# Sizing Power Components of an Electrically Driven Tail Cone Thruster and a Range Extender

Ralph H. Jansen, Dr. Cheryl Bowman and Amy Jankovsky

*NASA Glenn Research Center, Cleveland, Ohio, 44135*

# Outline

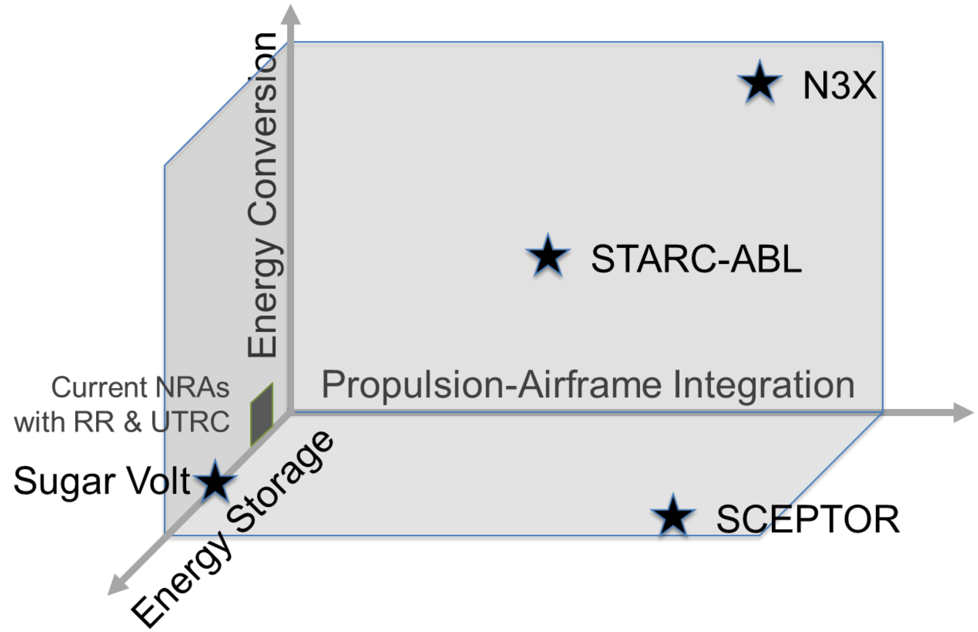
- Motivation for turboelectric and hybrid electric aircraft propulsion work.
- Overview of aircraft configurations
- Overview of Advanced Air Transportation Technology (AATT) Project, Hybrid Gas Electric Subproject
- Some key research areas
- Sizing of Power Components for
  – Electrically Driven Tail Cone Thruster
  – Range Extender

# Introduction

- The aeronautics industry has been challenged on many fronts to increase efficiency, reduce emissions, and decrease dependency on carbon-based fuels.
- Electrification of aviation propulsion through turboelectric or hybrid electric propulsion is one of many exciting research areas which has the potential to revolutionize the aviation industry.
- The focus of efforts in AATT are for future 150 passenger, single aisle transport planes.
  - 40 percent of fleet fuel is used by single aisle 150 to 210 passenger size class vehicles
  - aircraft larger than 100 passenger account for 87 percent of fleet fuel consumption.

# Hybrid Electric Trade Space

- Origin
  - single aisle transport aircraft with two turbo-fan engines
- Energy Conversion
  - At minimum, no jet fuel is converted into electricity for propulsion purposes
  - At maximum, all of the turbine energy is converted to electricity
- Energy Storage
  - At minimum, all energy stored in jet fuel
  - At maximum, all energy stored in batteries or equivalent




- Integration Axis
  - wing tip propulsors
  - boundary layer ingestion
  - distributed propulsion

