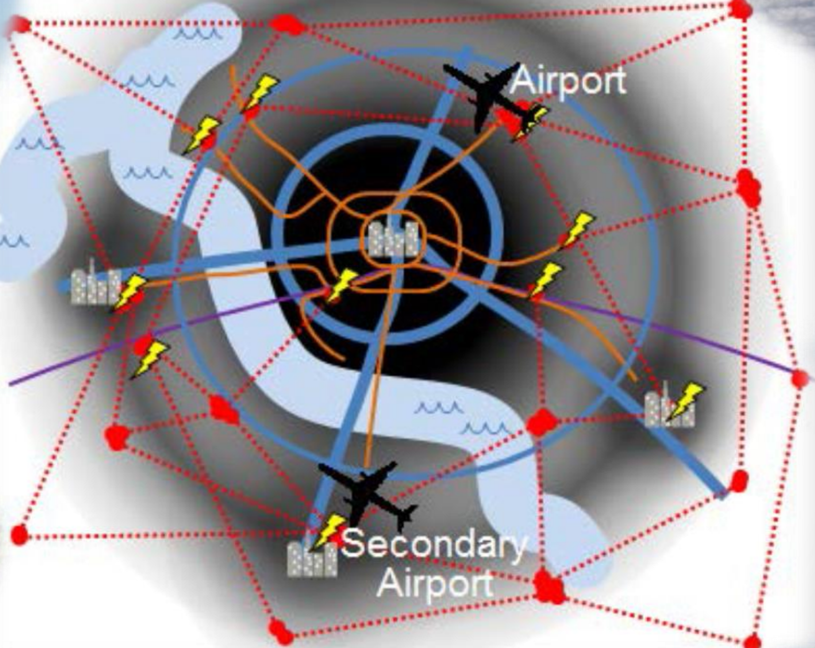
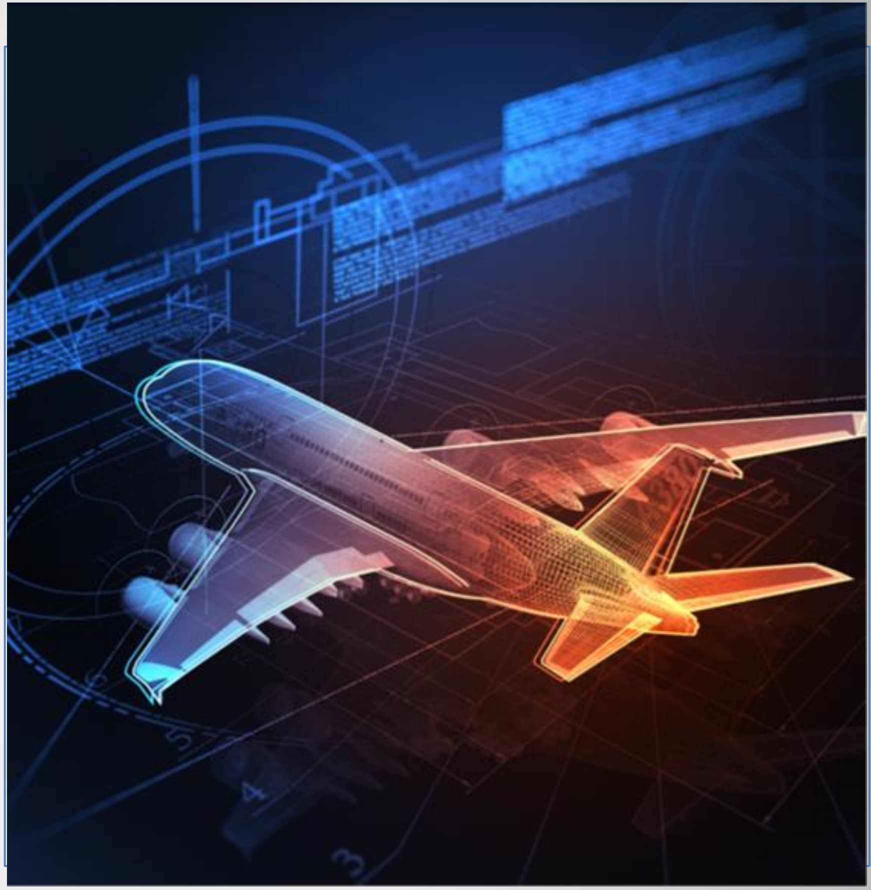
NASA Hybrid Electric Aircraft Propulsion



Dr. Rodger Dyson
NIEA Biomimicry Summit
Hybrid Gas Electric Propulsion Technical Lead
NASA Glenn Research Center
Cleveland, OH
Oct. 4, 2017

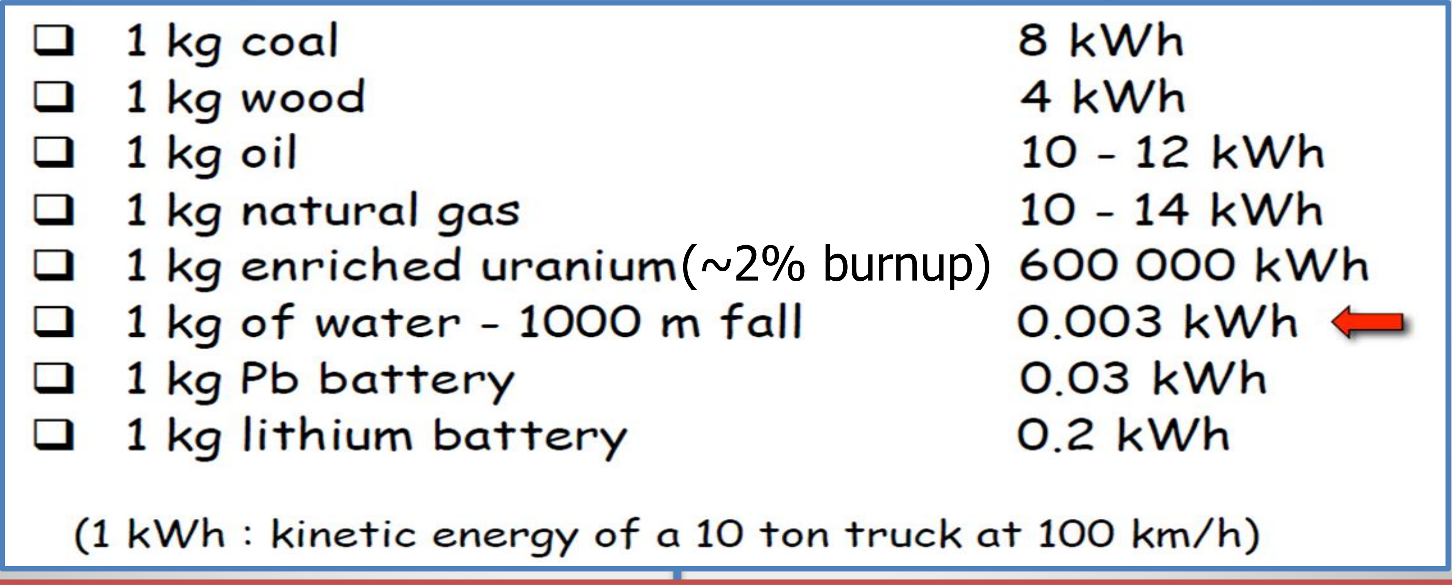
Electrically Enhanced Propulsion

- Why electric?
    - Fewer emissions
    - Quieter flight
    - Fuel savings
    - New mobility options
    - Better utilization of infrastructure



Aircraft Energy Sources

Jet Fuel is Light-Weight and Low-Cost



☐ 1 kg coal	8 kWh
☐ 1 kg wood	4 kWh
☐ 1 kg oil	10 - 12 kWh
☐ 1 kg natural gas	10 - 14 kWh
☐ 1 kg enriched uranium(~2% burnup)	600 000 kWh
☐ 1 kg of water - 1000 m fall	0.003 kWh ⬅
☐ 1 kg Pb battery	0.03 kWh
☐ 1 kg lithium battery	0.2 kWh

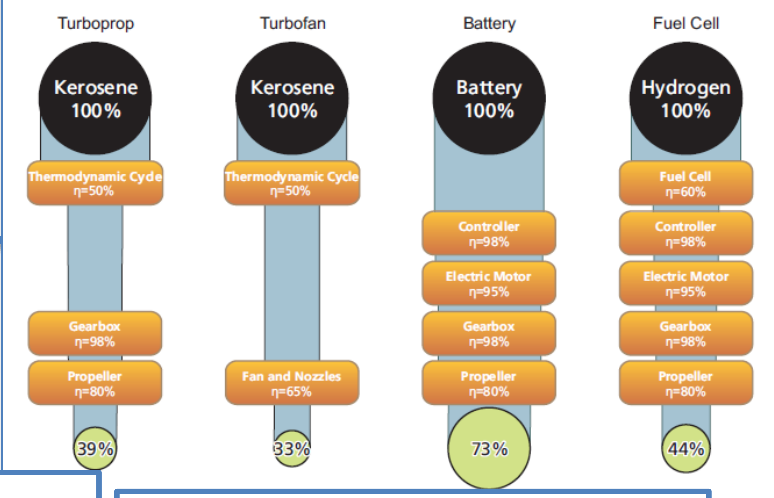
(1 kWh : kinetic energy of a 10 ton truck at 100 km/h)

Required mission power level determines energy source

Electrically Enhanced Propulsion

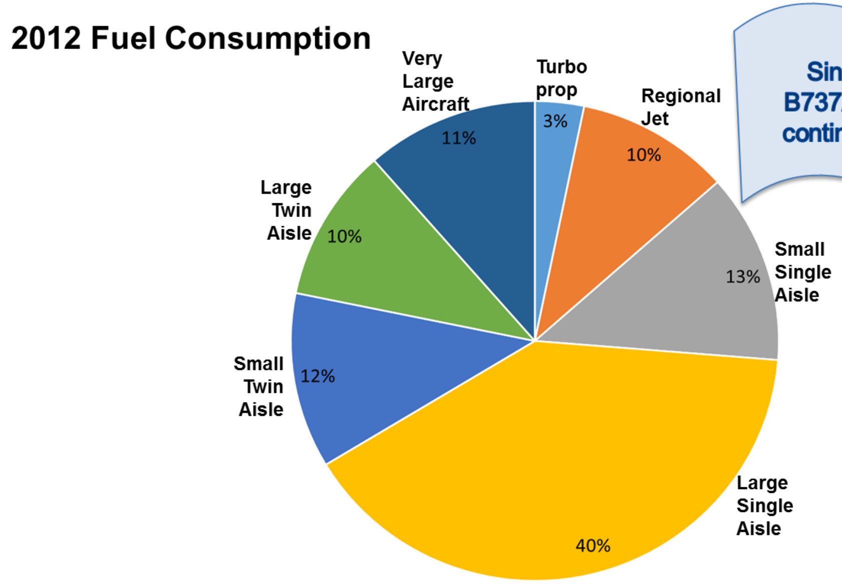
Well to Wake Energy Benefit

- Fuel Savings
- Noise Reduction
- Carbon and NOx Reduction
- Mobility and Safety



