Superconducting Turboelectric Distributed Aircraft Propulsion

Michael Armstrong
Rolls-Royce North American Technologies Inc

- Cryogenic Engineering Conference / International Cryogenic Materials Conference
- July 1, 2015
Rolls-Royce Products Today

**Civil Aerospace**
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**
Design authority for the Royal Navy's naval nuclear plant.
A brief history of Rolls-Royce

1884 FH Royce & Co
1906 Rolls-Royce Ltd
1931 'R' Engine wins Schneider Trophy
1940 Merlin helps win Battle of Britain
1969 1st run of RB211
1990 1st run of Trent
2013 TrentXWB Certification

1880 1900 1920 1940 1960 1980 2000

1880 1900 1920 1940 1960 1980 2000

1904 Rolls meets Royce
1914 1st R-R Aero Engine
1940s R-R begins Gas Turbine Development
1953 Dart & Avon enter Civil Market
1966 Bristol Aero Engines acquired
1999 Vickers acquired
2000 BMW Aero Engs acquired
1995 Allison acquired

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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

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Power Requirements [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>500</td>
</tr>
<tr>
<td>1990</td>
<td>1000</td>
</tr>
<tr>
<td>2000</td>
<td>1500</td>
</tr>
<tr>
<td>2010</td>
<td>10000+</td>
</tr>
<tr>
<td>2020</td>
<td>10000+</td>
</tr>
<tr>
<td>2030</td>
<td>10000+</td>
</tr>
</tbody>
</table>

- **Conventional B767**
- **F4 - 60kW**
- **F14**
- **A380**
- **B787**
- **More Electric Aircraft**
- **F35**
- **Hybrid / All Electric Aircraft**
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)

ADAM III Fighter
(hot gas redirection)

NASA STOL Transport
(Pneumatic bleed driven)

NASA CESTOL Aircraft
(multiple engines)

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

Rolls-Royce Lift System
(mechanical, bleed, and hot gas redirection)

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Distributed Propulsion with Boundary Layer Ingestion

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

1. Maximises opportunity for BLI
2. Facilitates of 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

Viscous drag build up with BLI (Cores under wing)

\[ CD_{viscous} = CD_{friction} + CD_{form} \]

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD_{viscous} (upper)</td>
<td>26.3</td>
</tr>
<tr>
<td>CD_{viscous} (ingested)</td>
<td>10.67</td>
</tr>
<tr>
<td>CD_{friction} (upstream of slot)</td>
<td>7.8</td>
</tr>
<tr>
<td>Totals:</td>
<td>46.83</td>
</tr>
</tbody>
</table>

\[ \Delta CD_{viscous} = -0.57 \]

\[ \% Aircraft drag = -0.4\% \]
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

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range</strong></td>
<td>7500nm</td>
</tr>
<tr>
<td><strong>Payload</strong></td>
<td>118100 lbm</td>
</tr>
<tr>
<td><strong>M&lt;sub&gt;cruise&lt;/sub&gt;</strong></td>
<td>0.84</td>
</tr>
<tr>
<td><strong>Cruise alt</strong></td>
<td>34,000 ft</td>
</tr>
<tr>
<td><strong>RTO</strong></td>
<td>85,846</td>
</tr>
<tr>
<td><strong>TOC</strong></td>
<td>33,405</td>
</tr>
<tr>
<td><strong>TSFC – lbm/hr/lbf</strong></td>
<td>0.2174 / 0.3125</td>
</tr>
<tr>
<td><strong>Effective BPR</strong></td>
<td>36.1 / 30.1</td>
</tr>
<tr>
<td><strong>Empty Weight</strong></td>
<td>420,000 lbm (Baseline B777-200LR) (Δ69,197)</td>
</tr>
<tr>
<td><strong>Block Fuel Weight</strong></td>
<td>76,171 lbm (Baseline B777-200LR) (Δ203,629)</td>
</tr>
<tr>
<td><strong>Number of Propulsors</strong></td>
<td>16 (function of aircraft width, FPR, boundary layer, and net thrust)</td>
</tr>
<tr>
<td><strong>Thrust Power Required</strong></td>
<td>~50MW</td>
</tr>
<tr>
<td><strong>Motor/propulsor</strong></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

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*Revolutionary Aeropropulsion concept for Sustainable Aviation - Turboelectric Distributed Propulsion* ISABE-2013-1719

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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>
<thead>
<tr>
<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>
Architecture Overview

- Multiple transmission lines and feeders provide spatial redundancy
- Decoupling power and propulsion function provides beneficial flexibility
  - Eliminate adverse yaw with OEI and branch failures

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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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OEL 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

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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 resulted from 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


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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

