High Voltage Insulation for Electrified Aircraft

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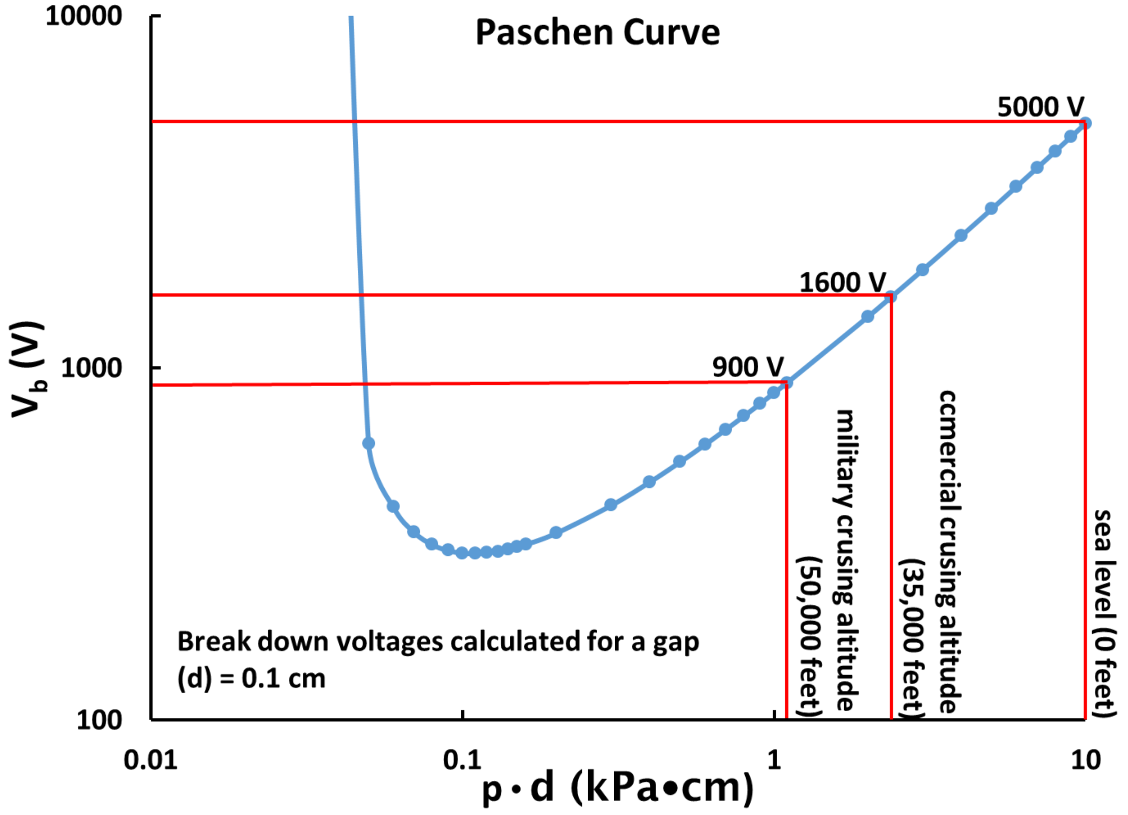
Electrical Insulation?

Paschen's Law: Breakdown voltage decreases with pressure



Note: The Paschen's Law graph is calculated for the case of two parallel plates. Other geometries can drastically reduce the breakdown voltage

Failure of insulation is the most likely cause of TWA 800 crash

Is this electrical insulation central to electrified aircraft technology: YES

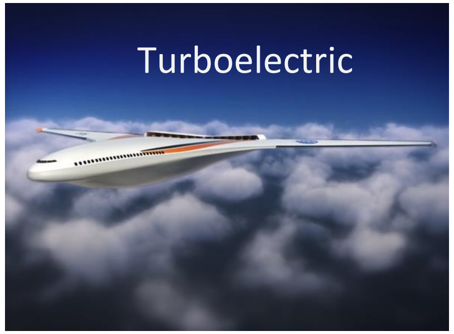
Does NASA need to be involved: ABSOLUTELY

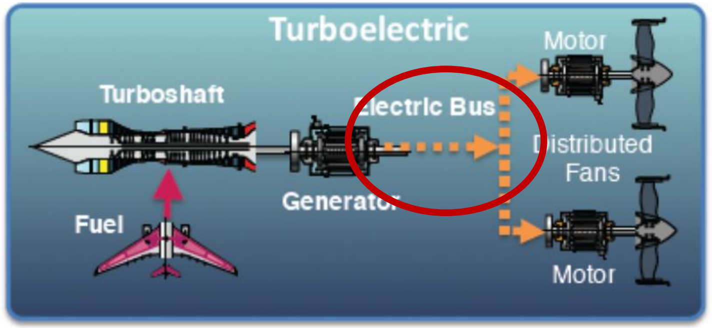
National Transportation Safety Board accident report for TWA Flight 800

