What does the future bring?

A look at Technologies for Commercial Aircraft in the years 2035-2050
OUTLINE

- Demographics and Economics
- The future…What does the customer want?
- The propulsion world going forward
- Airplane Aerodynamics
- Structures, Materials, and Manufacturing
- What does it all mean?
- The challenges and opportunities
Demography
source: UN/ESA World Population Prospects

Populations
Now up to 2100: 10 billions
Europe decreasing after 2020
North America still growing
Asia decreasing after 2050
Africa towards 1/3 of the world!
The Relative Weight of Different Zones is of Importance for the Traffic

GDP en % GDP WORLD
source World Bank + CEPII

Europe
North America
China world
80% of the international demand over the next 20 years will be within Asia-Pacific, North America and Europe
Estimated Fleet Evolution by Aircraft Category

Total number of aircraft doubling between 2010 and 2050

2010: 20331 aircraft

2050: 40593 aircraft

The Future… What Priorities?

What does the customer want?

Speed?
Noise?
Fuel Burn?
Low Cost?
Environment… CO₂, NOₓ, etc?

A delicate balance as we move forward
Competitive Business Environment

**Business Case**
- Development Cost
- Manufacturing Cost
- Revenue Stream
  - Unit Price
  - Sales Volume
  - Spares

**Customer Value**
- Revenue
  - Payload
  - Range
- Cost of Ownership
  - Price
  - Fuel Burn
  - Maintenance Cost

**Aircraft Requirements**
- Passengers
- Cruise Speed & Insertion Altitude
- Balanced Field Length
- Power & Bleed Off-takes

**Regulatory Requirements**
- Safety
- Noise
- Emissions
Propulsion Challenge

Industry Revenue/Profits

Sources: Air Transport Association/Bureau of Transportation Statistics

Airline Operating Costs

Source: A4A Quarterly Cost Index, US Airlines

Regulatory Challenges
- CAEP/6 2008 / 2013
- CAEP/8 2014 / 2018
- EU Carbon Trading 2012
- ICAO CO₂ Standard TBD
- FAR Stage 5 2020

Historical Fuel Prices

>15% Growth Rate

Sources: Air Transport Association, International Air Transport Association

Make airlines more profitable in an increasingly difficult environment

Advanced Concept Design and Challenges for Future Commercial Aircraft Propulsion
11 October 2013
Historical Fuel Burn Improvements

Fuel Efficiency (SFC)

45% Improvement

GE CJ805-23

GENX

OPR, Components & Materials

FPR / BPR
Fuel consumption . . .
Addressing every aspect - sfc

\[
\text{Fuel mileage} = \frac{V \cdot L/D}{sfc \cdot W}
\]

\[
SFC \approx \frac{v_0}{\eta_{\text{overall}} \cdot FHV} = \frac{v_0}{\eta_{\text{thermal}} \cdot \eta_{\text{transfer}} \cdot \eta_{\text{propulsive}} \cdot FHV}
\]

sfc . . . primary propulsion attribute
- Thermal efficiency - High OPR / high temp
  - Diminishing returns, but not at entitlement
  - Need cooled-cooling air or materials, or . . .
  - Component efficiencies and loss minimization
- Propulsive & Transfer efficiency - Low FPR, large fans & enablers
  - Unducted fans, propellers
- Or, new cycles
  - Adaptive or Non-Brayton cycles
  - Pulse detonation, constant volume
Efficiency Trends with Core and Propulsor Improvements

- Propulsion system improvements require advances in both propulsor and core technologies
Variation in Core Power with Turbine Inlet Temperature
Fuel consumption projections
A step-change is coming soon

- Prev Generation BPR=5-8
  2000 SOA
- Cur Generation BPR=8-10
  Products
- Adv Turbo Fans
  with BPR 10-12
- Open Rotor
  BPR>35
- ADVENT & HEETE
- Hvbrids
- Alternative Cycles
- Integrated Propulsion
- Inter-Cooled
- Variable Cycle
New Engine Architectures and New Challenges