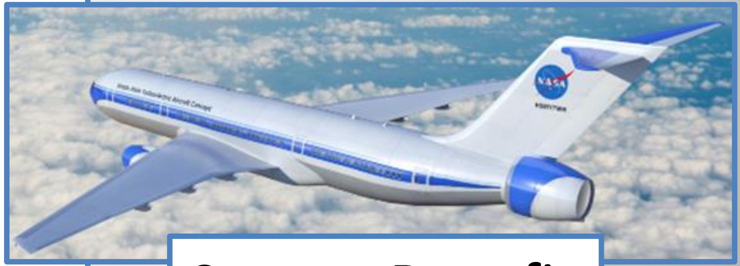
Powertrain Efficiency

39%, 33%, 21%, 13%
Well to Wake



Single-aisle 150 pax B737/A320 class vehicle continues to be the main focus

40% of fuel use in 150-210 pax large single-aisle class
87% of fuel use in small single-aisle and larger classes (>100 pax)
13% of fuel use in regional jet and turboprop classes



System Benefit

7-12%
Well to Wake

On-Demand and Large Transport

All & Hybrid Electric, Distributed Propulsion

- On Demand Mobility
- Small Plane Focused

Enable New Aero Efficiencies

Power Sharing

Distributed Thrust Control

Certification Trailblazing

Energy & Cost Efficient, Short Range Aviation

SUGAR Volt

Turbo Electric, Distributed Propulsion

- Fuel Efficient Propulsion
- Transport Class Focused

Enable New Aero Efficiencies

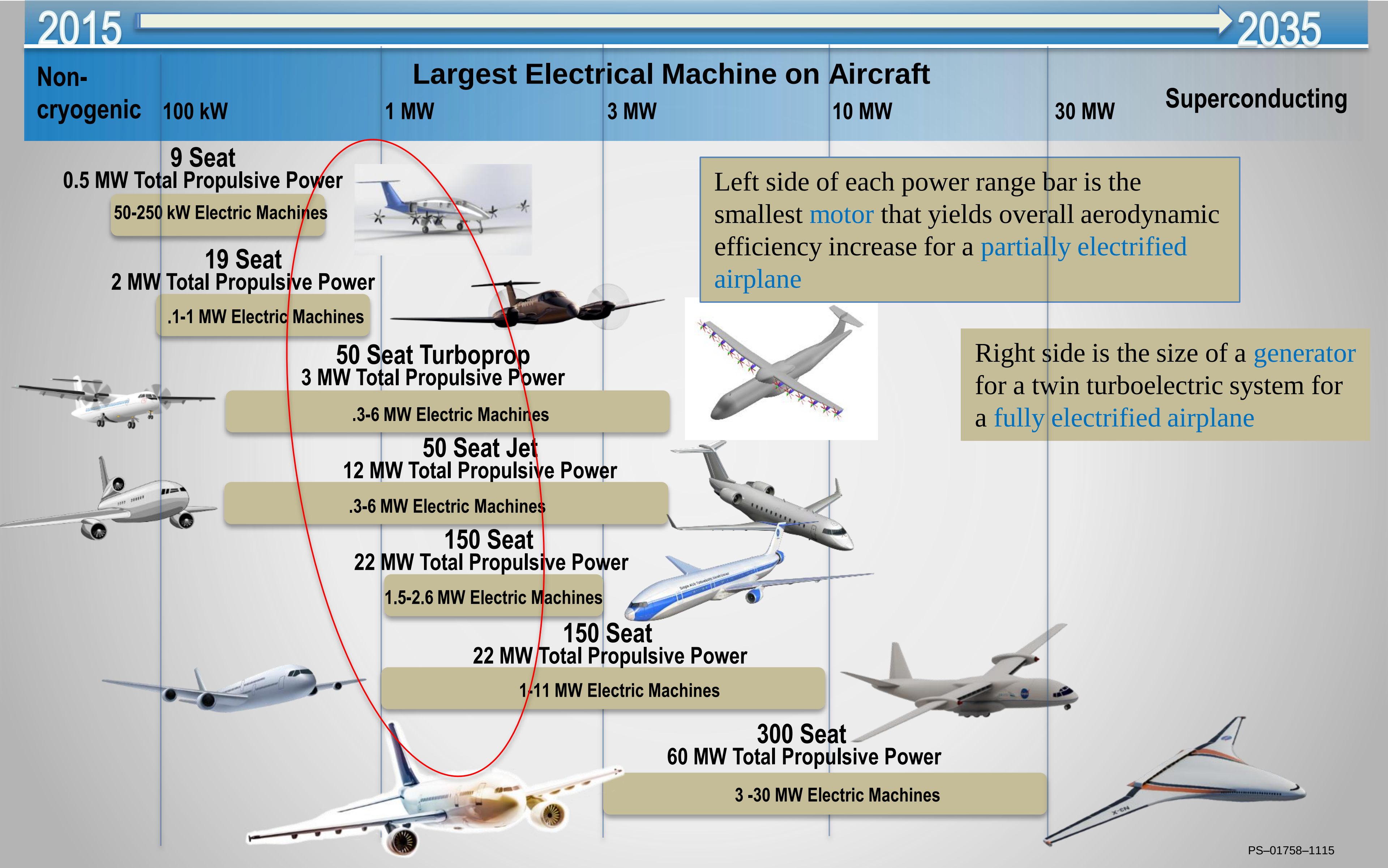
High Efficiency Power Distribution

Power Rich Optimization

Non-flight Critical First Application

Energy & Cost Efficient, Transport Aviation

Range of Required Machine Power



Left side of each power range bar is the smallest motor that yields overall aerodynamic efficiency increase for a partially electrified airplane

Right side is the size of a generator for a twin turboelectric system for a fully electrified airplane

NASA Electrified Aircraft Technology (NEAT)

Technology: Vehicle and propulsion concepts and benefits studies

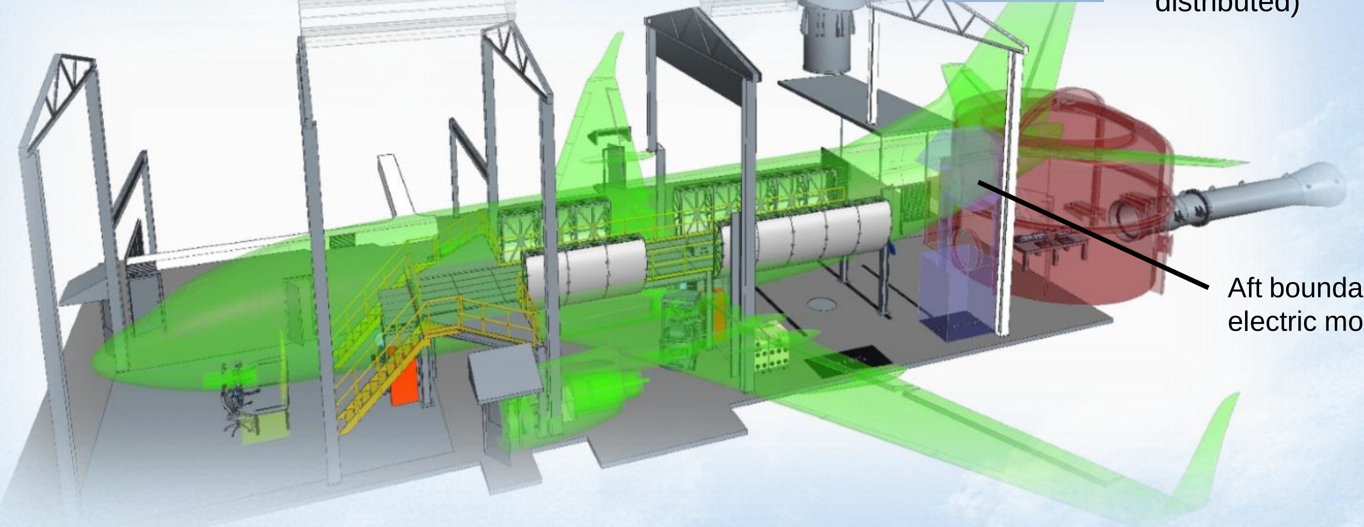
- Design and test electrified airplane powertrains that are flightweight, safe, reliable, fault tolerant
- NASA's STARC-ABL configuration to be tested in NEAT testbed in 2018 at full power

X-Planes: Near and Mid-term

- Regional Jet or Single Aisle demo before 2025
- Thin Haul Commuter
- Low cost fixed wing vertical take-off and landing (VTOL)
- Maxwell X-57 (battery, distributed)

Full-Scale Ground Tests:

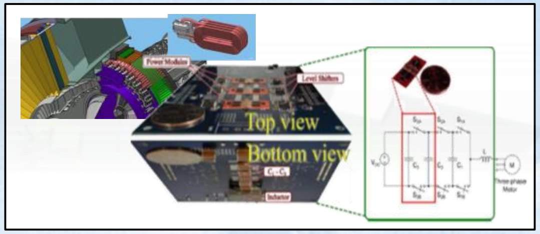
NASA Electric Aircraft Testbed (NEAT)



Aft boundary ingesting electric motor

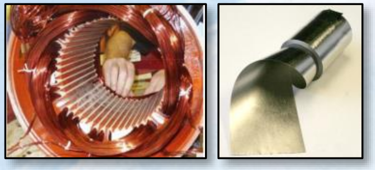
Technology: Powertrain Components

- Electric machines
- Power electronics
- Integrated turbines, generators
- Controls
- Transmission



Technology: Enabling Materials and Devices

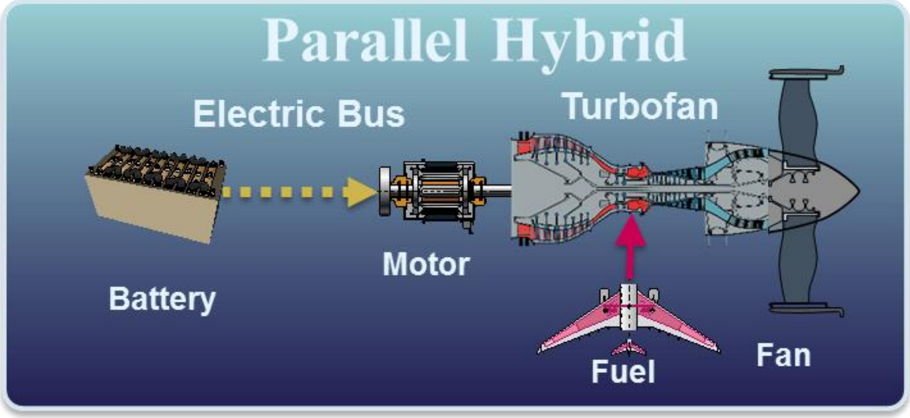
- Insulation
- Conductors
- Magnetic materials
- Power electronics devices