Maricela Lizcano Team Lead

Unique High Voltage Power Transmission Application: Light Weight High Voltage

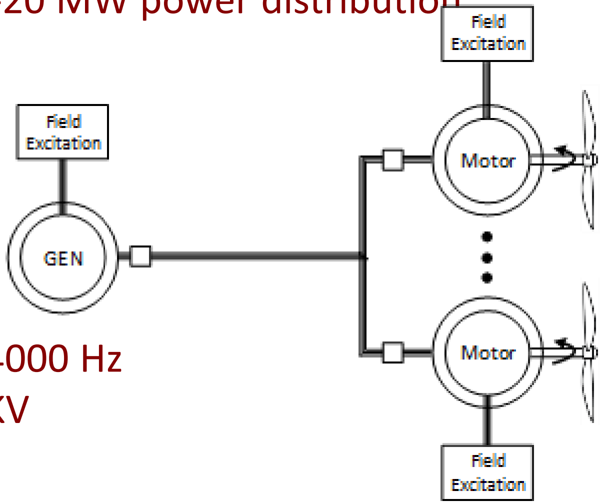
Aeronautics Research Mission Directorate (ARMD)
Transformative Aeronautics Concepts Program (TCAP)
Convergent Aeronautic Solutions (CAS) Project





High Voltage Hybrid Electric Propulsion (HVHEP) Architecture

Future Aircraft will require ~10-20 MW power distribution



High Voltage, 3-Phase AC,
Variable Frequency 400 Hz to 4000 Hz
V_{max} = 20 KV Design for V > 41 KV

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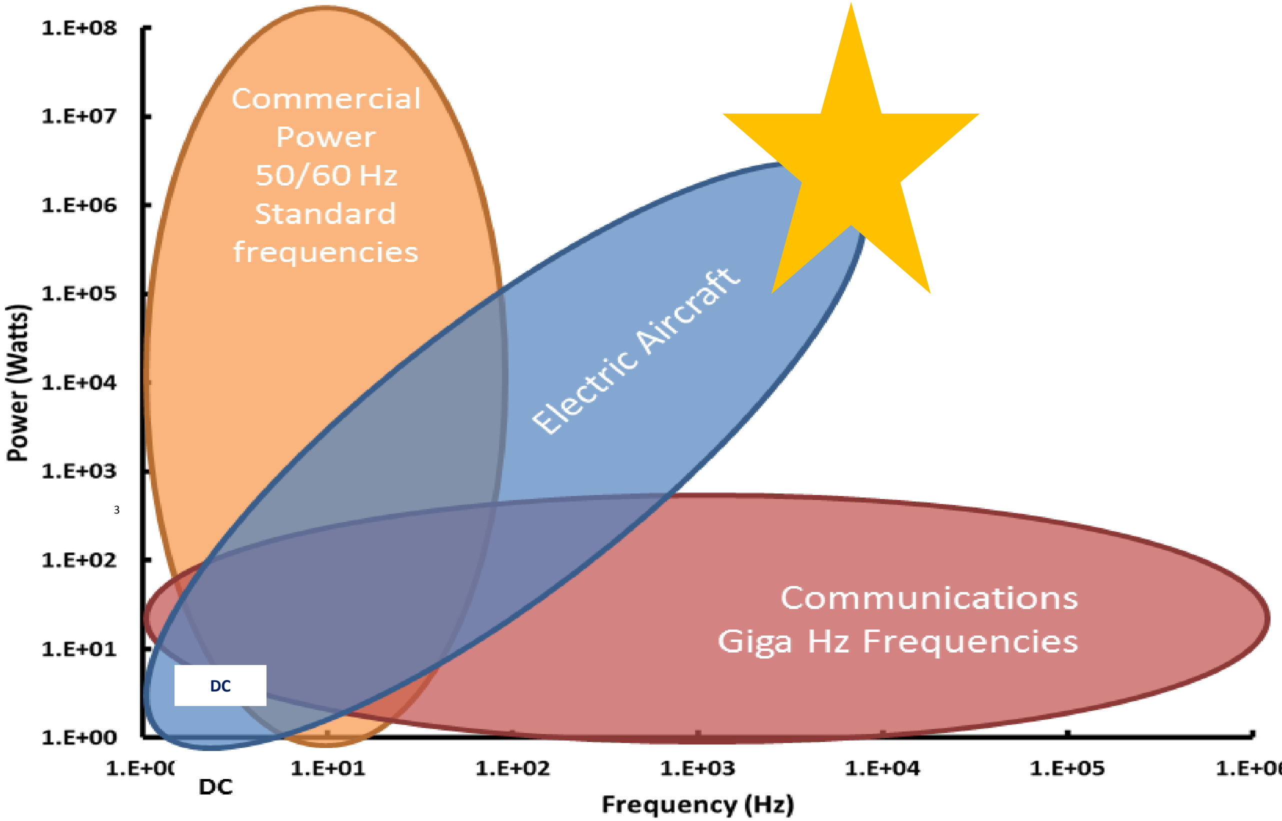
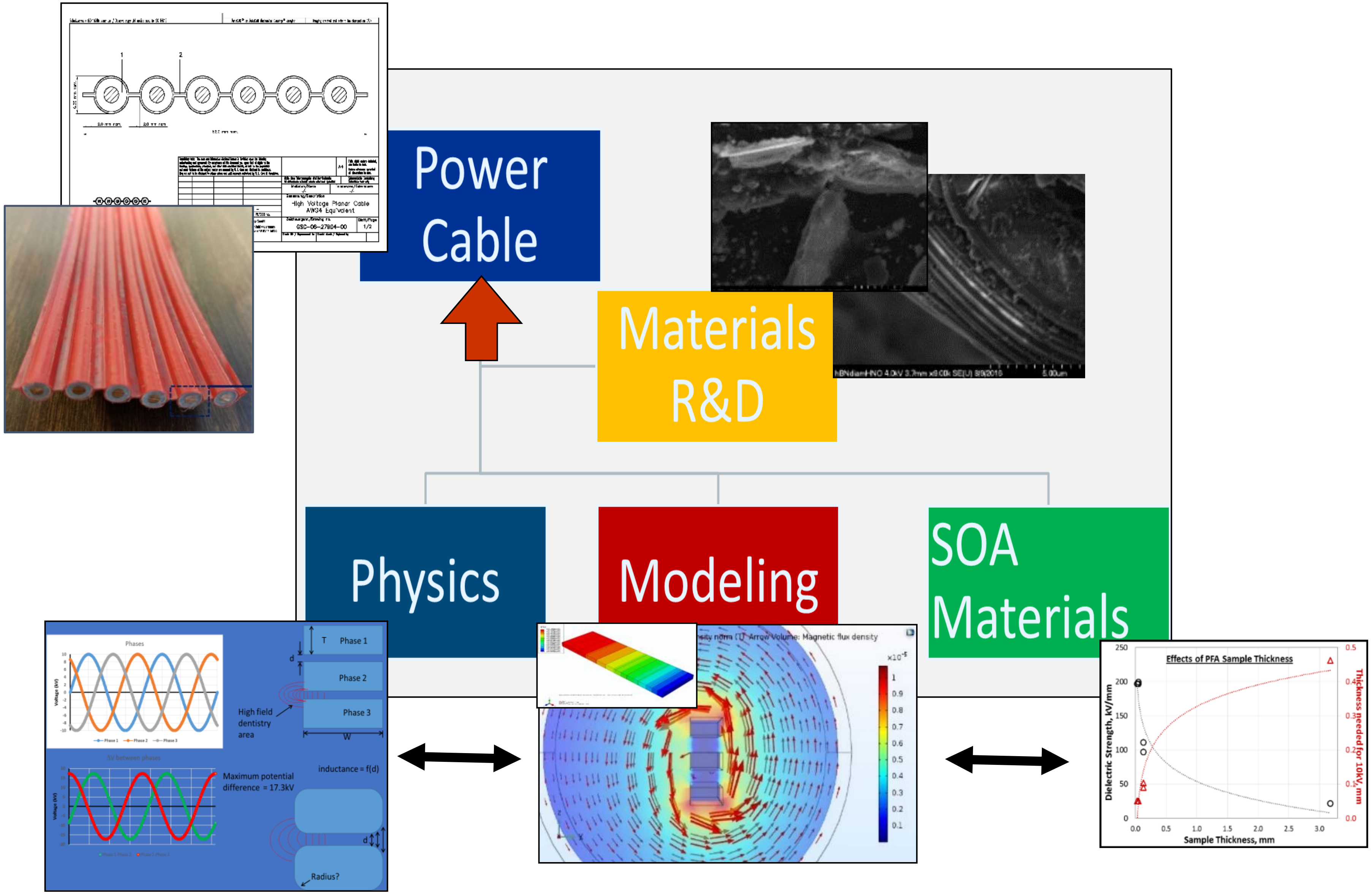
Notional Current Technology Description