# Overview of Select Studies

- The Boeing SUGAR Volt[1]
  - design was an extension of the SUGAR High,[2] which used a parallel hybrid electric drive concept
  - Although the fuel and emission goals were met, it was found that the overall vehicle energy efficiency was not improved
- N3-X[3]
  - Fully turboelectric and fully distributed propulsion using superconducting electric machines and power distribution
  - Approximately 50 percent of the fuel consumption improvement came from the airframe configuration, and another 20 percent from the turboelectric distributed propulsion

| | Improvements Relative to Baseline[a] | | |
|---|---|---|---|
| | Noise Margin[b] | LTO NOx[c] | Fuel Consumption |
| **N+3 Goals** | **52 dB** | **80%** | **60%** |
| SUGAR High[2] | 23 to 30 dB | 78 % | 54% |
| [d]SUGAR Volt[1] | 24 to 31 dB | 83 to 90% | 60% |
| MIT D8.5 [4] | 60 dB | 87% | 70% |
| [d]N3-X[3] | 32 to 64 dB | 85% | 70% |

# Example aircraft concepts

- **STARC-ABL 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

- **Thin Haul concept**
  - 9 passenger plane, battery powered with turbine range extender
  - Much more efficiency, cost effective and quiet than comparable aircraft

IMPACT: Drastically increase use of small and medium airports and cut emissions

- Key Technologies