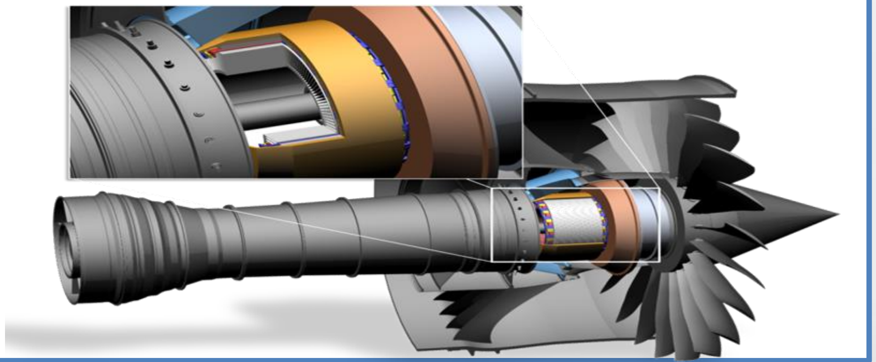


Goal: Flight tests, ground demo's and technology readiness by 2025 to support 2035 Entry into Service

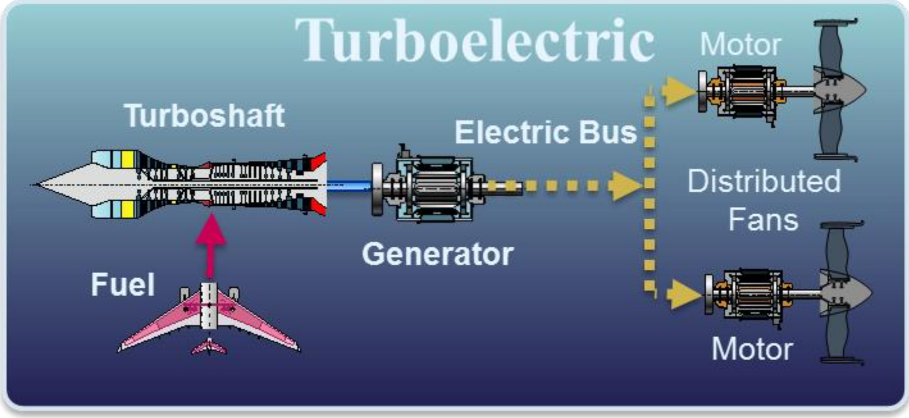
Near Term Propulsion Options

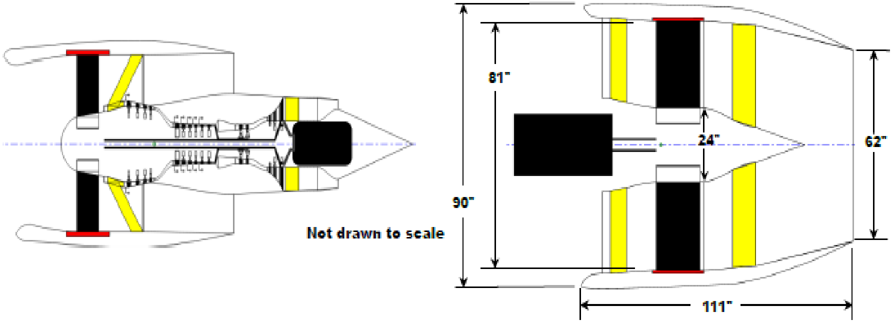
Parallel - Motor with Engine



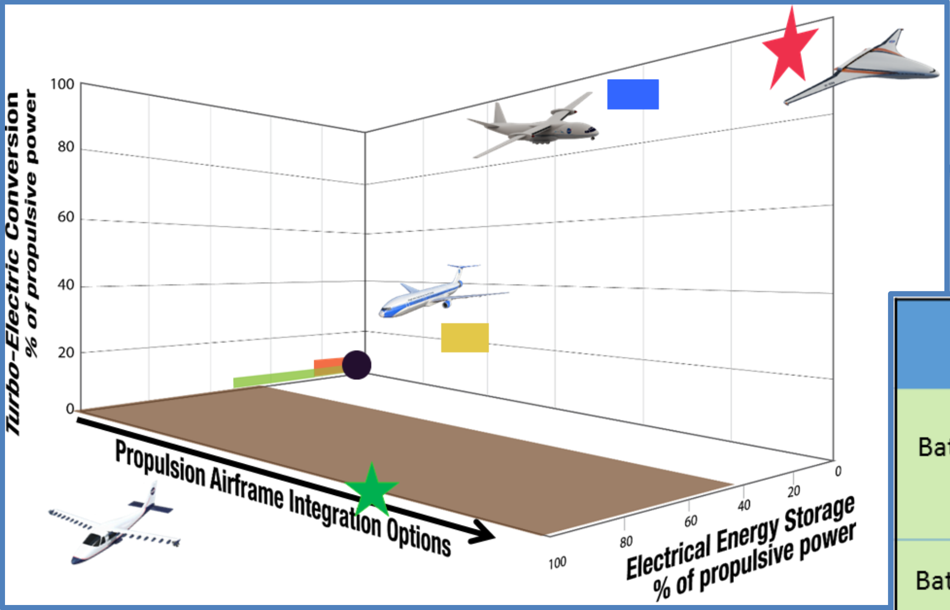


Turboelectric – Motor



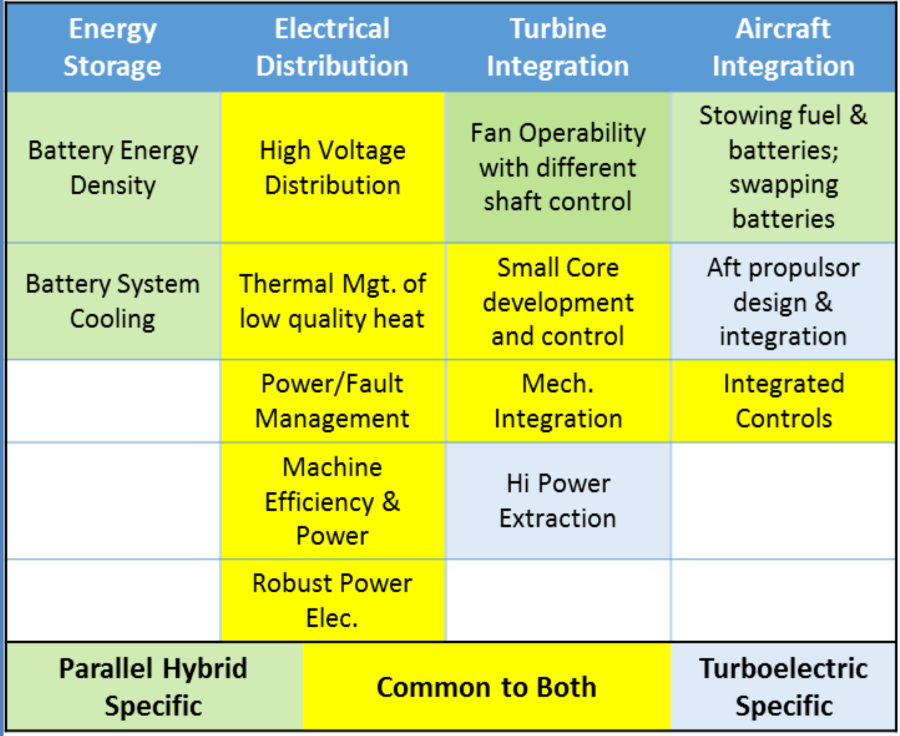


Vehicle Configuration Trade-offs



VEHICLE CONFIGURATION EXAMPLES

- Voltage vs. Efficiency
- Thermal vs. Mass
- Stability vs. Integration

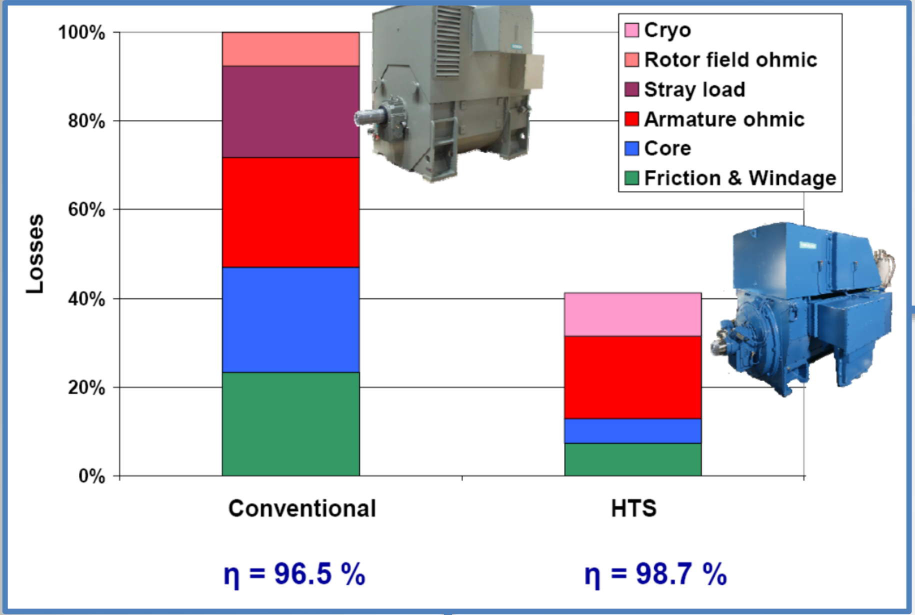


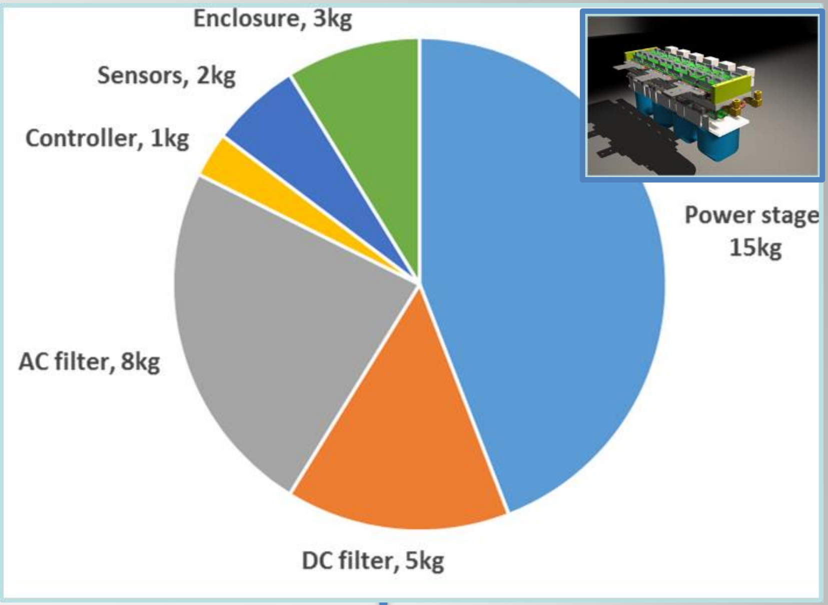
Energy Storage	Electrical Distribution	Turbine Integration	Aircraft Integration
Battery Energy Density	High Voltage Distribution	Fan Operability with different shaft control	Stowing fuel & batteries; swapping batteries
Battery System Cooling	Thermal Mgt. of low quality heat	Small Core development and control	Aft propulsor design & integration
	Power/Fault Management	Mech. Integration	Integrated Controls
	Machine Efficiency & Power	Hi Power Extraction	
	Robust Power Elec.		

