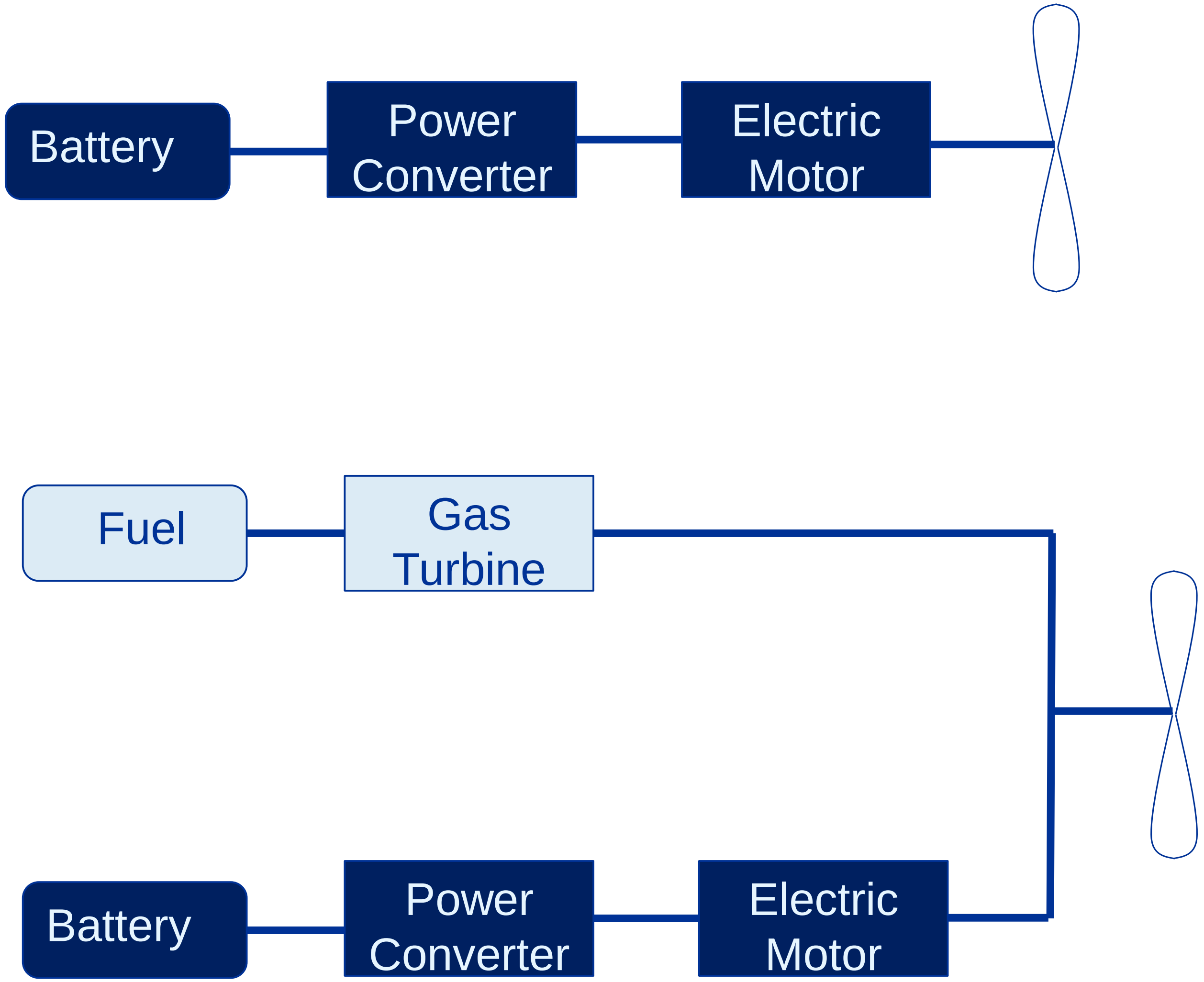
Evolution of Fundamental Technologies for Future Electrified Aircraft

Dr. Ajay Misra
Deputy Director, Research and Engineering
NASA Glenn Research Center

Electric and Hybrid Aerospace Technology Symposium, Cologne, Germany, November 16 - 17

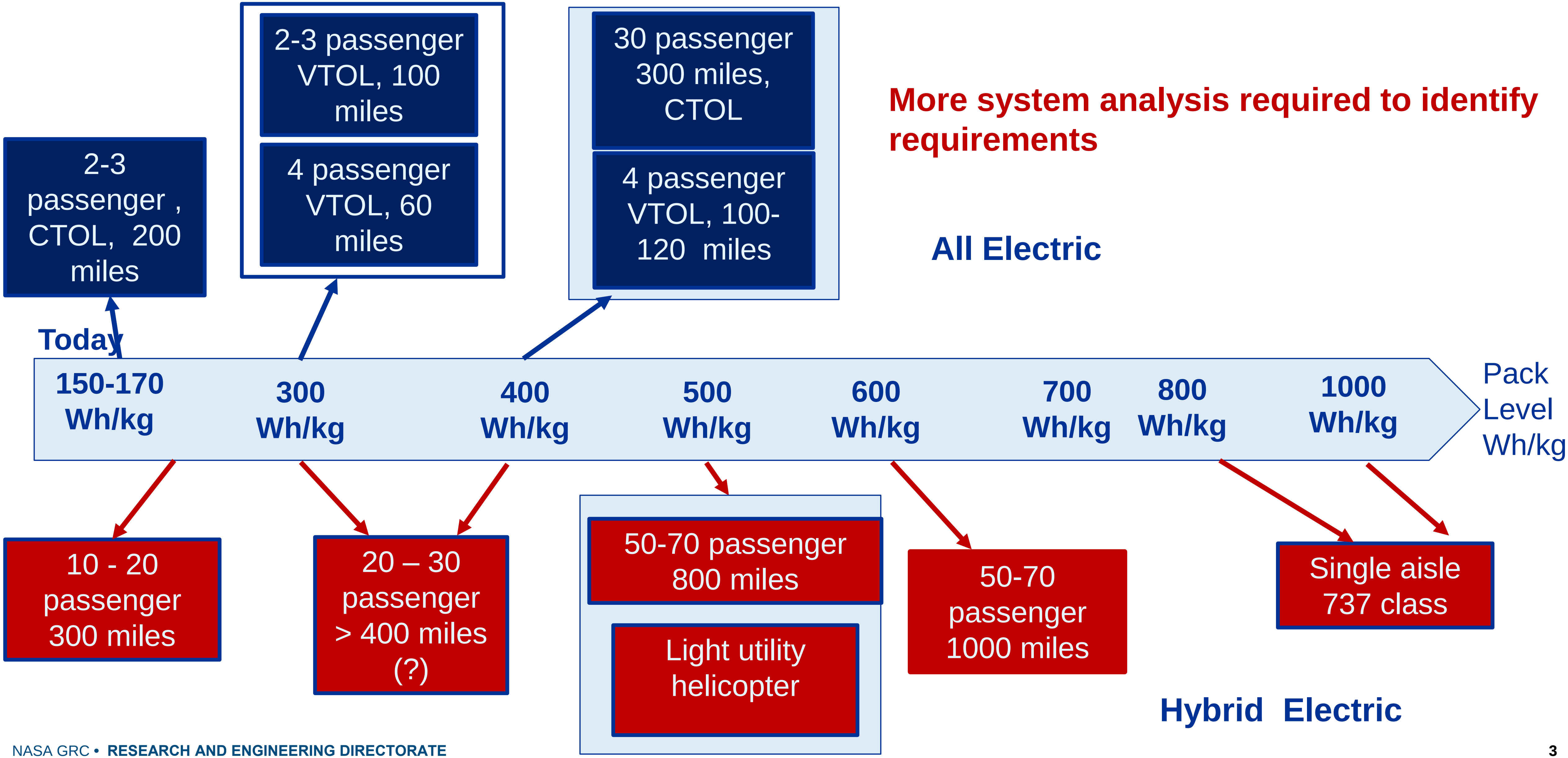
Electrical Component Technologies for Electrified Aircraft



Key Technologies:

- Battery with 3-5X increase in specific energy
- Electric motor with 3-5X increase in power density
- Power converter with 3-5X increase in power density

Battery Requirement for Electrified Aircraft (Notional)



2-3 passenger VTOL, 100 miles

4 passenger VTOL, 60 miles

30 passenger 300 miles, CTOL

4 passenger VTOL, 100-120 miles

More system analysis required to identify requirements

2-3 passenger , CTOL, 200 miles

All Electric

Today

150-170 Wh/kg

300 Wh/kg

400 Wh/kg

500 Wh/kg

600 Wh/kg

700 Wh/kg

800 Wh/kg

1000 Wh/kg

Pack Level Wh/kg

10 - 20 passenger 300 miles

20 – 30 passenger > 400 miles (?)

