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

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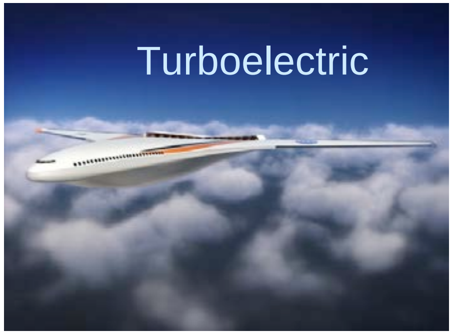
Aeronautics Research Mission Directorate (ARMD) Transformative Aeronautics Concepts Program

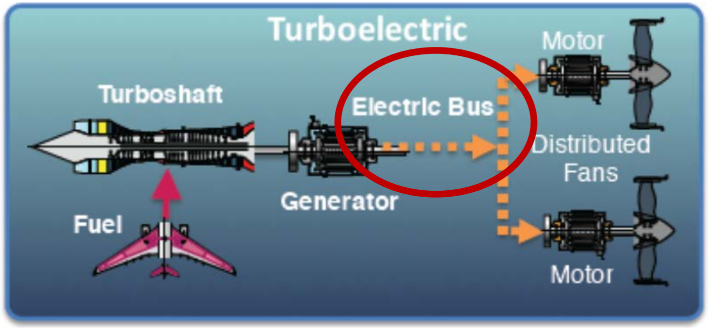
Our project was a sub-task of the High Voltage Hybrid Electric Propulsion task, (PI Ray Beach and Co-PI Linda Taylor). It was supported by NASA's Convergent Aeronautics Solutions (CAS) Project. The sub-task was a 2 year feasibility study to investigate the possibility of improving the performance of 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.

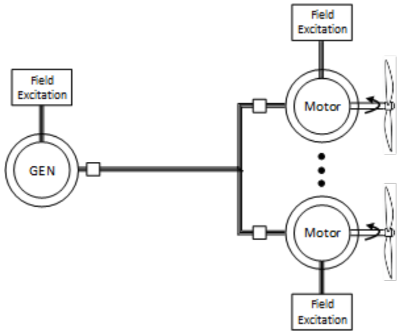
https://www.nasa.gov/aeroresearch/programs/tacp

Lightweight High Voltage Power Transmission





High Voltage Hybrid Electric Propulsion (HVHEP) Architecture



Future Aircraft will require ~20 MW power distribution

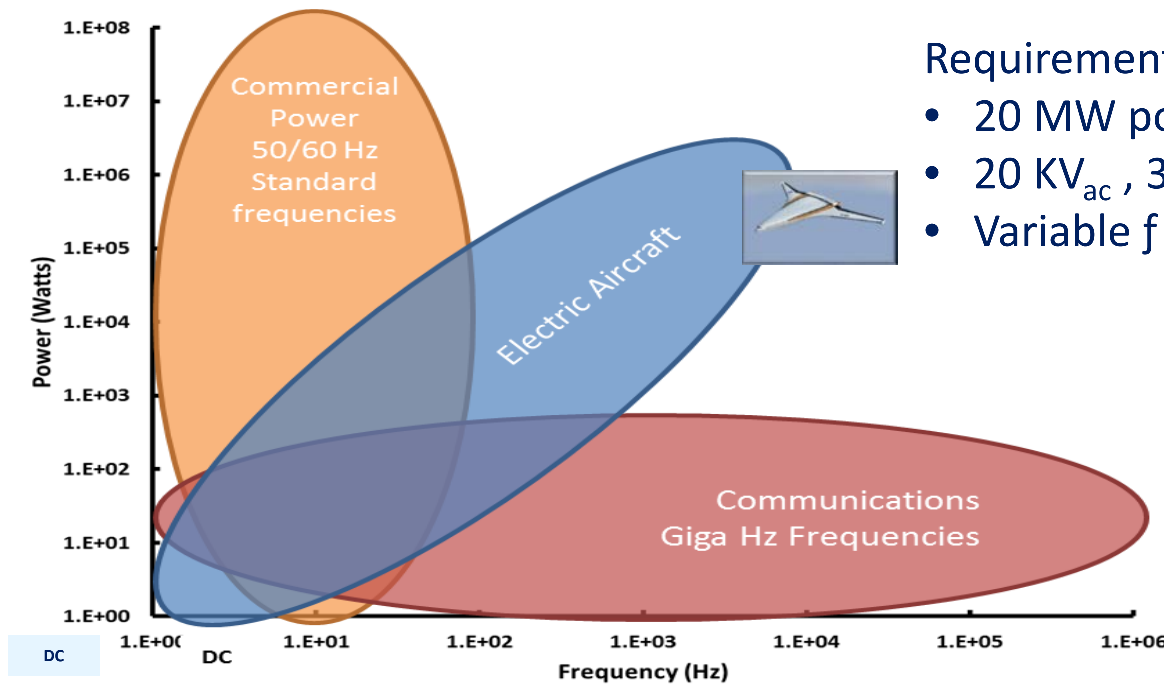
High Voltage, VAC_{max} = 20 KV
Must Design for > 40 KV
Variable Frequency (400-4000 Hz)