Complete microgrid configuration with unique sizing objectives

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 (16x5m)</td>
<td>6.25</td>
</tr>
<tr>
<td>16</td>
<td>1.79 (16x5m)</td>
<td>1.5625</td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td>4</td>
<td>12.5 (2x30m, 2x40m)</td>
<td>6.25</td>
</tr>
<tr>
<td>Feeder</td>
<td>16</td>
<td>1.79 (16x5m)</td>
<td>1.5625</td>
</tr>
<tr>
<td>16</td>
<td>1.34 (16x5m)</td>
<td>0</td>
<td></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 (16x5m)</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 (16x5m)</td>
<td>1.5625</td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>1.34 (16x5m)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>12.5 (16x5m)</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 (16x5m)</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 (16x5m)</td>
<td>1.5625</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>1.34 (16x5m)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>12.5 (16x5m)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>En. storage SMES</td>
<td>4</td>
<td>12.5</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>440</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The material is based upon work supported by the National Aeronautics and Space Administration under Contract Number NNC13TA7T.
Voltage Sensitivity Model Integration

Architecture

Requirements and Configurations

Systems

Interactions and Interdependencies

Components

Derived Requirements

Subcomponents

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## Component Descriptions

<table>
<thead>
<tr>
<th>Component</th>
<th>Assumptions</th>
<th>Image/Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Machines</td>
<td>• Superconducting machines with BSCCO rotor and stator windings&lt;br&gt;• Sizing models provided by NASA</td>
<td><img src="image1.png" alt="Electric Machines Diagram" /></td>
</tr>
<tr>
<td>Power Electronics</td>
<td>• Current source converters with low temperature IBGT switching operation <em>(scaling from state of the art IGBT data)</em>&lt;br&gt;• Presspack diodes for overvoltage protection <em>(scaling state of the art diode data)</em>&lt;br&gt;• Layered aluminum polypropylene film capacitor&lt;br&gt;• LN$_2$ cooled superconducting inductor&lt;br&gt;• Packaging estimates by extrapolation from state of the art</td>
<td><img src="image2.png" alt="Power Electronics Diagram" /></td>
</tr>
<tr>
<td>Cables</td>
<td>• Nexans triax bipolar DC cable topology with YBCO tape superconductor&lt;br&gt;• Vacuum jacket insulation with heat leakage&lt;br&gt;• Conduction losses sensitive to critical current margin&lt;br&gt;• Laminated Polypropylene Paper dielectric protection&lt;br&gt;• LN$_2$ cooled&lt;br&gt;• Weight and geometry sensitive to required layer thicknesses</td>
<td><img src="image3.png" alt="Cables Diagram" /></td>
</tr>
</tbody>
</table>

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# Component Descriptions

<table>
<thead>
<tr>
<th>Component</th>
<th>Assumptions</th>
<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)* | ![Image](image1.png) |
| **SSCB** | - Solid state circuit breaker with surge arrestor,  
- Low temperature IGBT switching operation  
- *(Similar sizing approach to converter sizing)* | ![Image](image2.png) |
| **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 | ![Image](image3.png) |
| **Cryo Systems** | - Estimated 30% Carnot efficiency Brayton cycle  
- Assumed 3 kg/kW power density for cryocooler | ![Image](image4.png) |

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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>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline switching loss</td>
</tr>
<tr>
<td>Baseline system</td>
<td>±4.5 kV</td>
</tr>
<tr>
<td>W/o protection SSCBs and all SFCLs</td>
<td>±3 kV</td>
</tr>
<tr>
<td>W/o energy storage, protection SSCBs and SFCLs</td>
<td>±2 kV</td>
</tr>
</tbody>
</table>

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Challenge: Lightweight, Efficient, Reliable, >1kW Cryocoolers

Cryogenic Cooling for Distributed Propulsion

Projected Development of Aerospace Cryocoolers

Aerospace Cryocooler Specific Mass (kg/kW Input Power)

Actual

Estimated

NASA/DEAP project 2035 Target – 3 kg/kW

Courtesy of NASA

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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

![Graph showing 20% Variability in Cryogenic System Mass Due to Architecture]
## TeDP Electrical Systems Observations

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

- **Medium voltage system** balances electrical equipment weight with cryocooling penalties.
- **Dynamic protection and conversion requirements** have large impact on overall system mass and efficiency.

- **Need for semiconductor technology improvements** and protection system architectures to minimize mass, losses, and cryocooling requirements.
- **Need coordinated cryogenic system and electrical system transient analysis** to verify and ensure safety, stability, and efficiency and confirm protection requirements.
Conclusions

• Advancements in superconducting technologies and cryocooling solutions have the potential to provide revolutionary improvements in 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.