50-70 passenger 800 miles

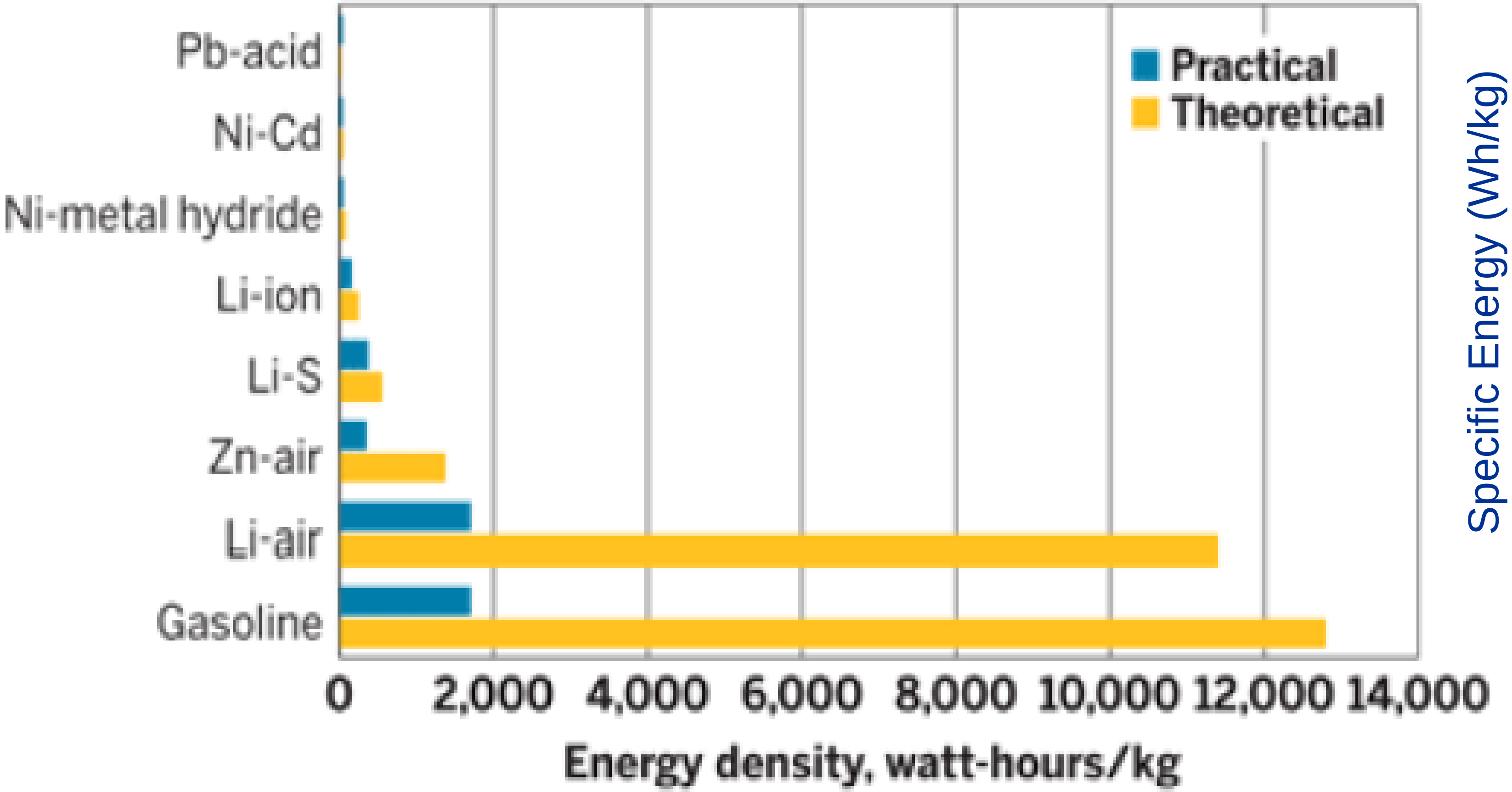
Light utility helicopter

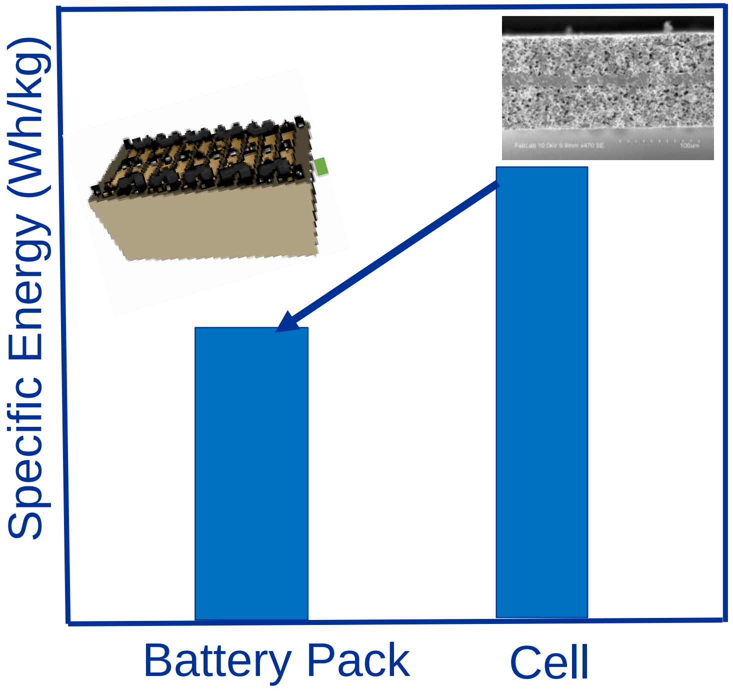
50-70 passenger 1000 miles

Single aisle 737 class

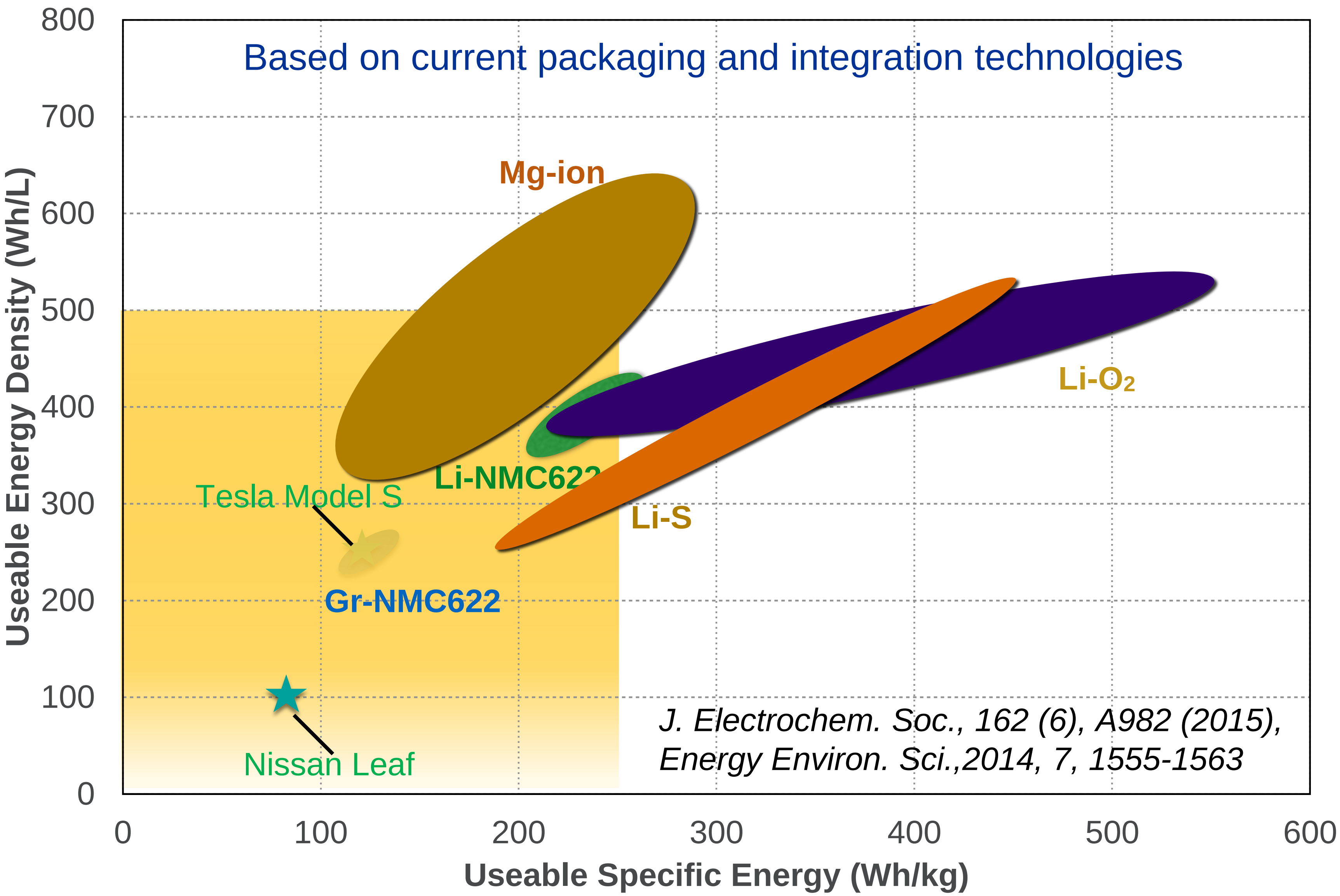
Hybrid Electric

Battery Chemistry Possibilities



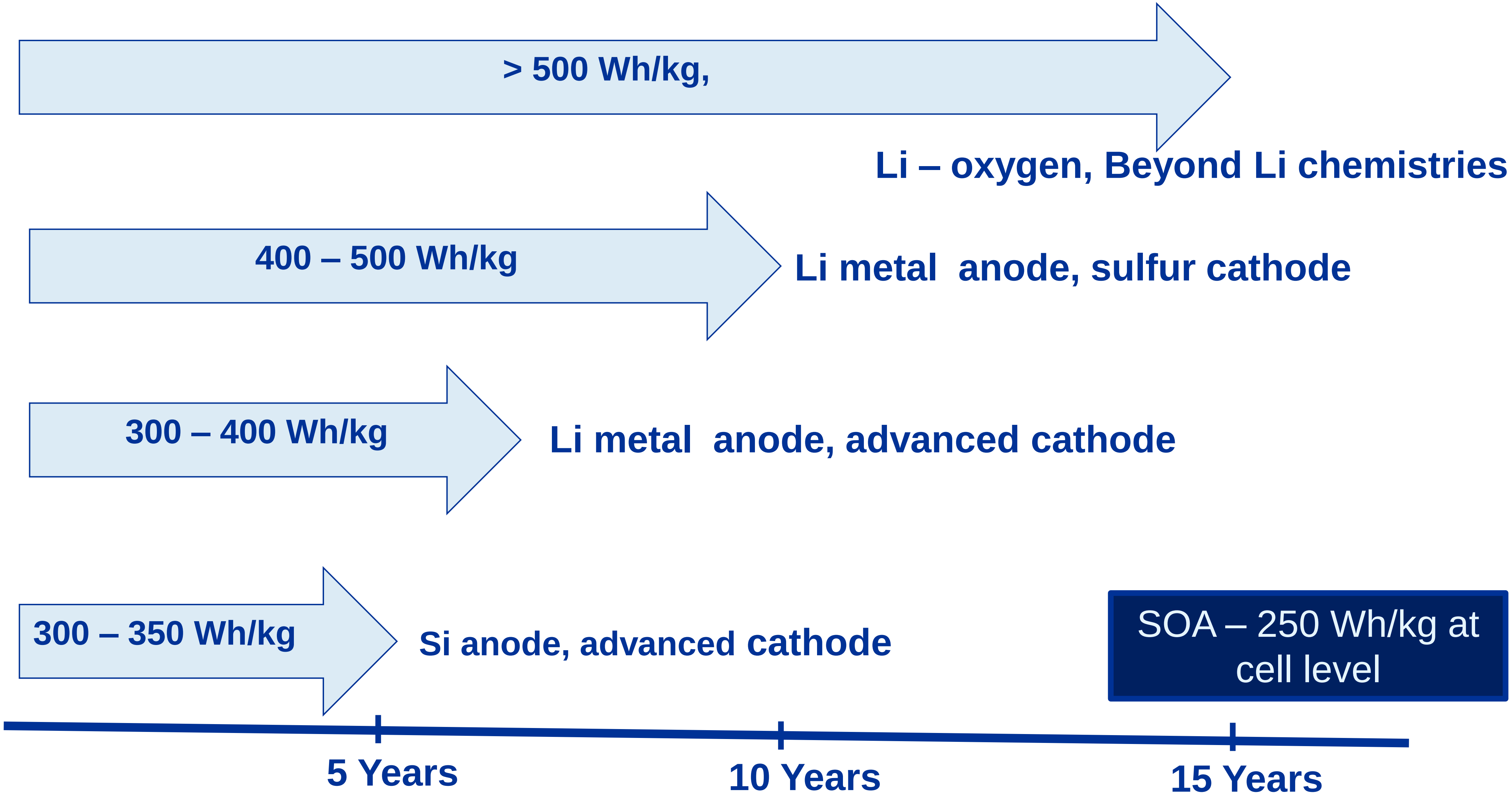


Limits on Useable Specific Energy



J. Electrochem. Soc., 162 (6), A982 (2015), Energy Environ. Sci.,2014, 7, 1555-1563

Notional Progression of Battery Capability at Cell Level



> 500 Wh/kg,

Li – oxygen, Beyond Li chemistries

400 – 500 Wh/kg

Li metal anode, sulfur cathode

300 – 400 Wh/kg

Li metal anode, advanced cathode

300 – 350 Wh/kg

Si anode, advanced cathode

SOA – 250 Wh/kg at cell level

5 Years

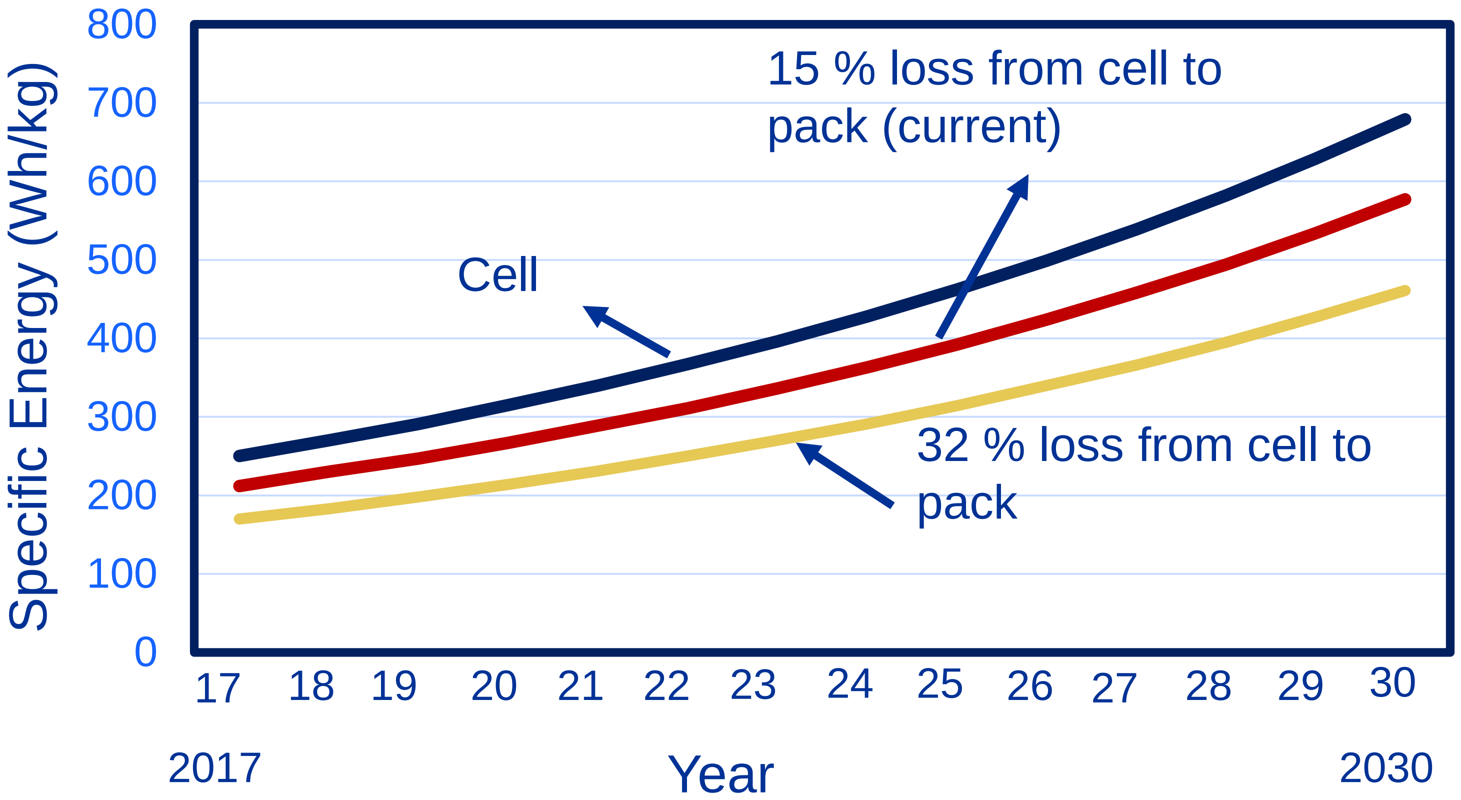
10 Years

15 Years

Projected Advances in Battery Technology

Rate of increase in specific energy is typically on the order of 5 – 8% per year
Specific energy loss from cell to pack is typically 50 to 60%

Assuming 8% increase per year at cell level