Combination of power and frequency make this a unique application space. Current high voltage cable technology is not suitable for high altitude operation.



Power Cable Insulation Development Approach



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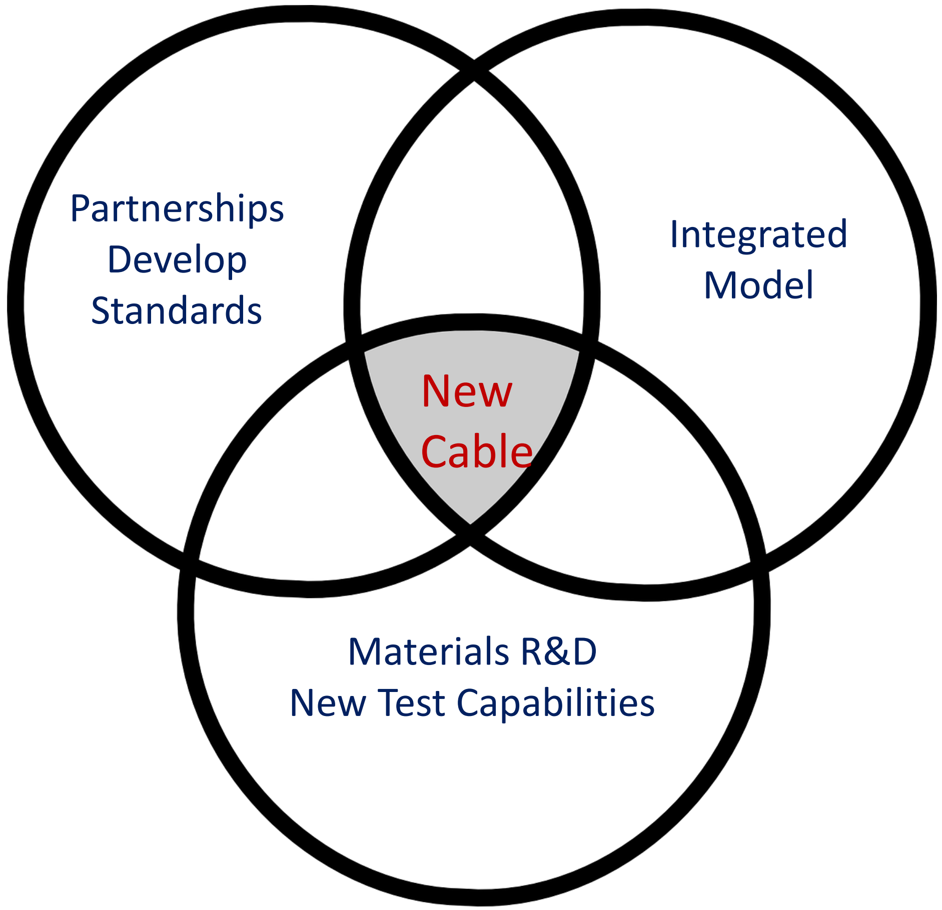
Key Findings: HVHEP Convergent Aeronautics Solutions Task

