Multilayered Functional Insulation System (MFIS) for AC Power Transmission in High Voltage Hybrid Electrical Propulsion

Team Lead Maricela Lizcano, PhD
Research Materials Engineer
Materials Chemistry and Physics Branch
NASA Glenn Research Center
Cleveland, OH 44135
Our project was a sub-task of the High Voltage Hybrid Electric Propulsion task, (PI Ray Beach and Co-PI Linda Taylor). It was supported by NASA’s Convergent Aeronautics Solutions (CAS) Project. The sub-task was a 2 year feasibility study to investigate the possibility of improving the performance of insulation materials used to protect high voltage power transmission from electrical arcing events.

The project has been transitioned to the Transformational Tools and Technology (T^3) Project to continue developing innovative concepts for future hybrid electric aircraft. Both CAS and T^3 are part of NASA’s Transformative Aeronautics Concept Program.
**Lightweight** High Voltage Power Transmission

High Voltage Hybrid Electric Propulsion (HVHEP) Architecture

Future Aircraft will require ~20 MW power distribution

High Voltage, $\text{VAC}_{\text{max}} = 20 \text{ KV}$

Must Design for > 40 KV

Variable Frequency (400-4000 Hz)
Combination of power and frequency make this a unique application space. Current high voltage cable technology is not suitable for high altitude operation.

Requirements
- 20 MW power cable
- 20 K\textsubscript{V}\textsubscript{ac}, 3-phase
- Variable \( f = 400-4000 \text{ Hz} \)
At high altitude electrical breakdown of an air gap or between uninsulated conductors become more prevalent. Voltages as low as 327 V will cause corona discharge and arcing events in air gaps. At higher frequencies, this minimum voltage decreases.
Insulation Aging and Dielectric Breakdown

Electrical, thermal and mechanical stresses decrease the performance life of insulating materials.

- Corona discharge contributors to material aging and failure.
- Material carbonization and material degradation from ozone generation.
- Higher voltages and frequencies.
- Increased electrical and thermal stresses.
- System operating temperature.
- Thermal cycling and thermal degradation.

Damage from dielectric breakdown in ceramic and polymeric material.

SEM of damage on ceramic.
Functional Insulation System
Initial Concept Development

- Al, Cu, or Hybrid Conductor
- SOA Dielectric Insulation
- EMI Shielding
- Protective Covering

Layered Composite System
Electrical Insulation and
Thermal Management

Basic Cable Construction

Which layer should be deposited first?

Thermally conductive layer or Insulation layer

Physical Vapor Deposition

Thermally Conductive Layer or Dielectric layer

Lightweight Composite Conductor

Decomposed Polyimide layer → Graphene

Graphene layer

Copper

Copper

Thermal Management
Multilayered Conductor

Conductor
Multidisciplinary Approach

Power Cable

Materials R&D

Physics

Modeling

SOA Materials
Physics

\[ d_{Cu-4kHz} = 1.0 \text{ mm, } 5 \times d_{Cu-4kHz} = 5.0 \text{ mm} \]
\[ d_{Al-4kHz} = 1.3 \text{ mm, } 5 \times d_{Al-4kHz} = 6.5 \text{ mm} \]

Weight Comparison
\[ R = 3.26 \times 10^{-7} (\text{W/m}) \]
Cu = 4.5 kg/m
Al = 2.3 kg/m
High field dentistry area

Maximum potential difference = 17.3kV

\[ \Delta V \text{ between phases} \]

\[ \text{inductance} = f(d) \]
Electro-Thermal Modeling

The electro-thermal FE model of a “conductor+3 layers of insulation” was constructed. Application of AC current through a user-defined routine was successfully developed. Joule heating estimation for some chosen geometries was estimated for AC current (400 Hz and 4000 Hz).

<table>
<thead>
<tr>
<th>Metal</th>
<th>Conductor Width (m)</th>
<th>Thickness (m)</th>
<th>Area m^2</th>
<th>Length (m)</th>
<th>Voltage (V)</th>
<th>Amps (A)</th>
<th>AC/DC</th>
<th>Frequency Hz</th>
<th>Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>0.1</td>
<td>0.005</td>
<td>5.00E-04</td>
<td>20</td>
<td>1000</td>
<td>1000</td>
<td>AC</td>
<td>400</td>
<td>67</td>
</tr>
<tr>
<td>Cu</td>
<td>0.1</td>
<td>0.005</td>
<td>5.00E-04</td>
<td>20</td>
<td>5000</td>
<td>200</td>
<td>AC</td>
<td>400</td>
<td>31</td>
</tr>
<tr>
<td>Al</td>
<td>0.13</td>
<td>0.0065</td>
<td>8.45E-04</td>
<td>20</td>
<td>1000</td>
<td>1000</td>
<td>AC</td>
<td>400</td>
<td>64</td>
</tr>
<tr>
<td>Al</td>
<td>0.13</td>
<td>0.000325</td>
<td>4.23E-04</td>
<td>30</td>
<td>40000</td>
<td>125</td>
<td>AC</td>
<td>400</td>
<td>35</td>
</tr>
<tr>
<td>Cu</td>
<td>0.1</td>
<td>0.005</td>
<td>5.00E-04</td>
<td>20</td>
<td>1000</td>
<td>1000</td>
<td>AC</td>
<td>4000</td>
<td>65</td>
</tr>
<tr>
<td>Cu</td>
<td>0.1</td>
<td>0.005</td>
<td>5.00E-04</td>
<td>20</td>
<td>5000</td>
<td>200</td>
<td>AC</td>
<td>4000</td>
<td>31</td>
</tr>
<tr>
<td>Al</td>
<td>0.13</td>
<td>0.0065</td>
<td>8.45E-04</td>
<td>20</td>
<td>1000</td>
<td>1000</td>
<td>AC</td>
<td>4000</td>
<td>61</td>
</tr>
<tr>
<td>Al</td>
<td>0.13</td>
<td>0.000325</td>
<td>4.23E-04</td>
<td>30</td>
<td>40000</td>
<td>125</td>
<td>AC</td>
<td>4000</td>
<td>34</td>
</tr>
</tbody>
</table>
# Dielectric Breakdown Modeling