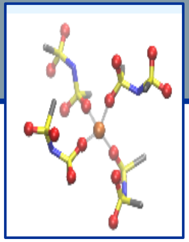
Innovation required in:

- New chemistries and materials for cells
- Pack design and integration

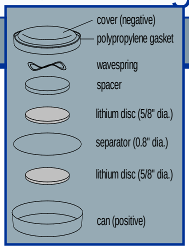
Interdisciplinary Approach for Li – Air Battery Development

NASA Team

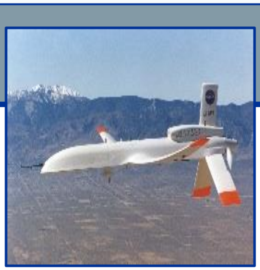
ARC Team
Atomic Simulations, Computational Chemistry, Multiphysics Modeling



GRC Team
Development of materials for cathode and electrolyte, Experimental Characterization, Battery Pack Design

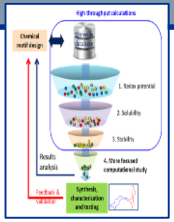


AFRC
Electric Aircraft Requirements, Electric UAV Demo

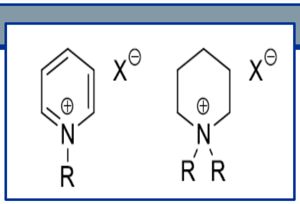


External Partners

CMU
Computational Chemistry Screening



IBM Almaden
Fundamental Chemistry Synthetic Chemistry



UC Berkeley/LBNL
Characterization Methods

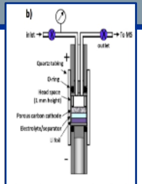
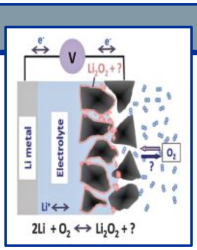
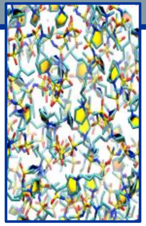


Figure 8: A custom-built differential electrochemical mass spectrometer cell. From McCloskey *et al.*, *J. Phys. Chem C*, 2012.