3

Power Distribution and Transmission Technology

Notional Current Technology Description

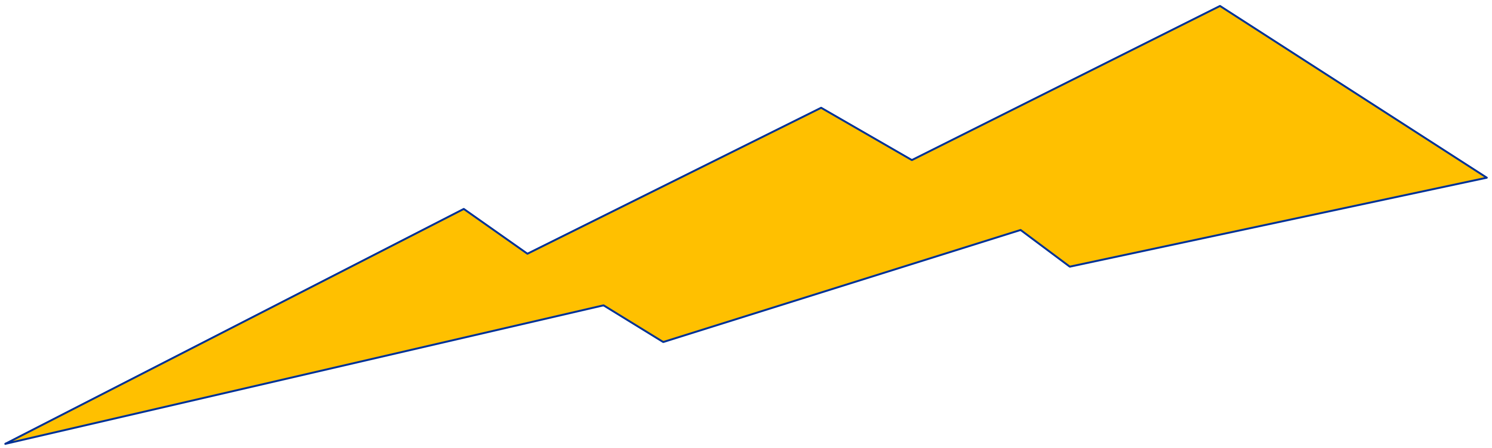
Combination of power and frequency make this a unique application space.
Current high voltage cable technology is not suitable for high altitude operation.



Requirements

- 20 MW power cable
- 20 KV_{ac} , 3-phase
- Variable ƒ = 400-4000 Hz

Electrical Arcing Events at High Altitude



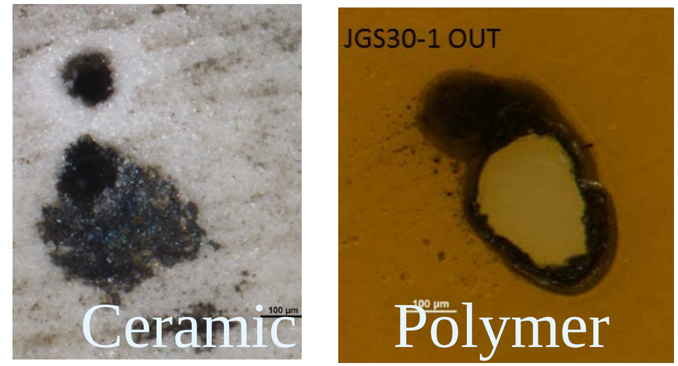
Paschen's Curve

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.

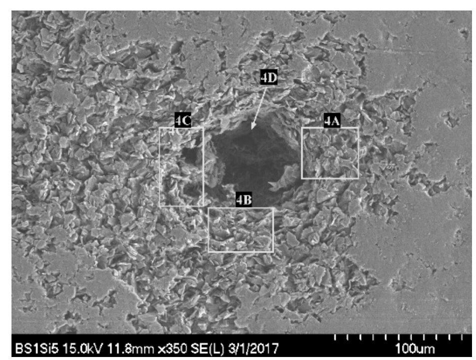
Insulation Aging and Dielectric Breakdown

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



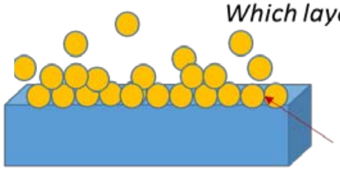
Damage from dielectric breakdown in ceramic and polymeric material



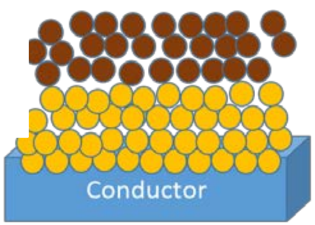
SEM of damage on ceramic

Functional Insulation System
Initial Concept Development

Which layer should be deposited first?