• **Geared Turbofan (P&W)**
  • *Small, high density engine core*—required to achieve higher fan bypass ratio without significantly increasing fan diameter
  • *Aerodynamic performance*—larger fan diameter means larger nacelle and higher drag
  • *Installation*—increasingly larger diameter engines means limited application for current, low wing aircraft designs

• **Open Rotor (GE)**
  • *Noise*—rotor blade noise radiates unobstructed to the environment, well above current aircraft noise regulation limits
  • *Installation*—very large blade diameters mean significant aircraft installation problems, perhaps requiring all new aircraft design
  • *Power*—slow, counter-rotating rotors requires novel turbine power distribution designs to optimize turbomachinery efficiency
Pratt & Whitney Geared TurboFan (GTF)

- Low PR Fan
- Low Tip Speed
- BPR ~ 9 - 12

- Fan Drive Gear System
- 5 Planets
- Gear Ratio ~ 3

- Low-Emissions Combustor
- High-Speed Low Spool
- Compact LPC, LPT

Fundamental Aeronautics Program
PW Geared V.S. LEAPx Fuel Burn Evaluation

Geared turbo fan: 81” dia.

Engine SFC: 0.3%

Propulsion Systems: 0.5%

+0.7%

+0.9%

+1.6%

+0.3%

+0.3%

+0.2%

.8%

LEAP-X Adv.

Gear Box

Frame & Heat Exchanger losses

Improved BPR, Fan and LPT efficiency

Core Technology

Drag

Weight

Architectures Within 1% Fuel Burn

Direct-drive turbofan: 78” dia.
Open Rotor Technology has potential for significant performance improvement, but with noise goal challenges.

![Graph showing % Improved fuel burn for different technologies](image)
Leveraging the NASA/GE UDF Experience and UHB Partnership

- Extensive 1980s collaborative testing experience of counter-rotation, open rotor concepts by NASA and GE, resulting in substantial experimental database to guide new activity.
- Improved Computational Aeroacoustics developed by NASA/GE/Universities to evaluate new open rotor concepts.
- Improved design and system analysis tools to screen potential candidates and minimize scale model test configurations.
- Utilize proven NASA test facilities, improved diagnostic testing techniques and existing scale model test articles.
- Build on GE expertise in composite construction and advanced core technology to achieve full Open Rotor potential.
Opportunities for the Future

Range = \left( \frac{V_0}{SFC} \right) \cdot \left( \frac{L}{D} \right) \cdot \ln \left( \frac{W_{initial}}{W_{final}} \right)

= (FHV \cdot \eta_{thermal} \cdot \eta_{transfer} \cdot \eta_{propulsive}) \cdot \left( \frac{L}{D} \right) \cdot \ln \left( 1 + \frac{W_{fuel}}{W_{payload} + W_{empty}} \right)

- **N+1**: Highly Loaded Compressors
- **N+2**: High OPR Low Emissions Combustors
- **N+2**: Adaptive cycles
- **N+2**: Constant Volume Combustion
- **N+3**: Hybrid Electric Propulsion
- **N+3**: Low Loss Inlets
- **N+3**: Variable Low Loss Exhausts
- **N+3**: Distributed Power Transmission
- **N+3**: Very High BPR Turbofans
- **N+3**: Ultra High BPR Turbofans
- **N+3**: Open Rotors
- **N+3**: Distributed Propulsion
- **N+3**: Wake Ingestion
- **N+3**: Novel Alloys / MMC’s
- **N+3**: Non-metallics
- **N+3**: Advanced Engine Architectures
2030 – 2050 Propulsion System Vision

Non-Brayton Cycle Propulsion (Fuel Cells)

Battery Electric Thrust Augmentation

Turboelectric Distributed Propulsion*

Distributed Propulsion (Gear Driven)

Brayton Cycle Propulsion (Turbo Gas Generators)

Open Rotor

NASA N3-X

*Key Technologies to Bridge The Gaps
- High OPR Cores
- Electrical Systems (Fuel Cells, Batteries, Motors)
- Superconductivity / Cryo Systems

1950

GE-IA

Timeframe

2050
Distributed Propulsion Options

- Multiple gas generators (2-3)
- Multiple gear driven fans for each generator with boundary layer ingestion capabilities