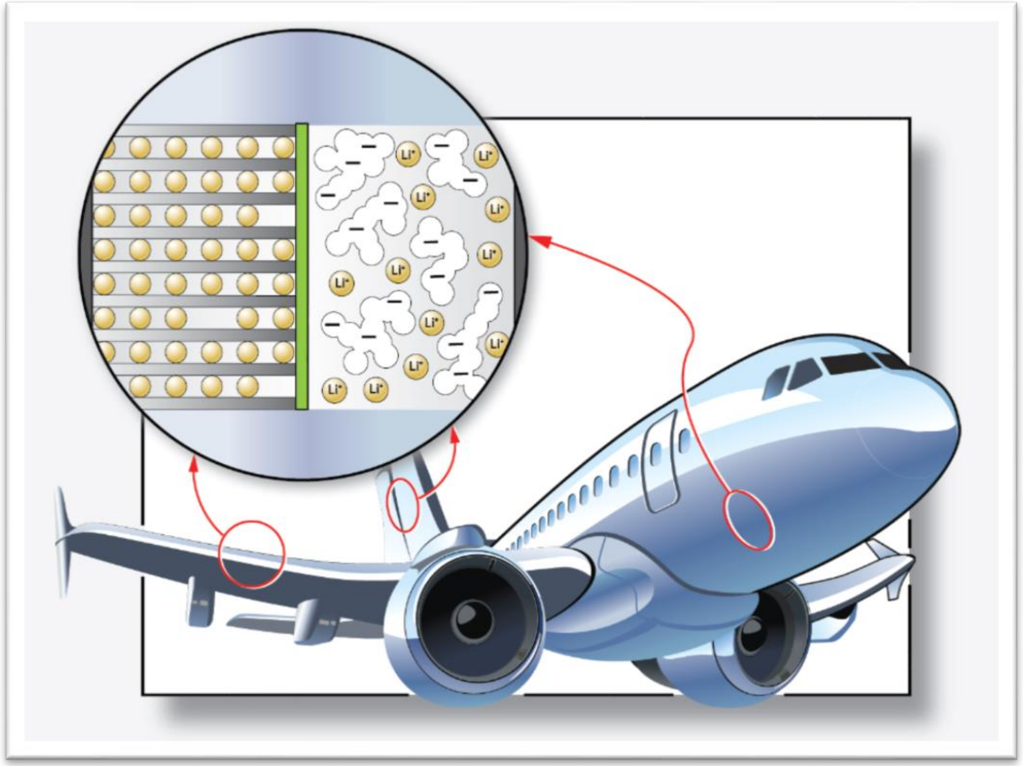
Stanford/SLAC
Adv. Characterization

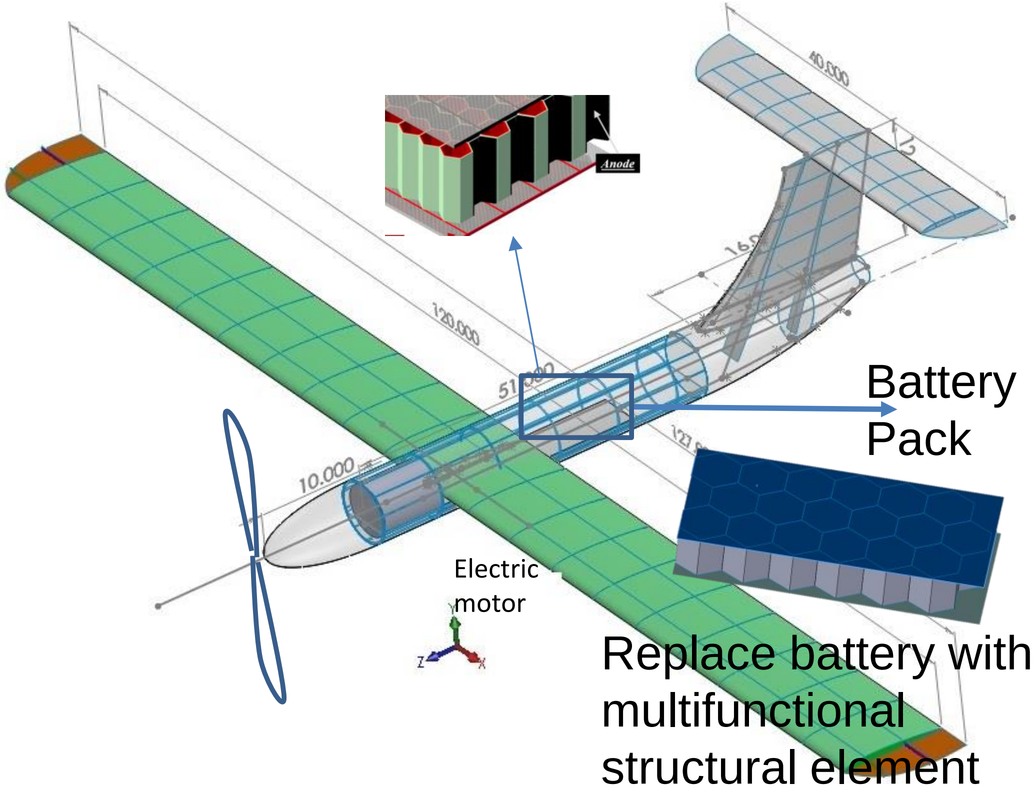


ARL
Atomistic Simulations



Multifunctional Structures With Energy Storage Capability





Battery Pack

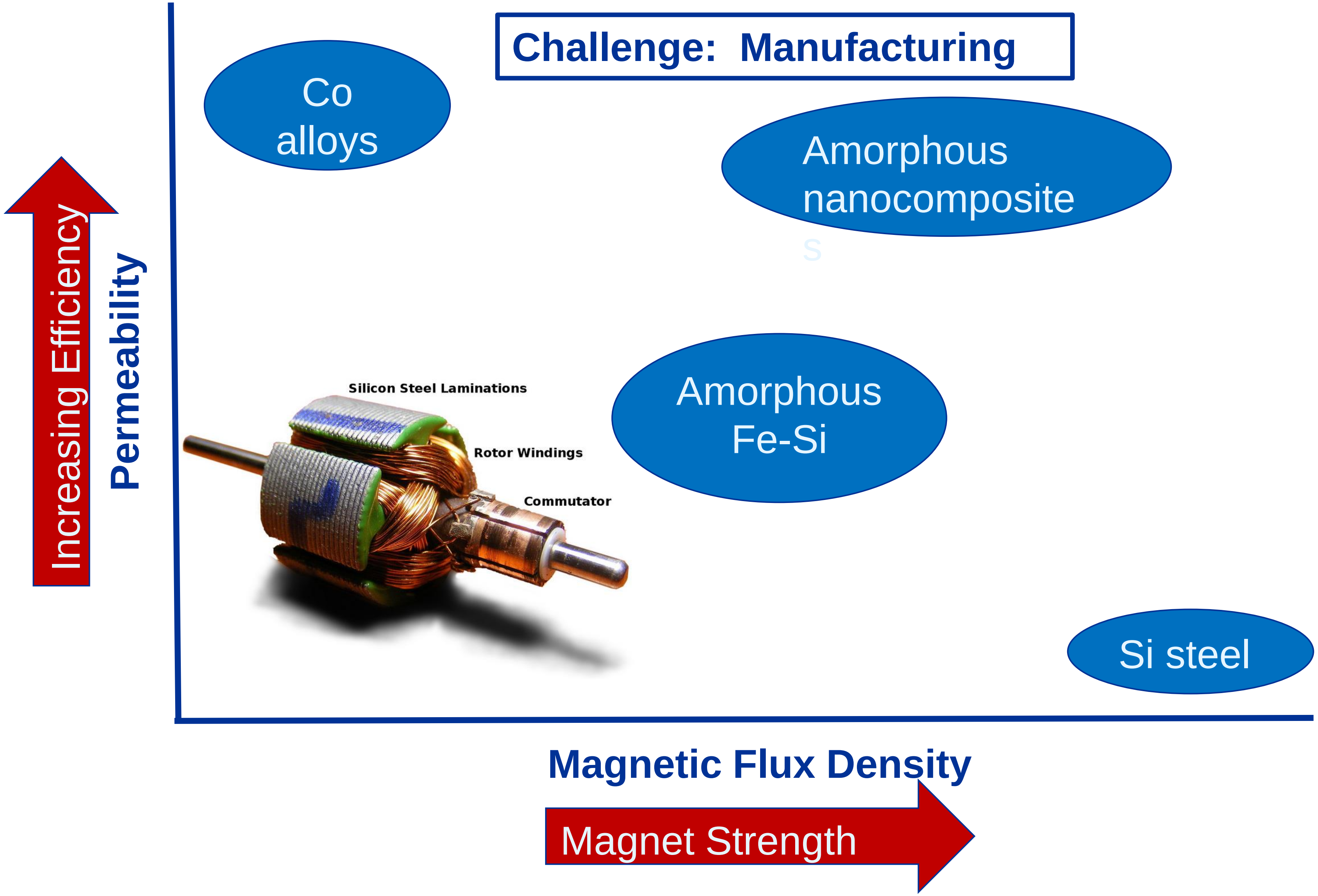
Replace battery with multifunctional structural element

Batteries with some load bearing capability or structure with energy storage capability ????

