# Material Challenges and Opportunities for Commercial Electric Aircraft

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# NASA Goals for Fixed Wing Aircraft

v2013.1

| TECHNOLOGY BENEFITS* | TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6) | | |
|---|---|---|---|
| | N+1 (2015) | N+2 (2020**) | N+3 (2025) |
| Noise (cum margin rel. to Stage 4) | -32 dB | -42 dB | -52 dB |
| LTO NOx Emissions (rel. to CAEP 6) | -60% | -75% | -80% |
| Cruise NOx Emissions (rel. to 2005 best in class) | -55% | -70% | -80% |
| Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class) | -33% | -50% | -60% |

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

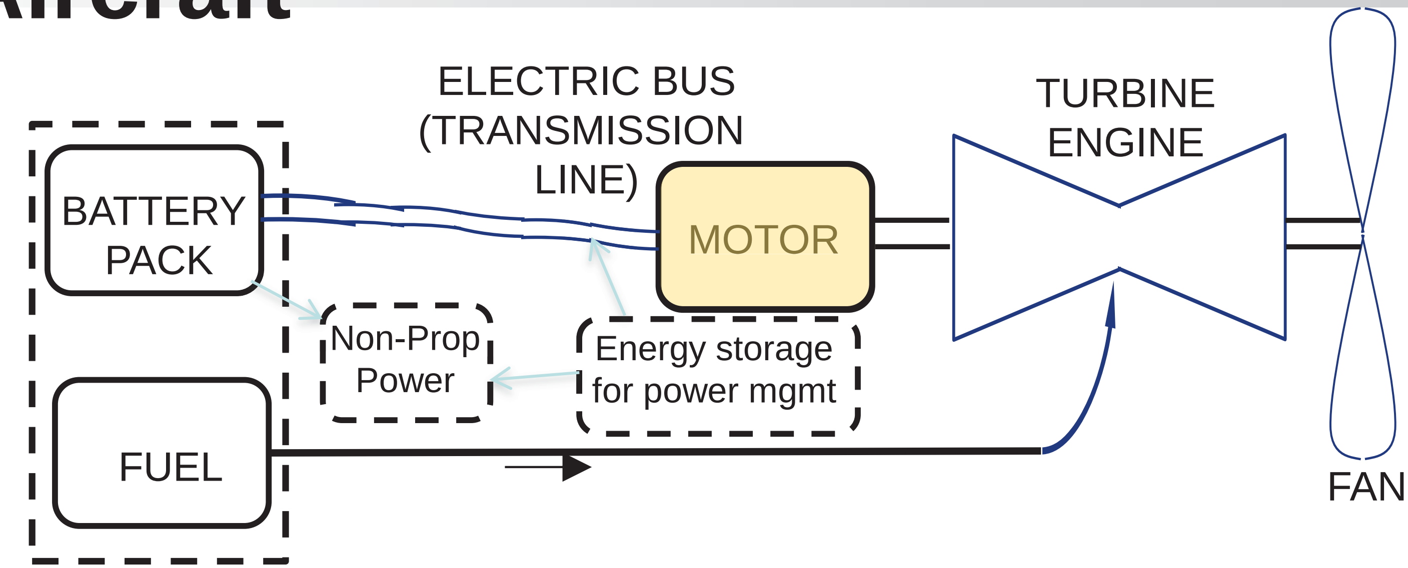
‡ CO2 emission benefits dependent on life-cycle CO2e per MJ for fuel and/or energy source used

# Benefits of Electric Propulsion

- Significantly reduced emission (near zero for certain concepts) – green system
- Significant reduction in fuel burn due to higher efficiency of electrical systems
- Reduction in noise
- Advanced concepts (such as distributed propulsion and boundary layer ingestion) might be enabled by certain electric propulsion concepts

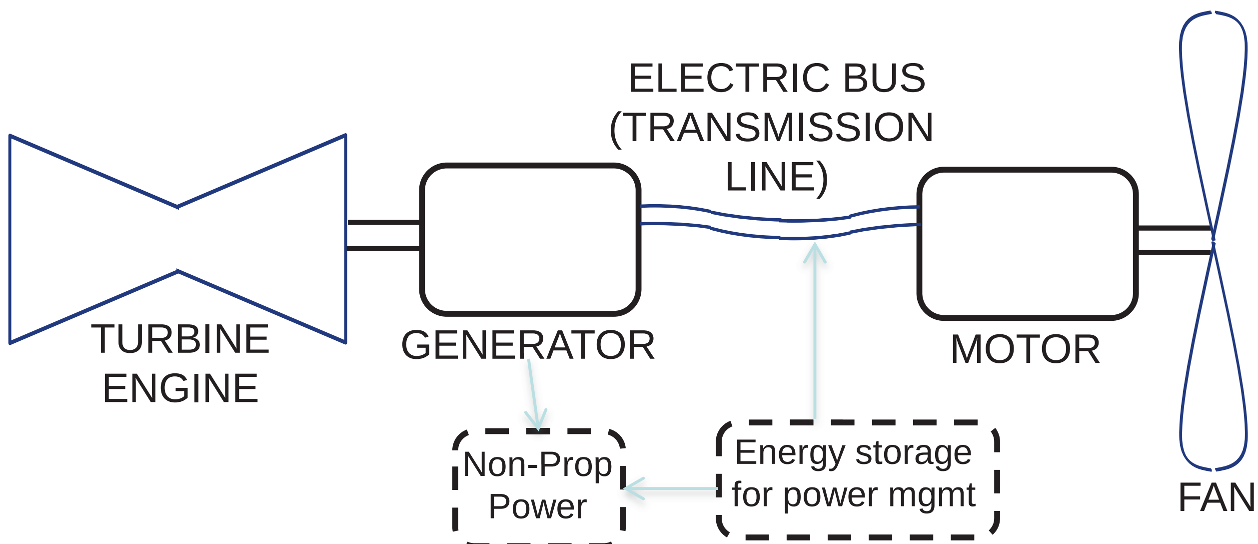
# Possible Future Commercial Large Transport Aircraft