- Need New Test Methods and Component Level Test Capabilities
  - → Current Test Methods may not be sufficient
  - Altitude/ Environment replication critical
- Materials Development + Modeling Tools
  - → Best Design
- Responsive to Outside Material Technology Development
  - Corona resistant materials
  - 2-D EMI Shielding
  - Composite conductors
  - Dielectric insulation
- Decrease materials stresses
  - → increase performance life
- Foster collaborations with industry and universities
  - Industry Provided Integration Paths
  - University Led Materials Research
  - Develop Testing Standards



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Multifunctional Materials for Electrical Systems

New FY18 TCAP/ Transformative Tools and Technology Project Research Area Funded:

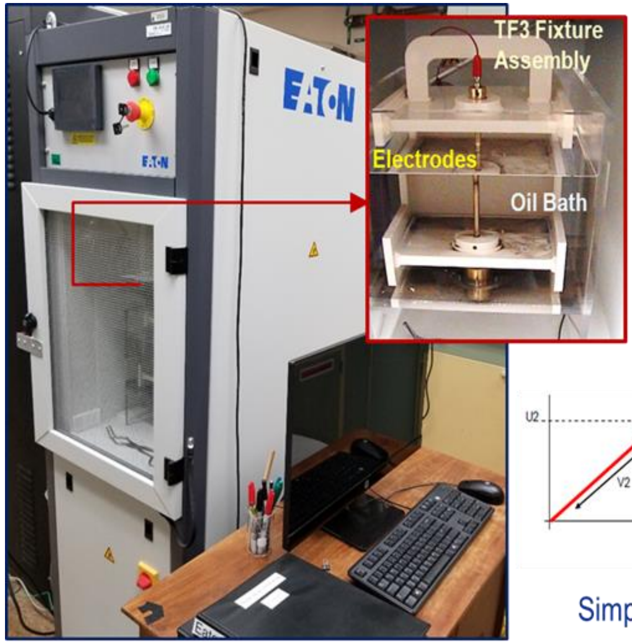
- Build HV Multi-stress Environmental Test Chamber Capability (2-3 Years)
- Demonstrate a 1-5 kV Power Transmission Cable (2-5 Years)
- Draft Standard Test Method of High Altitude High Voltage Power Transmission Insulation Materials/Cables (5 years)

<u>Eaton High Voltage Test Setup</u>

- Small sample to component testing
- ASTM testing at RT

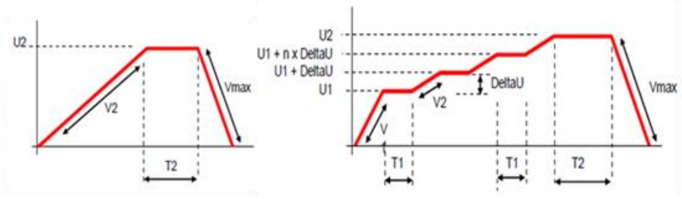
<u>GRC Corona Material Evaluation Testbed (CoMET)</u>

- Component to full-scale testing up to 40 kV, 2 MHz
- Replicate flight conditions (P, T, RH, vibration etc.) during testing

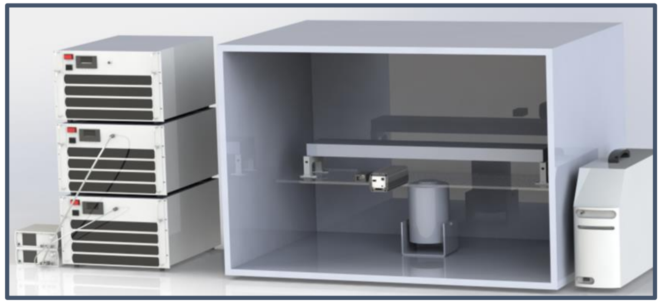


Electrical Characteristics

			AC	DC
Output voltage: kV		Max	60.0	84.4
		Min	1.8	2.6
	Regulation ±		0.4	0.6
	Resolution		0.017	0.024
Ramp Rate, kV/s		Max	5.5	7.8
(Average speed)		Min	0.6	0.5