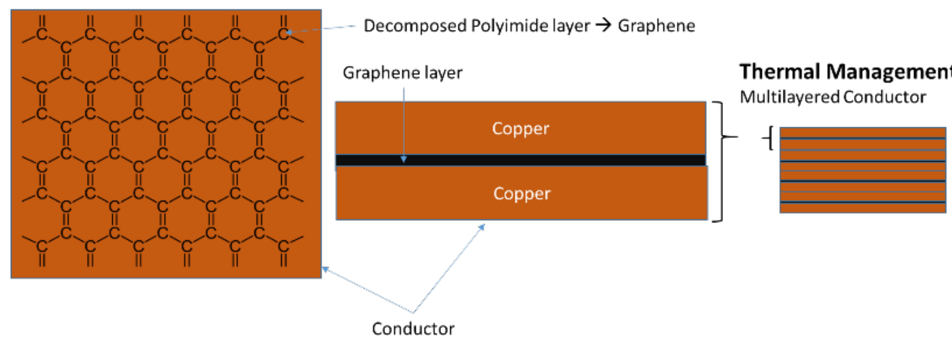


Physical Vapor Deposition



Layered Composite System
Electrical Insulation and
Thermal Management

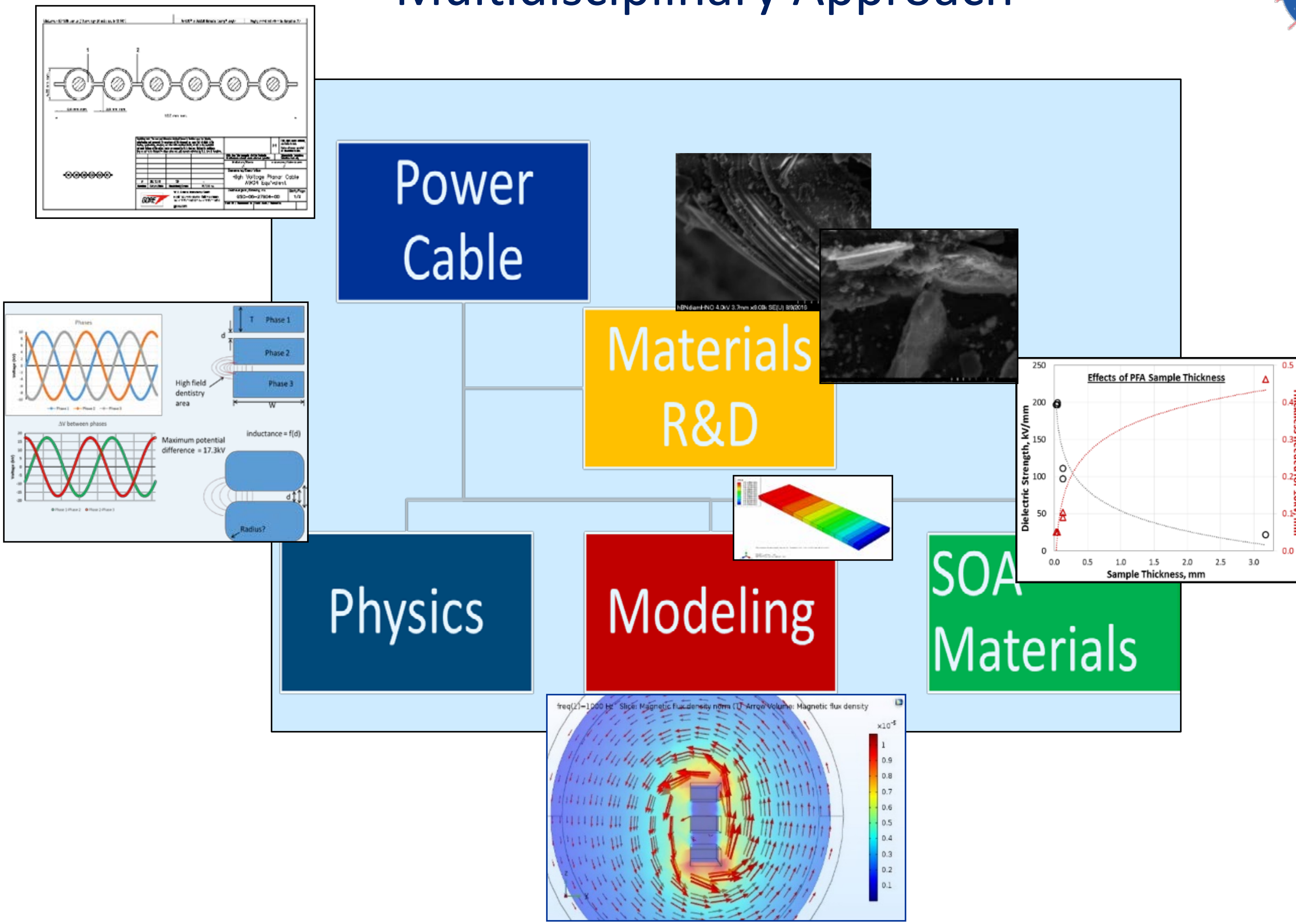
Lightweight Composite Conductor



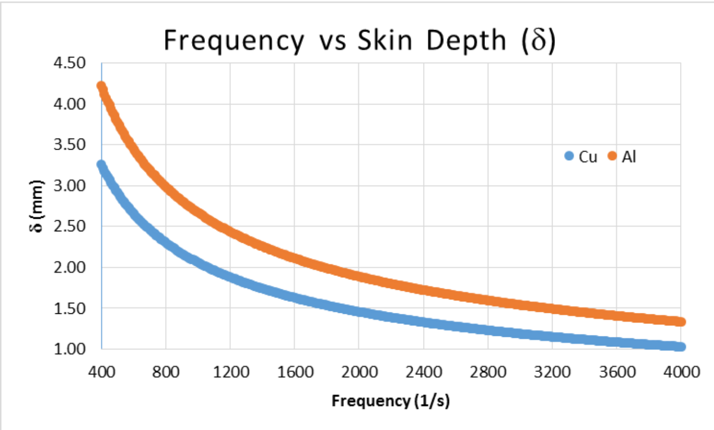
Basic Cable Construction

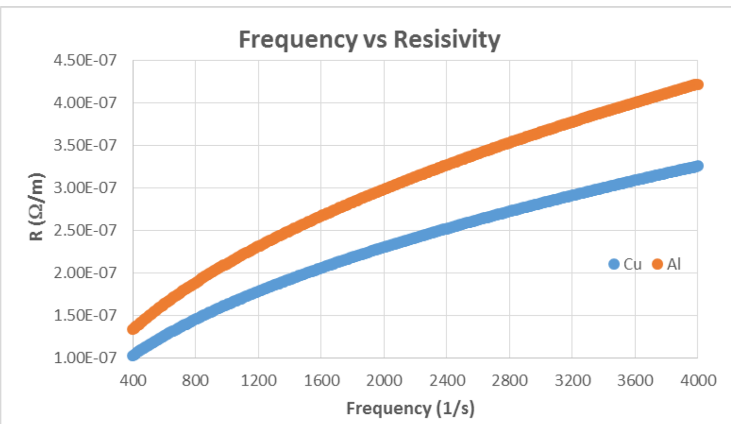
- SOA Dielectric Insulation
- EMI Shielding
- Protective Covering