## Hybrid Electric

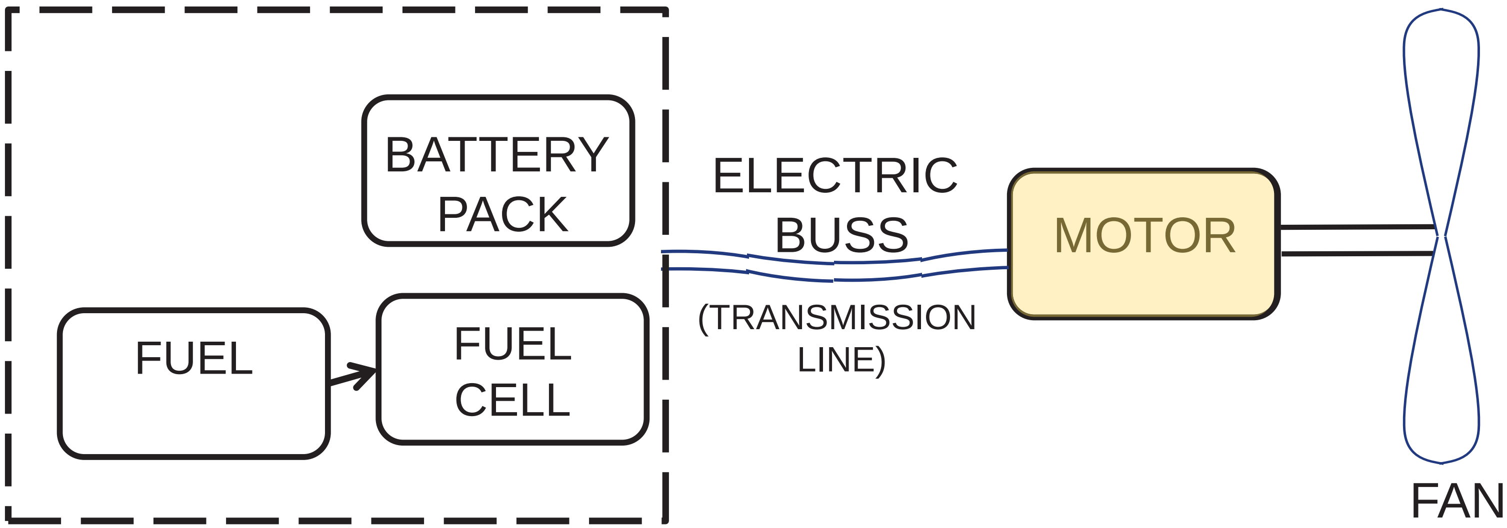




**Both Concepts can use either non-cryogenic motors or cryogenic superconducting motors.**

## Turbo Electric



# All Electric Propulsion

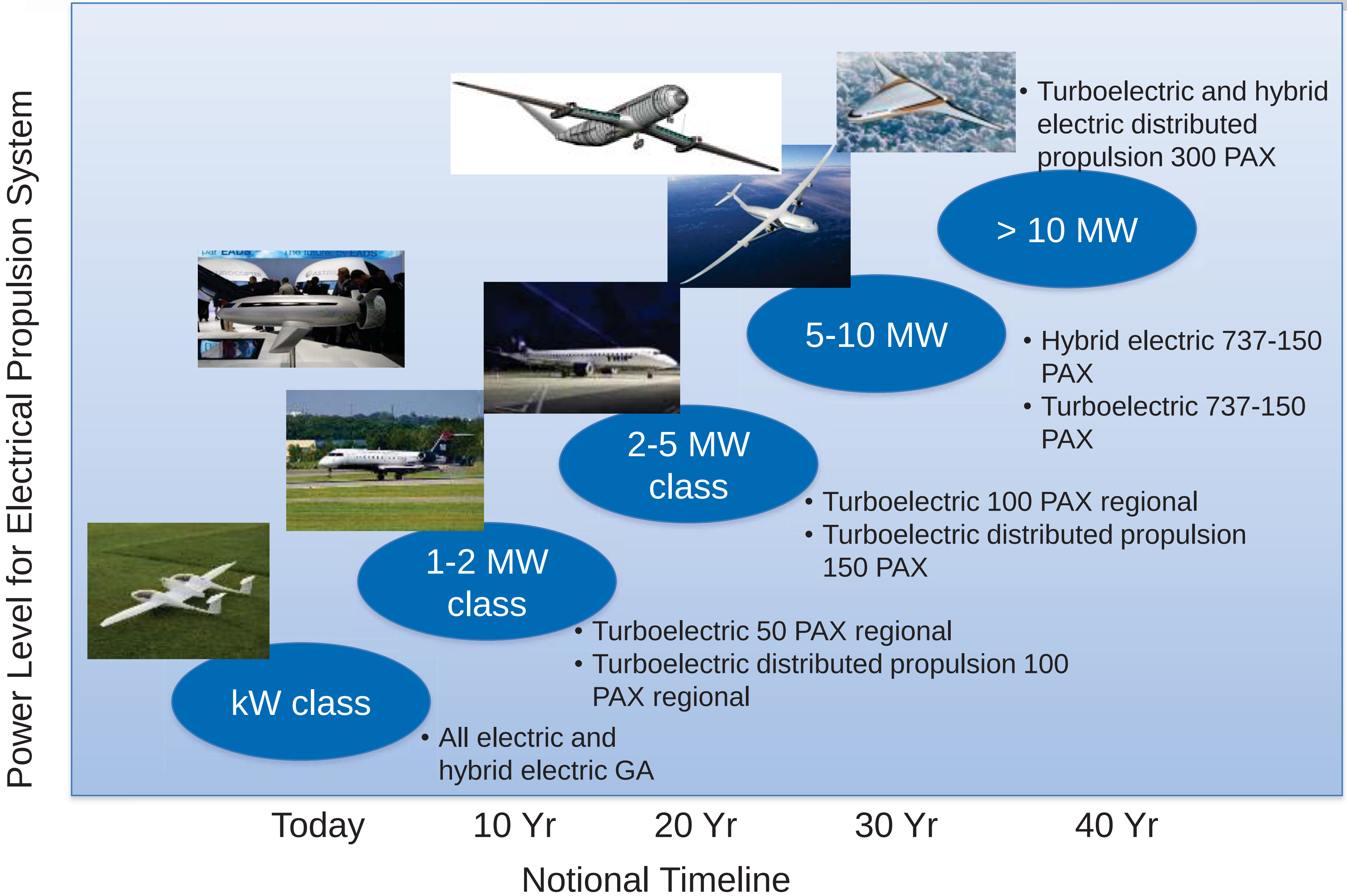




**EADS – VoltAirs concept**

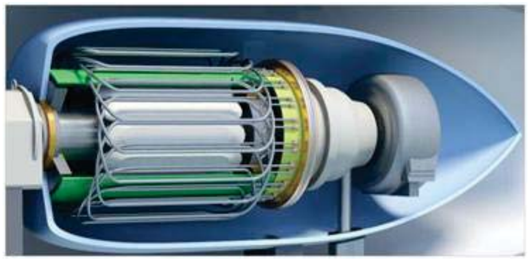
- Li-Air battery
- High temperature superconducting motor

# Progression of Adoption of Electric Propulsion in Aircraft



# Key Challenges for Large Commercial Electric Aircraft

High power density superconducting motor (cryogenic)