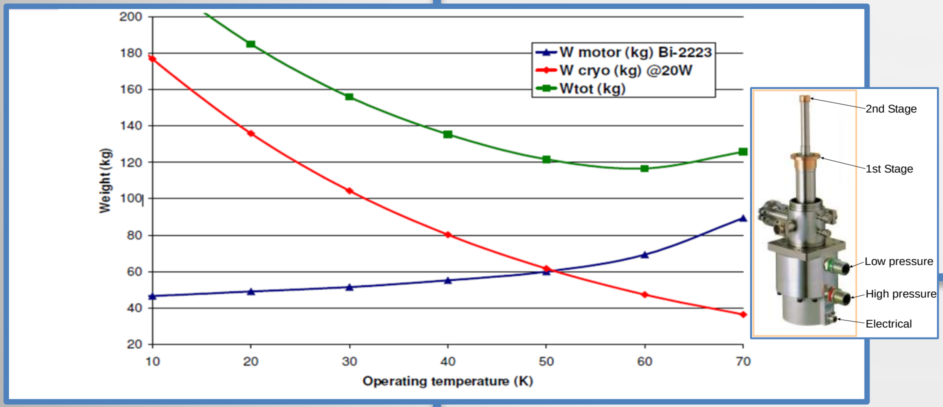
Parallel Hybrid Specific	Common to Both	Turboelectric Specific

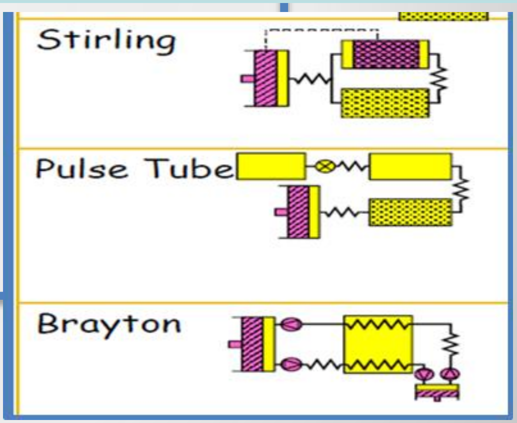
- Battery vs. Turbine Power
- Aerodynamics vs. Complexity

Powertrain System Optimization









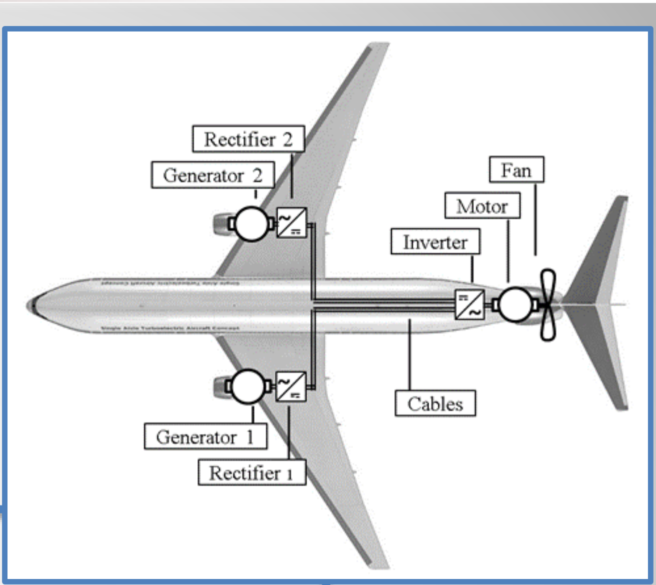
An optimization of the whole system has to be done in order to reach the minimum weight and/or volume

Tail-cone Thruster Propulsion

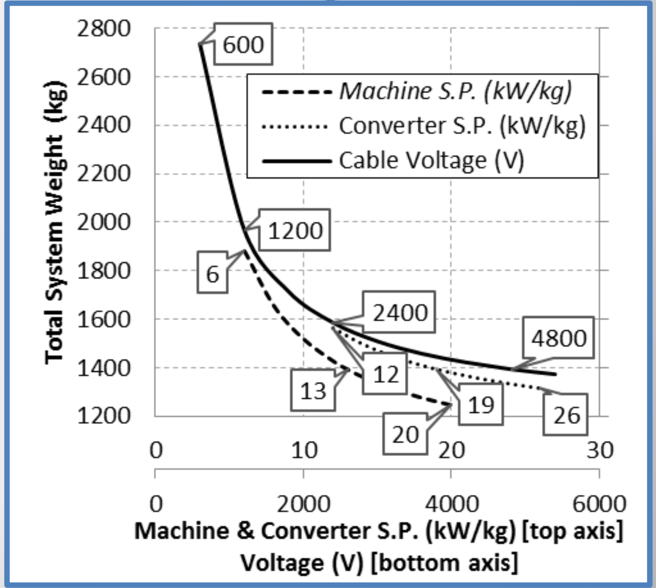
Tail-cone Motor Thruster concept

- 150 passenger plane with two turbines and 2.6MW electric motor driven tail cone thruster
- 7-12% fuel burn reduction
- Uses jet fuel, standard runways & terminals

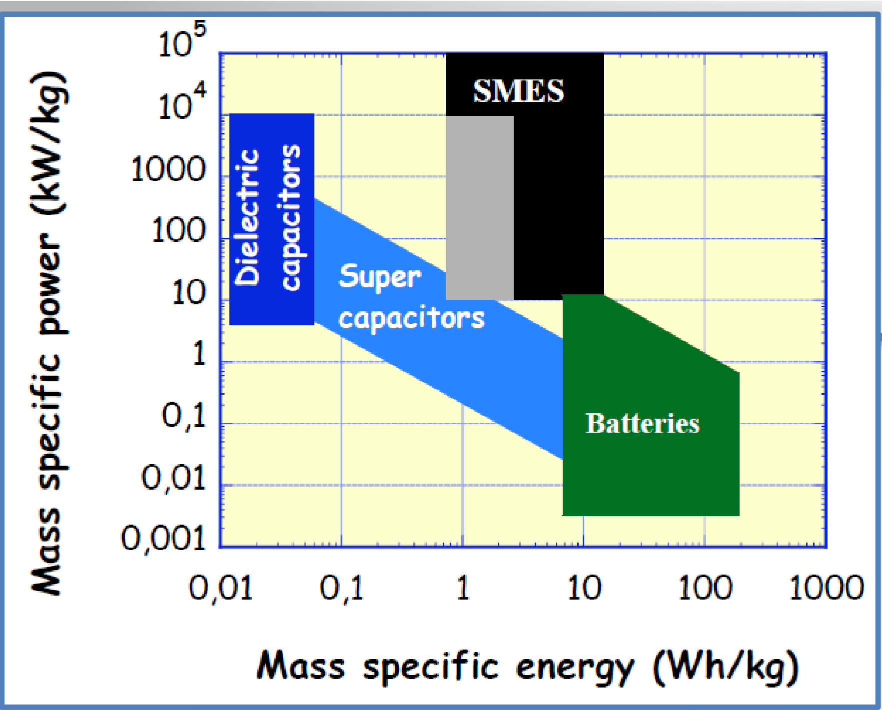
IMPACT: Reduce fuel use and emissions of biggest aircraft segment

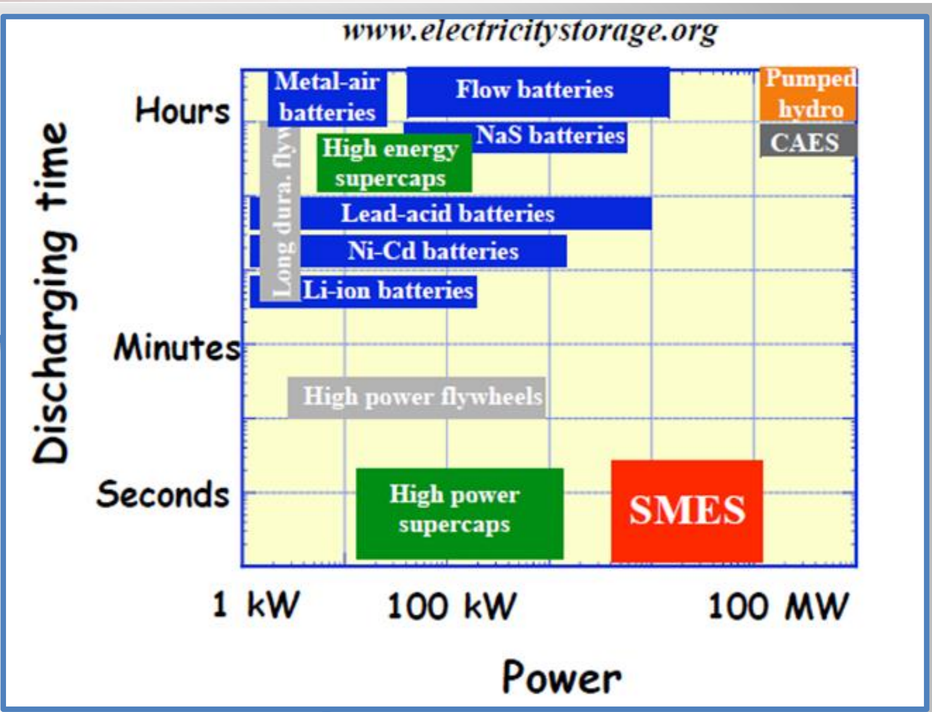


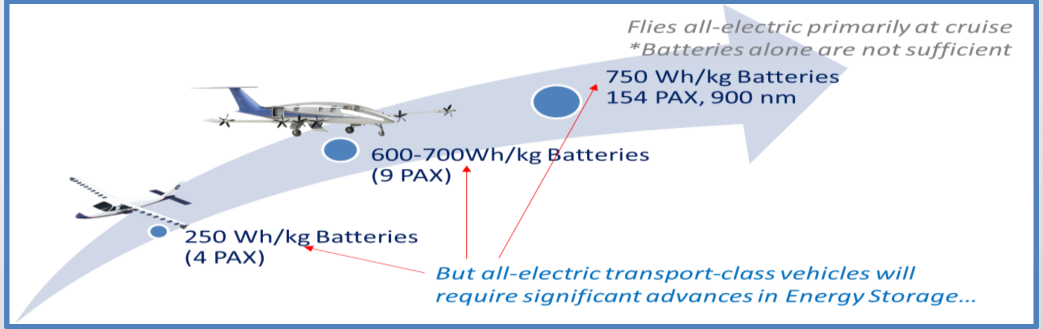
- Key Technologies
  - Aircraft System Analysis – modeling, analysis compared to key metrics
  - Engine technologies – >1 MW power extraction from turbofan
  - Propulsion/Airframe Integration – benefit of tail cone thruster (takeoff to 0.8 Mach)
  - Power – >1 MW efficient, high specific power
  - Materials – turbine, magnetic materials, cable materials, insulation



Aircraft Energy Storage



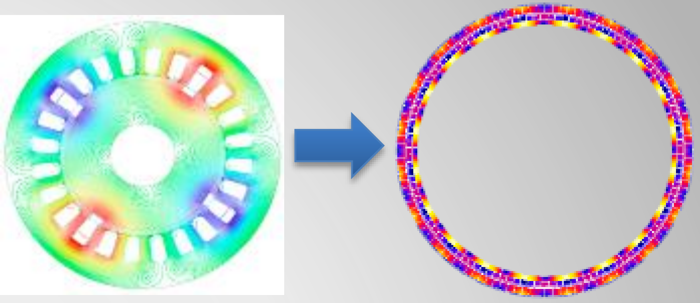

www.electricitystorage.org


Flies all-electric primarily at cruise
**Batteries alone are not sufficient*

But all-electric transport-class vehicles will require significant advances in Energy Storage…