Multidisciplinary Approach

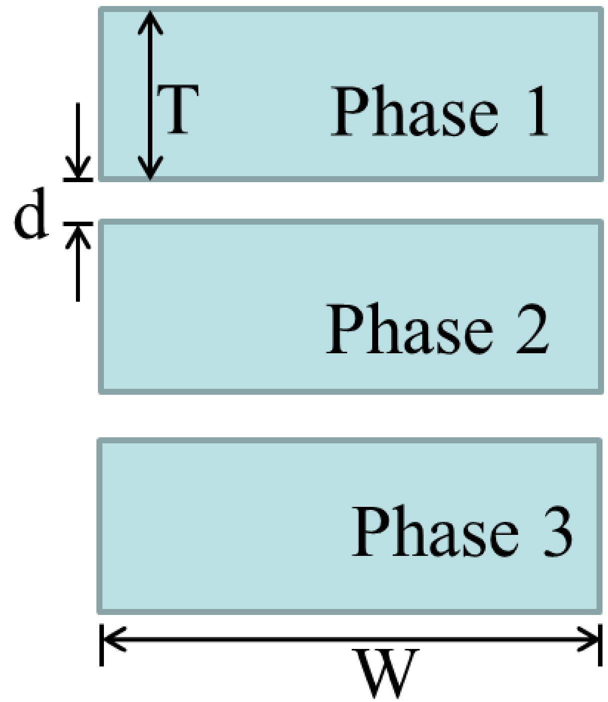


Physics

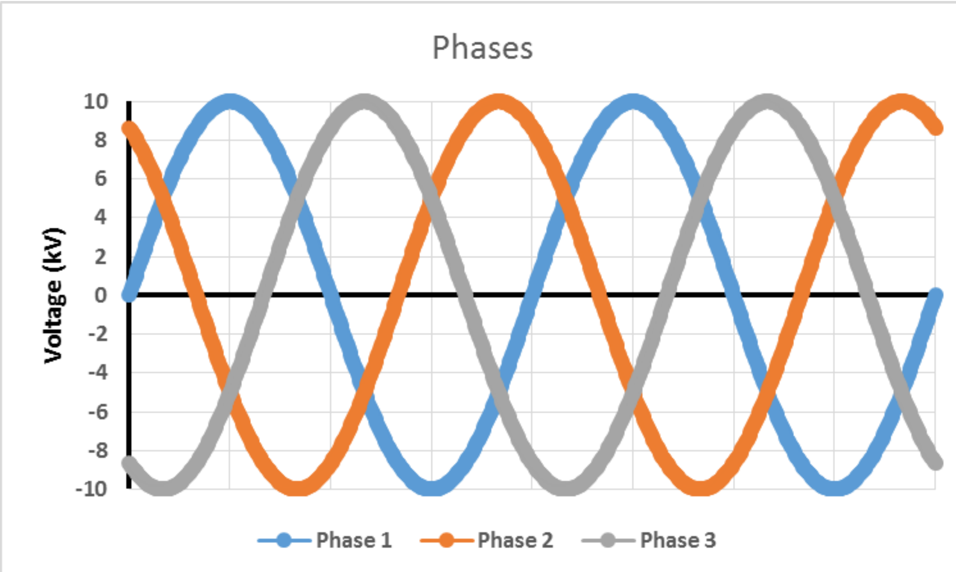




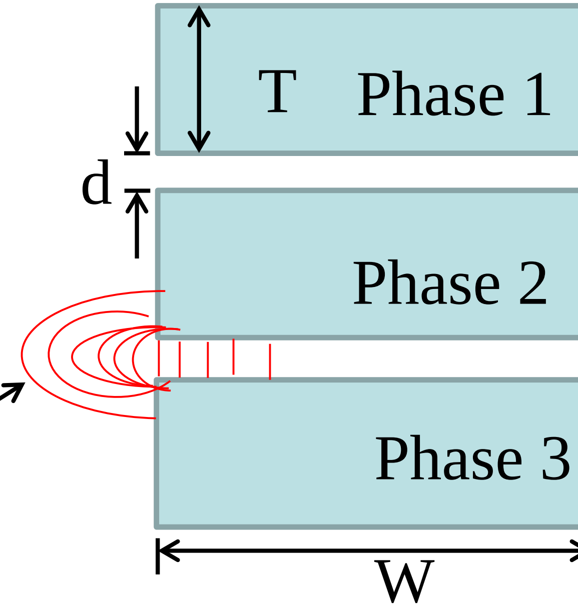
$d_{Cu\text{-}4kHz}$=1.0 mm, 5 x $d_{Cu\text{-}4kHz}$= 5.0 mm
$d_{Al\text{-}4kHz}$=1.3 mm, 5 x $d_{Al\text{-}4kHz}$= 6.5 mm