  - Aircraft System Analysis – modeling, analysis compared to key metrics
  - Propulsion/Airframe Integration – Blown wing and possible fuselage boundary layer ingestion (BLI) (0-200 knots)
  - Energy Sources – advanced batteries, structural batteries, fuel cells
  - Flight Controls – possible opportunities to reduce control surfaces

# Hybrid Electric Subproject

- The Hybrid Gas Electric Subproject (HGEP) of AATT has been envisioned as a long-term development effort to mature technologies and close gaps in key performance parameters for electric machines and power systems.

- The subproject investment is partitioned between
  - aircraft configuration system studies
  - power system studies and testing
  - advancement of electric machines and power electronics
  - development of enabling magnetic, insulation, and conductor materials.

# Hybrid Propulsion Technical Development

**For closure at aircraft level with net energy benefit, need subsystem improvements**

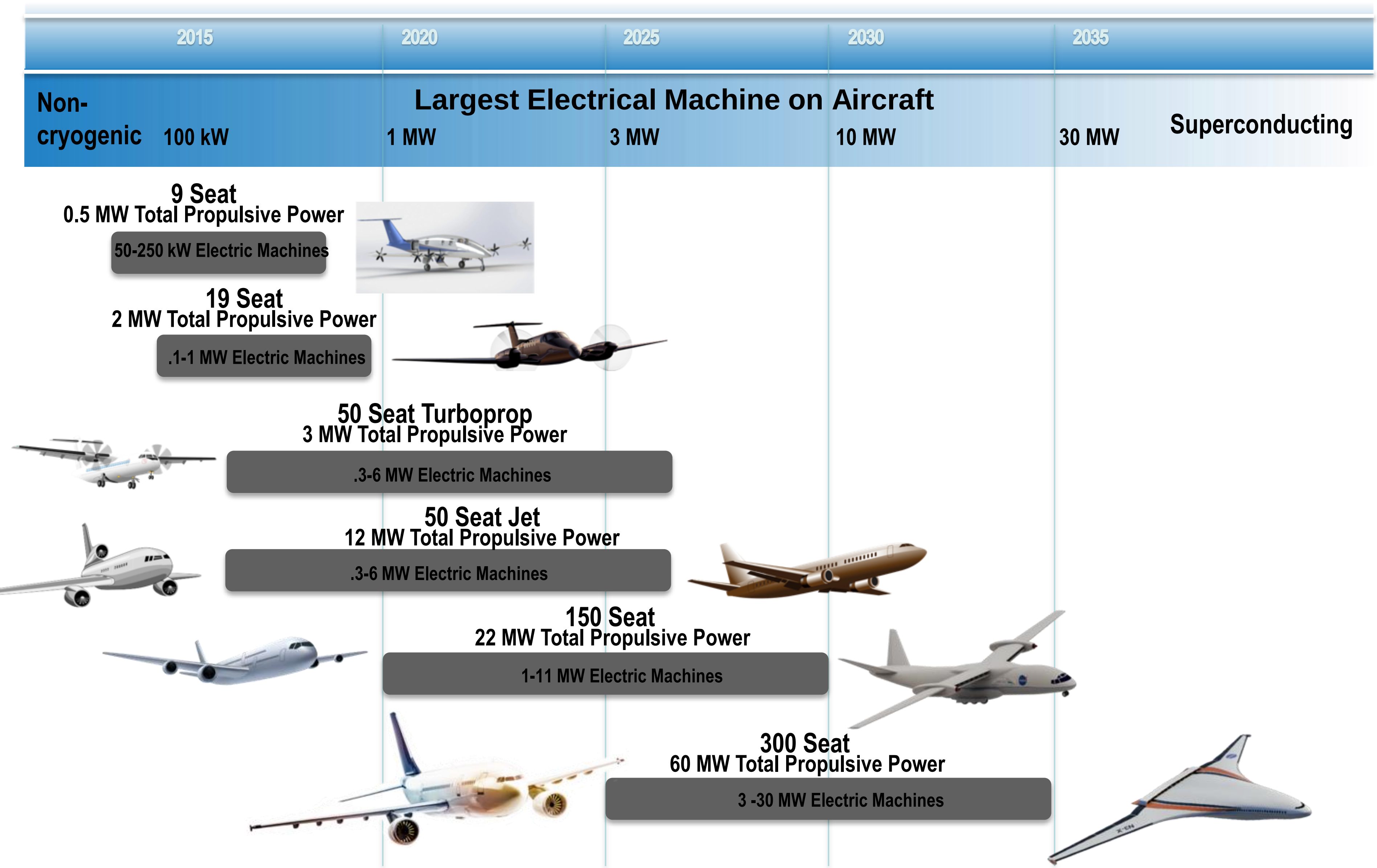
| | All Electric | All Turbo-electric | Hybrid Turbo Fan | Partial Turbo-electric |
|---|---|---|---|---|
| Electric Drive System | high | high | high | high |
| Turbine Power Extraction | low | high | med. | high |
| Thermal Management Systems | high | high | high | high |
| Energy Storage | high | low | high | med. |

