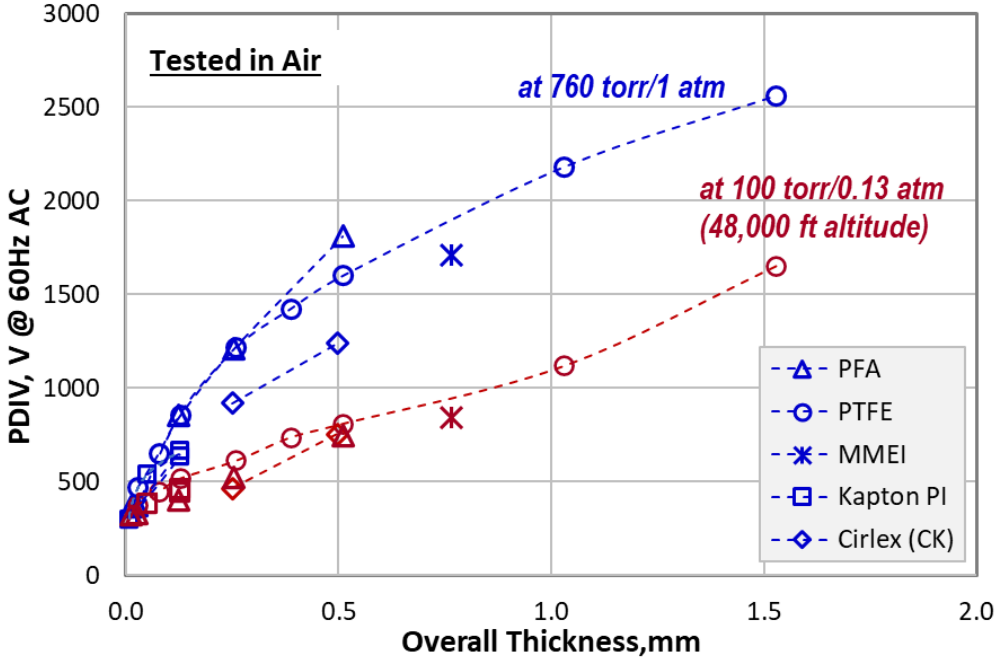
- Both passed HiPot breakdown test, >15 kV_{AC}, with leakage current < 0.5 mA.
- PD performance of Prototype #1 > #2, with thick Mica insulation which may not be suitable for power cable due to its rigidity → development of PD resistant MMEI system under way

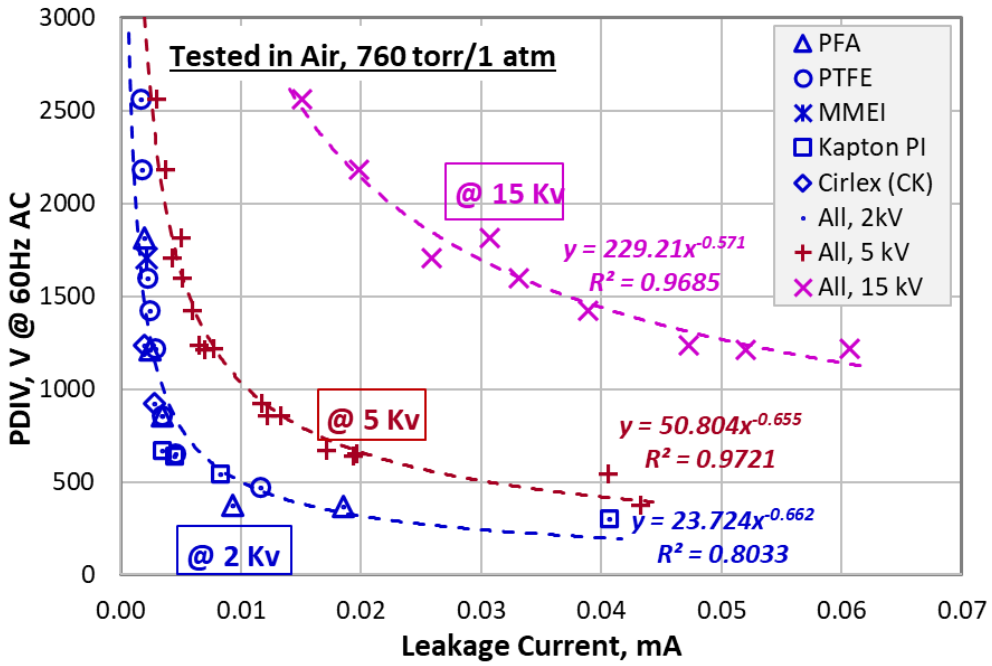
➢ acceptable results wrt both manufacturability and performance,