Technology Options for Increasing Power Density of Non-Cryogenic Electric Motors

- **High conductivity materials (better than Cu)**
- **Insulation materials with higher thermal conductivity**
- **Better magnetic core materials (high permeability and high magnetic strength)**
- **Higher slot fill at windings**
- **Advanced thermal management**
- **Lightweight structures**
- **Higher speed**
- **New topologies based on advanced materials**

Amorphous and Nanocomposite Magnets



Challenge: Manufacturing

Co alloys

Amorphous nanocomposites

Amorphous Fe-Si

Si steel

Increasing Efficiency

Permeability

Magnetic Flux Density

Magnet Strength

Amorphous and Nanocomposite Magnets:

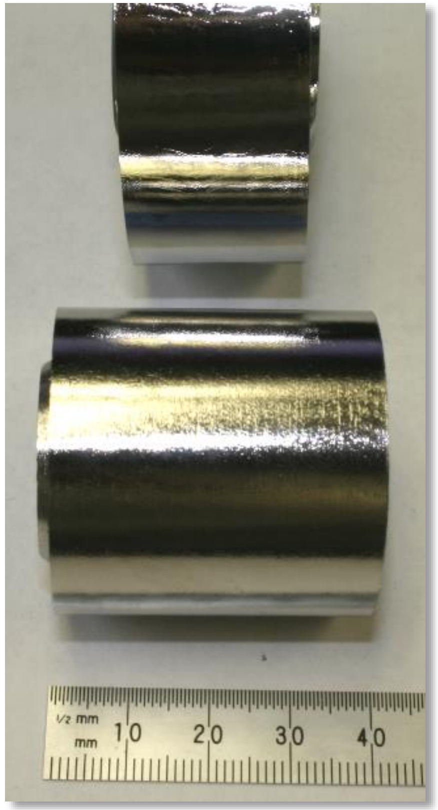
- **Reduction in core losses – higher frequency operation**
- **Higher rotational speeds**
- **Smaller and lighter motors for the same amount of power**

Fabrication Process Development at NASA GRC for Amorphous Magnetic Materials

Spin Caster

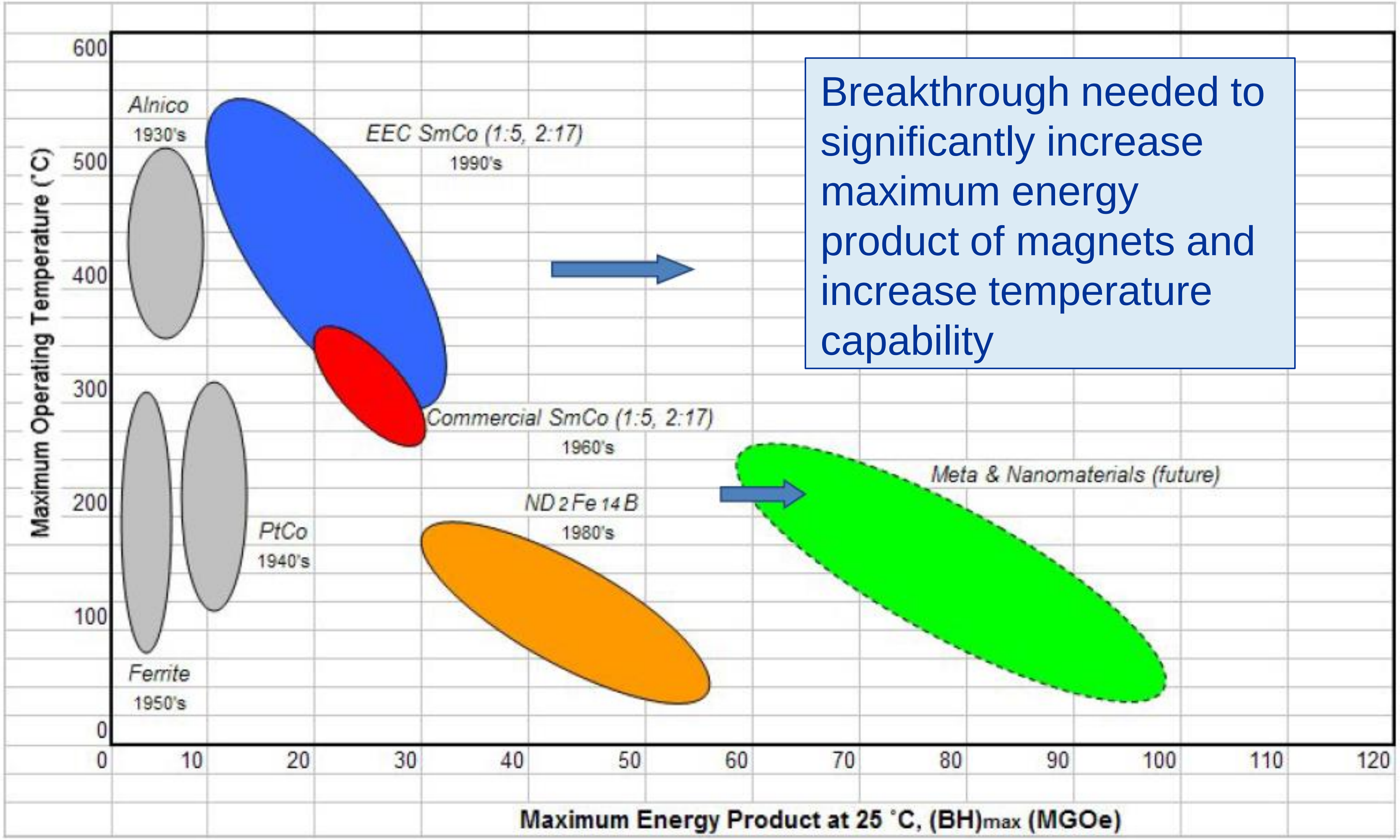
Casting Co alloy

(b) A 25-mm by 1.6-km spin cast ribbon



25 mm by 1.6 km Spin Cast Ribbon

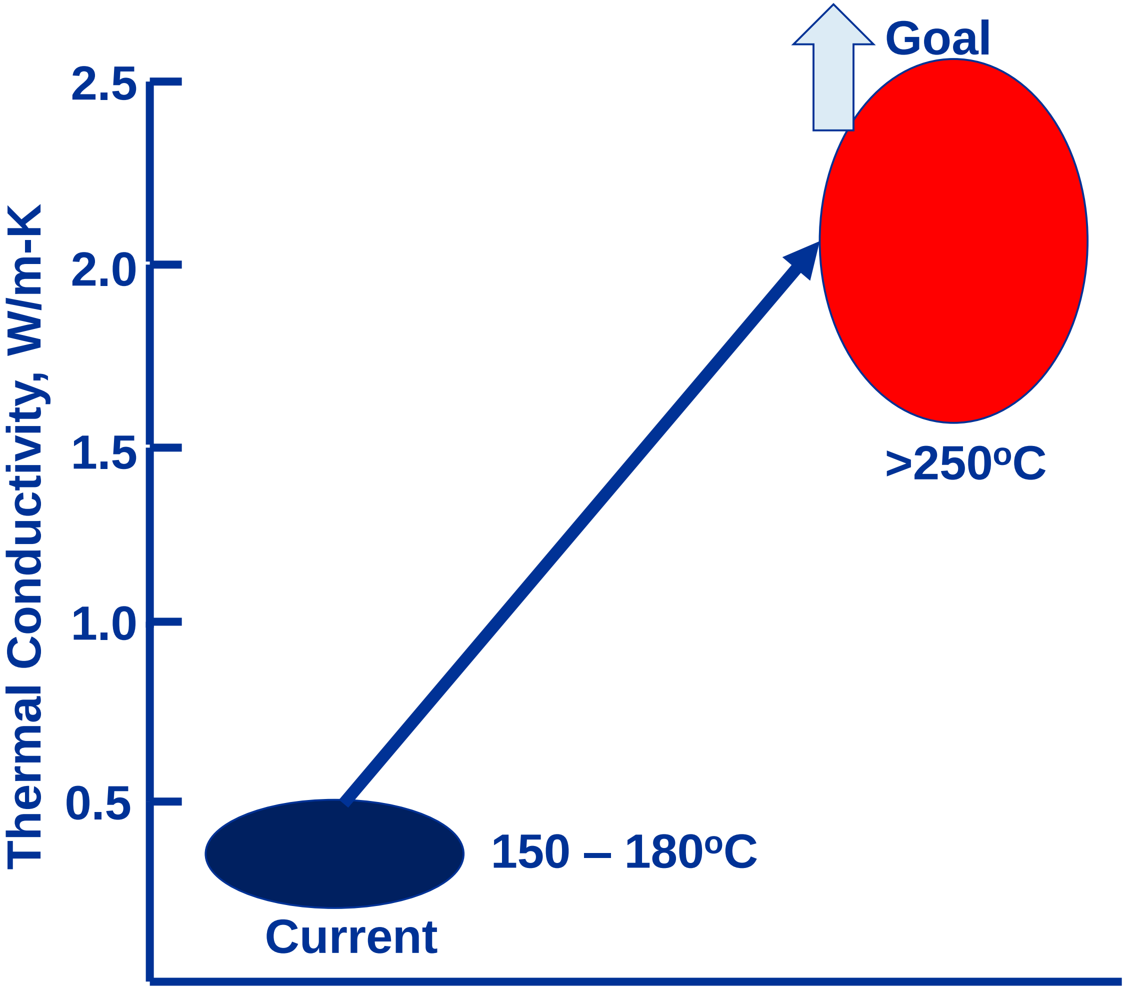
Advanced Permanent Magnets



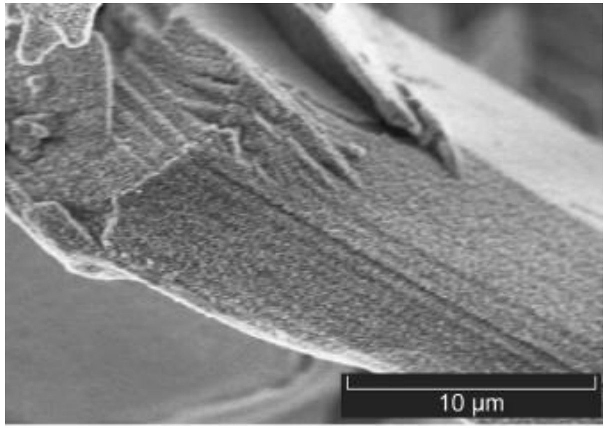
Breakthrough needed to significantly increase maximum energy product of magnets and increase temperature capability

Need computational design of new materials and development of advanced fabrication techniques for nanocomposites