Weight Comparison
R = 3.26 x 10^{-7}(W/m)
Cu= 4.5 kg/m
Al= 2.3.kg/m

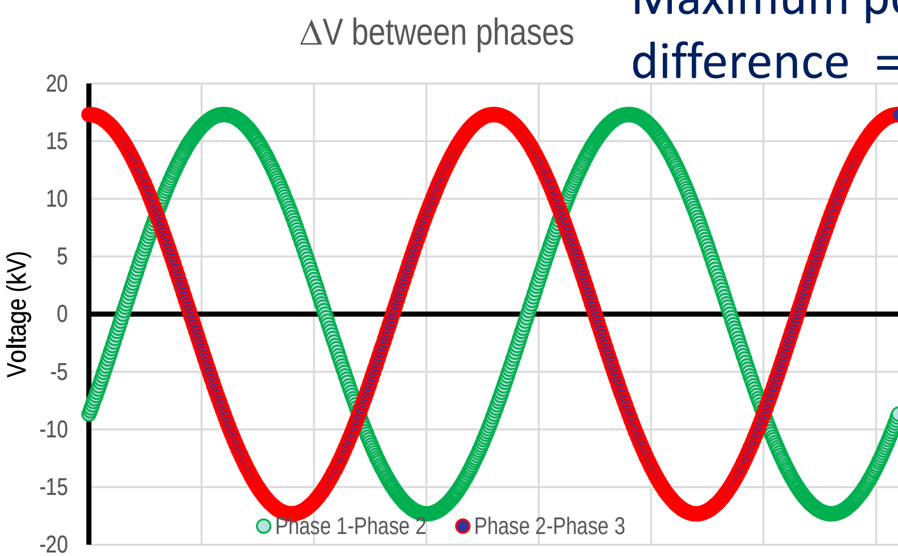


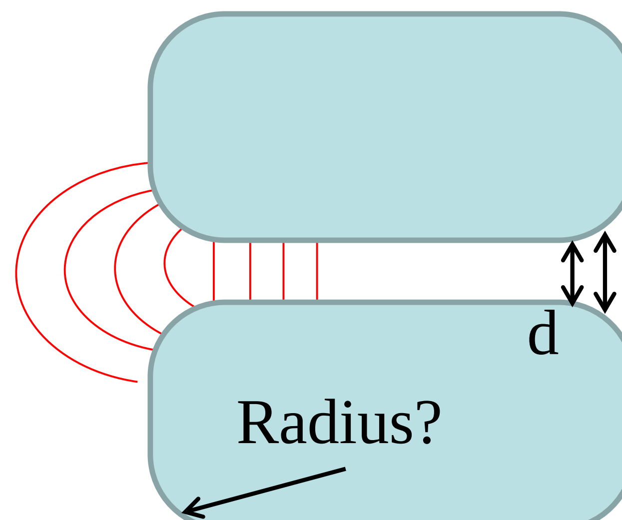
High field dentistry area



inductance = f(d)

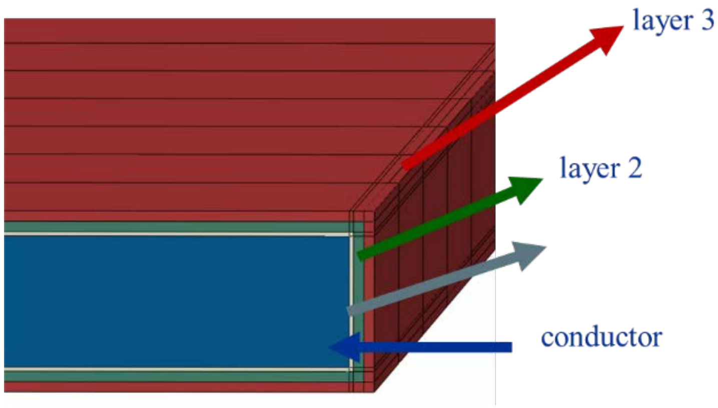
Maximum potential difference = 17.3kV

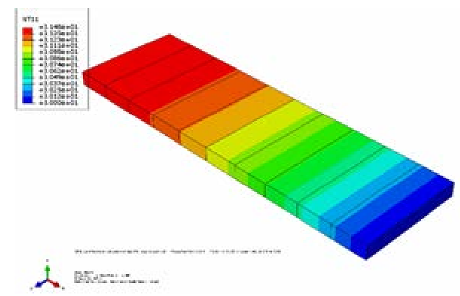




Electro-Thermal Modeling

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).





Conductor Metal	Width (m)	Thickness (m)	Area m^2	Length (m)	Voltage (V)	Amps (A)	AC/DC	Frequency Hz	Temp (C)
Cu	0.1	0.005	5.00E-04	20	1000	1000	AC	400	67
Cu	0.1	0.005	5.00E-04	20	5000	200	AC	400	31
Al	0.13	0.0065	8.45E-04	20	1000	1000	AC	400	64
Al	0.13	0.000325	4.23E-04	30	40000	125	AC	400	35
Cu	0.1	0.005	5.00E-04	20	1000	1000	AC	4000	65
Cu	0.1	0.005	5.00E-04	20	5000	200	AC	4000	31
Al	0.13	0.0065	8.45E-04	20	1000	1000	AC	4000	61
Al	0.13	0.000325	4.23E-04	30	40000	125	AC	4000	34

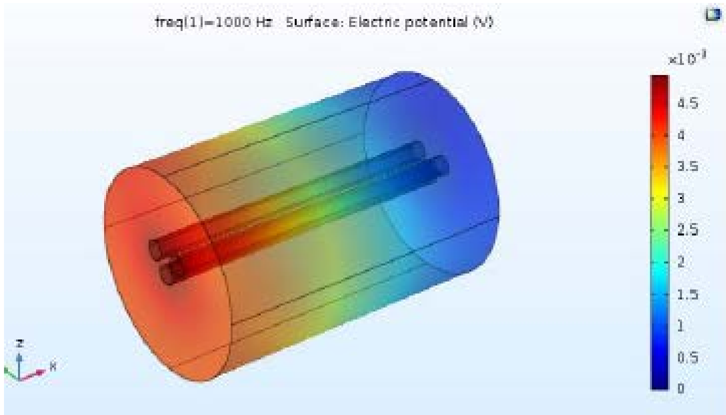
Dielectric Breakdown Modeling

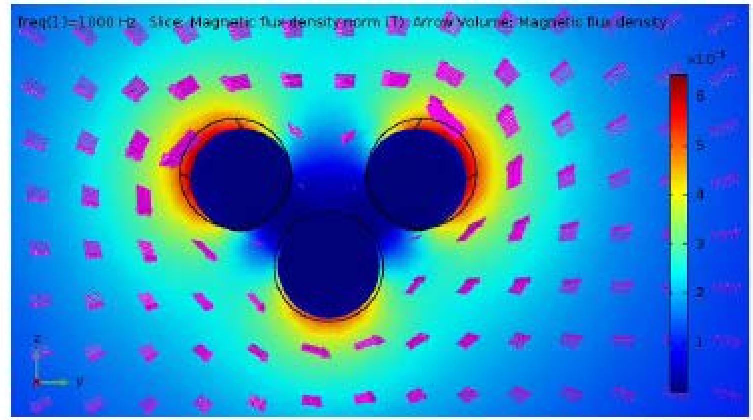
Model	Failure Mechanism	TF relationship
E-Model	Breakdown of bonds due to electrical and thermal energies	$\ln(TF) \propto \frac{\Delta E}{k_B T} - \gamma * E$
1/E-Model	Electron trapping leads to local current density	$t_{BD} = c * Exp(\frac{B+H}{E})$
√E-Model	Electron trapping leads to breakdown charge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