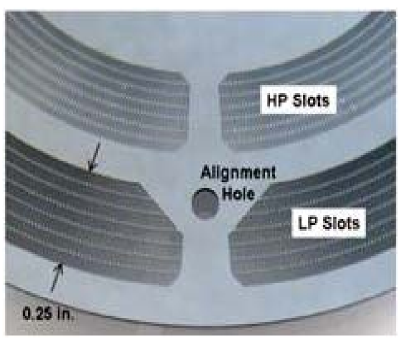


High power density power electronics

High power density non-cryogenic motor

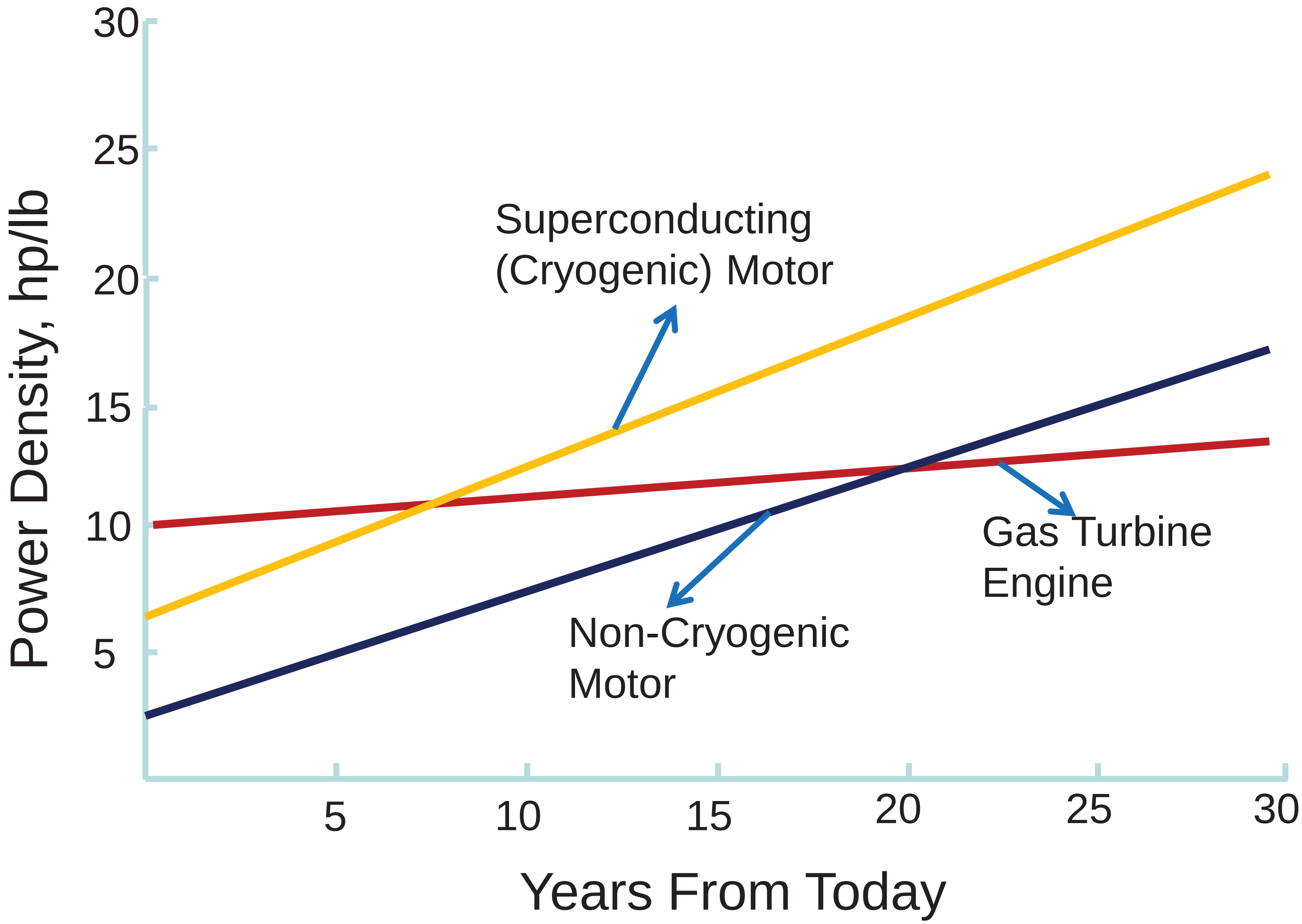
Lightweight power transmission cable

Lightweight thermal management system

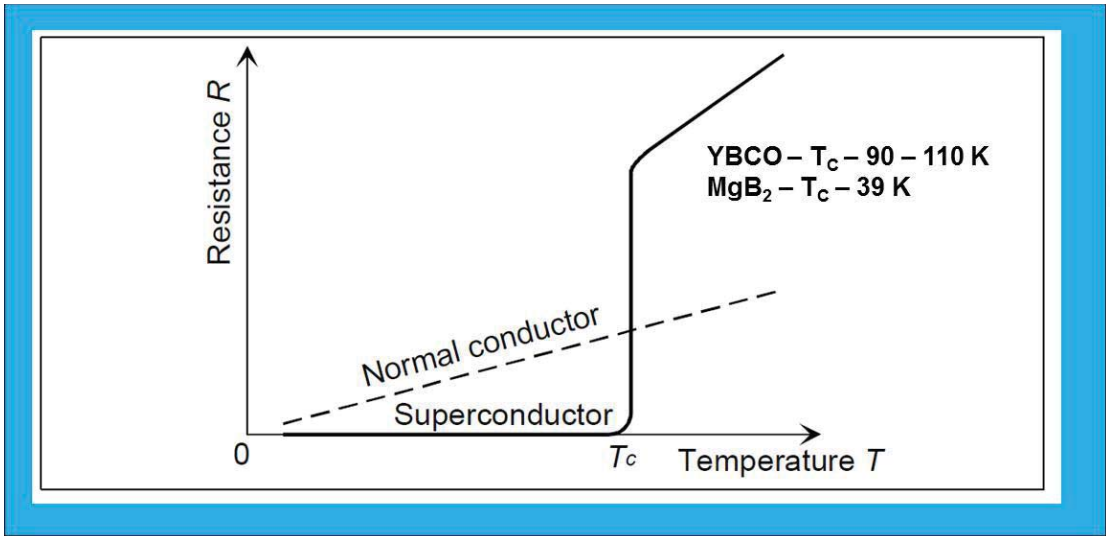


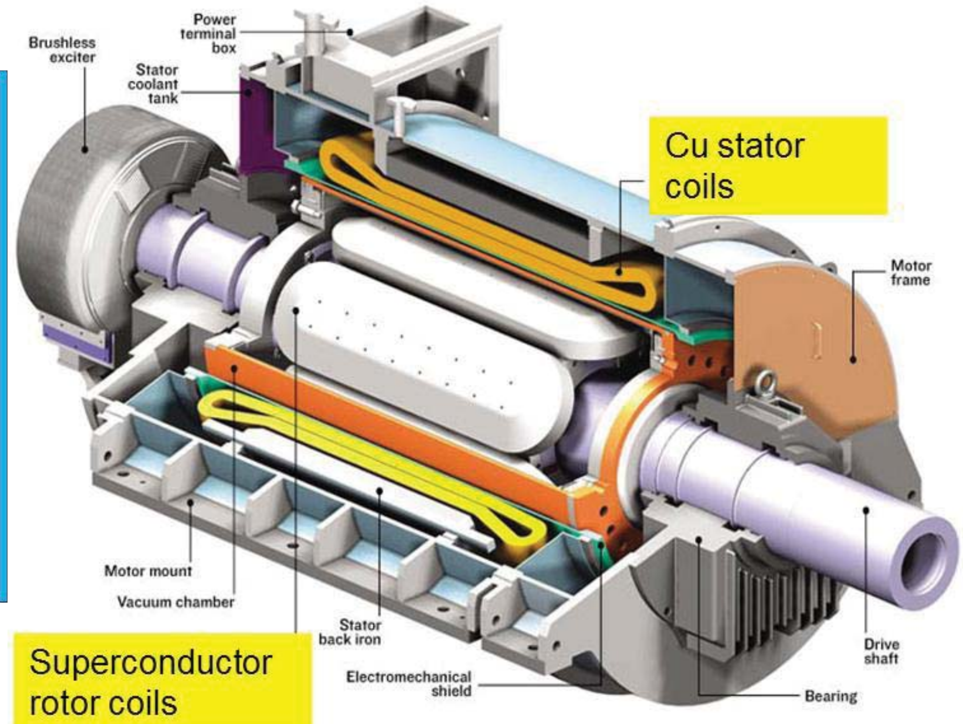

Energy storage system with high specific energy

# Power Density of Gas Turbine Engines Compared to Projected Power Density of Electric Motors



# Fully Superconducting Motors Needed for Electric Aircraft



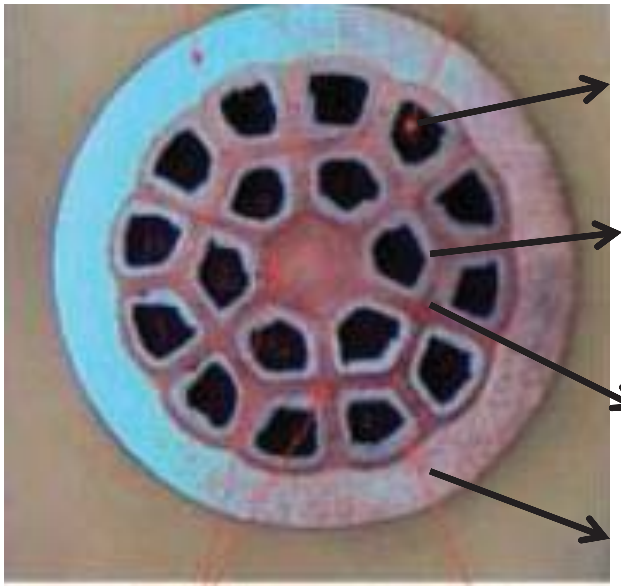




$MgB_2$ easy to fabricate in coil form – needs liquid hydrogen for cooling

- The state-of-the-art superconducting motor is limited to application of superconducting materials in rotor coils only
- Application of superconducting material in stator coils is limited by high ac losses due to the effect of varying magnetic field

The challenge for fully superconducting motor is to develop low ac-loss stator coils

# Key Materials Challenge for Fully Superconducting Motor




**Reduction of ac-loss in superconducting coil requires:**

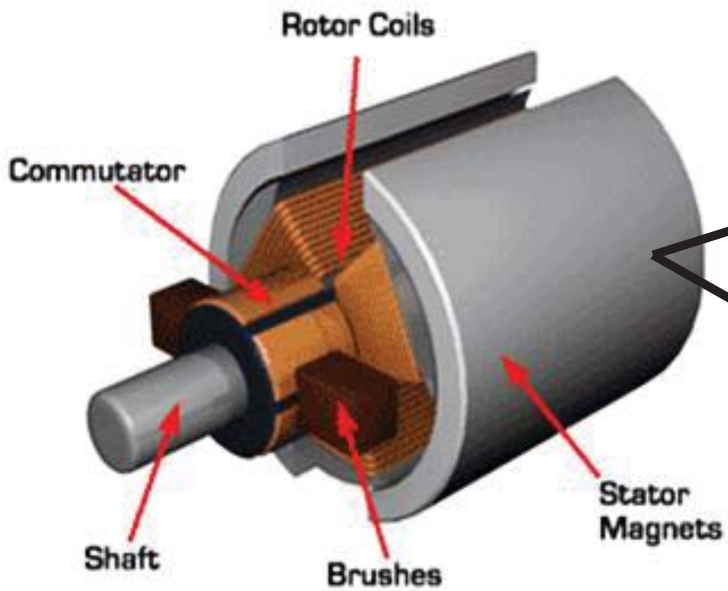
- Reducing filament size (state-of-the-art filament size on the order of 70-100 microns, experimental filaments of 30 micron diameter, need to reduce diameter to 10 microns or lower
- Twisting wire with reduction in twist pitch
- Increasing resistivity of sheath material and reaction barrier

Significant manufacturing challenge to develop 10 micron or less diameter $MgB_2$ filament with superconducting properties and required mechanical properties for stator coil application

# Material Advancements Needed for High Power Density Non-Cryogenic Electric Motor


Higher electrical conductivity coil

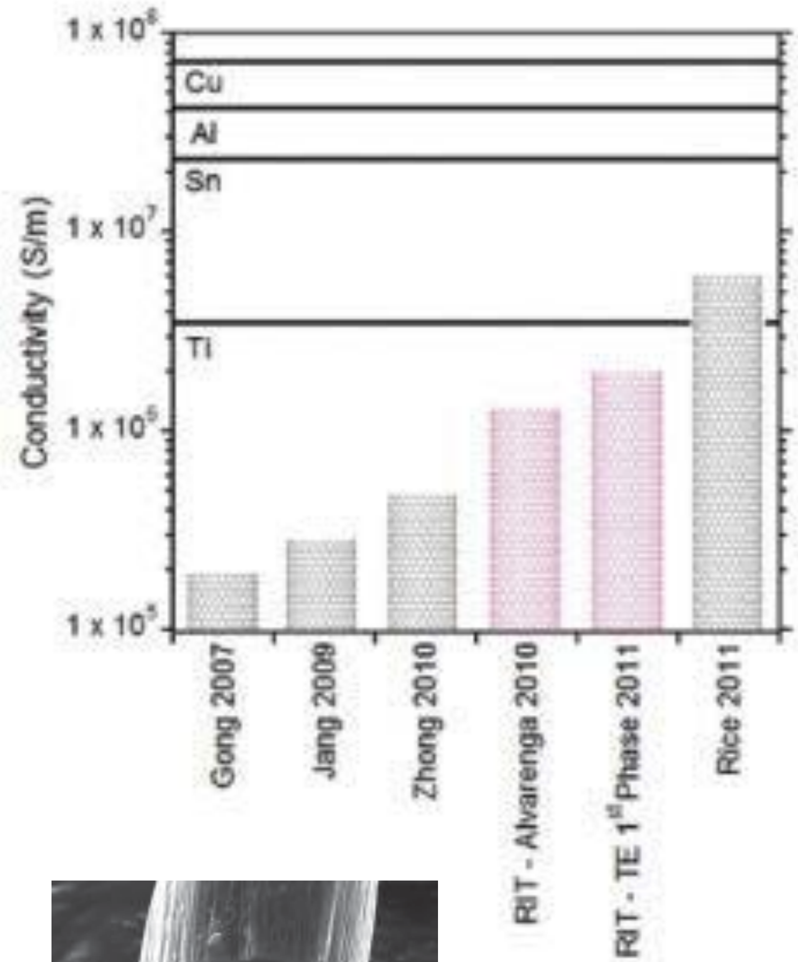
Stator coil insulation material with high thermal conductivity and higher temperature capability