Can choose high energy or power, mass is a challenge

Electric Machine Development



- NASA Sponsored Motor Research
  - 1MW
  - Specific Power > 8HP/lb (13.2kW/kg)
  - Efficiency > 96%
  - Awards
    - University of Illinois
    - Ohio State University
  - Phase 3 to be completed in 2018

Year 1 Technology Demo. Prototype Motor Parts

- NASA In-House Motor Research
  - Analytical Studies and Prototype Testing focused on ultra-high efficiency 99%

Power Electronics Development

NASA Sponsored Inverter Research

- 1MW, 3 Phase AC output
- 1000V or greater input DC BUS
- Ambient Temperature Awards
  - 3 Years (Phase 1, 2, 3)
  - GE – Silicon Carbide
  - Univ. of Illinois – Gallium Nitride
- Cryogenic Temperature Award
  - 4 years (Phase 1, 2, 3)
  - Boeing – Silicon CoolMOS, SiGe

Ambient Inverter Requirements

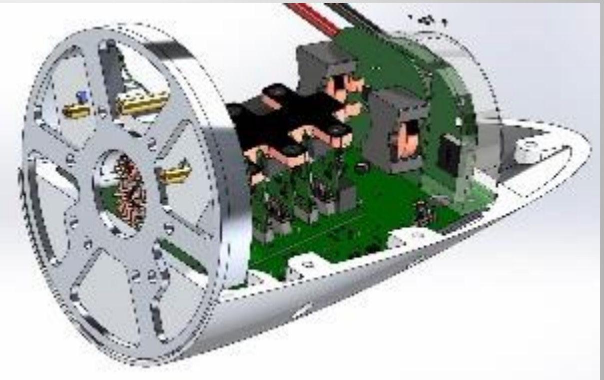
Key Performance Metrics	Specific Power (kW/kg)	Specific Power (HP/lb)	Efficiency (%)
Minimum	12	7.3	98.0
Goal	19	11.6	99.0
Stretch Target	25	15.2	99.5

Cryogenic Inverter Requirements

Key Performance Metrics	Specific Power (kW/kg)	Specific Power (HP/lb)	Efficiency (%)
Minimum	17	10.4	99.1
Goal	26	15.8	99.3
Stretch Target	35	21.3	99.4

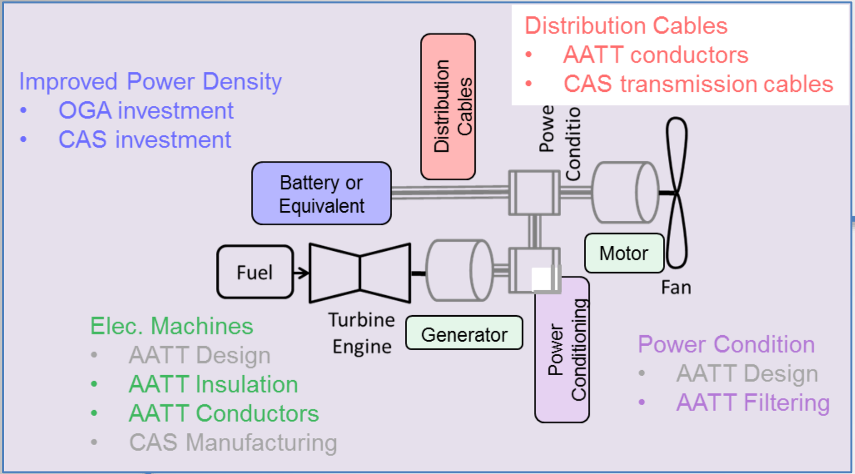
NASA In-House Inverter Research

- Designing 14 kW Inverter based on HEIST motor and nacelle cooling and packaging requirements
  - 99% efficiency driven by cooling requirements



Electric Powertrain Materials

Power System Weight Drivers



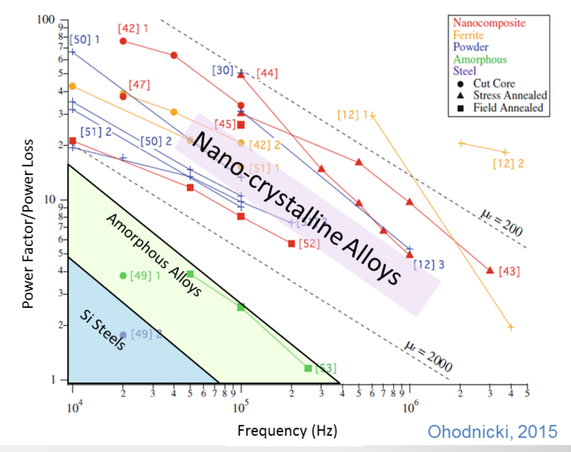
Distribution Cables
- AATT conductors
- CAS transmission cables

Improved Power Density
- OGA investment
- CAS investment

Elec. Machines
- AATT Design
- AATT Insulation
- AATT Conductors
- CAS Manufacturing

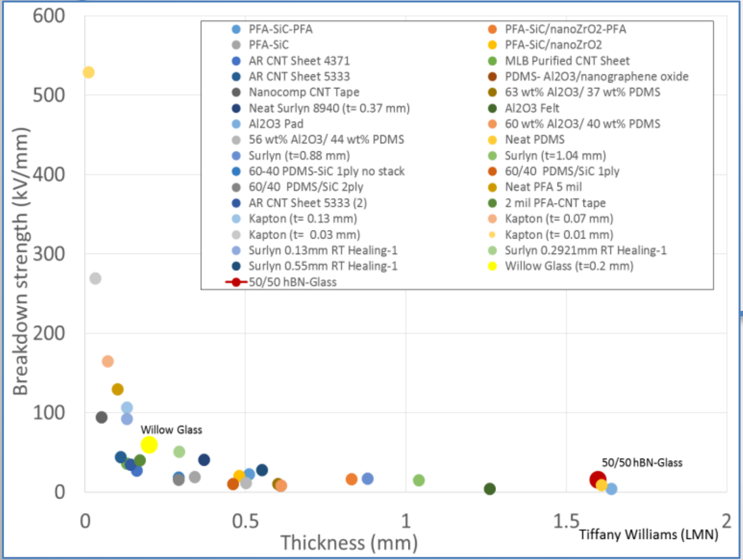
Power Condition
- AATT Design
- AATT Filtering

Magnetic Materials



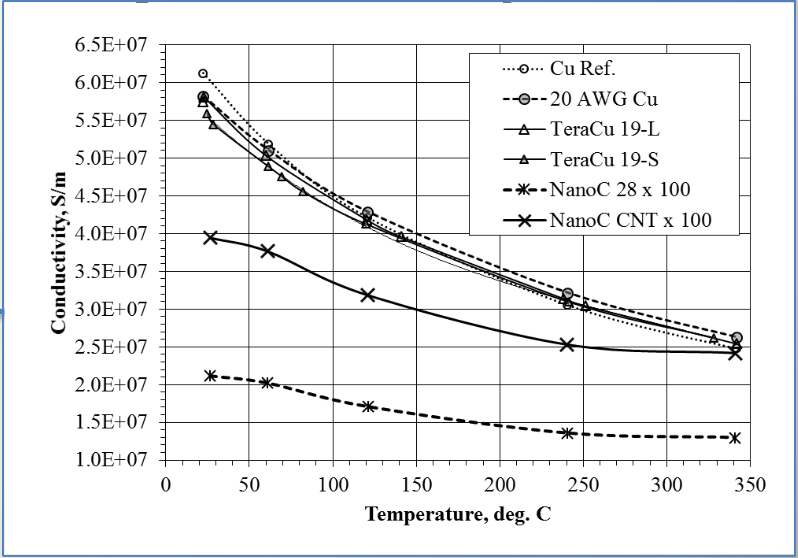
Ohodnicki, 2015

Insulation Materials



Tiffany Williams (LMN)