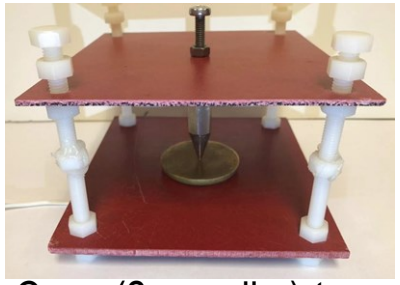
➢ validated MMEI system for various HV applications including electric aircrafts

Results & Discussions: PD behavior, correlation with LC

PD performance of SOA insulation materials & MMEI with CHPPE OSU





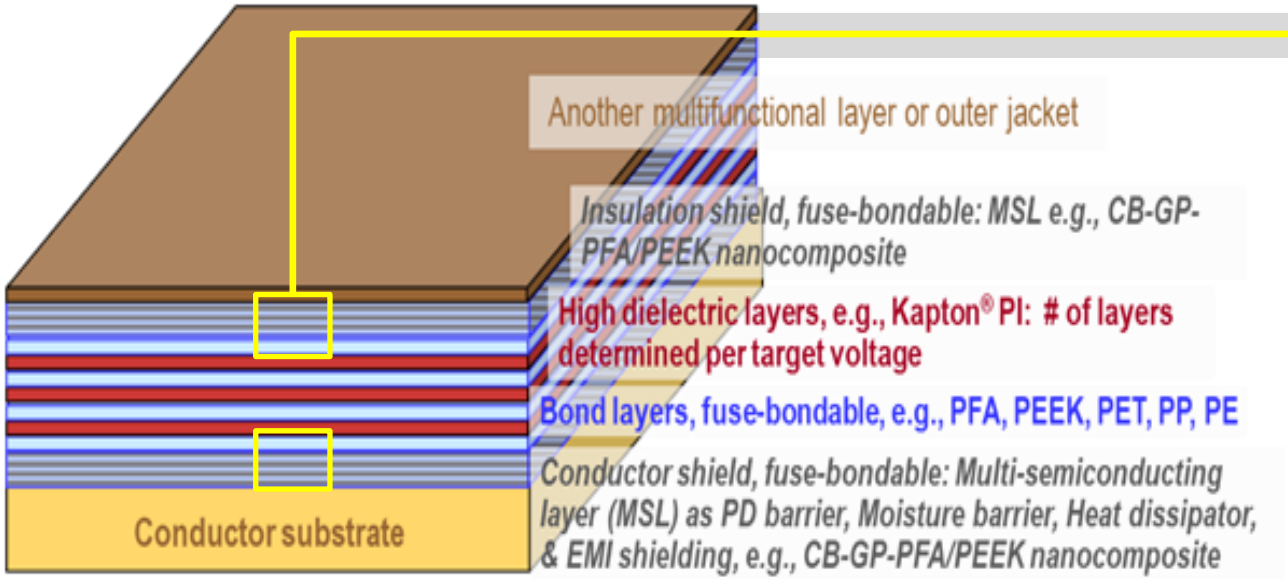


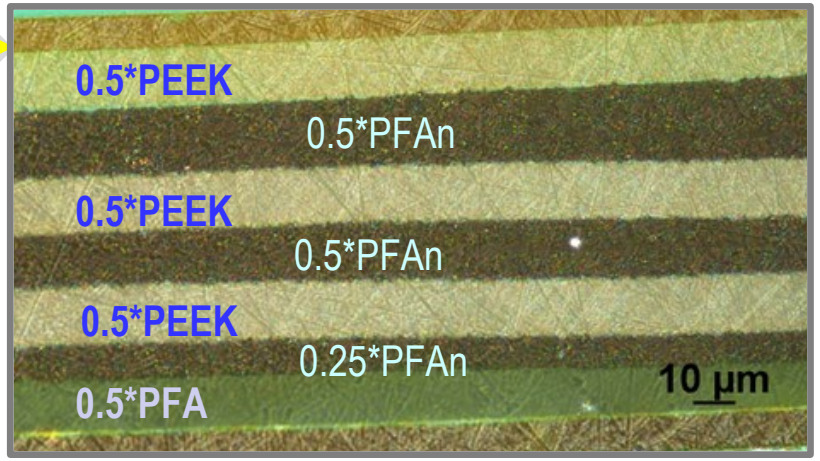
Cone (2 mm dia.)-to-Plate electrode setup in environmental chamber

- PDIV = f (t, P) for all material type
- PDIV of PFA, PTFE > others at 1 atm, but all worsened at 100 torr, i.e., challenges for high altitude application
- PDIV = $A*(LC)^{-B}$ per applied V, independent of material type → Practical correlations for material development
- In all cases, PDEV showed almost identical behavior as PDIV but at consistently lower values