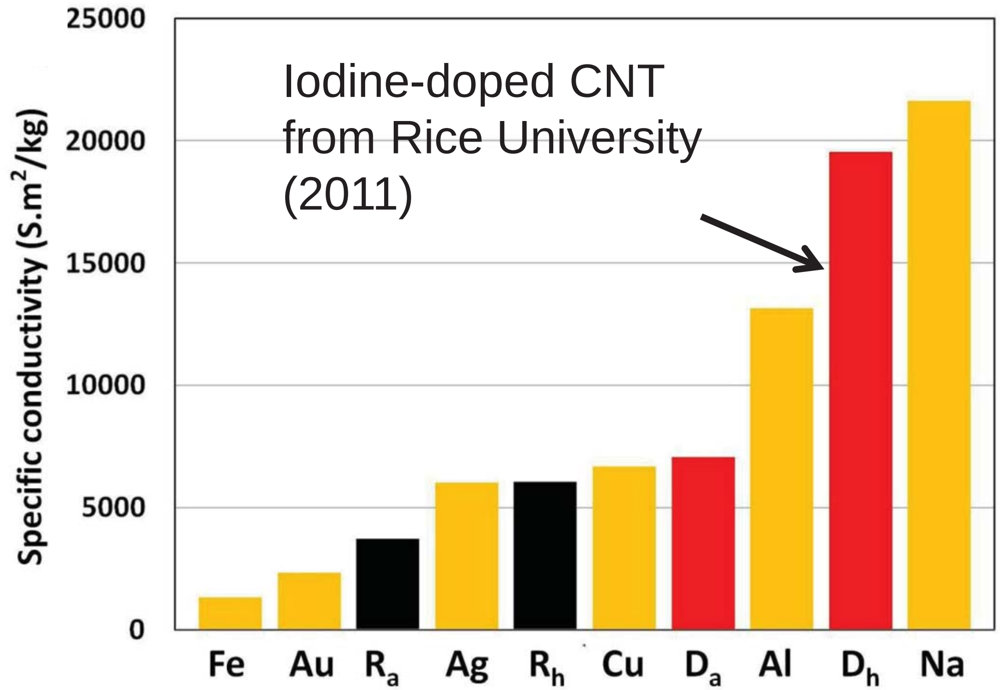


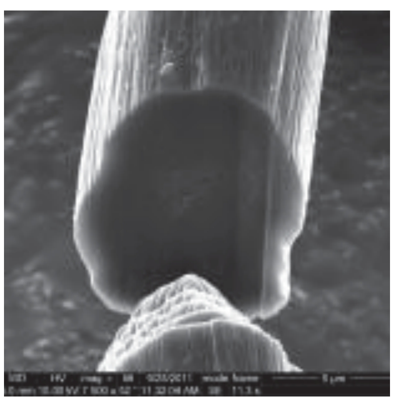

Magnets with higher energy product

Higher temperature magnets

# Coils With High Electrical Conductivity



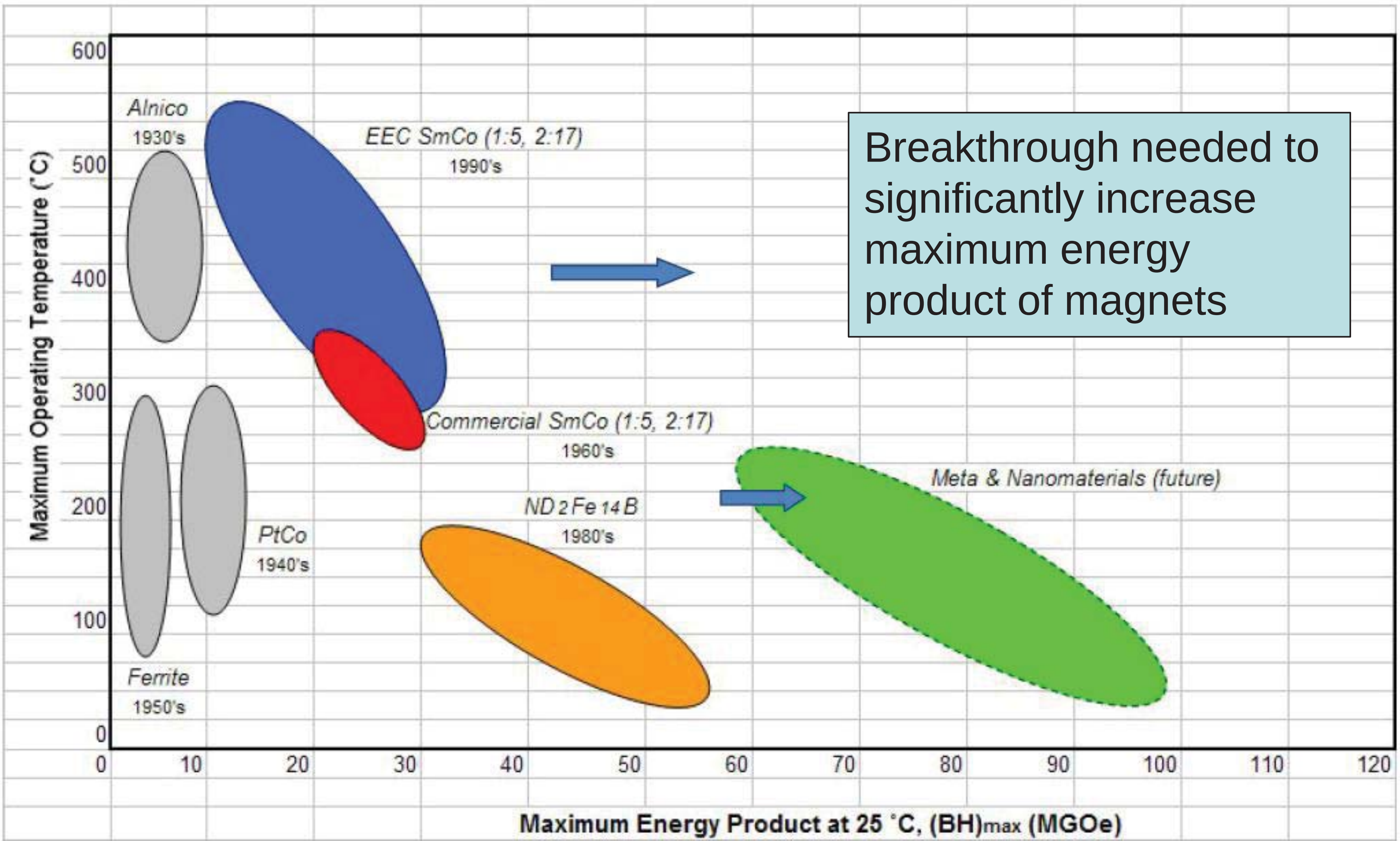



2013- carbon nanotube fiber with high specific electrical conductivity by Rice Univ.

Challenge:

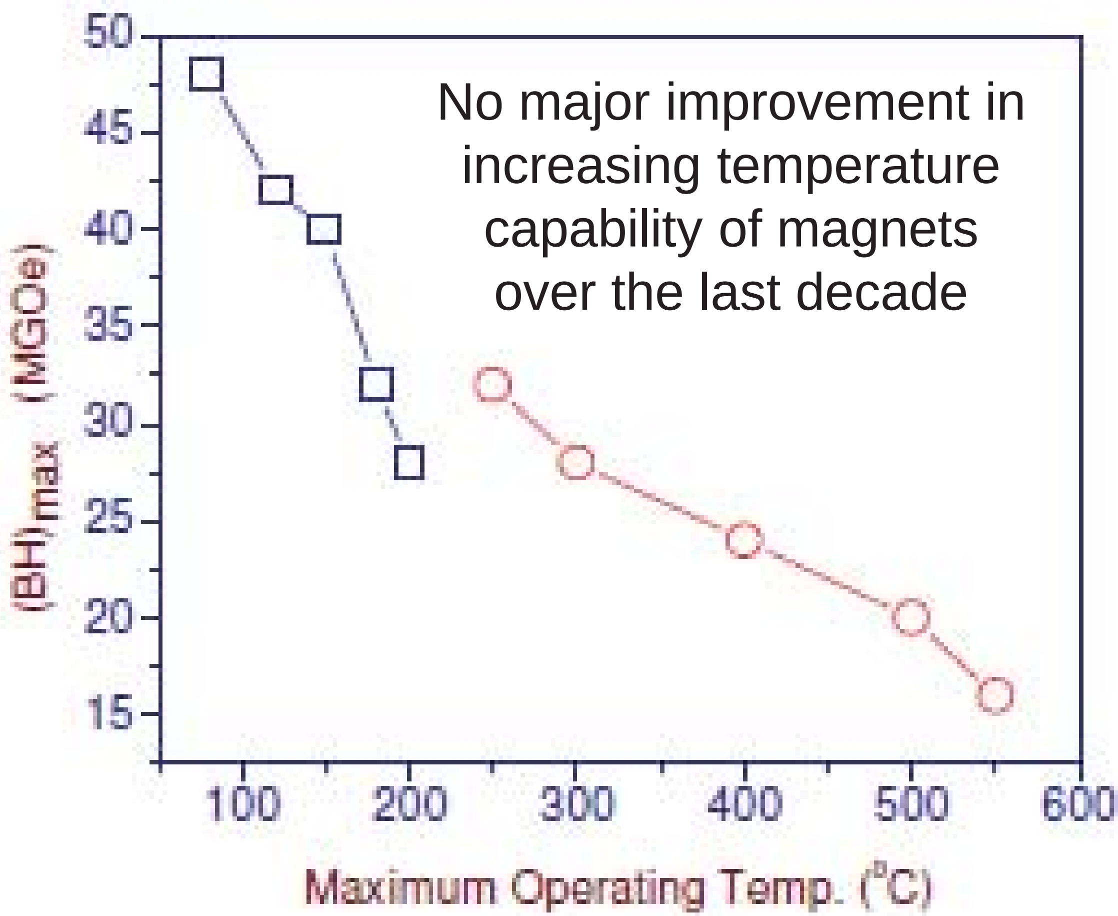
- CNT fiber with electrical conductivity greater than Cu
- Fabrication of coils with CNT fiber
- Motor design with CNT fiber

# Development of Advanced Magnets



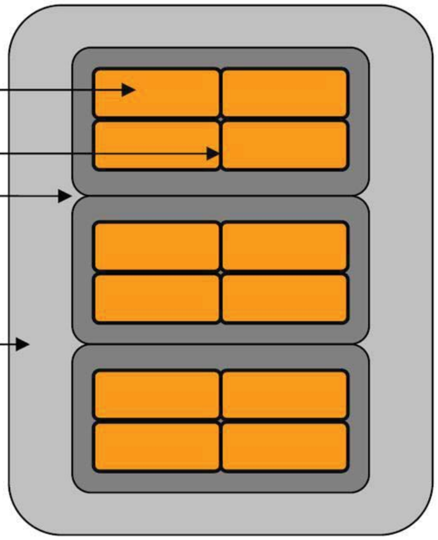

Breakthrough needed to significantly increase maximum energy product of magnets

# High Temperature Magnets




Challenge is to develop high temperature magnets with high maximum energy product (BH) and temperature capability greater than 400°C required

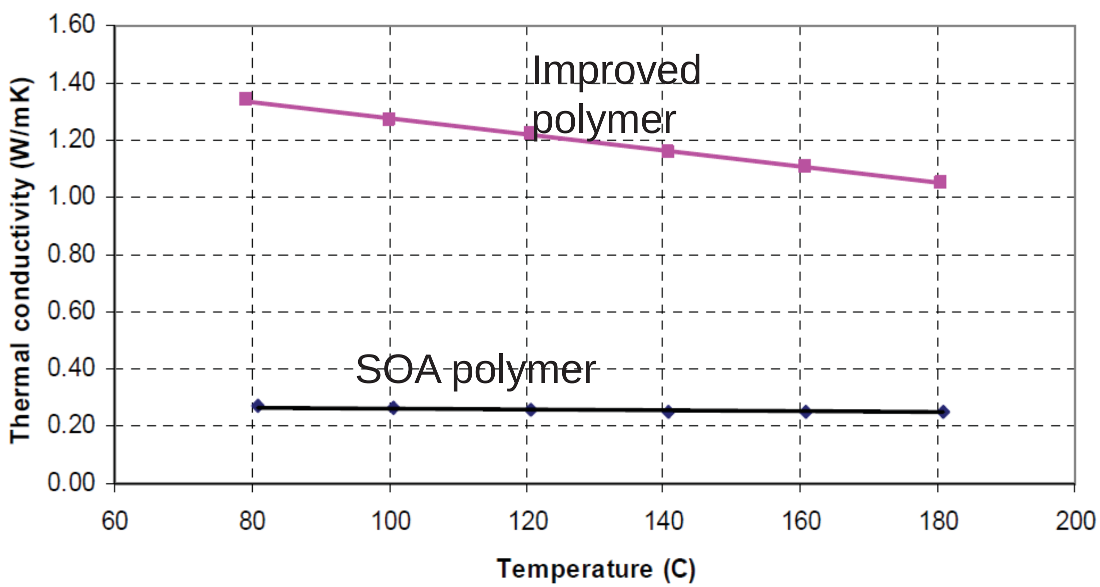
# Advanced Stator Coil Insulation Material