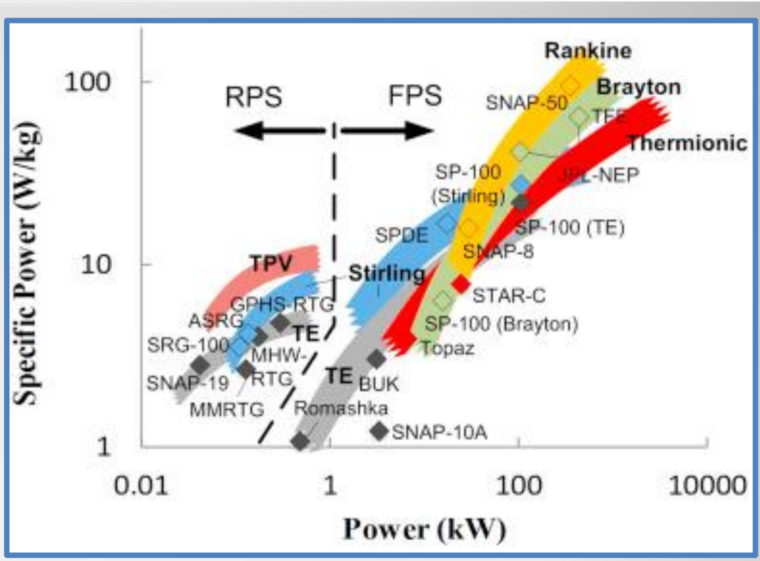
High Conductivity Materials

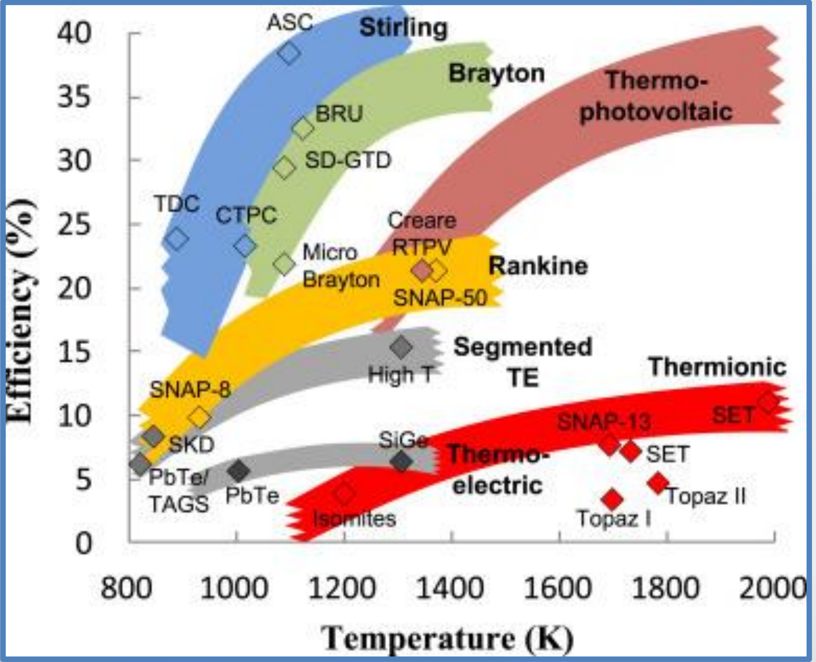


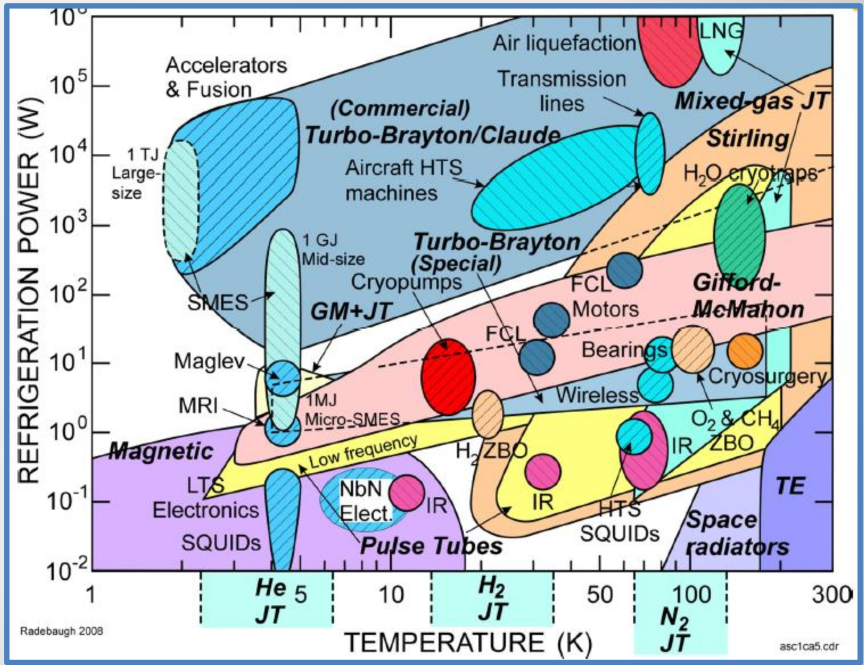
Aircraft Power/Cooling Options

Trade-space includes:

- Motor & Inverter Topologies
- Thermodynamic Cycles
- Storage and Regeneration
- Energy Source and Recycle





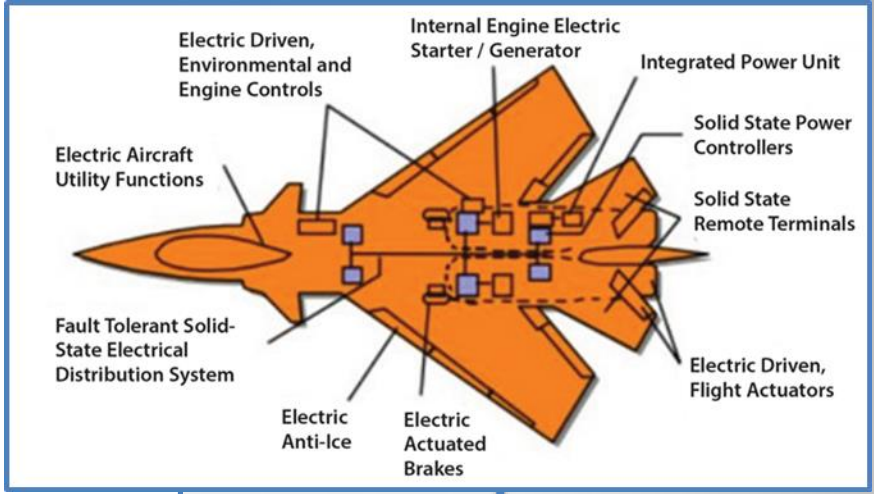


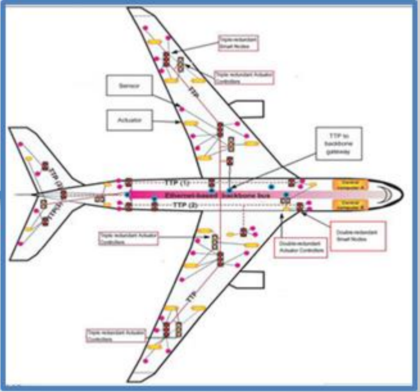
Thermal Challenge

50kW to 800kW of low grade thermal power trapped within composite aircraft body

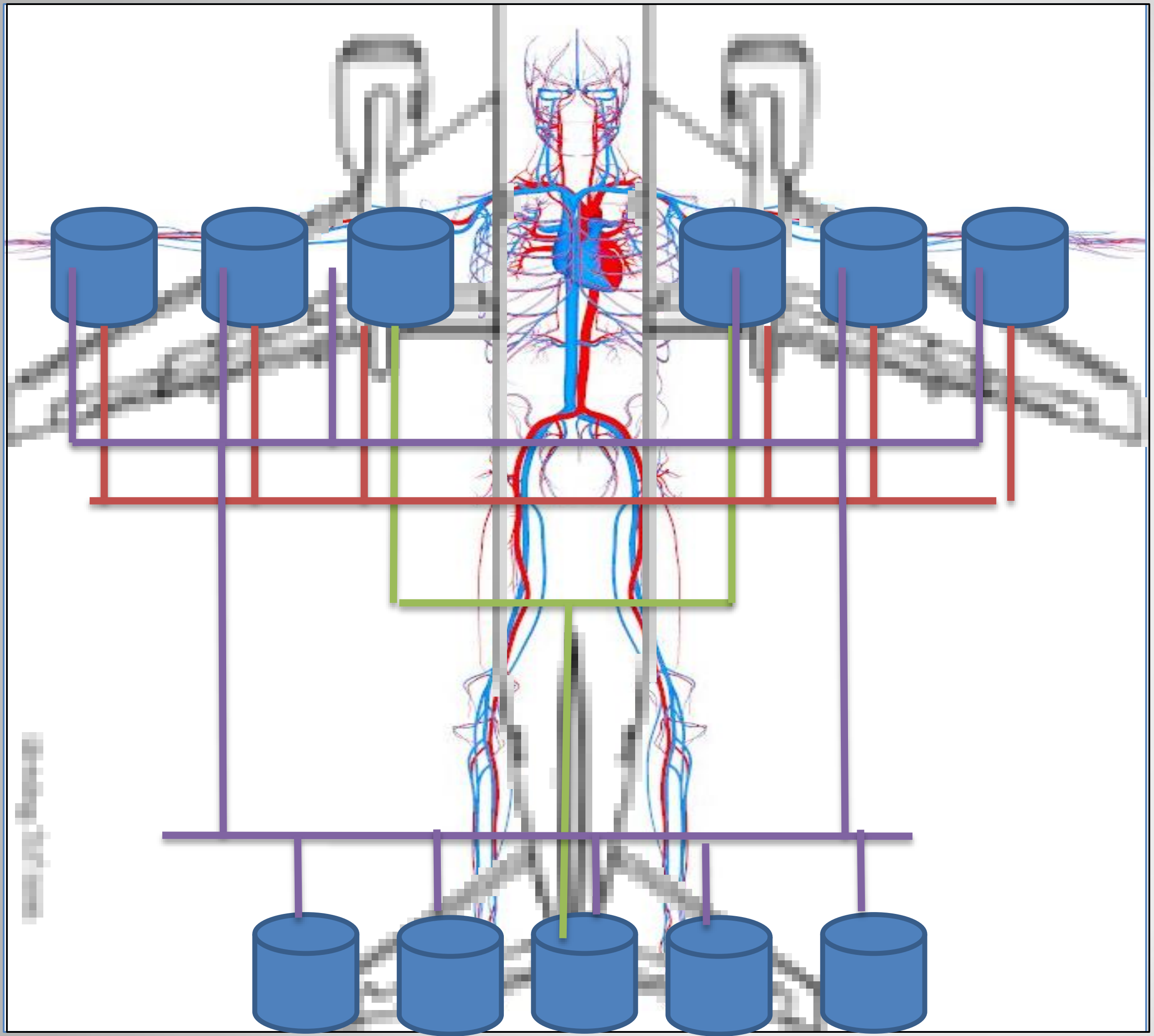
Current proposed solutions (and limits) include:

- ☐ Ram air HX
  - adds weight and aircraft drag
- ☐ Convective skin cooling HX
  - adds weight, drag, and inefficient
- ☐ Dumping heat into fuel
  - limited thermal capacity
- ☐ Dumping heat into lubricating oil
  - limited thermal capacity
- ☐ Active cooling
  - adds weight and consumes engine power
- ☐ Phase change cooling
  - adds weight and limited thermal capacity
- ☐ Heat pipe, pumped multiphase, vapor compression
  - adds weight and consumes engine power



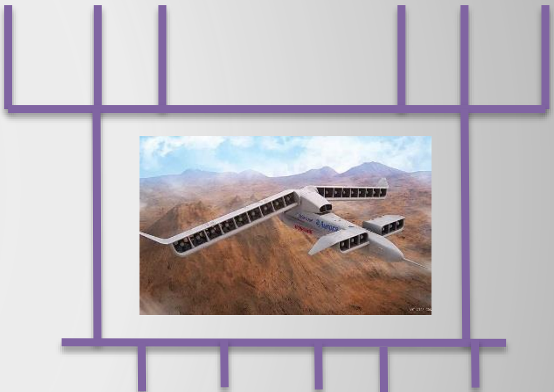


Natured-Inspired Integrated Power, Propulsion,Thermal



Several powertrains installed adjacently

STARC-ABL



DARPA

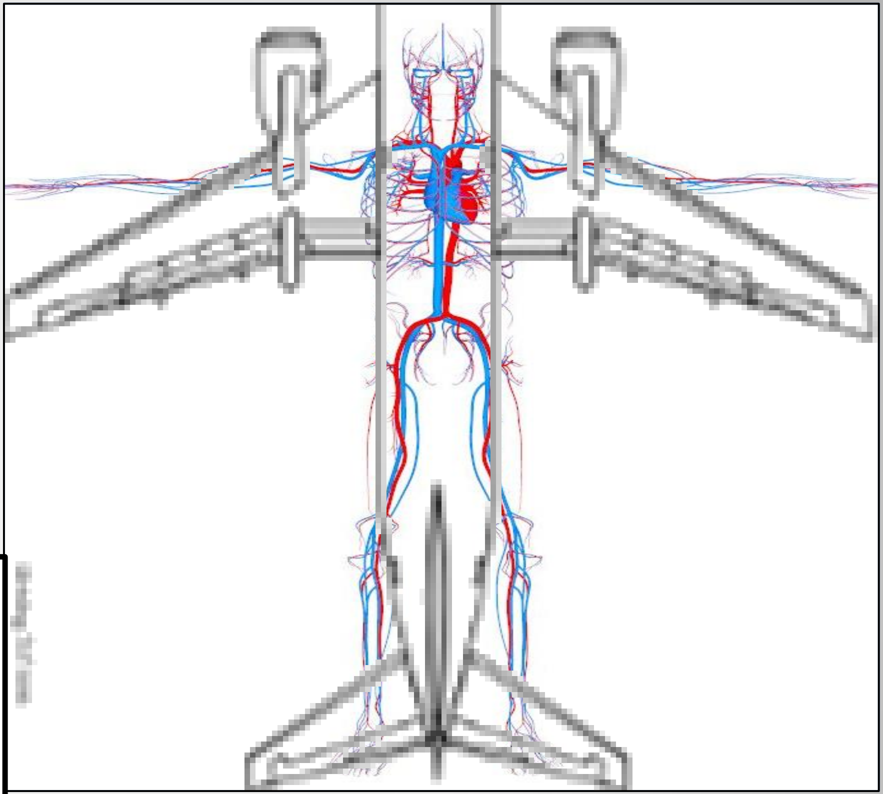
ECO-150

Aero-vascular Energy Management

Human	**Aircraft**
Heart	Turbofan
Artery	Acoustic Pipe
Vein	Heat Pipe
Skin	Skin
Blood	Helium/Gas