Starting with Electric Drive System technology as foundational and highest risk.

# AATT-HGEP Technology Metrics

- The subproject has defined key performance metrics to inform component and material development investments.
- For the motor and power electrics system
  - Specific power and efficiency are used as the two key performance parameters (KPPs) of the electric drive system
  - Specific Power is the ratio of the rated power to mass of the system.
  - Efficiency is the ratio of the output to the input power of the system.
  - Additionally, the system boundaries are carefully and consistently defined to maintain consistent comparisons across technologies.

# Timeline of Machine Power with Application to Aircraft Class



# Summary of Motor and Inverter NASA Research Announcement work

## NASA Sponsored Motor Work

- **1MW**
- **Specific Power > 8HP/lb (13.2kW/kg)**
- **Efficiency > 96%**
- **Awards**
  - 3 years (Phase 1, 2, 3)
  - University of Illinois
  - Ohio State University
- **Phase 1 work completed**

**Ambient Motor Requirements**

| Key Performance Metrics | Specific Power (kW/kg) | Specific Power (HP/lb) | Efficiency (%) |
|---|---|---|---|
| Goal | 13.2 | 8.0 | 96 |

## NASA Sponsored Inverter work

- **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

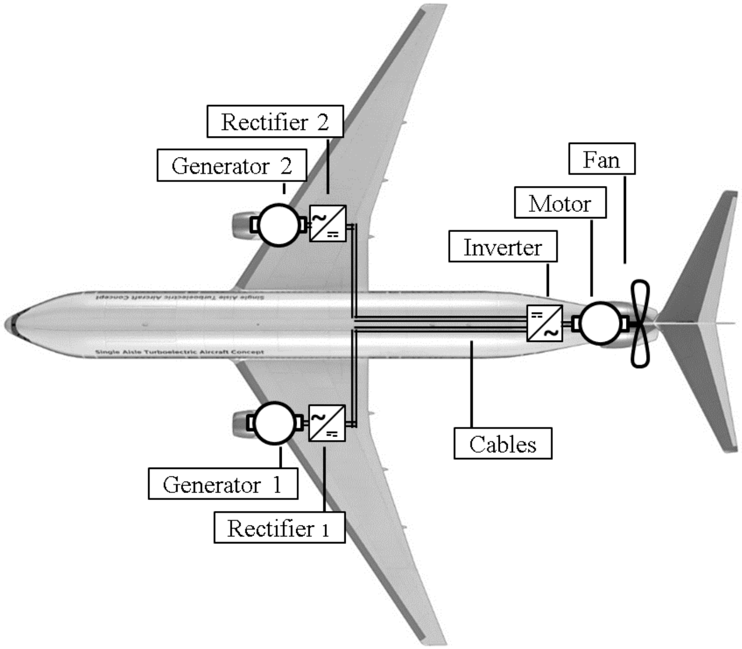
**Ambient Inverter Requirements**

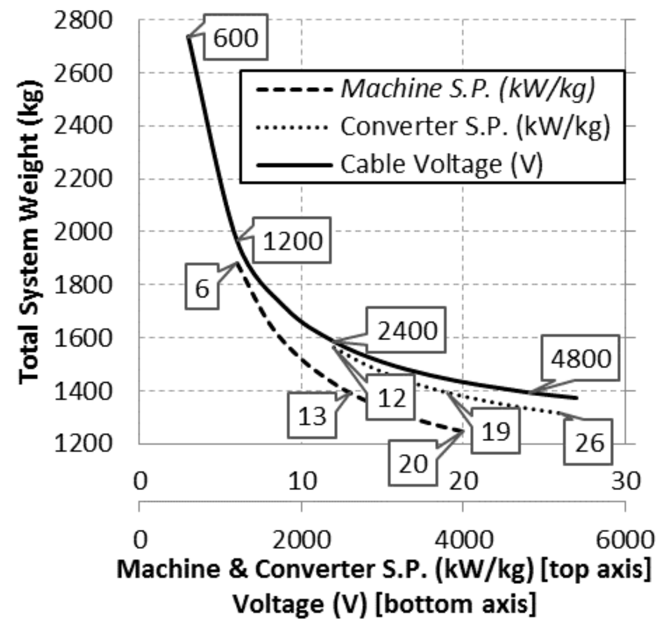
| Key Performance Metrics | Specific Power (kW/kg) | Specific Power (HP/lb) | Efficiency (%) |
|---|---|---|---|
| Minimum | 12 | 7.3 | 98.0 |
| Goal | 19 | 11.6 | 99.0 |
| Stretch Target | 25 | 15.2 | 99.5 |

**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 |

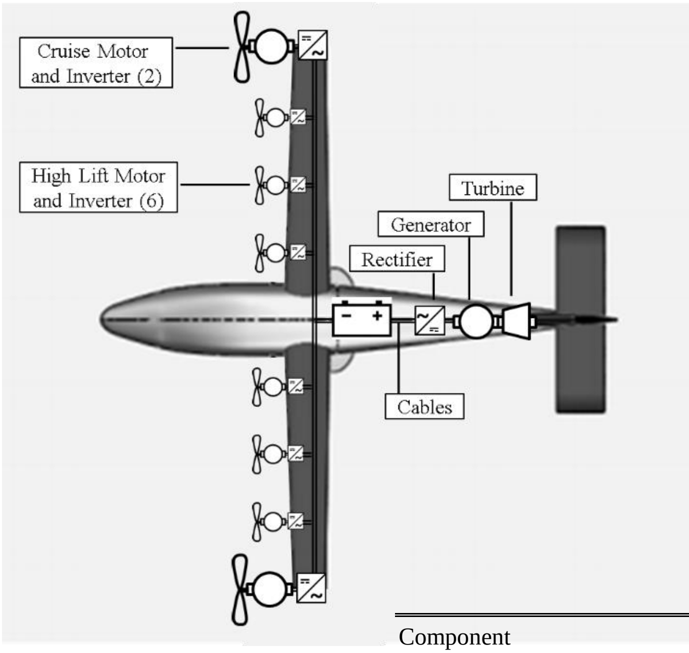
# Sizing Power Components of an Electrically Driven Tail Cone Thruster