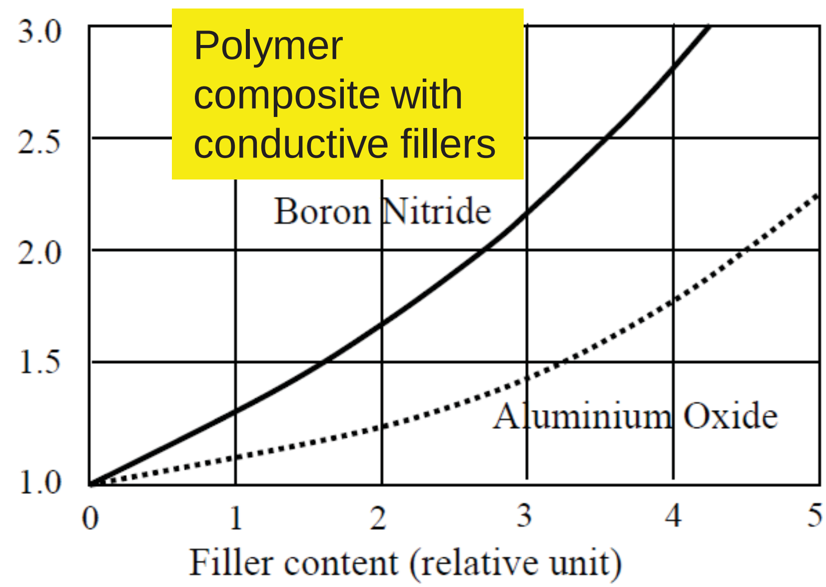



State-of-the-art insulation based on mica impregnated with epoxy or polyester resins, thermal conductivity < 0.5 W/m.K, temperature limit is 180ºC

Challenge:

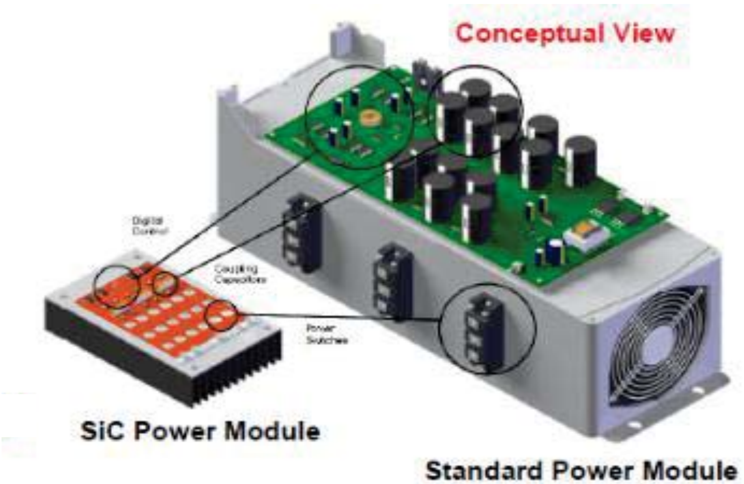
- Polymer composite stator coil insulation materials with order of magnitude increase in thermal conductivity
- Temperature capability of 400ºC or higher



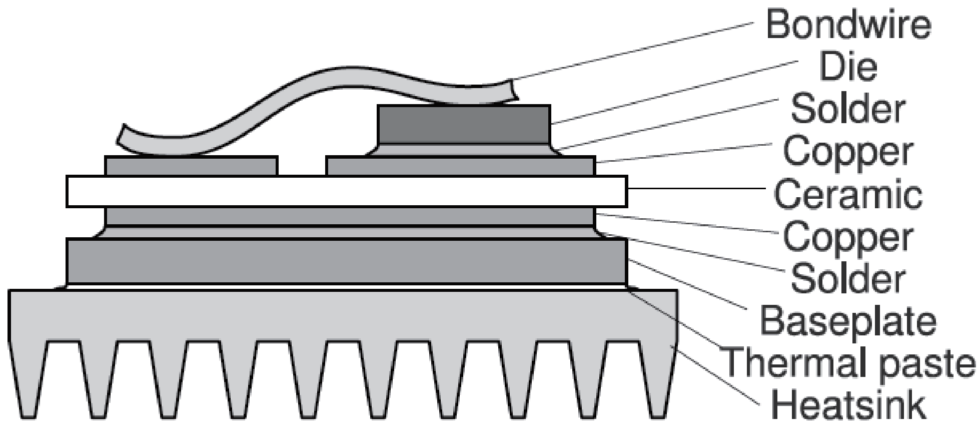



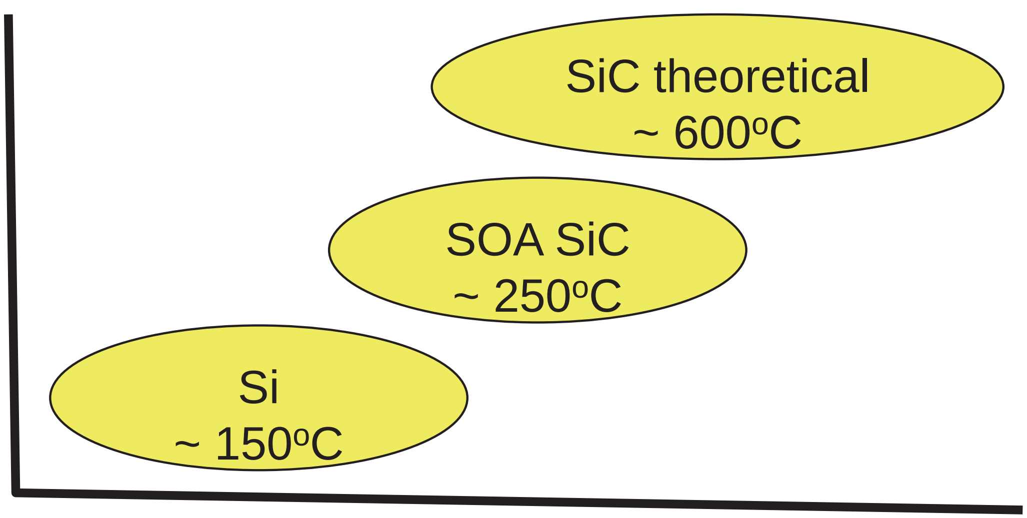
# Power Electronics Semiconductor

Increase in power density by increasing temperature capability of semiconductor

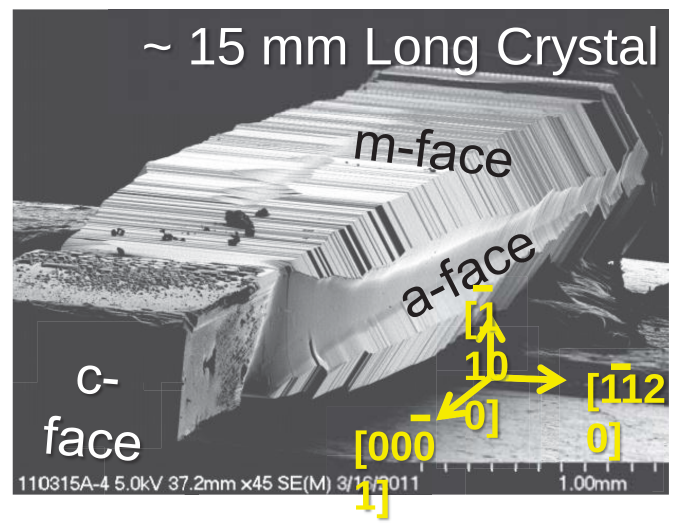



High temperature packaging is a major barrier



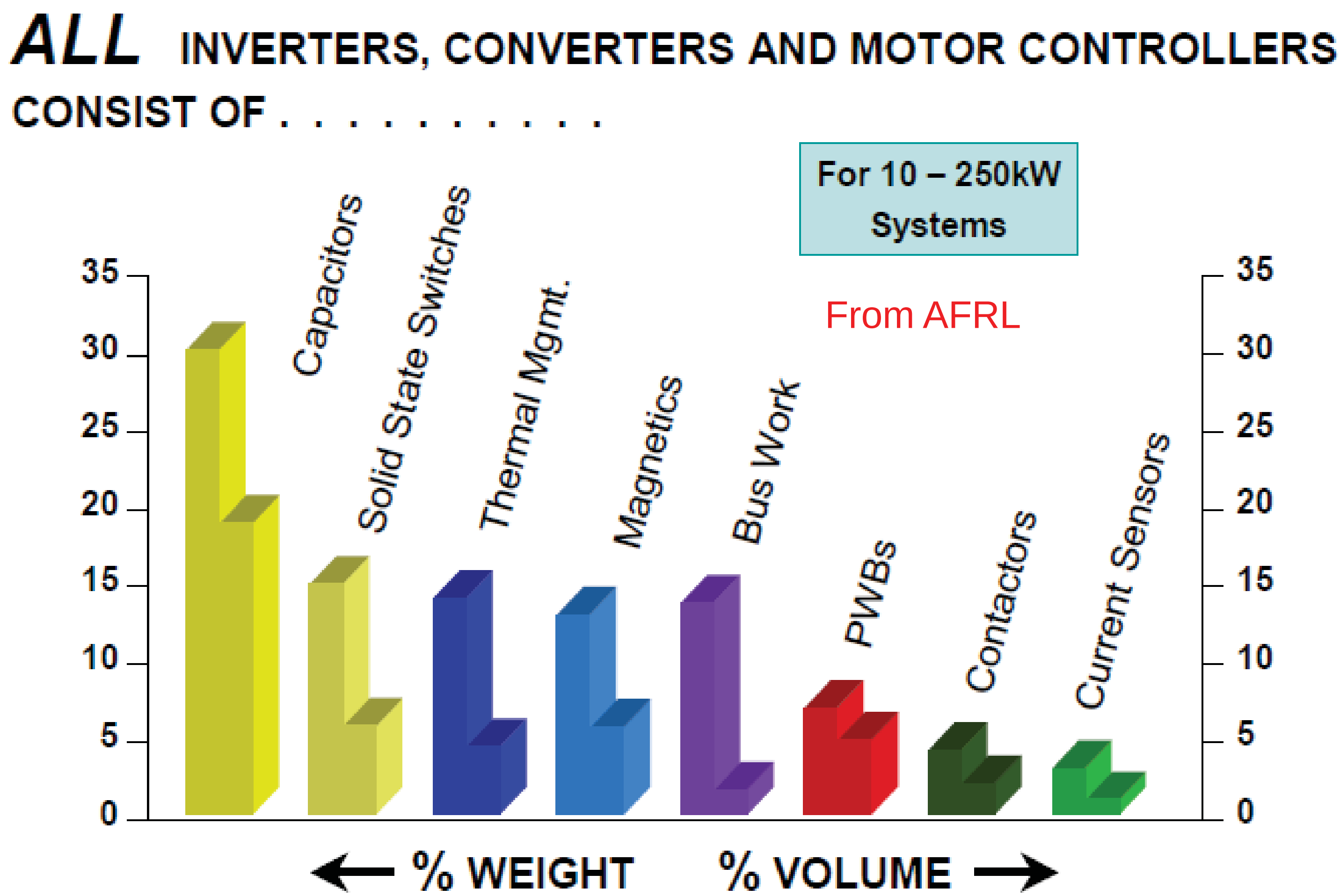




Need temperature capability beyond the current state-of-the-art (SOAA)