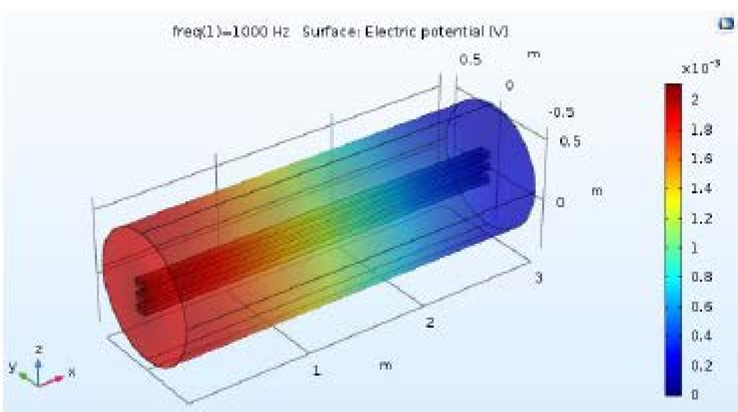
Time Dependent DB vs Voltage Ramp DB

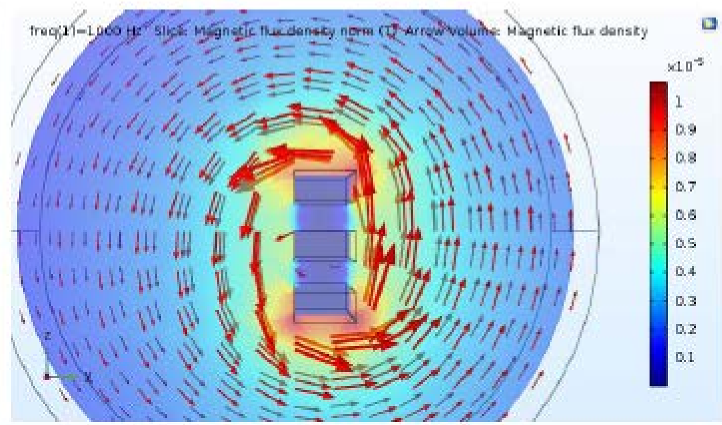
TDDB- low voltage, failure over long period of time
VRDB- voltage ramping, happens quickly

EM Field Modeling









EM field interactions between conductors will change With conductor geometry and spacing.

Dielectric Insulation Materials Testing Capabilities

Eaton High Voltage Test Set
Located at NASA GRC 106:B10

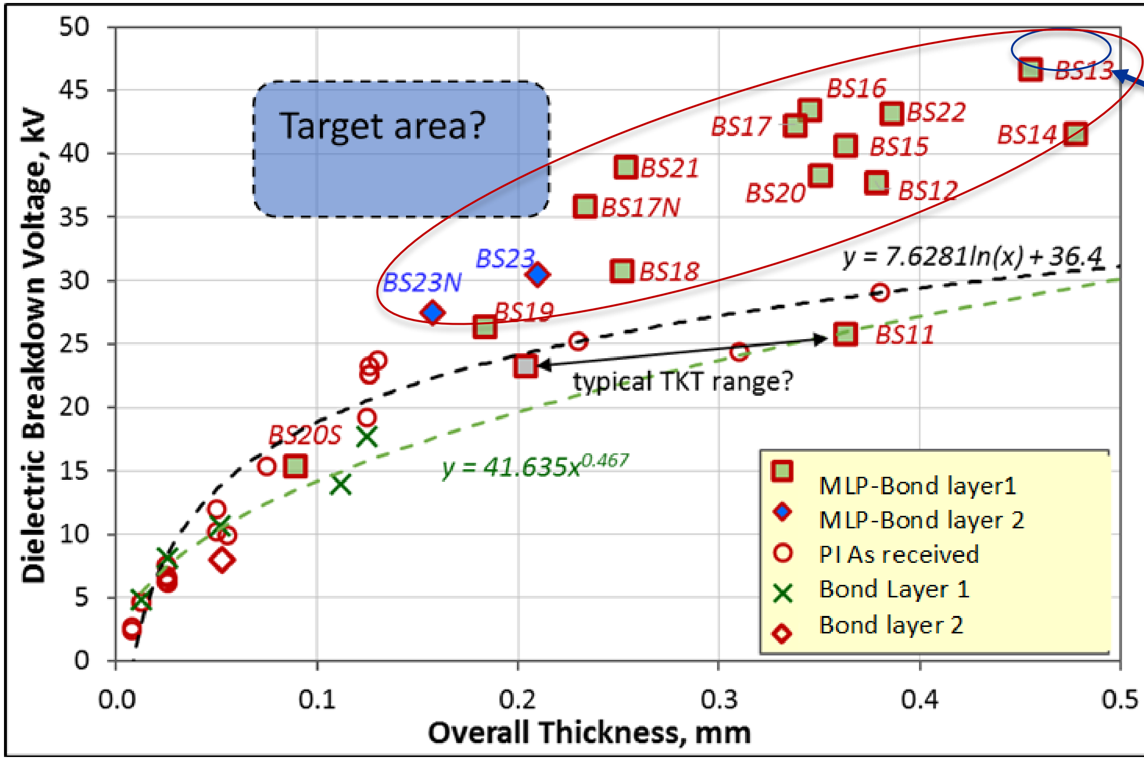
Dielectric Test Rig Specifications

		AC	DC	
Output voltage AC :	Vmax.	60.00	84.84	kV
	Vmin.	1.800	2.545	kV
Regulation:		+/-0.4	0.57	kV
Resolution:		0.017	0.024	kV
Ramp Rate:	max.	5.500	7.777	kV/s
(Average speed)	min.	1.100	1.555	kV/s