<table>
<thead>
<tr>
<th>Model</th>
<th>Failure Mechanism</th>
<th>TF relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Model</td>
<td>Breakdown of bonds due to electrical and thermal energies</td>
<td>$\ln(TF) \propto \frac{\Delta E}{k_B T} - \gamma \cdot E$</td>
</tr>
<tr>
<td>1/E-Model</td>
<td>Electron trapping leads to local current density</td>
<td>$t_{BD} = c \cdot \text{Exp}\left(\frac{B + H}{E}\right)$</td>
</tr>
<tr>
<td>$\sqrt{E}$-Model</td>
<td>Electron trapping leads to breakdown charge</td>
<td>$TF = B \cdot \text{Exp}\left(-r\sqrt{E}\right) \cdot (-\ln(1 - F))^{1/m}$</td>
</tr>
<tr>
<td>Power Model ($E^m$)</td>
<td>Breakdown of hydrogen bonds introduced to lattice</td>
<td>$TF \propto t_0 \cdot E^{-m}$</td>
</tr>
<tr>
<td>$E^2$-Model</td>
<td>Oxidizing copper leads to copper ions in dielectric. Makes dielectric conductive.</td>
<td>$TF = A \cdot \text{Exp}\left(\frac{E_a - \gamma E_{app}^2}{k_B t}\right) \cdot t_{mass}$</td>
</tr>
</tbody>
</table>

**Time Dependent DB vs Voltage Ramp DB**

TDDB- low voltage, failure over long period of time
VRDB- voltage ramping, happens quickly
EM Field Modeling

EM field interactions between conductors will change with conductor geometry and spacing.
Dielectric Insulation Materials Testing Capabilities

**Dielectric Test Rig Specifications**

<table>
<thead>
<tr>
<th></th>
<th>AC</th>
<th>DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage AC :</td>
<td>Vmax.</td>
<td>60.00</td>
</tr>
<tr>
<td></td>
<td>Vmin.</td>
<td>1.800</td>
</tr>
<tr>
<td>Regulation:</td>
<td>+/-0.4</td>
<td>0.57</td>
</tr>
<tr>
<td>Resolution:</td>
<td>0.017</td>
<td>0.024</td>
</tr>
<tr>
<td>Ramp Rate:</td>
<td>max.</td>
<td>5.500</td>
</tr>
<tr>
<td>(Average speed)</td>
<td>min.</td>
<td>1.100</td>
</tr>
</tbody>
</table>

**Electrode Test Fixtures**

Seven electrode test fixtures (T1-T7) available according to ASTM D149-09 for Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies

Eaton High Voltage Test Set
Located at NASA GRC 106:B10
As Received Kapton trend line

\[ y = 7.628 \ln(x) + 36.4 \]

\[ x = e^{((y - 36.4)/7.628)} \]

\[ x = e^{((46 - 36.4)/7.628)} \]

\[ x = 3.52 \text{ mm Kapton thickness} \]

86% decrease in insulation thickness. This also decrease volume of the cable.
Improvement in Dielectric Strength

Compared to as received Kapton, the dielectric strength of the functional insulation system also increases significantly for equivalent thickness.
Chemically tailoring the properties of a ceramic material to enhance dielectric and thermal properties of composites we can add functionality to cable insulation.
Next Steps: Transformational Tools and Technology

- Continue to foster and collaborate with universities and industry
- Build Test Chamber
- Cable design, conductor geometry based on modeling tools provides design and material options
- Advanced *lightweight* materials
  - Corona resistant materials
  - EMI Shielding
  - Lightweight composite conductors
  - Advanced dielectric insulators
- Minimize environmental stresses on materials will increase performance life

**Advance Materials Development:**
- Insulation
- EMI shielding
- Conductors

**New Cable**
- Collaboration with Partners
- Minimize electrical, thermal and mechanical stresses

**Develop EM Field and Joule heating Model**
5 Year Objectives

- Materials R&D: Insulation, EMI shielding, advanced conductor
- Build HVHF Environmental Test Chamber Capability
- Draft Standard Test Method of High Altitude High Voltage Power Transmission
- Development Integrated Modeling Tool
- Demonstration of HVHF Power Transmission System
Team Members

Andy Woodworth  
Eugene Shin  
Tiffany Williams  
Paria Naghipour  
Ben Kowalski  
Janet Hurst  
Fran Hurwitz  
Dan Scheiman  

Student Interns  
Jeremey Walker UH  
Taylor Ceh OSU  
Angel Chavez UC-Irving  
Mitsuo Inukai UTRGV  
Astrid Rodriguez UTRGV  
Victor Nguyen UAz  
Jonathan Li Yale  

Thanks Team!
Questions?