KEY REQUIREMENTS FOR AIRCRAFT ENGINES

Frank Haselbach
Global Head of System Design
Rolls-Royce plc

26th September 2016
ICAS conference, Daejeon, South Korea
Rolls-Royce product sectors

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
Reciprocating engines for propulsion and distributed energy systems

Nuclear
Design authority for the Royal Navy's naval nuclear plant
Rolls-Royce in numbers

- 5 major businesses
- 10 seconds between takeoffs
- 200 countries host our customers
- 4500+ large engines are operating today
- 51,000 employees deliver this in OE and services
- 400,000 people in the air relying on our products every moment

2015 financials

<table>
<thead>
<tr>
<th>order book</th>
<th>underlying Group revenue</th>
<th>underlying profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>£76.4 billion</td>
<td>£13.4 billion</td>
<td>£1.43 billion</td>
</tr>
</tbody>
</table>

Original Equipment: 48%  Services: 52%
Research and development

We develop technologies and intellectual property that provide competitive advantage in our chosen markets.

- £1,235m Invested in Research and Development in 2015
- 624 Patent applications in 2015
- 31 University Technology Centres worldwide
Invent once, use many times

- Titanium swept hollow fan is a key technology for the Trent 1000

- Combined into a friction-welded blisk, it powers the Joint Strike Fighter
Key Requirements

- Reliable Partnership
- Competitive, reliable products
- Cutting edge, proven technologies
- Integration capability and systems engineering on highest level
- World class servicing network and capabilities
- Solid industrialisation base and supply chain
- Ability to contribute to complex, multi-decade programmes and endeavours on global scale

…and….‘It shall weigh nothing, cost nothing, use no fuel, have infinite life and clean the air as it flies along…..’
Opportunity

Sources: Mark Litwintschik, Wikipedia, NASA
And we’ve made great progress so far

**CO₂ (Engine)**

- Trent 800
- Trent 500
- Trent XWB
- Trent 900

**NOx (Engine)**

- Trent 800
- Trent 500
- Trent XWB
- Trent 900

**Noise (Aircraft)**

- Trent 800 (Boeing 777)
- Trent 500 (Airbus A340)
- Trent XWB (Airbus A350XWB)
- Trent 1000 (Boeing 787)
- Trent 900 (Airbus A380)

**ACARE goal -75% CO₂ overall reduction:**
- -30% Rolls-Royce contribution*

**ACARE goal -90% NOx overall reduction:**
- -75% Rolls-Royce contribution*
- -15% from operational efficiency improvements

**ACARE goal -65% aircraft noise reduction:**
- -45dB cumulative

*Rolls-Royce provisional estimate - definitive ACARE level TBD

Trent family  ACARE (Advisory Council for Aviation Research and Innovation in Europe) Flightpath 2050 target
Fuel efficiency of long range aircraft

- Comet 4/ Avon
- Trent 1000
- Trent XWB

Engine Fuel Consumption

Aircraft Fuel Burn per Seat

1% fuel burn ~ $200,000 per a/c per year
Some basics

- Core thermal efficiency = \( \frac{E\text{-core}}{E\text{-fuel}} \)
- Transfer efficiency = \( \frac{(E\text{-jets} - E\text{-inlet})}{E\text{-core}} \)
- Propulsive efficiency = \( \frac{Fn.V0}{(E\text{-jets} - E\text{-inlet})} \)

State-of-the-Art Turbofan Cycle Efficiencies

<table>
<thead>
<tr>
<th>Efficiency Type</th>
<th>Thermal</th>
<th>Transfer</th>
<th>Propulsive</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>50%</td>
<td>80%</td>
<td>60%</td>
<td>40%</td>
</tr>
</tbody>
</table>

Rolls-Royce proprietary information
Driving for higher efficiency

Propulsive Efficiency

Approaching Theoretical Limit, of Propulsive Efficiency

Thermal “Cycle” Efficiency

Approaching practical limit for Low NOx combustion?