Advanced Insulation System



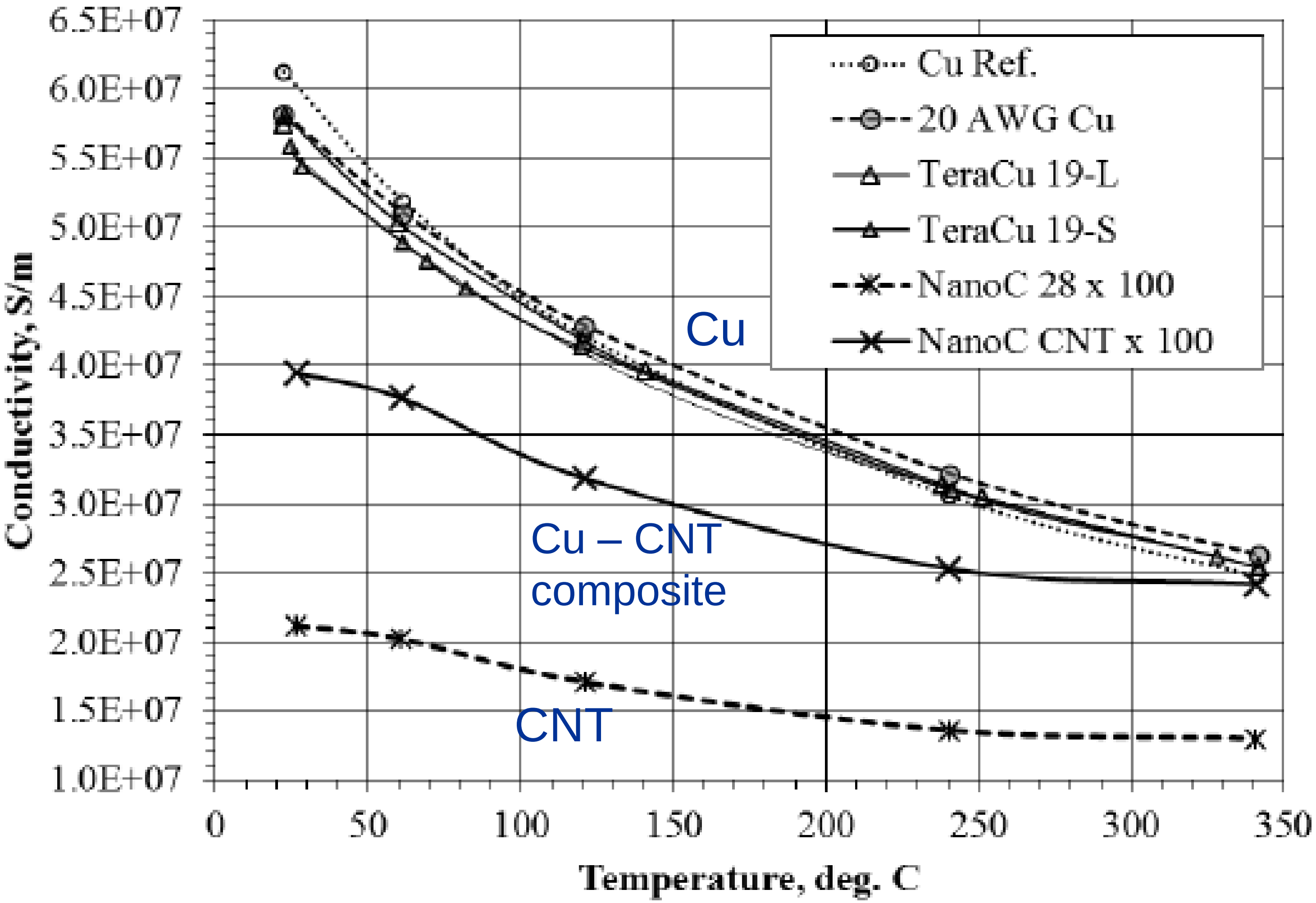
- Combination of low thermal conductivity of insulation and temperature constraints current that can be drawn through conductors
- Thin film insulation with higher thermal conductivity and temperature capability would increase fill factor in slot – more conductor in same space
- High voltage capability for insulation system



Polymer – boron nitride nanotube (BNNT) composite development

BNNT – Electrically insulating, high thermal conductivity

Potential for Carbon Nanotube Conductors



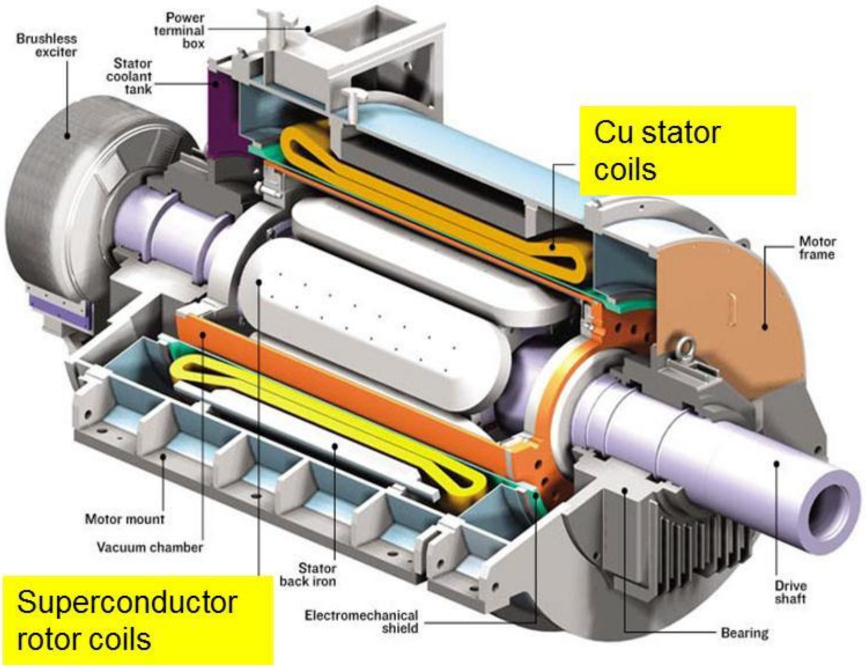
Cu

Cu – CNT composite

CNT

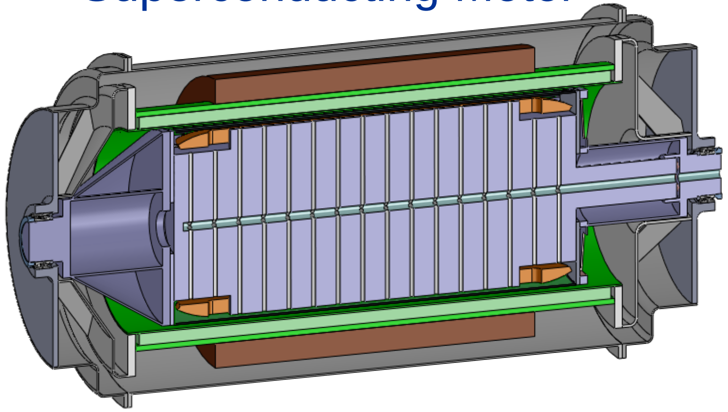
Theoretical electrical conductivity of Carbon nanotube (CNT) higher than Cu, but significant processing challenges remain to separate non-metallic from metallic