Simple Ramp   Ramp by Steps



Conceptual drawing of multi-stress environmental test setup

Test chamber under consideration for component environmental testing

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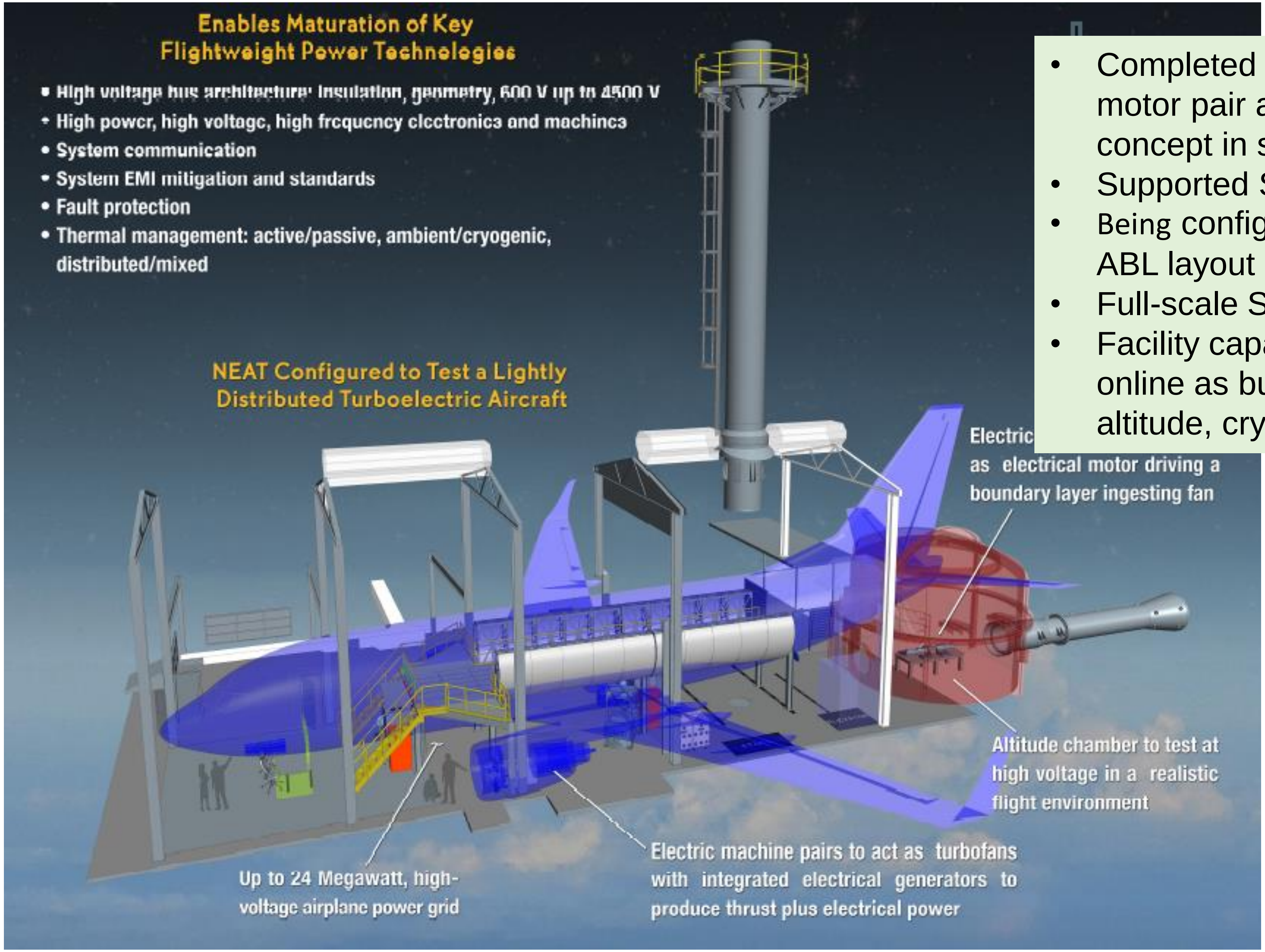
NASA Electric Aircraft Testbed (NEAT)



- Completed single-string testing of a motor pair and validated emulation concept in summer 2016
- Supported SCEPTOR EMI testing
- Being configured for 500 kW STARC-ABL layout in 2018
- Full-scale STARC-ABL will follow
- Facility capabilities being brought online as budget allows (cooling, altitude, cryo, etc)

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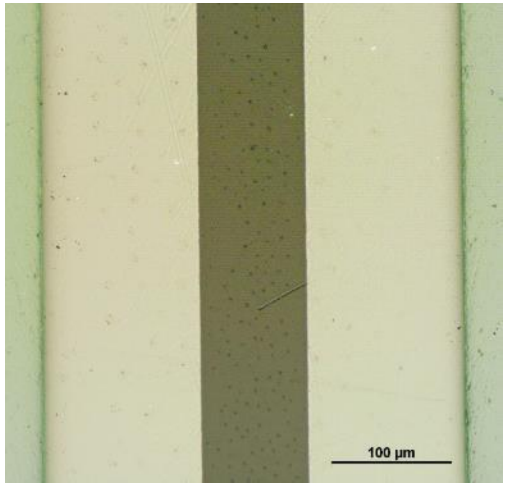
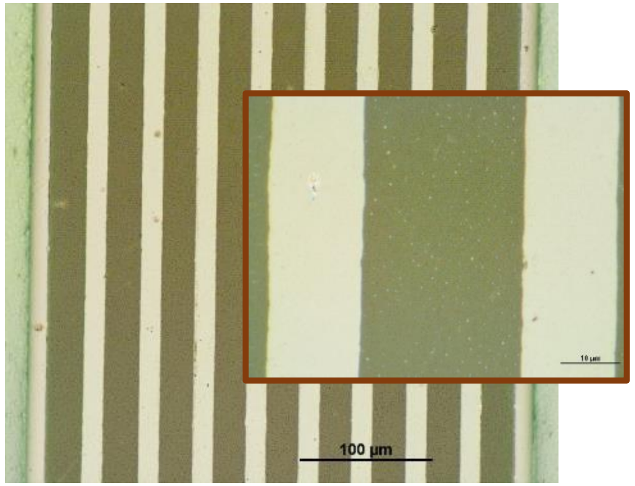
Micro-multilayer Multifunctional Electrical Insulation (MMEI) system