Results & Discussions: Development of PD-resistant MMEI

Conductive PFA nanocomposite (PFAn) & Multifunctional-Semiconductive Shield Layers (MSL)





Example of a thicker MSL from initial trials

- To significantly enhance PD resistance of MMEI for HV applications,
  - ✓ incorporated semiconductive shielding layers → PFAn
  - ✓ applied the advantages of multilayering thin insulation materials
  - ✓ combined various multifunctionalities

  → MSL as a subset of MMEI

PD-resistant MMEI: Materials

Optimizations of PFAn and MSL via Solution compression-casting with:

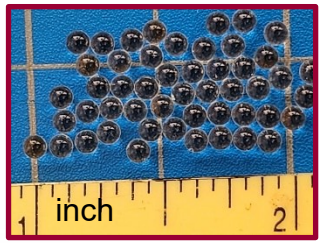
- Dyneon™ 6900GZ aqueous Perfluoroalkoxy (PFA) dispersion (3M, Advanced Materials Division): 50wt% solid, 235 nm average particle size (APS), 7wt% polyether-based emulsifier in distilled water; melting at 310 ºC
- Conductive nano-fillers
  - Carbon Black: 1) ACM1333864 (ALFA Chemistry), spherical particles with 150 nm APS; Specific surface area (SSA) >700 m²/g(CB1)

    2) Ketjenblack EC600-JD (MSE supplies), electro-conductive, spherical particles with 34 nm APS; BTE SSA = 1270 m²/g (CB2)
  - Graphene Powder (MSE supplies), multi-layer structures with <10 µm APS prepared by thermal exfoliation reduction; SSA = 400-550 m²/g (GP)
- Dispersant for CB dispersion: Marasperse CBOs-4 a highly modified sodium lignosulfonate based dispersant (Borregaard, Norway)

PD-resistant MMEI: Fabrication

Solution compression-casting of MSL, Step-by-step fabrication procedure:

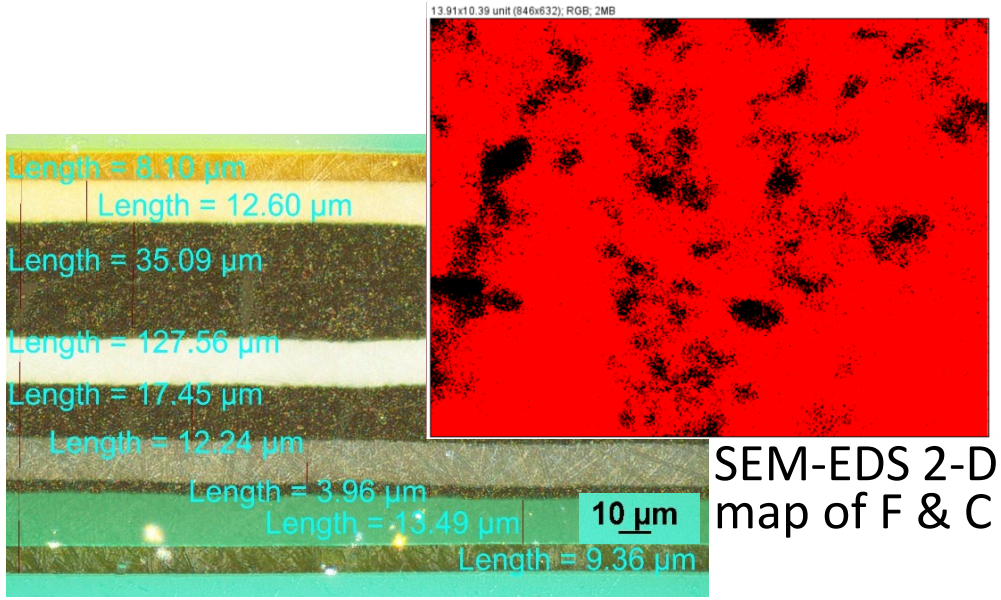
1. Dispersed conductive nano-filler(s) into dH_2O with dispersant
2. Mixed via ball-milling with Borosilicate beads in Resodyn Acoustic Mixer (LabRAM) followed by an optimized condition
3. Mixed both nano-filler dispersion (w/o beads) and PFA dispersion in LabRAM followed by an optimized condition→ PFAn dispersion
4. Applied thin layer of PFAn dispersion onto clean polymer insulation film, e.g., PEEK with high wettability
5. Dried at temperatures below 90ºC/194ºF
6. Stacked PFAn coated polymer films based on predetermined MSL layer configurations
7. Compression-casted the stacks at an air-circulated oven
   preheated to 350ºC/662ºF for 60 min, or
   Vacuum-bagged and autoclave processed for large-scale MSL