Superconducting Motor



- 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

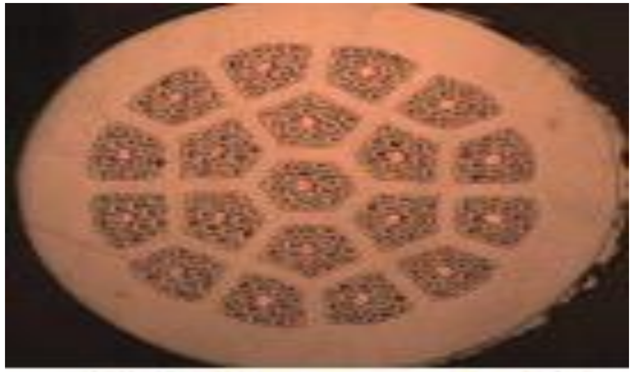
Design of Fully Superconducting Motor



CROSS SECTION OF FULLY SUPERCONDUCTING MACHINE

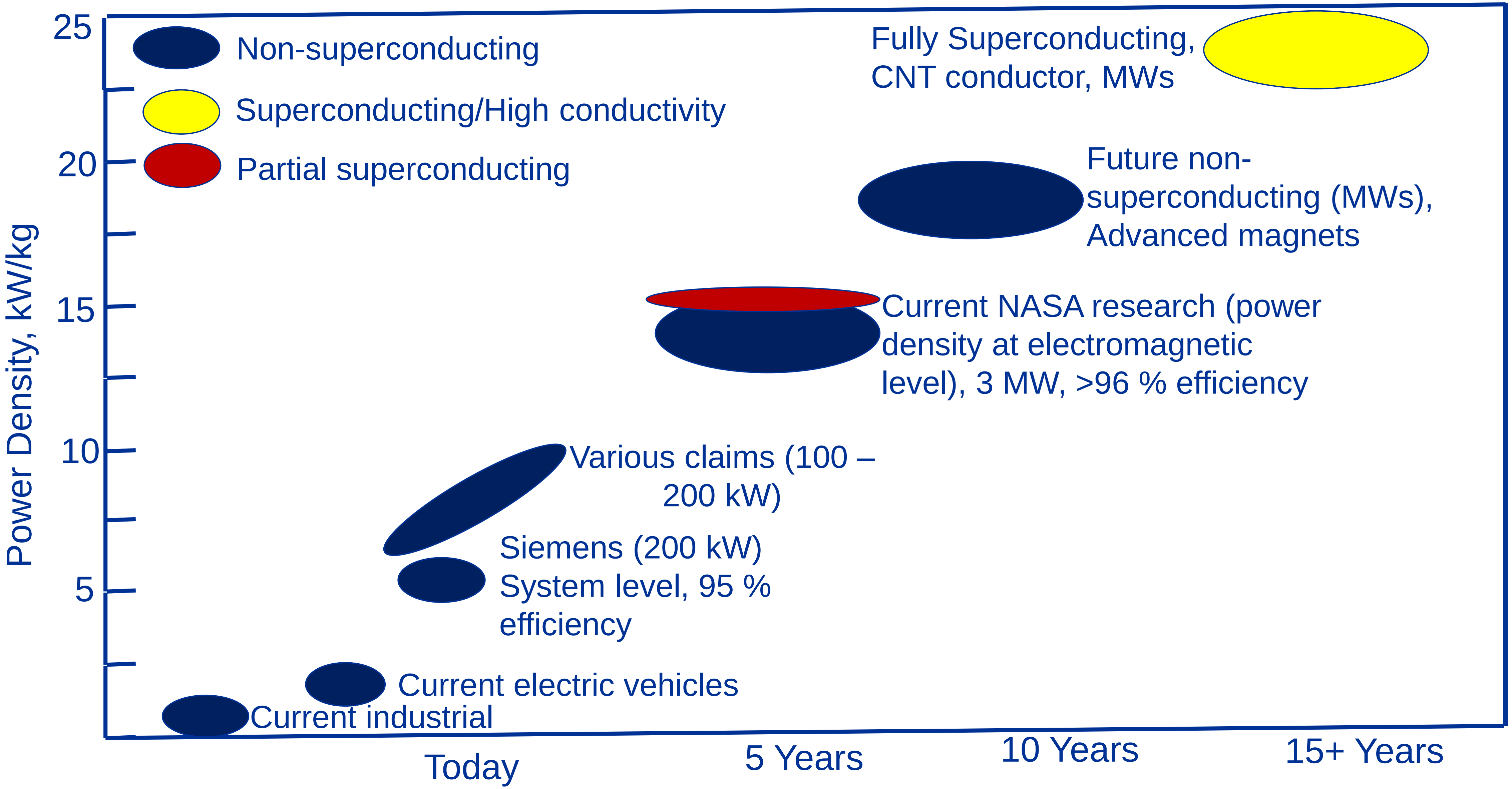
Small diameter superconducting filament development to reduce ac losses

MgB_2 superconducting composite wire: 216 20μm filaments

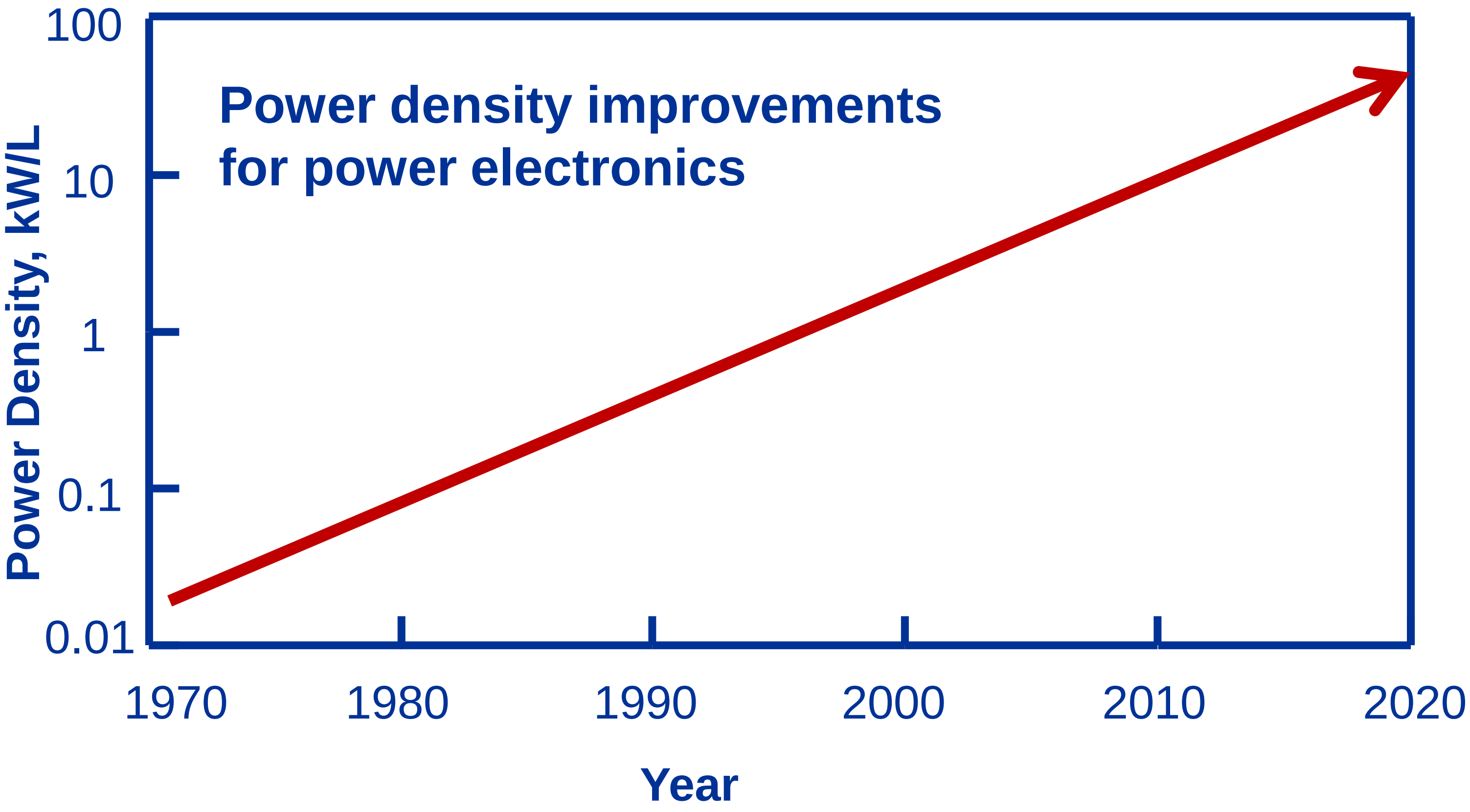


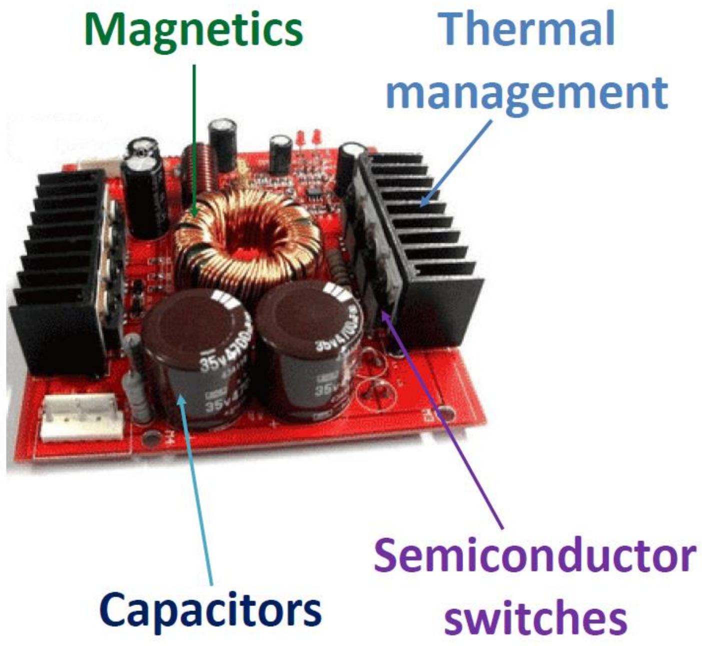
342 filaments @ 0.84 mm diam.

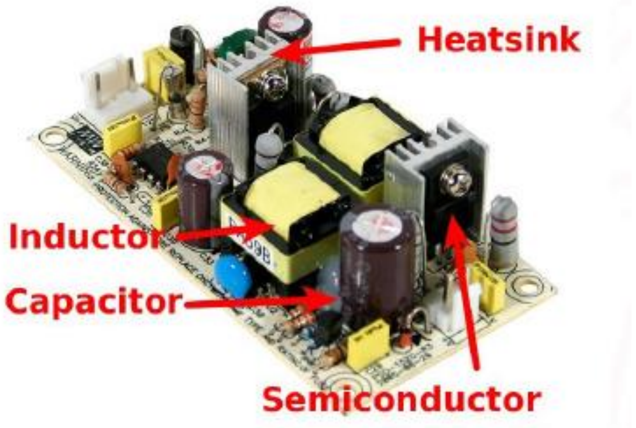
Notional Timeline for Increase in Motor Power Density



High Power Density Power Converters







Wide bandgap semiconductor (SiC and GaN) devices enable:

- Higher frequency operation (on the order of MHz) that reduces energy storage requirements for passives (inductors and capacitors)
- Smaller passives – reduced volume and weight
- Higher temperature operation – better thermal management