- 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>

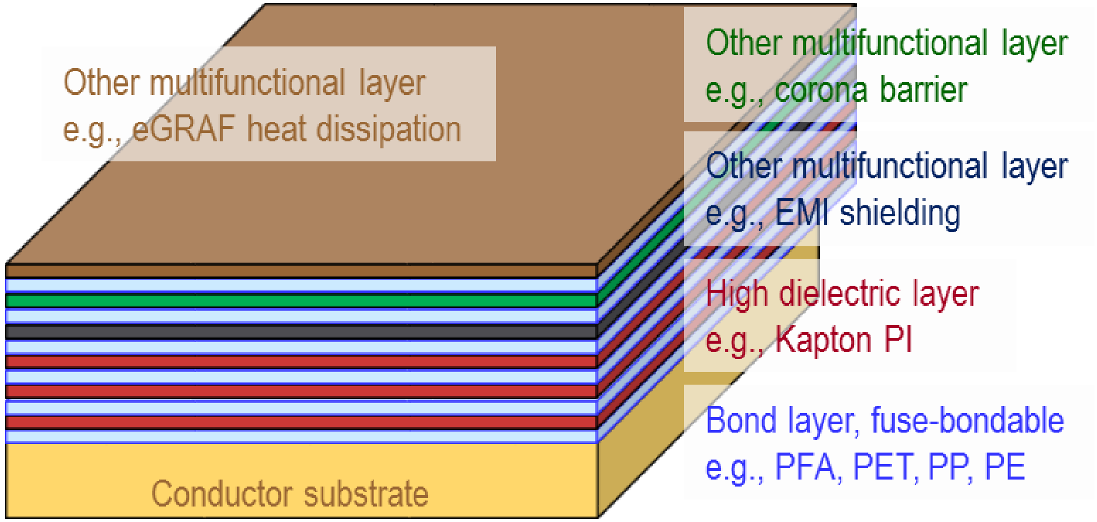
- Kapton® PI film alone, 0.38 mm thick, V_B=29 kV
- PFA film alone, 0.38 mm thick, V_B = ~27 kV
- 5*KBF/5*PFA/5*KBF: 3-layers/0.38 mm thick V_B=38 kV
- [0.5*HPP/1*PFA]$_9$ /0.5*HPP: 19-layers/0.38 mm thick V_B=46 kV



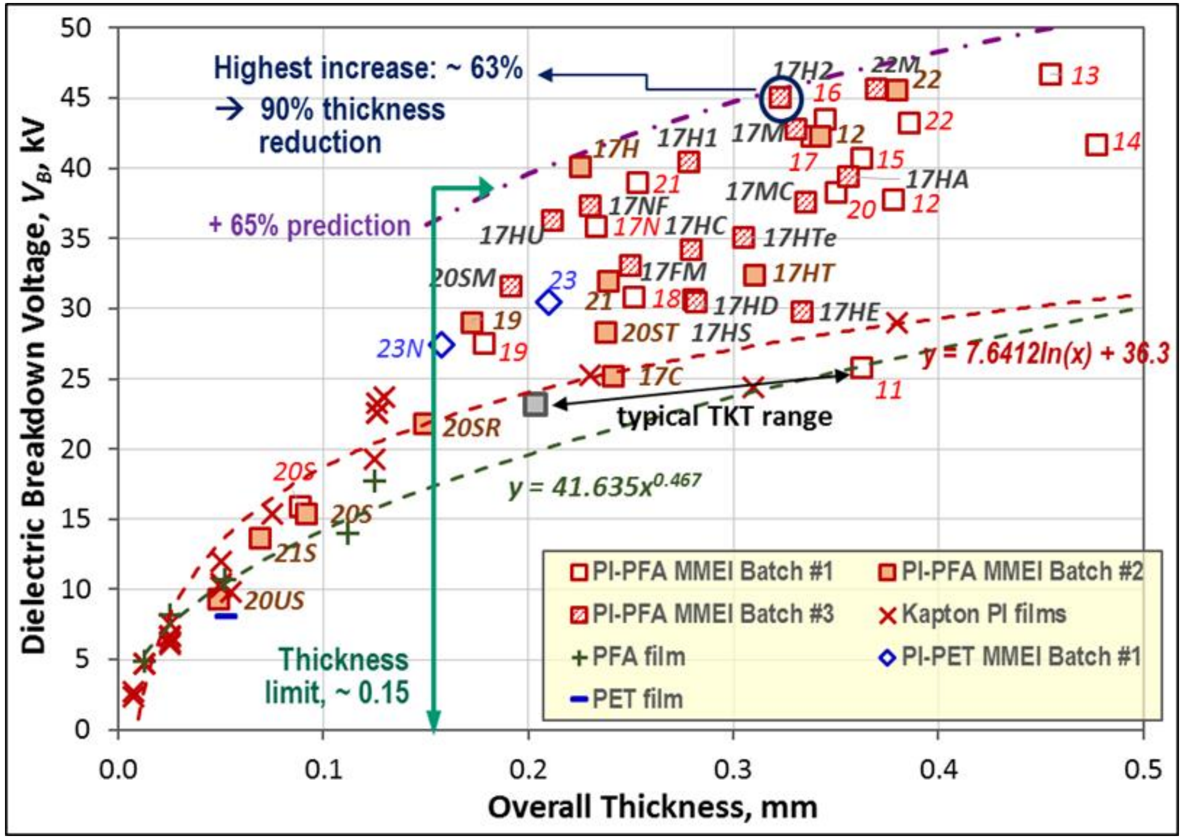


Heat Fuse-Bonding with excellent boding integrity

- MMEI structures can incorporate multifunctionalities by the nature of their design capabilities, such as Corona PD resistance, moisture barrier, EMI shielding, thermal management, and mechanical durability, etc.