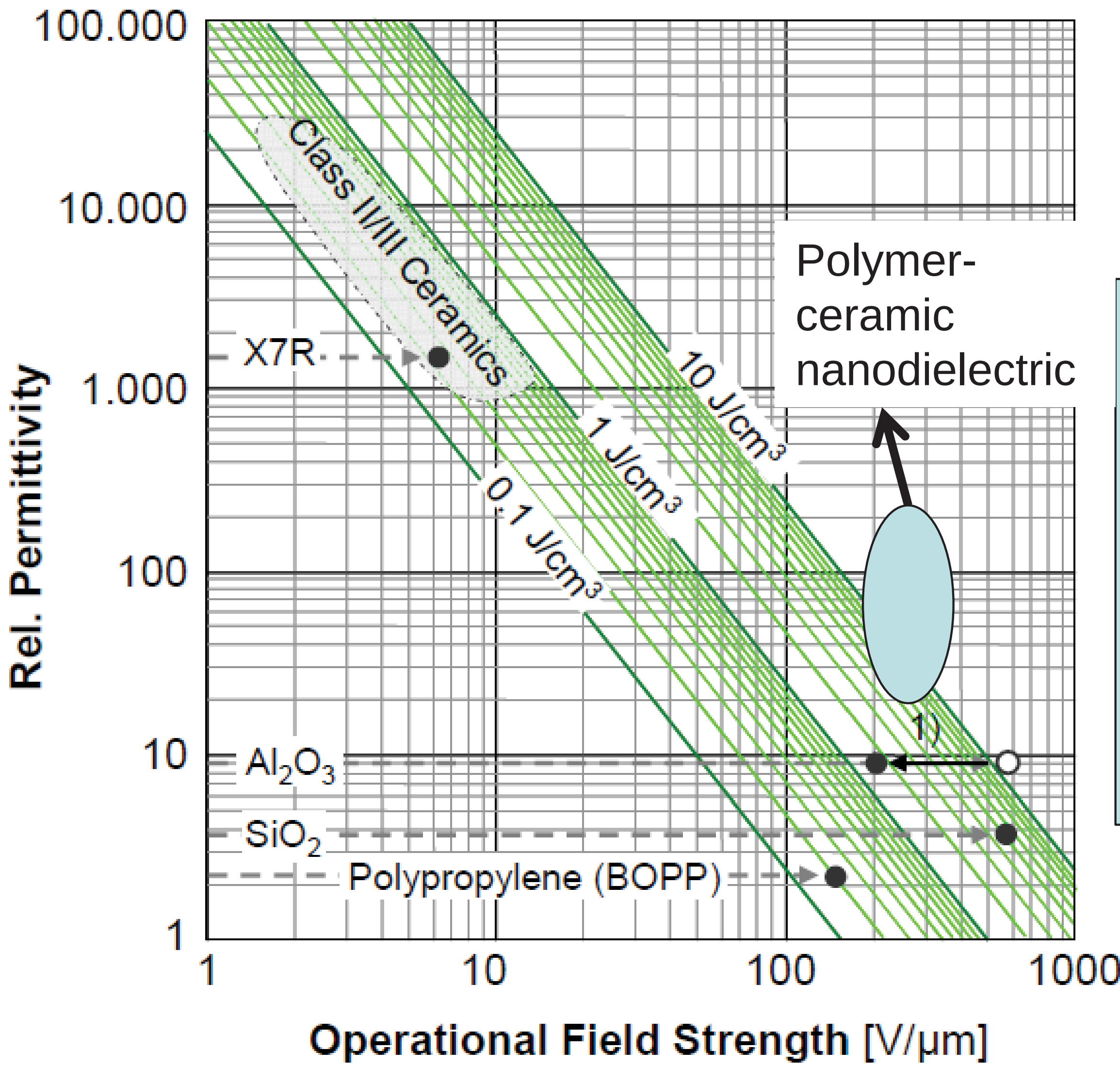

Defect-free SiC for large wafers is a technical challenge

# Capacitors for Power Electronics




Capacitors with higher energy density and higher temperature capability are required for increasing power density of power electronics

# Advanced Capacitors for High Power Density Power Electronics

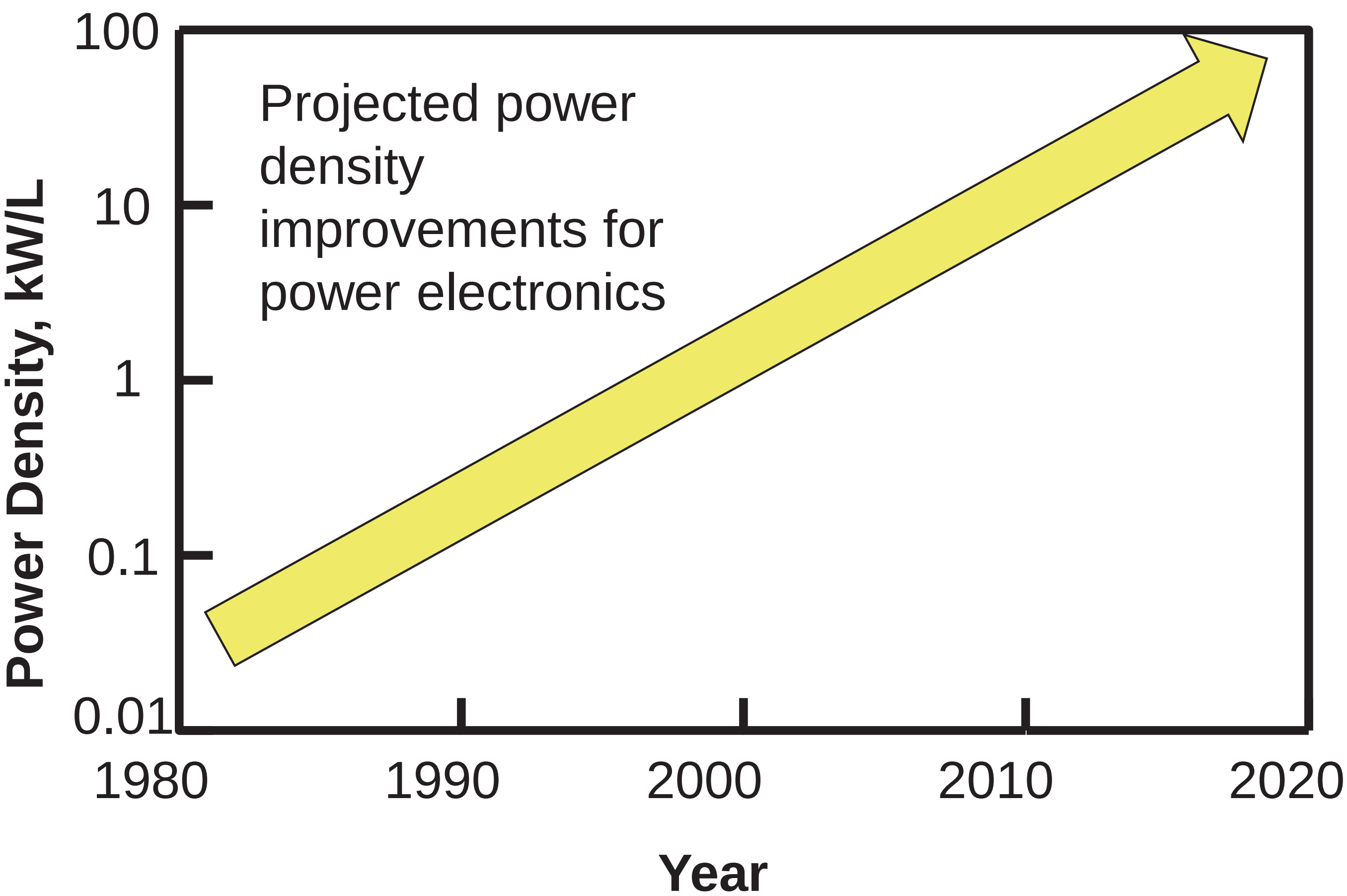


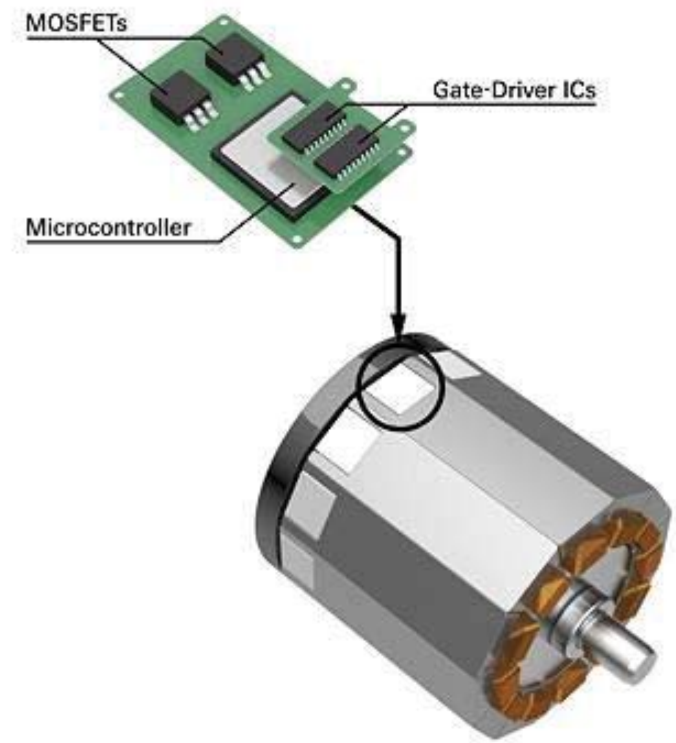

Ceramic capacitors with temperature capability beyond 200ºC, but have low breakdown strength

Challenge:

- Polymer-nanoceramic composite with energy storage capability greater than 20 $J/cm^3$
- High temperature ceramic capacitors with high breakdown strength