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

SOA and Functional Insulation System Testing



Sample BS13

V_b = ~ 46 kV

t= 0.48 mm

As Received Kapton trend line

y = 7.628 ln (x) + 36.4

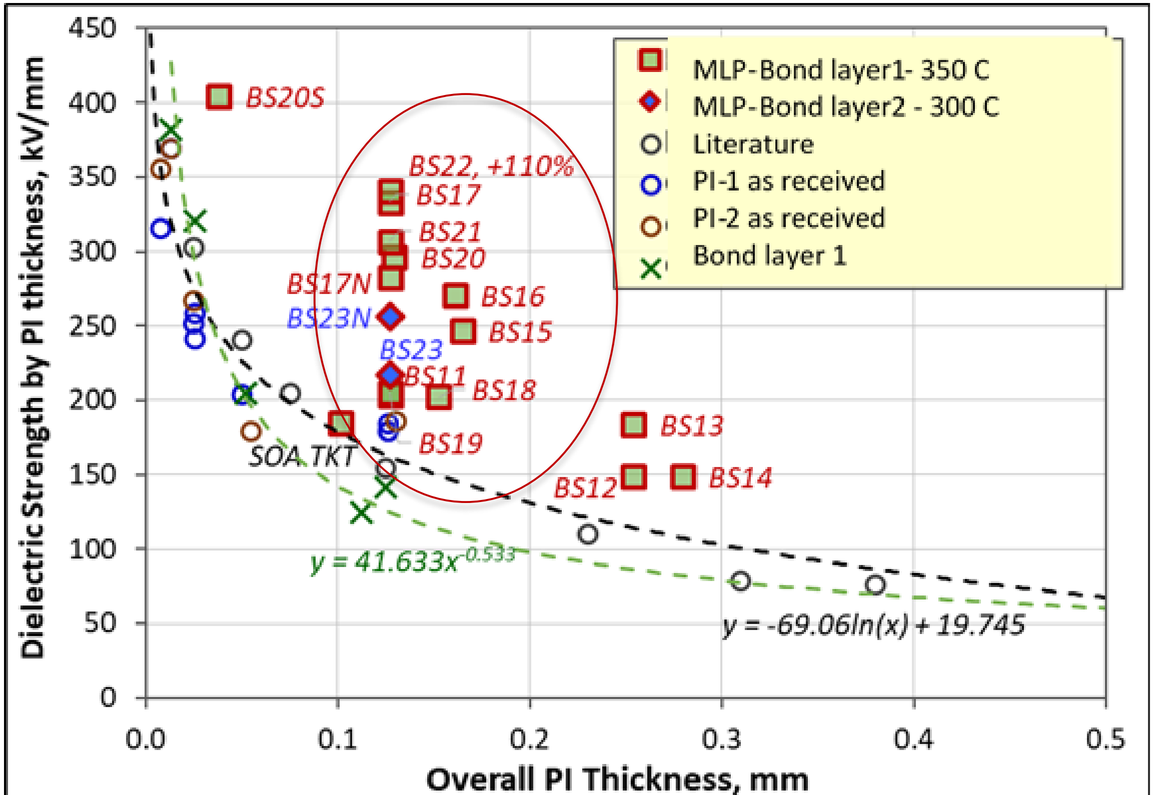
$x = e^{((y-36.4)/7.628)}$

$x = e^{((46-36.4)/7.628)}$

x = 3.52 mm Kapton thickness

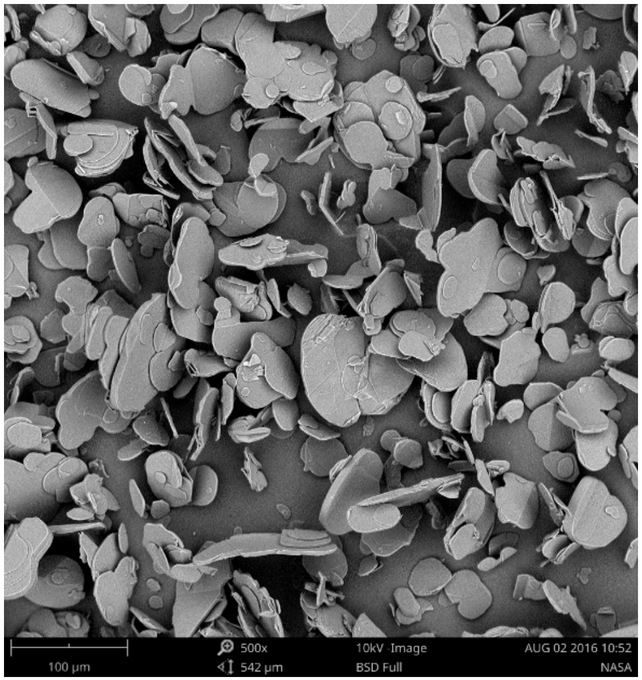
86% decrease in insulation thickness. This also decrease volume of the cable.