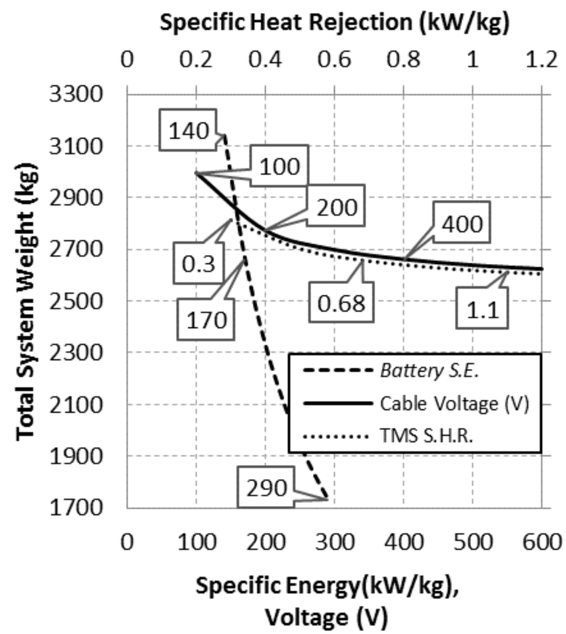



| Component | Quantity | Specific Power | Efficiency (%) | Power (kW) | Weight (kg) | Losses (kW) |
|---|---|---|---|---|---|---|
| Generator (2) | 2 | 13.0 kW/kg | 96.0% | 1400 | 215 | 117 |
| Rectifier (2) | 2 | 19.0 kW/kg | 99.0% | 1386 | 146 | 28 |
| Cable | 2 | 170 A/(kg/m) | 99.6% | 1380 | 192 | 11 |
| Circuit Protection | 4 | 200 kW/kg | 99.5% | 1373 | 13.6 | 28 |
| Inverter | 1 | 19.0 kW/kg | 99.0% | 2719 | 143 | 27 |
| Electric Motor | 1 | 13.0 kW/kg | 96.0% | 2610 | 201 | 109 |
| Thermal System | | 0.68 kW/kg | | 291 | 470 | |
| Total System | | | 89.1% | | 1394 | 320 |

# Sizing Power Components of a Range Extender




| Component | Quantity | Specific Power | Efficiency | Size | Weight (kg) | Losses (kW) |
|---|---|---|---|---|---|---|
| Battery | 1 | 208 W-hr/kg | 93.0% | 381 kW | 1833 | 36 |
| Generator | 1 | 6.0 kW/kg | 96.0% | 230 kW | 38.3 | 10 |
| Rectifier | 1 | 13.0 kW/kg | 98.0% | 225 kW | 17.3 | 5 |
| Cable (2 pairs × 33 ft), 400 V/477 A) | 2 | 170.0 A/(kg/m) | 99.6% | 191 kW | 112.1 | 2 |
| Circuit Protection (inverters, battery, rectifier) | | 200.0 kW/kg | 99.5% | 754 kW | 3.8 | 0 |
| High Lift Inverter | 6 | 13.0 kW/kg | 98.0% | 34 kW | 15.9 | 4 |
| High Lift Motor | 6 | 6.0 kW/kg | 96.0% | 33 kW | 33.0 | 8 |
| Cruise Inverter | 2 | 13.0 kW/kg | 98.0% | 156 kW | 24.0 | 6 |
| Cruise Electric Motor | 2 | 6.0 kW/kg | 96.0% | 150 kW | 50.0 | 13 |
| Thermal Management System | | 0.68 kW/kg | 0.0% | 83kW | 122.6 | |
| Total System | | | 82.1% | | 2250 | 83 |

# Conclusion

- Efforts to provide partially or fully electric propulsion for passenger aircraft are aided greatly by early infusion of electric components into propulsion strings in lower power applications—either in small flight demonstrations or in commercial use.
- The technology is disruptive to the degree that systems interactions such as controls, cooling, operations, and maintenance will need to be exercised and optimized
- Tail cone thruster sizing study
  – Bus voltage and resultant cable weight is a very important driver of power system weight. Voltage should be above 1000V.
- Range extender sizing study
  – Battery specific energy is very important.
  – Bus voltage is can have an impact is below a 200V