Large aircraft ideal for integration-allows each component to be at knee in the curve instead of Achilles Heal of vehicle

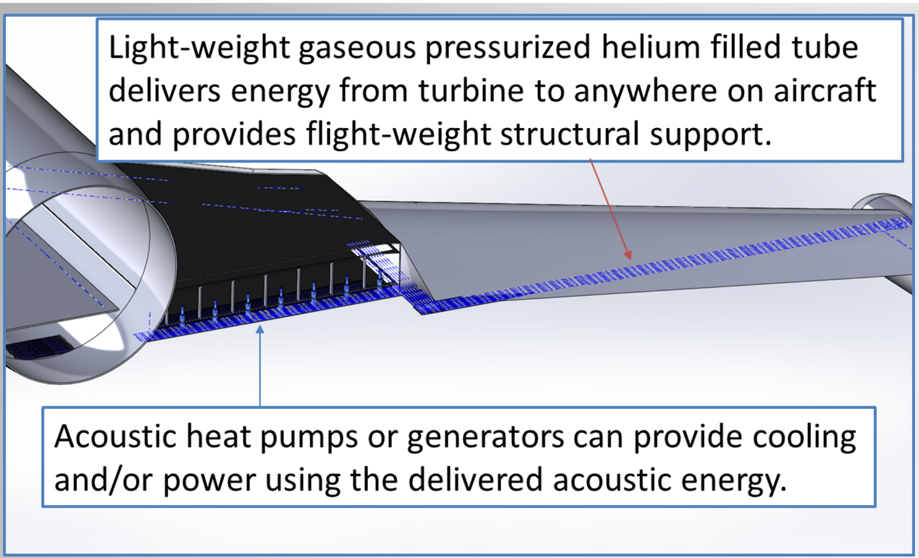
- Turbofan-45% eff.
- Powertrain-95% eff.
- Lifting surface
- ODM = city noise and traffic complexity
- Large transport highest impact



Human body circulatory system as model for aircraft

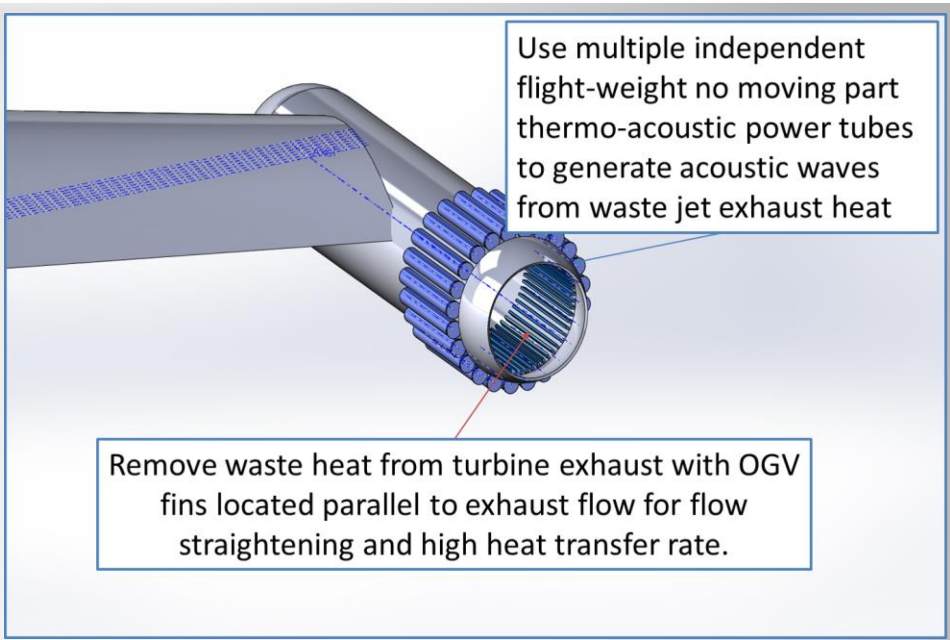
Three pillars: recycle, additive manufacture, integration/control

Energy transport with ducted acoustic wave



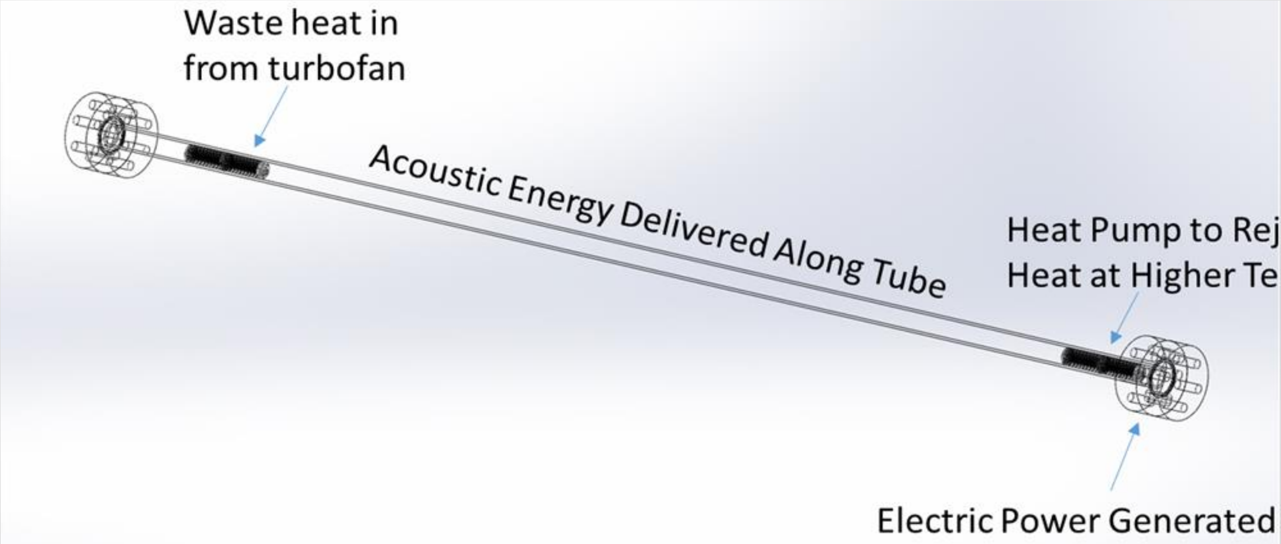
Light-weight gaseous pressurized helium filled tube delivers energy from turbine to anywhere on aircraft and provides flight-weight structural support.

Acoustic heat pumps or generators can provide cooling and/or power using the delivered acoustic energy.



Use multiple independent flight-weight no moving part thermo-acoustic power tubes to generate acoustic waves from waste jet exhaust heat

Remove waste heat from turbine exhaust with OGV fins located parallel to exhaust flow for flow straightening and high heat transfer rate.



