Superconducting Turboelectric Distributed Aircraft Propulsion

Michael Armstrong
Rolls-Royce North American Technologies Inc

• Cryogenic Engineering Conference / International Cryogenic Materials Conference
• July 1, 2015
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Our engines keep up **400,000** people in the air at any one time

**Defence Aerospace**
160 armed forces around the world depend on our engines

**Marine**
30,000 commercial and naval vessels use our marine equipment

**Power Systems**
Develop, produce and service energy markets under the MTU and Bergen engine brands

**Nuclear**
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A brief history of Rolls-Royce

1884 FH Royce & Co
1899 Royce Ltd

1904 Rolls meets Royce
1914 1st R-R Aero Engine

1906 Rolls-Royce Ltd
1914 1st R-R Aero Engine

1931 'R' Engine wins Schneider Trophy
1940s R-R begins Gas Turbine Development

1940 Merlin helps win Battle of Britain
1953 Dart & Avon enter Civil Market

1960 1st run of RB211
1966 Bristol Aero Engines acquired

1969 1st run of Trent
1999 Vickers acquired

2013 TrentXWB Certification
2000 BMW Aero Engs acquired

1880 1900 1920 1940 1960 1980 2000


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The move to the More Electric Engine & more!
The S-Curve of Technology Cycles

- Innovation:
  - Evolutionary
  - Disruptive

- Aircraft Engines
  - What's Next?
  - Brayton Turbofan
  - Incremental Improvements
    - Smaller and more efficient core, increased bypass ratio
  - Brayton Turbojet
  - Otto cycle IC

- Capability or Value vs. Time or Investment $
Presentation Outline

• Hybrid/Distributed Propulsion Aircraft

• TeDP Superconducting Electrical System Architecture

• Electrical System Requirements and Sensitivities

• Cryogenic Systems Targets
The move to a Electric Aircraft Propulsion

• Over the last 100 years transportation has become increasingly electrified

• Increased sharply over the last decade with the Boeing 787 ‘More Electric Aircraft’

• As we look to the future this trend will only increase...

• ... and the Engineering challenges are great!
How the More Electric Aircraft has changed the Gas Turbine

Progression of Aircraft Electrical Power Requirements

- **Power Requirements [kW]**
  - 10000+
  - 1500
  - 1000
  - 500

- **Year**
  - 1980
  - 1990
  - 2000
  - 2010
  - 2020
  - 2030

- **Aircraft Types**
  - Conventional
  - More Electric Aircraft
  - Hybrid / All Electric Aircraft

- **Examples**
  - B767
  - F4 - 60kW
  - F14
  - A380
  - F35
Large Bypass Challenges

\[ \eta_p = \frac{2}{1 + \frac{\text{Thrust Velocity}}{\text{Aircraft Velocity}}} \]

- **RB211**
  - Bypass Ratio = 5
  - Dia = 2.15m

- **Trent 1000**
  - Bypass Ratio = 11
  - Dia = 2.85m

Thrust Distribution

Wright Flyer (chain drive)

NASA STOL Transport (Pneumatic bleed driven)

ADAM III Fighter (hot gas redirection)

NASA CESTOL Aircraft (multiple engines)

Cambridge-MIT SAX-40 (mechanical shafting/gears)

Rolls-Royce Lift System (mechanical, bleed, and hot gas redirection)
Distributed Propulsion with Boundary Layer Ingestion

Benefit of BLI:
- Improves overall vehicle propulsive efficiency by reenergising low energy low momentum wake flow

![Conventional Propulsion](image1)

![Ideal BLI Propulsion](image2)

Distributed Propulsion Benefits

1. Maximises opportunity for BLI
2. Facilitates installation of low specific thrust propulsion
3. Structural efficiency/optimised propulsion system weight
4. Minimises asymmetric thrust, reducing vertical fin area
5. Reduced jet velocity & jet noise
Functional Implementation of Electric Propulsion

- Coupled Power Production and Propulsion Functions
- Decoupled Propulsion and Aircraft Aero Functions

- Coupled Power Production and Propulsion Functions
- Largely Decoupled Propulsion and Aircraft Aero Functions
- Alternative Source For Energy Storage

- Decoupled Power Production and Propulsion Functions
- Coupled Propulsion and Aircraft Aero Functions
- Optional alternative Source For Energy Storage
N3-X TeDP Vehicle Concept