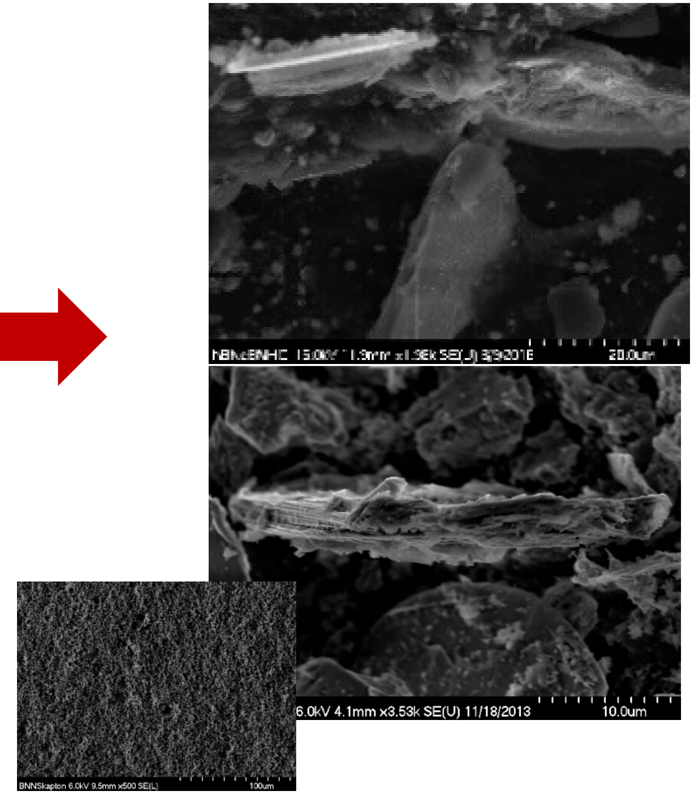
Improvement in Dielectric Strength



Compared to as received Kapton, the dielectric strength of the functional insulation system also increases significantly for equivalent thickness.

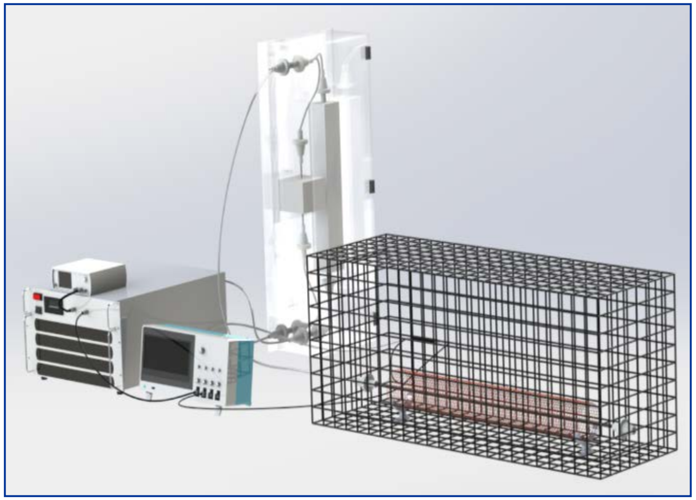
Materials R&D

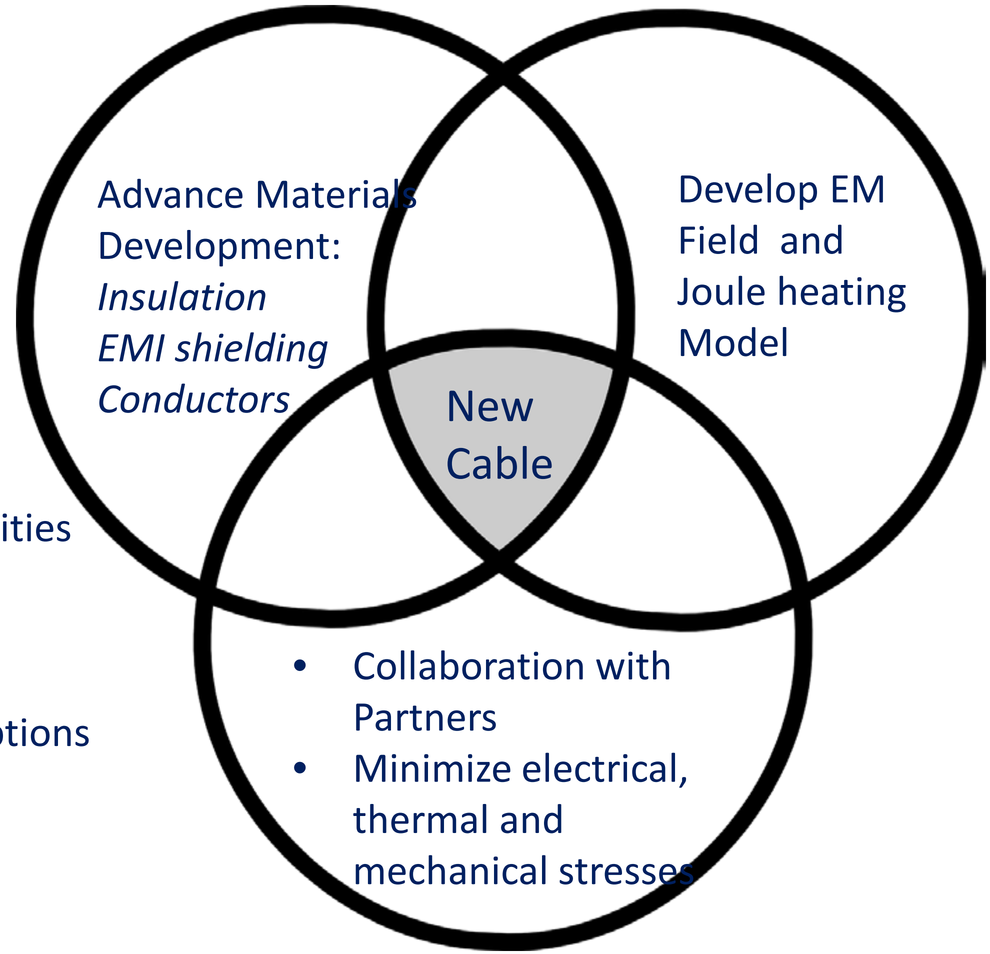




Chemically tailoring the properties of a ceramic material to enhance dielectric and thermal properties of composites we can add functionality to cable insulation.

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

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

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Thanks Team!

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Questions?