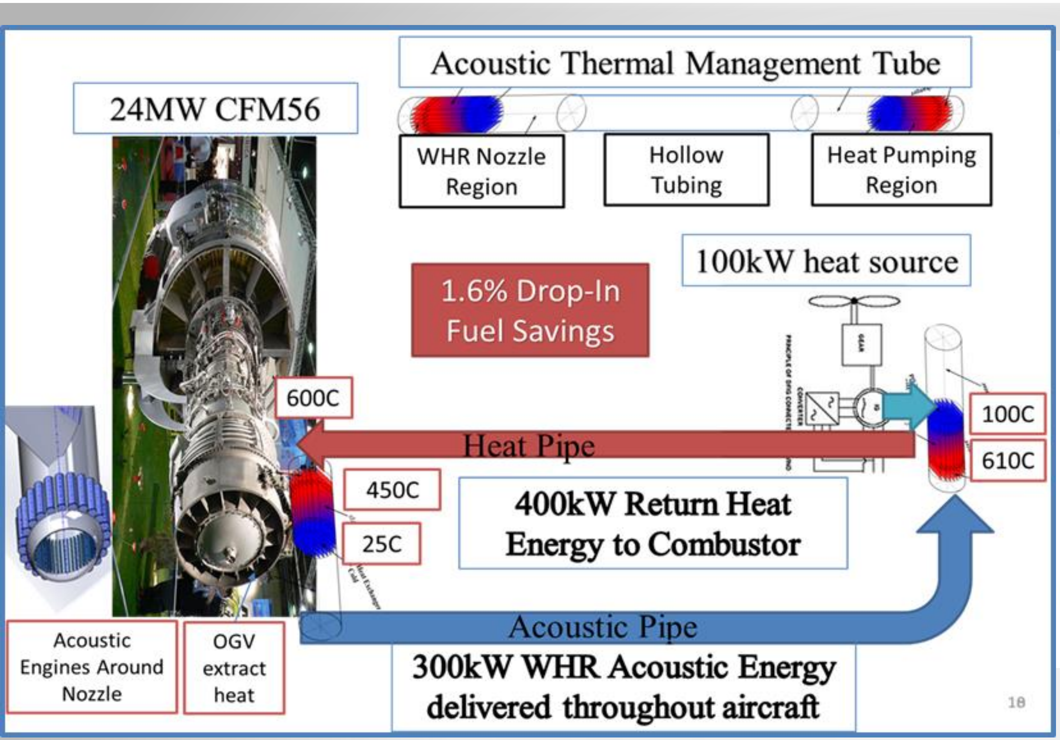
Waste heat in from turbofan

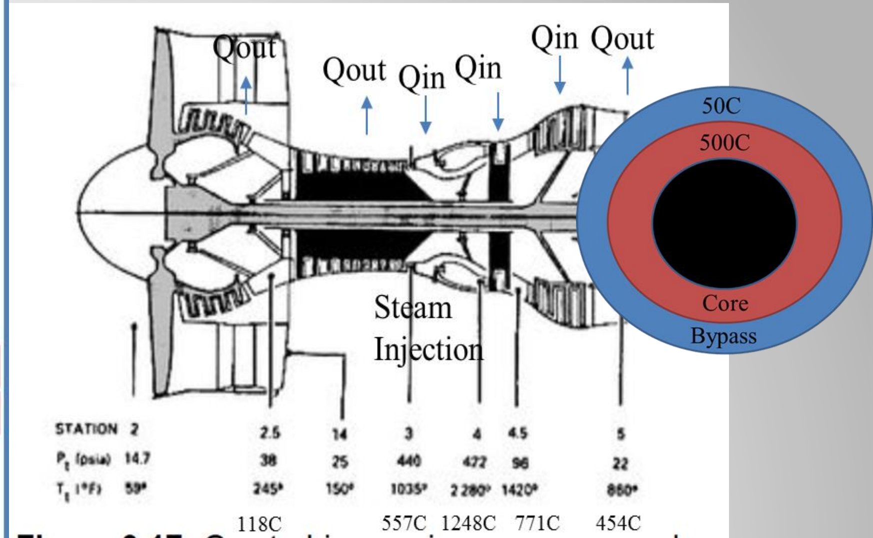
Acoustic Energy Delivered Along Tube

Heat Pump to Reject Electric Heat at Higher Temperature

Electric Power Generated

Recycling Thermal Energy



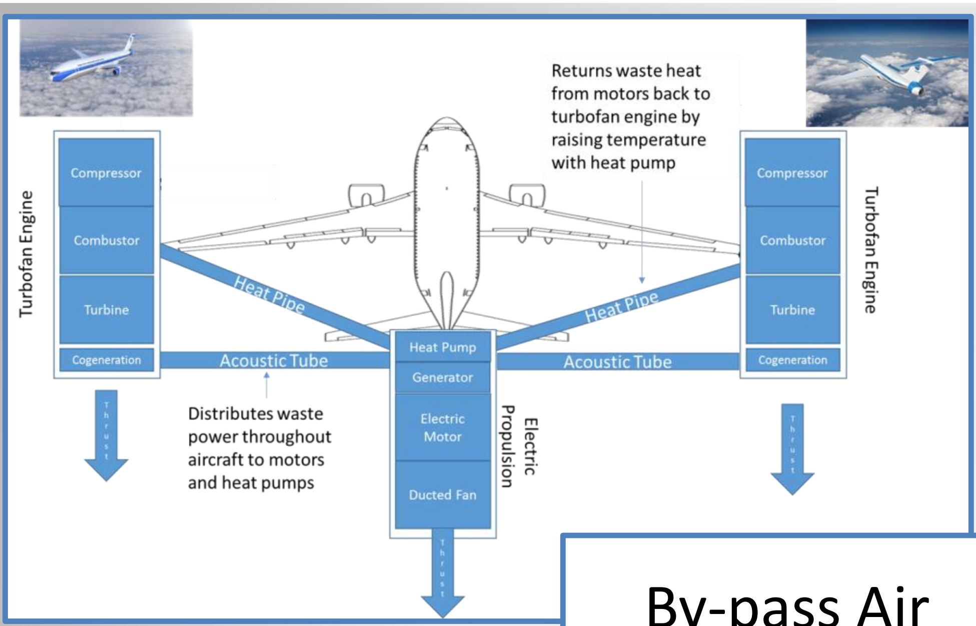


STATION	2	2.5	14	3	4	4.5	5
P_t (psia)	14.7	38	25	440	472	96	22
T_t (°F)	59°	245°	150°	1035°	2280°	1420°	850°
		118C		557C	1248C	771C	454C

Figure 3.17: Gas turbine engine pressures and temperatures

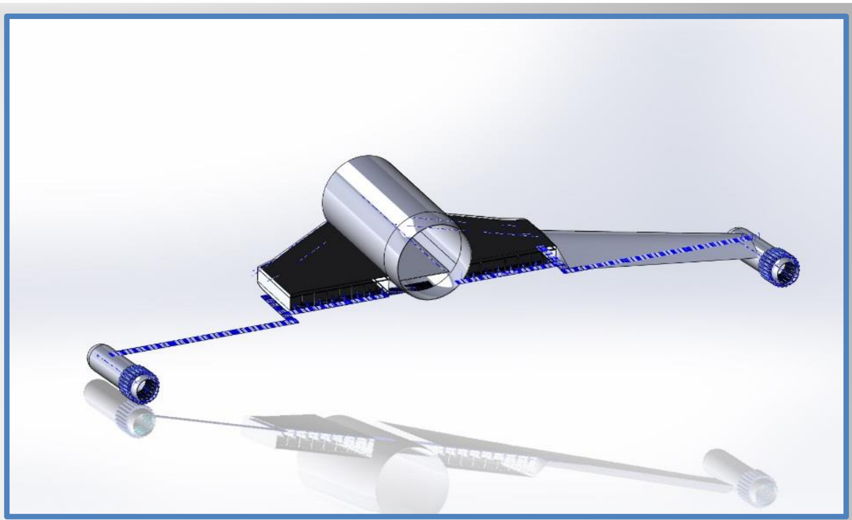
Areas where heat can be extracted or inserted for net efficiency gain in turbofan engine.

TREES Heat Recovery Cycle



Returns waste heat from motors back to turbofan engine by raising temperature with heat pump

Distributes waste power throughout aircraft to motors and heat pumps

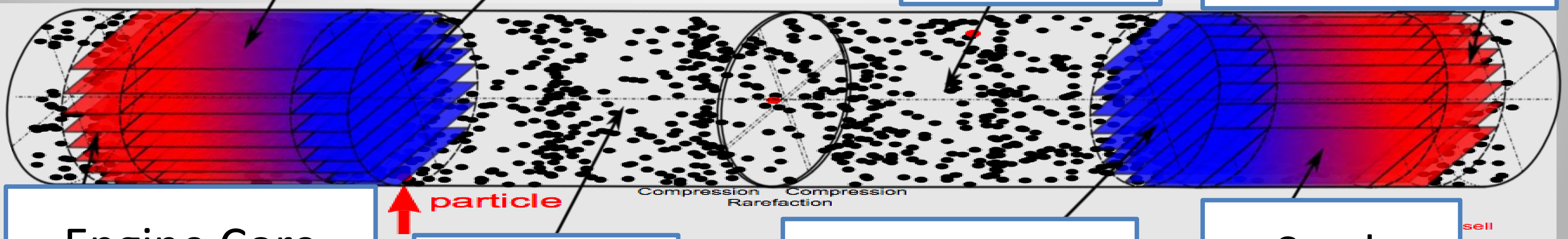


Stack

By-pass Air Heat Exchanger

Resonator

Heat Pipe Exchanger



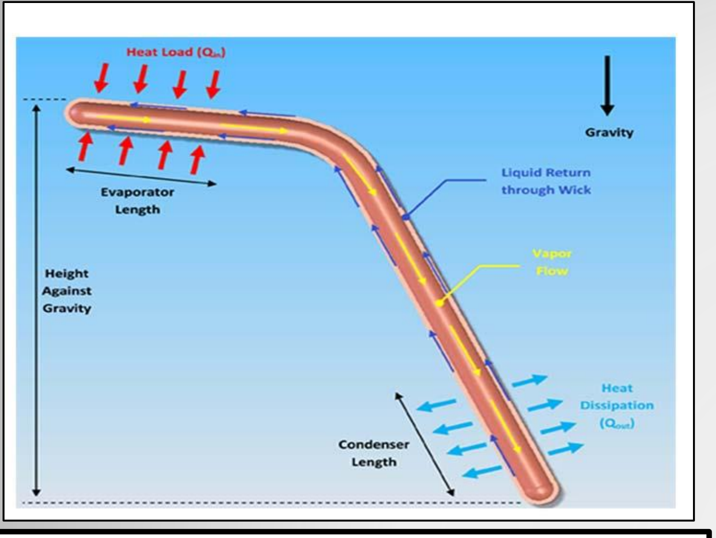
Engine Core Heat Exchanger

Resonator

Airframe Heat Exchanger

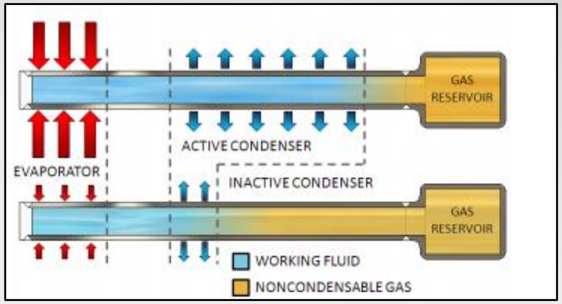
Stack

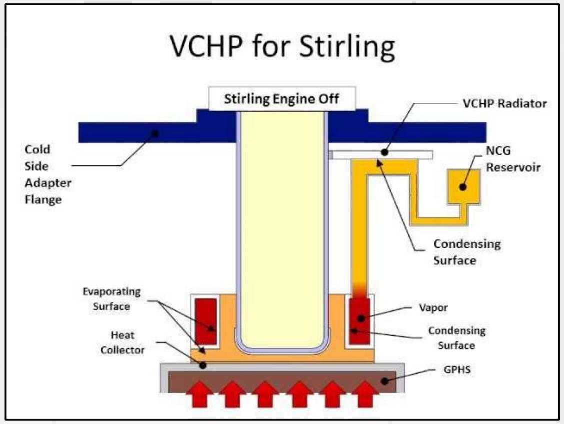
Variable Conductance Heat Pipe for Controlled Heat Delivery



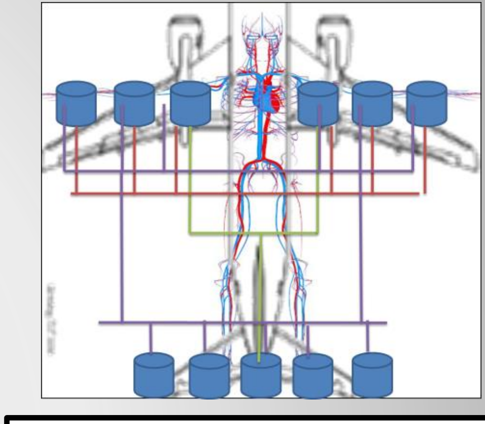
Solid-state (no moving part) energy recycle and control

- Localized skin heating for active lift/drag management, de-icing, powertrain cooling, cabin management, and military cloaking





Solid-state heat flow control to heat pump and combustor



Turbine Waste Energy Transmitted Acoustically, Powertrain Waste Energy Heat Pipe Delivered to Combustor

No moving part heat reuse and recycle

Conclusions

- Key Power, Energy Storage and Conversion Technologies are being developed that support On Demand Mobility and Transport Class Aircraft:
  - **MW Motors and Inverters** can support transport propulsion requirements
  - **Energy Storage** technology can safely support on demand mobility
  - **Energy Conversion** technology can thermally recycle all aircraft waste heat
- **Hybrid Gas Electric Propulsion** technology enables:
  - Heavier payloads,
  - Noise, emission, and operational cost reduction
  - New mission capability including duration and durability
- **Challenges** include:
  - Operational and regulatory change requirements
  - EMI standards and flight path management
  - Dispatch ability and Infrastructure

Power Technology is maturing at a fast pace!

Conclusion

TREES changes aircraft thermal management from being a necessary burden on aircraft performance to a desirable asset. It improves the engine performance by recycling waste heat and ultimately rejecting all collected aircraft heat out through the engine nozzle.

- **Key Features Include:**
  - **Turbofan waste heat is used to generate ducted acoustic waves that then drive distributed acoustic heat pumps and/or generate power.**
  - **Low grade powertrain waste heat is converted into high grade recycled heat and returned to the engine combustor via heat pipes**
  - **Pressurized acoustic and heat pipe tubes can be directly integrated into the airframe to provide structure support with mass reduction.**
  - **Fuel savings of 16% are estimated with a purpose-built system**
  - **All aircraft heat is rejected through engine nozzle**
  - **Non-provisional Patent Filed With Priority Date November 6, 2015.**

Thank you for attending!
Any Questions?