### Aircraft Attributes

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>7500nm</td>
</tr>
<tr>
<td>Payload</td>
<td>118100 lbm</td>
</tr>
<tr>
<td>$M_{cruise}$</td>
<td>0.84</td>
</tr>
<tr>
<td>Cruise alt</td>
<td>34,000 ft</td>
</tr>
<tr>
<td>$F_n$ - lbf</td>
<td>85,846</td>
</tr>
<tr>
<td>$TSFC$ – lbf/hr/lbf</td>
<td>0.2174</td>
</tr>
<tr>
<td>Effective BPR</td>
<td>36.1</td>
</tr>
<tr>
<td>Empty Weight</td>
<td>420,000 lbm (Baseline B777-200LR) (Δ69,197)</td>
</tr>
<tr>
<td>Block Fuel Weight</td>
<td>76,171 lbm (Baseline B777-200LR) (Δ203,629)</td>
</tr>
<tr>
<td>Number of Propulsors</td>
<td>16 (function of aircraft width, FPR, boundary layer, and net thrust)</td>
</tr>
<tr>
<td>Thrust Power Required</td>
<td>~50MW</td>
</tr>
<tr>
<td>Motor/propulsor</td>
<td>~3.3 MW</td>
</tr>
</tbody>
</table>

Cryogenically Cooled Superconducting DC TeDP Electrical System

- Tasked with providing aircraft propulsion and some level of differential thrust for directional control
Power Systems Architectures

- Multi-kV power system architecture and associated control system for transmission and use of multi-MW power in aircraft
- Integrated thermal management and motor control schemes
- Enabling materials and manufacturing technologies
TeDP Architecture Design

Challenge in defining a Safety Critical, Flight Weight, Superconducting, DC Microgrid

- Off-nominal requirements drive the overall mass and efficiency of the system

<table>
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<th>Architecture Requirements</th>
<th>Dynamic Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Reliability</td>
<td>• Regulation</td>
</tr>
<tr>
<td>• Redundancy</td>
<td>• Response</td>
</tr>
<tr>
<td>• Reconfigurability</td>
<td>• Recovery</td>
</tr>
</tbody>
</table>

Multiple transmission lines and feeders provide spatial redundancy

Decoupling power and propulsion function provides beneficial flexibility
- Eliminate adverse yaw with OEI and branch failures
Overall System

- Definitions
  - Turbogen (x2)
    - Turbine Engine
    - Generator (x2)
  - Branch (x4)
    - Generator
    - Rectifier
    - Transmission Lines
    - Associated Protection
    - Bus
    - Primary Feeders (x4)
    - Propulsor (x4)
  - Feeder (x32)
    - Primary (x16)
    - Secondary (x16)
  - Propulsor (x16)
    - Motor
    - Converter
    - Fan

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Overall System

- **Protection Equipment**
  - Coordination of Superconducting fault current limiters (SFCL) and solid state circuit breakers (SSCB)

- **Reconfigurability**
  - Distribution Interconnectivity
  - Primary/Secondary Propulsor Feeders
  - UPS (SMES Energy Storage)

- **Branch Similarity**
  - Equivalent number of propulsors per bus and per engine
  - Common component rating between branches
  - Similar performance lapse with failures

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OEI Power Rerouting

- Engine sees step change in power required from 50% to 100%
- System sized by fail safe requirements

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Operating Voltage Standards

- Bulk Power, Microgrid, Marine, and Aerospace voltage standards have repeating themes:
  - Steady state regulation
  - Transient behavior
  - Fault tolerance and recovery
  - Distortion and harmonics

- Unique airborne, flight critical, superconducting TeDP microgrid considerations:
  - Regulated utilization equipment loads
  - FAR imposed segregation, redundancy, response
  - Pressurized fluid environment
Operating Voltage Standards

- Aircraft electrical safety has not been designed to optimize the electrical system but resulted from either what has always been done or conservative estimates
  - The electrical system has not considered what is possible but what has been
  - The TeDP system has the opportunity to be designed by what is possible and requires this to achieve the benefits of the TeDP

- Why current voltage levels?
  - First airplanes used car batteries which had cell voltage that were in multiples of 6 so a voltage of 24VDC was initially used
  - The 270 voltage level result of Paschen’s curve

- Standards typically evolve slowly. TeDP systems are a radical departure.
  - IEEE Std. 1709
Terrestrial Superconducting Systems

Voltage Range

- Preliminary voltage range baselined against conventional terrestrial systems
  - Min of 0.8kA, Max of 10kA*
  - Preliminary voltage range of 2.5 kV to 40kV