* Co-extrusion process to be also considered for industrial-scale manufacturing

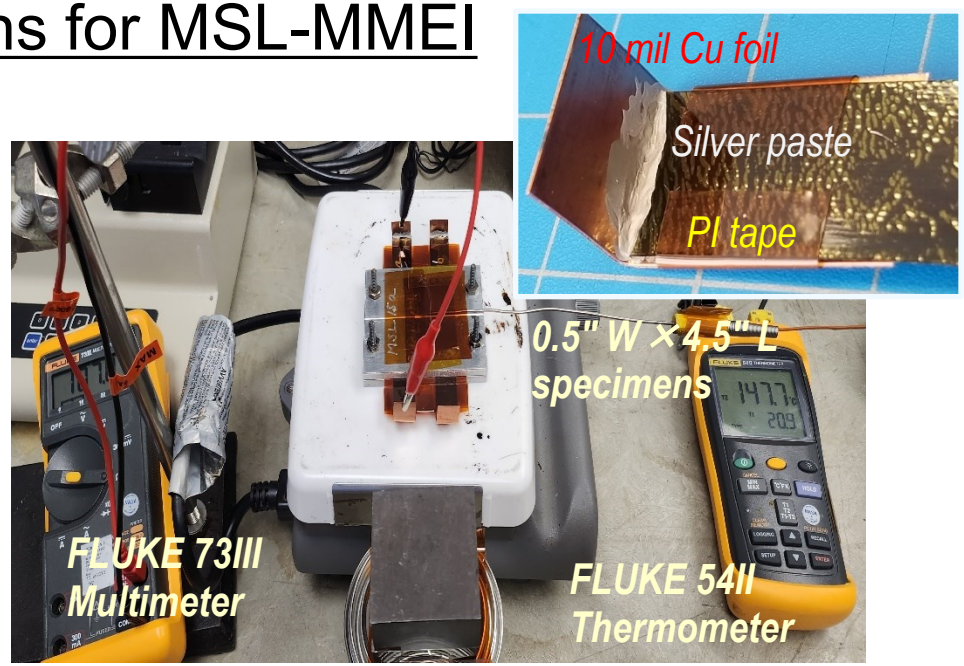
Results & Discussions: Development of PD-resistant MMEI

Optimized PFAn compositions and MSL configurations for MSL-MMEI



SEM-EDS 2-D map of F & C

TC by C-Therm Trident



In-plane electrical resistance setup

- Best PFAn composition: ***2.5wt% CB2+ 0.5wt% GP+ PFA***, and Most effective MSL configuration: ***[0.5*PEEK/0.5*PFAn]$_2$***, in terms of dispersion characteristics, ρ up to 300ºC, TC, V_B & LC, processibility & layer uniformity/connectivity, inter-layer bonding integrity, and other potential multifunctionalities
  - CB2 w/ greater SSA provided much lower electrical percolation threshold than ~20wt% of CB1 for <1,000 Ω·cm
  - Adding GP increased packing density, agglomeration or degree of chain formation in addition to the anticipated thermal stability of semi-conductivity

Summary and Conclusions

- The newly developed MMEI system was further optimized and validated:
  - Optimized MMEI structures outperformed most of the SOA insulation materials regardless of test conditions.
  - Potential Mechanisms responsible for MMEI performance were identified experimentally via 3-D dielectric damage and failure mode analyses.
- Scalability, manufacturability, and commercial applicability of MMEI were successfully demonstrated with 1 m long, 3-phase full-scale bus bar prototypes for > 15 kV_{AC}.
- Unique and practical PDIV/PDEV-LC correlations were experimentally determined from various SOA insulation materials and MMEIs for future insulation development.
- Significant progress was made in developing PD-resistant MMEI system via incorporating Multifunctional-Semiconductive Shield Layers (MSL) as a subset of MMEI:
  - Semi-conductive PFA nanocomposite, PFAn, was designed with CB and GP, and their fabrication processes including optimum mixing conditions for uniform/random dispersions were developed
  - Best PFAn composition and Most effective MSL configuration were determined based on systematic process-structure-property relations

Future Work Plan

The following tasks are planned for improvement and implementation 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
- More extensive, systematic performance evaluations of the MSL-MMEI structures/prototypes including (i) thermal-mechanical-physical performance characterizations including interlayer bonding integrity and (ii) synergistic durability assessment
- Continuation of scale up, prototype development of power cables, manufacturability assessment, and commercialization

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