Status of MMEI Invention



	ID	Layer Configuration
Batch #1	11	5*PFA/5*KBF/5*PFA
	12	5*KBF/5*PFA/5*KBF
	13	2*PFA/5*KBF/5*PFA/5*KBF/2*PFA
	14	5*KBF/5*PFA/1*KBF/5*PFA/5*KBF
	15	[2*PFA/2*KBF]$_3$/2*PFA
	16	1*KBF/2*PFA/2*KBF/5*PFA/2*KBF/2*PFA/1*KBF
	17	[1*KBF/2*PFA]$_4$/1*KBF
	17N	[1*KBF/1*PFA]$_4$/1*KBF
	18	[0.5*PFA/1*KBF]$_6$/0.5*PFA
	19	[1*KBF/0.5*PFA]$_4$/1*KBF
	20	[0.3*HN/0.5*PFA]$_{16}$/0.3*HN
	20S	[0.3*HN/0.5*PFA]$_4$/0.3*HN
	21	[0.5*HPP/0.5*PFA]$_9$/0.5*HPP
	22	[0.5*HPP/1*PFA]$_9$/0.5*HPP
	23N	[1*KBF/2*PET]$_4$/1*KBF
	23	[1*KBF/2*PET]$_4$/1*KBF
Batch #2	12	5*KBF/5*PFA/5*KBF
	17H	[1*HN/1*PFA]$_4$/1*HN
	17C	[1*CRC/1*PFA]$_4$/1*CRC
	17HT	2*PTFE/1*PFA/[1*HN/ 1*PFA]$_4$/1*HN
	19	[1*KBF/0.5*PFA]$_4$/1*KBF
	20S	[0.3*HN/0.5*PFA]$_4$/0.3*HN
	20SR	[0.3*HN/1*PFA]$_4$/0.3*HN
	20ST	[0.3*HN/2*PFA]$_4$/0.3*HN
	20US	[0.3*HN/0.5*PFA]$_2$/0.3*HN
	21	[0.5*HPP/0.5*PFA]$_9$/0.5*HPP
	21S	[0.5*HPP/0.5*PFA]$_2$/0.5*HPP
	22	[0.5*HPP/1*PFA]$_9$/0.5*HPP

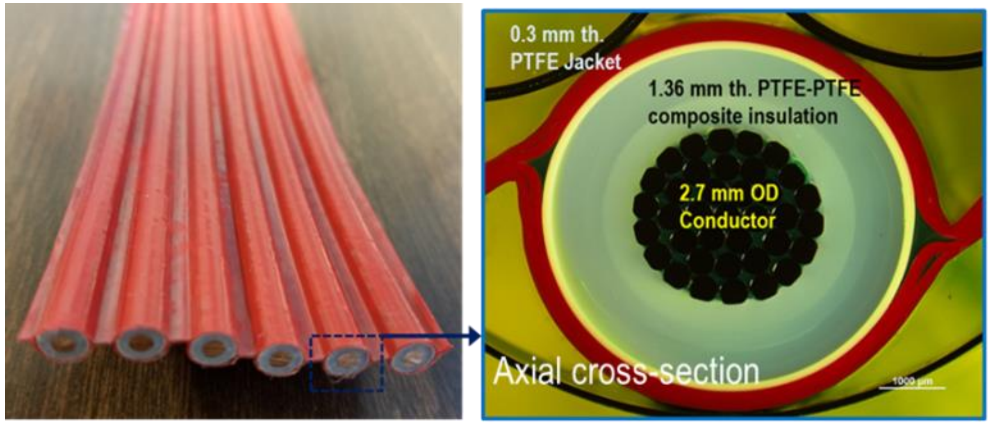
Batch #3	17M	[1*HN/1*PFA/0.5*HPP/1*PFA]$_2$/[0.5*HPP/1*PFA/1*HN/1*$_{\rightarrow}$0*PFA]$_2$
	17MC	[1*HN/1*PFA/0.5*HPP/1*PFA]$_2$/[0.5*HPP/1*PFA/1*CRC/1*$_{\rightarrow}$0*PFA]$_2$
	17HTe	2*PTFEe/1*PFA/[1*HN/ 1*PFA]$_4$/1*HN
	17F	[1*FPC/1*PFA]$_4$/1*FPC
	17FM	1*FPC/1*PFA/[0.5*HPP/5x0.5*$_{\rightarrow}$1*PFA]$_6$/1*FPC
	17HC	[1*HN/1*PFA]$_5$/1*CRC
	17HD	[1*HN/1*PFA]$_4$/[1*CRC/1*$_{\rightarrow}$0*PFA]$_2$
	17HE	[1*HN/1*PFA]$_4$/[1*$_{\rightarrow}$2x1*PFA/1*CRC]$_2$
	17HA	[1*HN/1*PFA]$_5$ /4*Mica
	17HS	1*CRC/1*PFA/[1*HN/1*PFA]$_4$/1*CRC
	17HU	[1*HN/0.5*PFA]$_5$/1*HN
	20SM	[0.5*HPP/0.5*PFA/0.3*HN/0.5*$_{\rightarrow}$1*PFA]$_2$/ [0.3*HN/0.5*PFA/0.5HPP/0.5*$_{\rightarrow}$0*PFA]$_2$
	22M	[0.5*HPP/1*PFA]$_4$/2*KBF/[1*PFA/0.5*HPP]$_4$
	17H1	[1*HN/ 1*PFA]$_5$/1*HN
	17H2	[1*HN/ 1*PFA]$_6$/1*HN