# Material Advances Critical for Increasing Power Density of Power Electronics



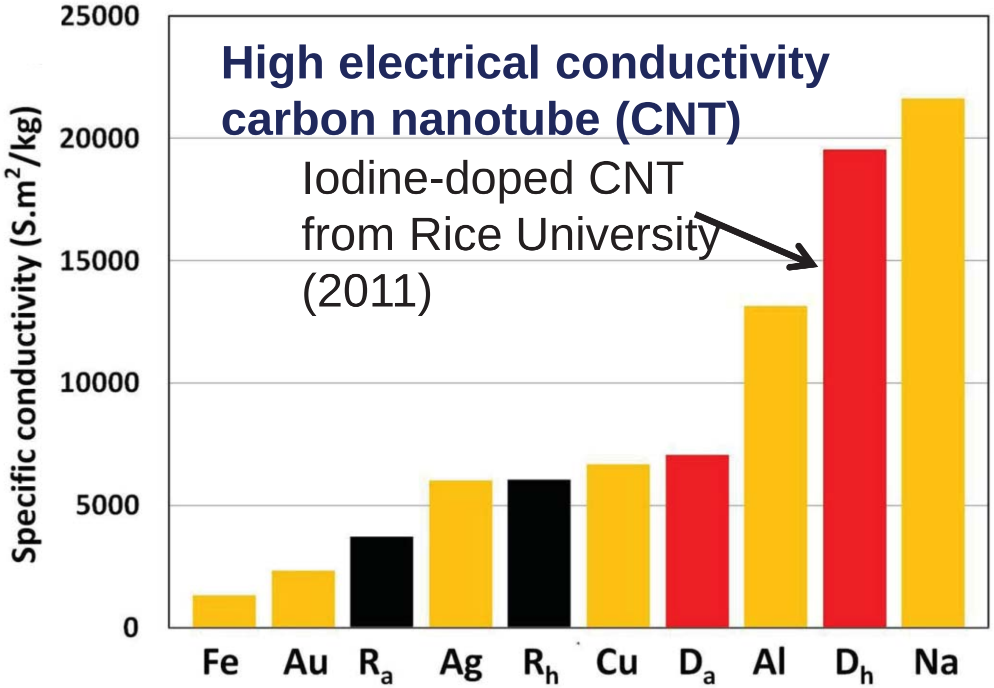




Higher temperature and compact power electronics will enable placement of power electronics on motor

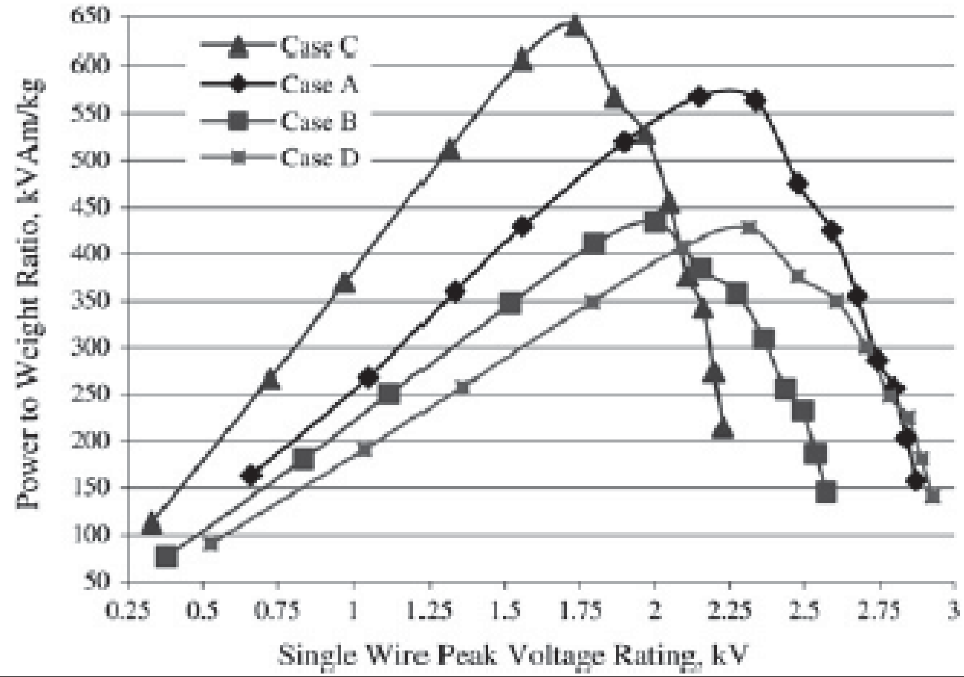
Materials advances (higher temperature SiC semiconductor, high temperature packaging, and higher temperature capacitor with high energy density) are critical for 10-fold increase in power density of power electronics

# Lightweight Power Transmission

- Electrical cables contribute to significant weight in commercial aircraft
  - 140 miles of Cu electrical wiring in Boeing 747 contributing to 3500 lb of wiring
- Transfer of MW of power in turboelectric and hybrid electric aircraft will require significantly large diameter of Cu cables, adding significant weight
- Lightweight power transmission system required




## High voltage transmission

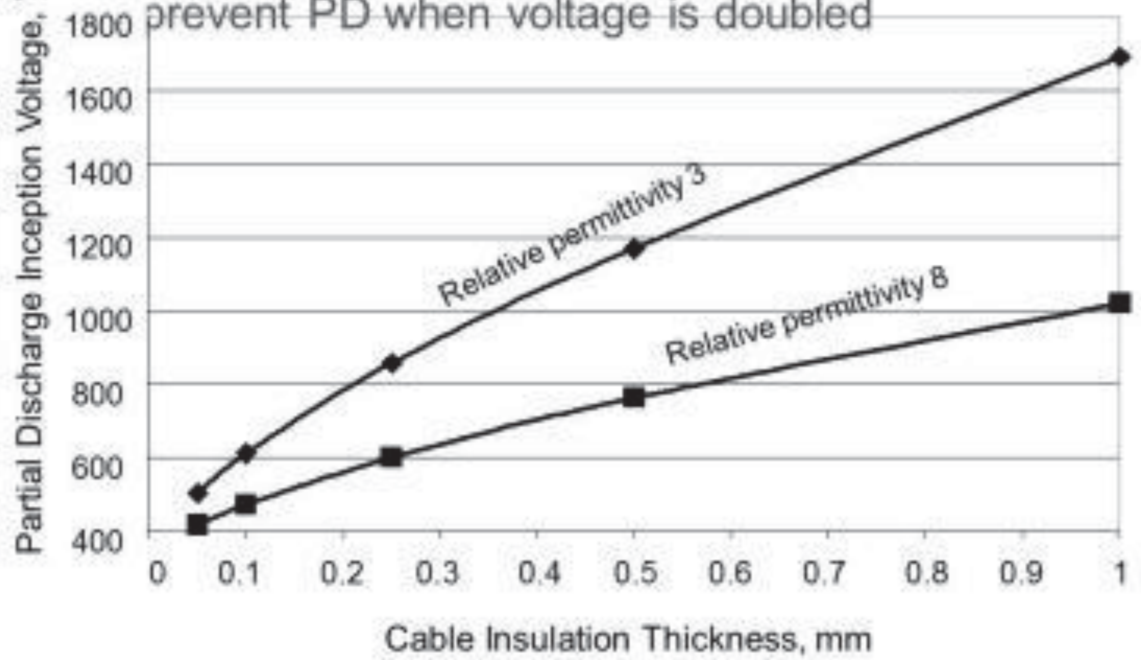



**Superconducting transmission lines between generators and motors**

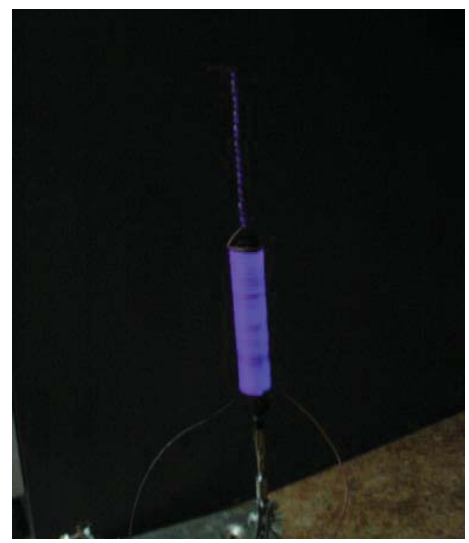
**Higher temperature electrical insulation with high thermal conductivity (enables more current to pass through wire, allowing for use of fewer wire)**

# Material Challenges with Higher Voltage Power Transmission

- Insulation thicknesses must more than double to prevent PD when voltage is doubled