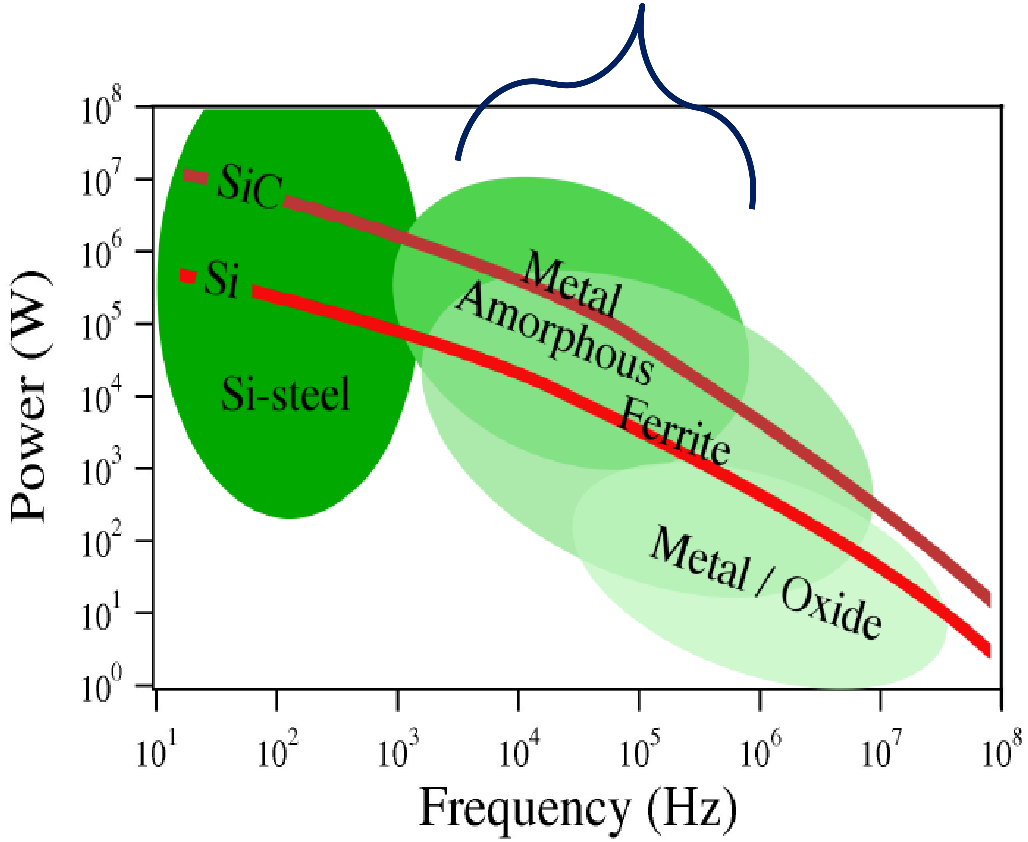
Current NASA-Funded Research on High Power Density Power Converters

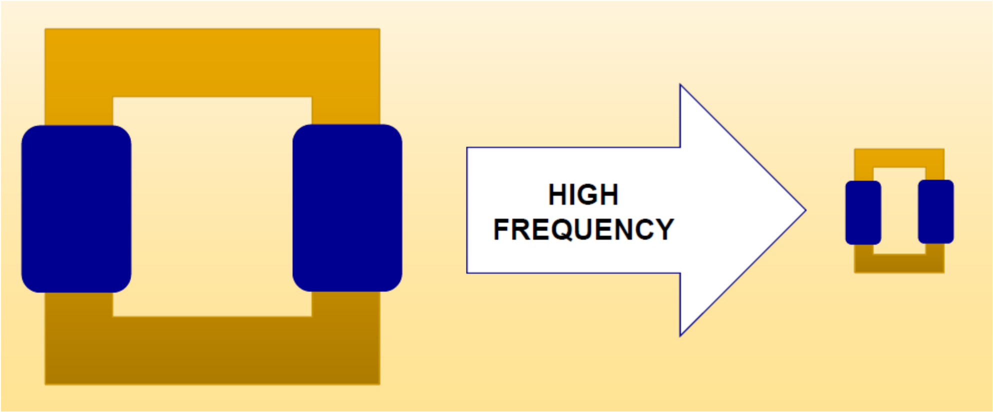
	Continuous power rating, MW	Specific power goal, kW/kg	Efficiency goal, %	Topology	Switch material	Cooling
General Electric	1	19	99	3 level	SiC/Si	Liquid
University of Illinois	0.2	19	99	7 level	GaN	Liquid
Boeing	1	26	99.3		Si	Cryogenic

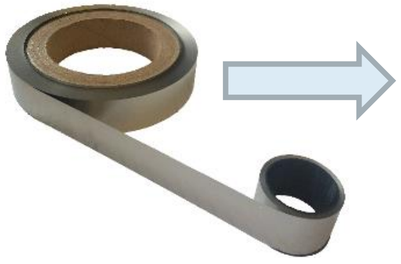

GE – 1 MW Inverter


University of Illinois – 200 kW Inverter

Development of Amorphous Magnetic Materials for High Frequency Inductors and Transformers







Cast ribbon

Strain annealing

Coated transformer core

Enablers for Increasing Power Density of Power Converters Based on Wide Bandgap Devices

- High temperature packaging technology for SiC-based devices – durability at high temperature is key

- Higher switching frequency enabled by wide bandgap semiconductor devices (SiC and GaN) - reducing the size of passives (inductors, transformers, and capacitors)

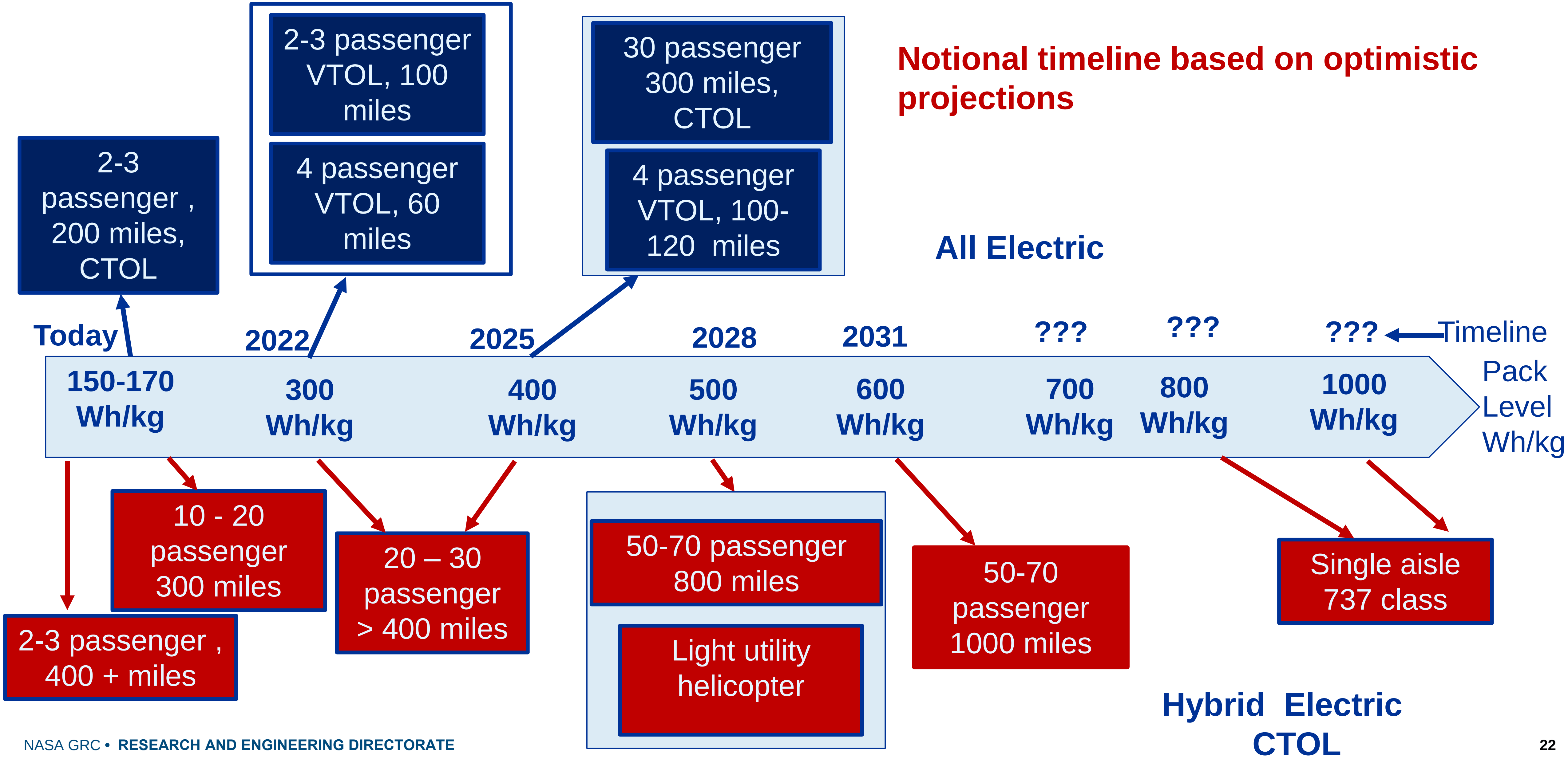
- Advanced magnetic materials with capability for high frequency operation

- Full use of high frequency feature of SiC devices require thin film capacitor with high current carrying capability at high temperature

- Passives and EMI will be enabler for increasing power density

- Innovative topology enabled by advances passives and high switching frequency

Progression of All Electric and Hybrid Electric Aircraft Limited by Advances in Battery Technology



Notional timeline based on optimistic projections

All Electric

Today: 2-3 passenger , 200 miles, CTOL

2022: 2-3 passenger VTOL, 100 miles; 4 passenger VTOL, 60 miles

2025: 30 passenger 300 miles, CTOL; 4 passenger VTOL, 100-120 miles

Today **2022** **2025** **2028** **2031** **???** **???** **???** ← Timeline

150-170 Wh/kg **300 Wh/kg** **400 Wh/kg** **500 Wh/kg** **600 Wh/kg** **700 Wh/kg** **800 Wh/kg** **1000 Wh/kg** Pack Level Wh/kg

Hybrid Electric CTOL

150-170 Wh/kg: 2-3 passenger , 400 + miles; 10 - 20 passenger 300 miles

300 Wh/kg and 400 Wh/kg: 20 – 30 passenger > 400 miles

500 Wh/kg: 50-70 passenger 800 miles; Light utility helicopter

600 Wh/kg: 50-70 passenger 1000 miles

800 Wh/kg and 1000 Wh/kg: Single aisle 737 class

Enabling Technologies for All Electric and Hybrid Electric Aircraft

- High specific energy battery technologies for cell and battery pack
- Advanced magnets
- High-conductivity electrical conductors
- Advanced capacitors
- Advanced insulation system