High temperature, high pressure, smaller cores. Enabled by:
- High efficiency components
- High temperature materials and advanced cooling
  - CMCs,
  - Low NOx combustion
- More novel configurations
  - Cooled cooling air
  - Intercooling

Larger lower pressure ratio, lower speed fans. Enabled by:
- High efficiency fan and LPT
- Lightweight LP systems
  - Composite fan, TiAl
- Lightweight low drag nacelles
- More novel configurations
  - Gear driven fans
  - Variable pitch fans
  - Open rotor
  - Distributed propulsion

Improving specific fuel consumption

Approaching Theoretical Limit, for conventional gas turbines

Near Stoichiometric TET, Ultimate Component Efficiencies

Approaching practical limit for Low NOx combustion?
## Technology programmes

<table>
<thead>
<tr>
<th>Architecture and design</th>
<th>Manufacture</th>
<th>Advanced materials</th>
<th>Intelligent systems</th>
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</thead>
<tbody>
<tr>
<td>Advance</td>
<td>Advanced manufacturing research centres</td>
<td>Advanced alloys</td>
<td>Future systems</td>
</tr>
<tr>
<td>Lean burn combustor</td>
<td>Additive Layer Manufacturing</td>
<td>TiAl</td>
<td>Aerothermal excellence</td>
</tr>
<tr>
<td>UltraFan</td>
<td>Specialist turbine manufacture</td>
<td>Ni Alloys</td>
<td></td>
</tr>
<tr>
<td>Virtual engine</td>
<td></td>
<td>Ceramic Matrix Composites (CMCs)</td>
<td></td>
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<tr>
<td>Small engine core technologies</td>
<td></td>
<td>Lightweight CTi fan system</td>
<td></td>
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<tr>
<td>Small blisked fan</td>
<td></td>
<td>Advanced concepts (Vision 20)</td>
<td></td>
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</tbody>
</table>

Underpinning our Vision strategy
UltraFan™ – key technologies

- **Variable Pitch / Variable Area Nozzle**
- **Low Speed CTi Fan system**
- **High power density gearbox**
- **Fully Integrated slim-line nacelle**
- **Advanced lightweight IMC**
- **Advanced Cooling and CMC aerofoils**
- **Multi Stage high speed IP Turbine**
- **High Aspect Ratio TiAl / CMC IP Turbine Aerofoils**
- **Next Gen High Strength Ni Alloy**

**Key Benefits**
- Fuel Burn
- Environment
- Maintenance
The Backbone: An Agile Design Systems
The optimum validated design in application
Advanced manufacturing research centres

Advanced Manufacturing Research Centre (AMRC) Sheffield 2008
Advanced Forming Research Centre (AFRC) – Glasgow 2010
Manufacturing Technology Centre (MTC) Coventry 2011
Advanced Remanufacturing & Technology Centre (ARTC) Singapore 2013
Network of Advanced Manufacturing Research Centres AxRCs
National Composites Centre (NCC) Bristol 2011
Commonwealth Centre for Advanced Manufacture (CCAM) Virginia 2012
Manufacturing Technology Research Centre Singapore 2011
Nuclear Advanced Manufacturing Research Centre (NAMRC) Sheffield 2011
Comprehensive demonstration

Target Products

Whole Engine & Flight Demo

Core Integration Vehicles

Component / Capability Technologies

Proven maturity through multilevel demonstration
Full scale demonstration

ALPS

Advance

ALECSYS

EFE & HT3

UltraFan
**Getting us closer to our FP2050 goals**

<table>
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<tr>
<th>CO₂ (Engine)</th>
<th>NOx (Engine)</th>
<th>Noise (Aircraft)</th>
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<tbody>
<tr>
<td>[Graph showing CO₂ emissions]</td>
<td>[Graph showing NOx emissions]</td>
<td>[Graph showing noise reduction]</td>
</tr>
<tr>
<td>Trent 800</td>
<td>Trent 800</td>
<td>Trent 800</td>
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<tr>
<td>Trent 500</td>
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**ACARE goal -65% aircraft noise reduction:**
- -45dB cumulative
- Operational improvements and aircraft design will give significant further reductions

[Graph showing ACARE goals]

Rolls-Royce proprietary information
The longer term Future……
Concept studies for Vision 20 and beyond
Vision 20 and beyond

Better power for a changing world
The Design/Make of Tomorrow

ICAS, 26th September 2016
Better power for a changing world