*EPRI discusses a 100kA upper limit for terrestrial power distribution, Adopting this range would yield a lower limit of 250V

Integration of superconducting component into normally conducting system
Architecture Decomposition

- 440 pieces of electrical equipment
  - 20 machines
  - 20 converters
  - 20 AC Cables
  - 36 DC Cables (bi-polar)
  - 206 SSCBs (1 per phase, 1 per pole)
  - 136 SFCLs (1 per phase, 1 per pole)
  - 4 SMES (w/ h-bridge)

- Each component to be decomposed to the device level for system sizing and sensitivity trades

Baseline system equipment list for 25MW thrust power rated system

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Count</th>
<th>Single engine out rating at takeoff (MW)</th>
<th>Nominal rating at cruise (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Machines</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generator</td>
<td>4</td>
<td>12.5</td>
<td>6.25</td>
</tr>
<tr>
<td>Motor</td>
<td>16</td>
<td>1.79</td>
<td>1.5625</td>
</tr>
<tr>
<td>Converter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC/DC converter</td>
<td>4</td>
<td>12.5</td>
<td>6.25</td>
</tr>
<tr>
<td>DC/AC inverter</td>
<td>16</td>
<td>1.79</td>
<td>1.5625</td>
</tr>
<tr>
<td>DC/DC converter for SMES</td>
<td>4</td>
<td>12.5</td>
<td>0</td>
</tr>
<tr>
<td>Cables</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>4</td>
<td>12.5</td>
<td>6.25</td>
</tr>
<tr>
<td>Transmission</td>
<td>4</td>
<td>12.5</td>
<td>6.25</td>
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<tr>
<td>Feeder</td>
<td>16</td>
<td>1.79</td>
<td>1.5625</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>1.34</td>
<td>0</td>
</tr>
<tr>
<td>Breakers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>12</td>
<td>12.5</td>
<td>6.25</td>
</tr>
<tr>
<td>48</td>
<td>1.79</td>
<td>1.5625</td>
<td></td>
</tr>
<tr>
<td>DC</td>
<td>16</td>
<td>12.5</td>
<td>6.25</td>
</tr>
<tr>
<td>64</td>
<td>1.79</td>
<td>1.5625</td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>1.34</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>SFCL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>12</td>
<td>12.5</td>
<td>6.25</td>
</tr>
<tr>
<td>48</td>
<td>1.79</td>
<td>1.5625</td>
<td></td>
</tr>
<tr>
<td>DC</td>
<td>8</td>
<td>12.5</td>
<td>6.25</td>
</tr>
<tr>
<td>32</td>
<td>1.79</td>
<td>1.5625</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>1.34</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>12.5</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>En. storage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMES</td>
<td>4</td>
<td>12.5</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>440</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Complete microgrid configuration with unique sizing objectives

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Voltage Sensitivity Model Integration

Architecture

Systems

Interactions and Interdependencies

Components

Derived Requirements

Subcomponents
Architecture Decomposition

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# Component Descriptions

<table>
<thead>
<tr>
<th>Component</th>
<th>Assumptions</th>
<th>Image/Diagram</th>
</tr>
</thead>
</table>
| **Electric Machines** | • Superconducting machines with BSCCO rotor and stator windings  
      • Sizing models provided by NASA                                                                                                             |               |
| **Power Electronics** | • Current source converters with low temperature IBGT switching operation *(scaling from state of the art IGBT data)*  
      • Presspack diodes for overvoltage protection *(scaling state of the art diode data)*  
      • Layered aluminum polypropylene film capacitor  
      • LN$_2$ cooled superconducting inductor  
      • Packaging estimates by extrapolation from state of the art                                                                                   |               |
| **Cables**       | • Nexans triax bipolar DC cable topology with YBCO tape superconductor  
      • Vacuum jacket insulation with heat leakage  
      • Conduction losses sensitive to critical current margin  
      • Laminated Polypropylene Paper dielectric protection  
      • LN2 cooled  
      • Weight and geometry sensitive to required layer thicknesses                                                                                   |               |

