High Voltage Insulation for Electrified Aircraft

Andrew A. Woodworth¹, E. Eugene Shin², and Maricela Lizcano¹
¹NASA-GRC, ²Ohio Aerospace Institute

EnergyTech 2018
October 22 - 25, 2018, Cleveland, Ohio
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

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

Maricela Lizcano Team Lead

National Transportation Safety Board accident report for TWA Flight 800
Unique High Voltage Power Transmission Application: Light Weight High Voltage Technology

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

Maricela Lizcano Team Lead
Power Cable Insulation Development Approach
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

Maricela Lizcano Team Lead
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)

**Eaton High Voltage Test Setup**
- Small sample to component testing
- ASTM testing at RT

**GRC Corona Material Evaluation Testbed (CoMET)**
- Component to full-scale testing up to 40 kV, 2 MHz
- Replicate flight conditions (P, T, RH, vibration etc.) during testing

**Electrical Characteristics**

<table>
<thead>
<tr>
<th>AC</th>
<th>DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage: Max</td>
<td>60.0</td>
</tr>
<tr>
<td>kV  Min</td>
<td>1.8</td>
</tr>
<tr>
<td>Regulation ± 0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Resolution 0.017</td>
<td>0.024</td>
</tr>
<tr>
<td>Ramp Rate, kV/s Max</td>
<td>5.5</td>
</tr>
<tr>
<td>(Average speed) Min</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Conceptual drawing of multi-stress environmental test setup

Test chamber under consideration for component environmental testing

Maricela Lizcano Team Lead
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)
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 ($V_B$), if well-bonded;

- Kapton® PI film alone, 0.38 mm thick, $V_B = 29$ kV
- PFA film alone, 0.38 mm thick, $V_B = \sim 27$ kV
- $5^{th}$KBF/$5^{th}$PFA/$5^{th}$KBF: 3-layers/0.38 mm thick $V_B = 38$ kV
- $[0.5^{th}$HPP/$1^{st}$PFA]$^9$/$0.5^{th}$HPP: 19-layers/0.38 mm thick $V_B = 46$ kV

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.

Heat Fuse-Bonding with excellent bonding integrity
Status of MMEI Invention

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

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 total overall thickness, individual layer thickness, total accumulated thickness of constituent materials, overall thickness ratio of constituent materials, and total number of layers or interfaces in addition to bonding integrity.

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.