Extensive MMEI database (total 43 different configurations)

* indicated thickness in mil (1/1000 inch)

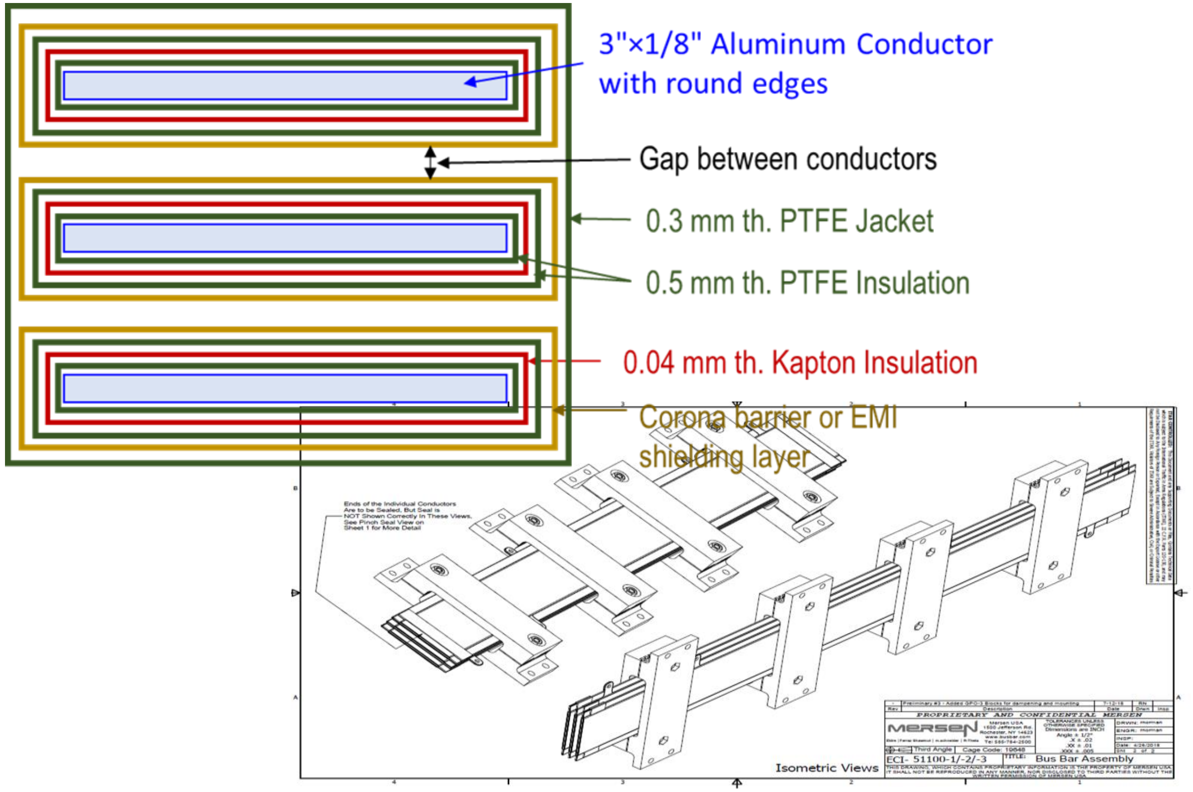
- From systematic parametric analysis, dielectric performance of MMEI was synergistically controlled by <u>total overall thickness</u>, <u>individual layer thickness</u>, <u>total accumulated thickness of constituent materials</u>, <u>overall thickness ratio of constituent materials</u>, and <u>total number of layers or interfaces</u> in addition to <u>bonding integrity</u>.
- Also by dielectric breakdown failure modes.

Commercial Benefit/Applicability of MMEI Structures



HV HP Flat Pod Cable with GORE

- Unique design to carry 0.25 MW at 15 kV (but rated to 40 kV), for -80 °C to >260 °C use temperature
- Consisted of six identical conductor pods insulated by the GORE's proprietary PTFE-PTFE composite and arranged horizontally by a corona resistant PTFE jacket
- Efforts to apply MMEI system on the Pod cable are under way:
  - Finalization of material selection, layer configuration, and fabrication process and procedures
  - Development of systematic performance evaluation methods and procedures



HV high frequency bus bar with MERSEN

- A three-phase system for 1 MW up to 10 MW operating power with operating voltage of 20 kV (designed for 40 kV), high frequency (400 Hz up to 4000 Hz), and temperature up to 180 °C
- MMEI system to be applied for direct performance comparison

Cable Insulation Work Takeaways

- High Voltage is the “tallest” poll
    - Can’t take advantage of large distances and heavy systems (over design) other HV systems can use (terrestrial, ships and trains)
    - Thermal is a life time limiting issue and will have be delta with eventually

- Testing Important:
    - Multi scale testing is necessary
        - coupon
        - component/subsystem
        - system
    - Must test like you fly
        - multi-stress environment

- Potential disruptive technology of MMEI system
    - Thin, lightweight, and durable structures
    - Multifunctional structures including corona resistance, moisture barrier, EMI shielding, and thermal management
    - Applicable to various full-scale power transmission, e.g., power cable, bus bar, inter-connect, etc.