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## Component Descriptions

<table>
<thead>
<tr>
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<th>Image/Diagram</th>
</tr>
</thead>
</table>
| **SFCL** | • Solonoidal resistive type SFCL  
• BSCCO windings with quench transition dynamics sensitive to fault current ratio  
• LN$_2$ sub-cooling (*assuming no boil-off cooling*) | ![SFCL Diagram](image) |
| **SSCB** | • Solid state circuit breaker with surge arrester,  
• Low temperature IGBT switching operation  
• (*Similar sizing approach to converter sizing*) | ![SSCB Diagram](image) |
| **SMES** | • Toroidal SMES inductor with layered Force Balance Coil (FBC) winding configuration  
• Application of Moone’s approach using virial theorem to estimate structural mass  
• H-bridge for charge and discharge  
• Hydrogen cooled YBCO superconductor | ![SMES Diagram](image) |
| **Cryo Systems** | • Estimated 30% Carnot efficiency Brayton cycle  
• Assumed 3 kg/kW power density for cryocooler | ![Cryo Systems Diagram](image) |

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Selection of $V_{\text{nom}}$

- **Trends are dominated by the mass and the conduction and switching losses from semiconductors**
  - SSCB’s and Power Electronics
  - Inefficiency $\rightarrow$ Cryocooling requirements

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### Effect of Protection Solution Architecture and Technology Improvements

#### Nominal Voltage Range Selection
- Semiconductor efficiency characteristics play a major role in sizing system.
- Minimize mass by improving component performance or removing semiconducting equipment from the system.

<table>
<thead>
<tr>
<th>Architecture Improvement</th>
<th>Technology Improvement</th>
<th>Baseline switching loss</th>
<th>50% improvement in converter losses</th>
<th>90% improvement in converter losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline system</td>
<td></td>
<td>±4.5 kV</td>
<td>±4.5 kV</td>
<td>±4.5 kV</td>
</tr>
<tr>
<td>W/o protection SSCBs and all SFCLs</td>
<td></td>
<td>±3 kV</td>
<td>±3 kV</td>
<td>±4.5 kV</td>
</tr>
<tr>
<td>W/o energy storage, protection SSCBs and SFCLs</td>
<td></td>
<td>±2 kV</td>
<td>±3 kV</td>
<td>±4.5 kV</td>
</tr>
</tbody>
</table>

The material is based upon work supported by the National Aeronautics and Space Administration under Contract Number NNC13TA7T.
Challenge: Lightweight, Efficient, Reliable, >1kW Cryocoolers

Cryogenic Cooling for Distributed Propulsion

![Image of cryocooler](image-url)

**Projected Development of Aerospace Cryocoolers**

- **Actual**
- **Estimated**

NASA/DEAP project 2035 Target ~ 3 kg/kW

**Aerospace Cryocooler Specific Mass (kg/kW Input Power)**

- **2050**
- **2040**
- **2030**
- **2020**
- **2010**
- **2000**
- **1990**
- **1980**

**Courtesy of NASA**
# Lightweight Cryogenic Technology Needs

## Cryocooler

**Compressor**
- Use of aerospace technology; multi-stage axial flow compressors

**Cycle Design**
- Combined cycle and recuperation, exploitation of synergies with other systems (ECS, Gas Turbine, fuel systems)

**Heat Exchangers**
- High surface area, ultra lightweight heat exchangers

## Cryogenic System

**Materials**
- Aerospace materials and coatings; hydrides, alloys, ceramics, composites, laminates

**Cryostat**
- Actively monitored cryostat with reactive vacuum and boil-off control

**Cryogen Storage**
- Low-mass, high strength storage vessels with diffusion protective coatings
Cryogenic System

- Coordinated Design of Cryogenic Cooling System and Electrical System Zonal Protection
  - Distributed and/or Centralized Cryo-Cooling Systems
  - Fault accommodation and cascading failures
  - Mass minimization

20% Variability in Cryogenic System Mass Due to Architecture
## TeDP Electrical Systems Observations

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<td>• Recovery</td>
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</tbody>
</table>

- **Medium voltage system balances electrical equipment weight with cryocooling penalties**
- **Need for semiconductor technology improvements and protection system architectures to minimize mass, losses, and cryocooling requirements**
- **Dynamic protection and conversion requirements have large impact on overall system mass and efficiency**
- **Need coordinated cryogenic system and electrical system transient analysis to verify and ensure safety, stability, and efficiency and confirm protection requirements**

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Conclusions

• Advancements in superconducting technologies and cryocooling solutions have the potential to provide revolutionary improvements air vehicle performance
• Many technical challenges remain to realize large platform hybrid/distributed electric propulsion
• Many of the TeDP electrical systems design challenges are cryogenic challenges
• Feasibility/viability of TeDP systems require light weight solutions which afford the required redundancy, reliability, and maintainability
• An integrated architecting approach (electric and cryo systems) is necessary to realize potential vehicle benefits

Thank you for your time & attention
Questions?