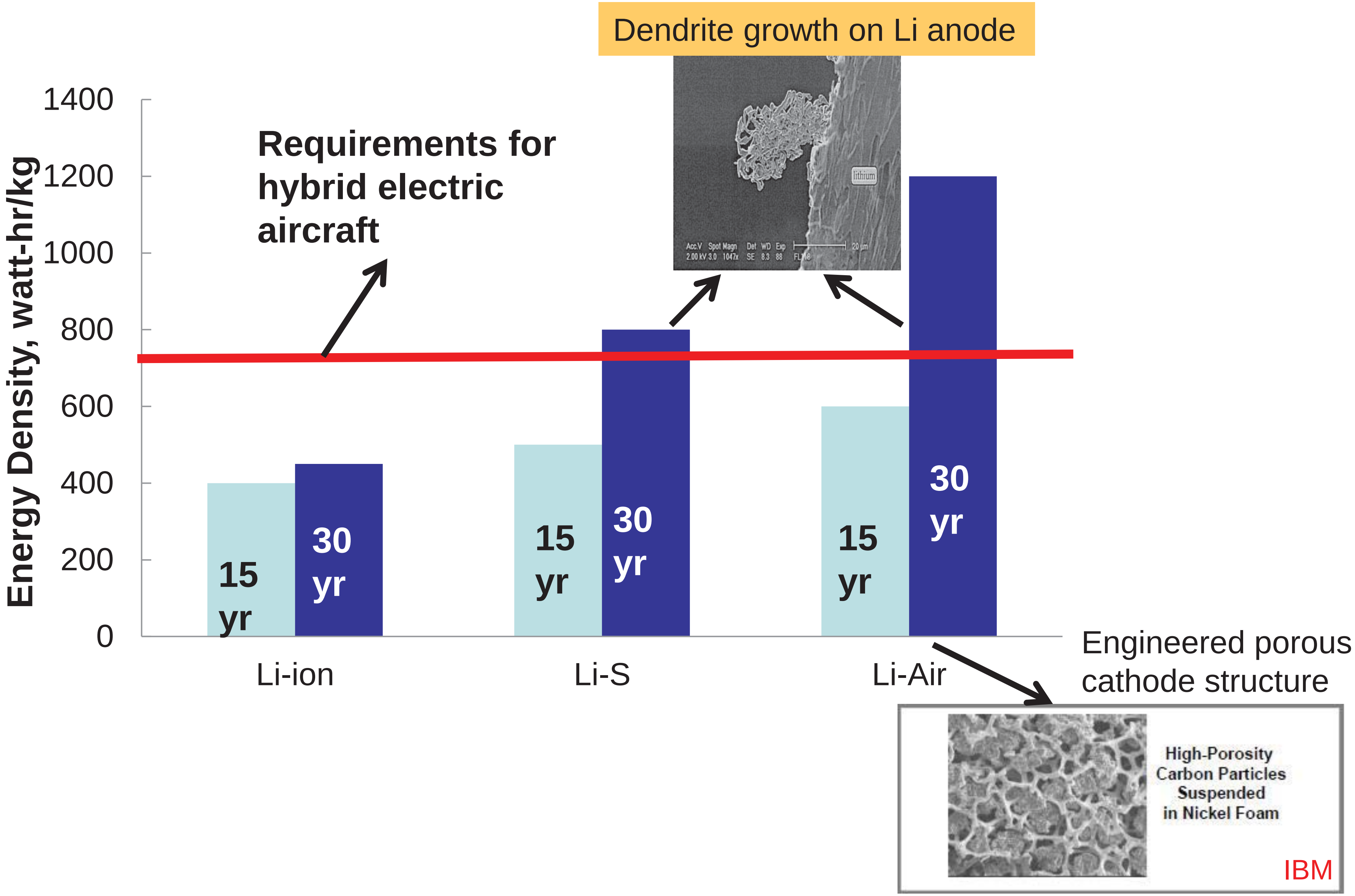



Corona discharge problem at high voltage



Require materials with high relative permittivity and high breakdown voltage

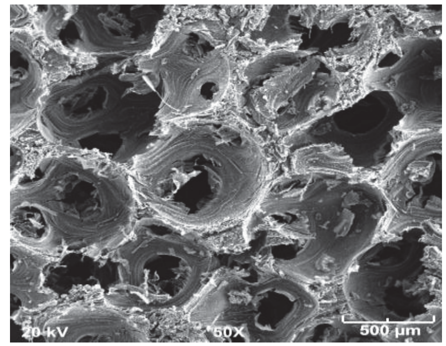
# High Energy Density Batteries Require Significant Advances in Materials



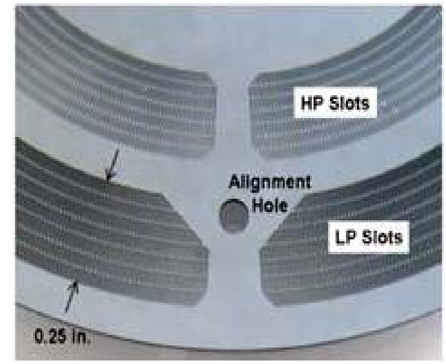
# Thermal Management Challenge

- 10 MW power system with 1% loss = 100 kW of heat to be rejected; 3 % loss = 300 kW of heat to be rejected
- Thermal management of each component – motors, power electronics, power transmission
- Integrated thermal management strategy required
- Lightweight thermal management system required

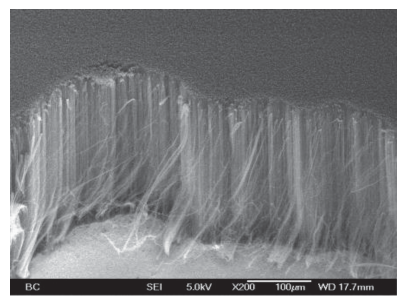
**Material advances critical for lightweight thermal management system**




Graphite foam heat exchanger




Lightweight recuperator materials for cryocooler

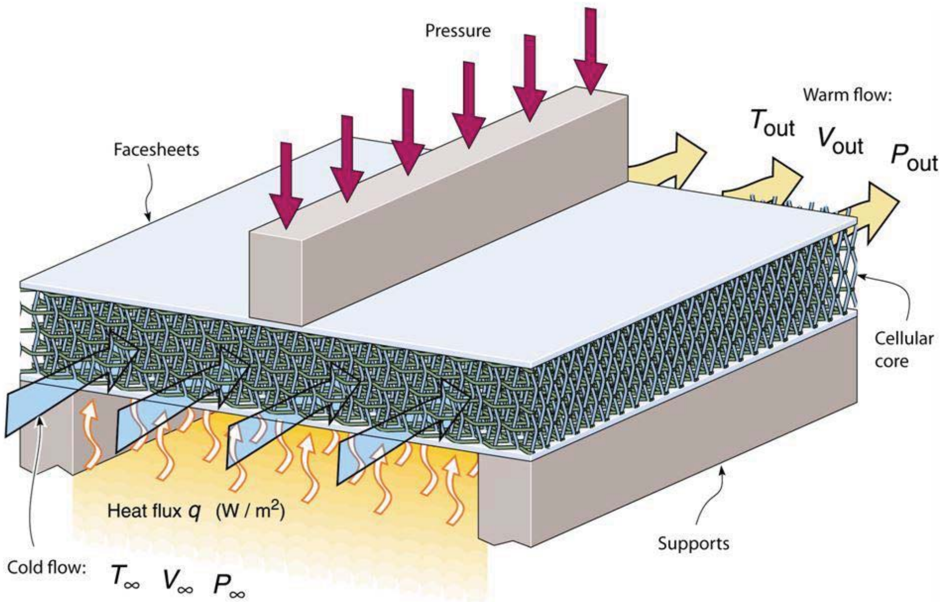



Aligned nanotube as thermal interface material

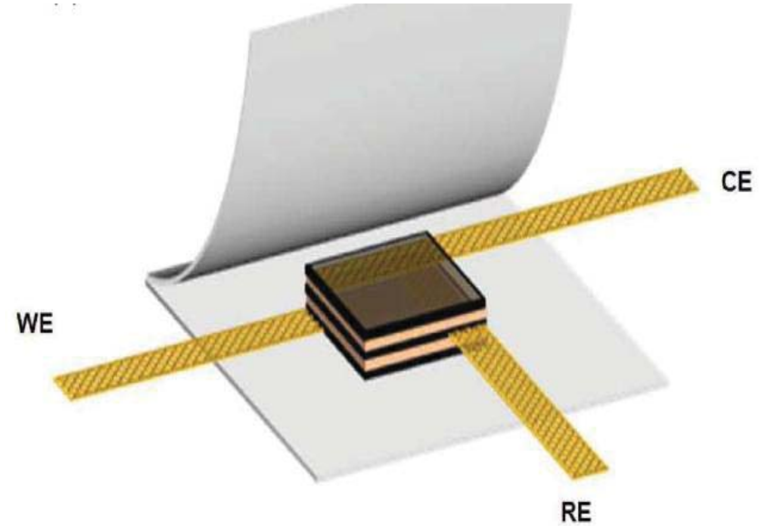
Flexible and mechanically strong aerogel insulation

# Multifunctional Structures Enabling for Reducing Weight of Commercial Electric Aircraft

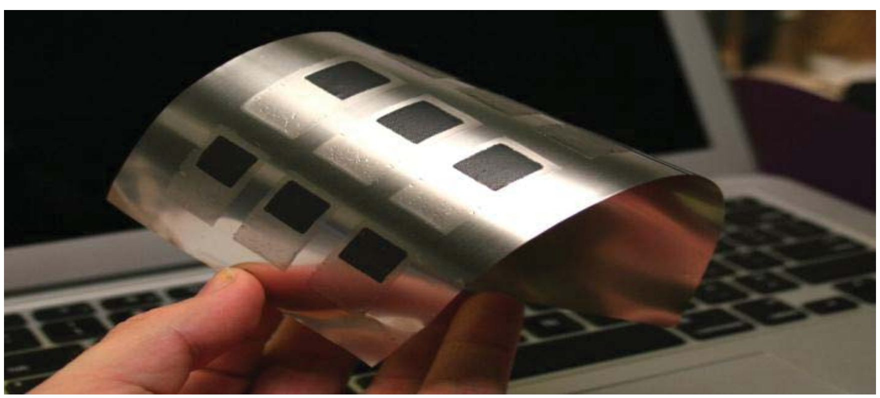
Multifunctional structure with load-bearing and thermal management capability



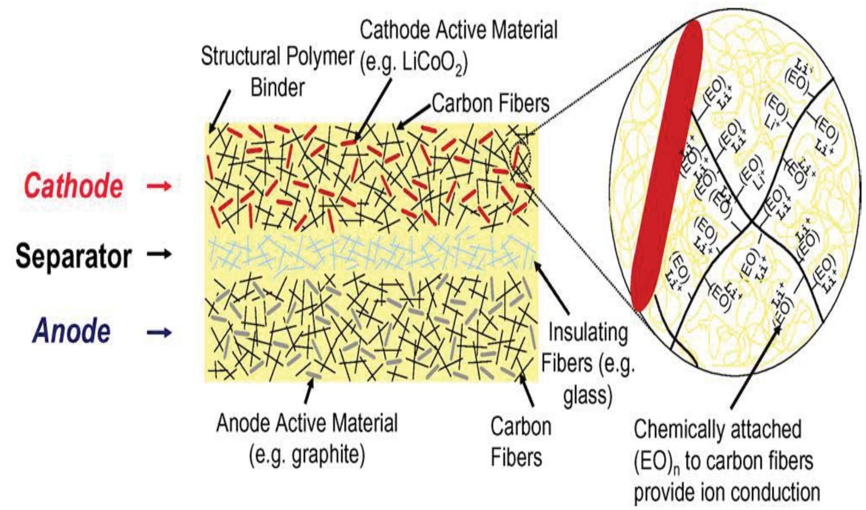

Batteries incorporated inside structure




Conformal thin film battery



Multifunctional battery with load-bearing capability



# Summary

**Material advances critical for future large commercial electric aircraft:**

- Materials with electrical conductivity higher than that of Cu
- High temperature electrical insulation materials with high relative permittivity and high breakdown voltage strength
- Magnets with high maximum energy product $(BH)_{max}$
- Higher temperature magnets
- Higher temperature power electronics semiconductor and packaging technology
- Materials to enable orders of magnitude increase in energy density and power density of energy storage system
- Lightweight thermal management materials
- Multifunctional materials

- 5X increase in power density of electrical motors
- 10X increase in power density of power electronics
- 10X reduction in weight of power transmission
- 10X reduction in weight of thermal management system