- Two gas generators
- Multiple electrically powered embedded fans with boundary layer ingestion capabilities

Boeing/NASA N2B

- Liquid hydrogen cooled superconducting TeDP
- Embedded fans

ESAero/NASA Concept

- Two or more gas generators
- Multiple distributed open rotor fans for each generator

NASA Concept

Advanced Concept Design and Challenges for Future Commercial Aircraft Propulsion
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High Efficiency High OPR Gas Generators

- Now driving to Bypass Ratios of 20+
- Highly loaded front block Compressor
- Minimizing the core size
- Hot section materials
- 1500°F HP Compressor
- 3000°F HP Turbine blades/vanes
High Efficiency High OPR Gas Generators

- Ceramic Matrix Composites
- NextGen disk material
- Tip/End Wall Aerodynamics
- Turbine Clearance Controls
- Low NOx Combustors
- Core Noise

Advanced fuel stage injector concepts
Propulsion Airframe Integration

- High Bypass Installations
- Slim Line Nacelles
- Adaptive Lightweight Fan Blade
- Distortion Tolerant Fans
- Multi-Degree of Freedom Acoustic Liners
- Low Jet Flap Acoustic Interactions
Airplane Aerodynamic Improvements

- Laminar flow nacelles
- Laminar flow on wings
- Low friction paint coating
- Improved aero-transonic design
- Wingtip technology
- Variable camber
Airplane Aerodynamic Improvements

- Adaptive compliant trailing edge
- Active stability control
- Increased wing span
- Enhanced Vertical Tail

Location of AFC Actuators
Structure, Materials, and Manufacturing

- All composite aircraft
- Integrated structural health monitoring
- Advanced manufacturing technology
# Energy Transfer Options for Powering Remote Fans

<table>
<thead>
<tr>
<th>Shafting/Gearing Horsepower</th>
<th>Electrical Power to Motors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Benefits</strong></td>
<td><strong>Benefits</strong></td>
</tr>
<tr>
<td>• Lower FPR for a given packaging constraint</td>
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</tr>
<tr>
<td>• High temperature gas contained to core stream</td>
<td>• Fan functionality after failure of one generator</td>
</tr>
<tr>
<td>• High temperature gas contained to core stream</td>
<td>• Offers most flexibility in fan placement and number of fans</td>
</tr>
<tr>
<td><strong>Drawbacks</strong></td>
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</tr>
<tr>
<td>• Distance is restricted between gas generator and fans</td>
<td>• Need for development of superconductivity technologies</td>
</tr>
<tr>
<td>• Limited to ~3 fans</td>
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</tbody>
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Each Transfer Technology has Pros/Cons Depending on Specific Application
Light, Efficient Components Must Be Cryogenic or Superconducting

Technical challenges are soluble and being pursued:

- Superconducting transmission lines between generators and motors
  - Utilities & Air Force are working this

- Superconducting motors drive propulsive fan array

- Cryogenic Inverter for variable speed fans
  - Weight 1/10 SOA & ~1/10th SOA loss
  - Phase 2 SBIR @ MTECH Labs
  - In-House Cryo-inverter Tests

- Total electric system
  - Distribute ~50 MW in a stable & responsive grid
  - RTAPS Contract @ Liberty Works
  - In-House Subscale System Model

Turbine engine driven superconducting generator/motors
- 1/10th SOA weight & low AC losses
- NRA Advanced Magnet Lab

Cryocooler(s) for cryogenic components
- 1/5th SOA weight
- Phase 1 SBIR @ Creare, Inc.

Subsonic Fixed Wing Project
Fundamental Aeronautics Program
What does it all mean?

Projections for Single Aisle Aircraft

Baseline A320-200

Fuel Burn Improvements 2035+

Aerodynamics 14%
Engine 23%
Structures 8%
  45%

Noise: Will meet Stage 4 with 70dB margin
NOX: Will meet Cap 6 with 80% margin
What does it all mean?

Projections for Twin Aisle Aircraft

Baseline  B777-200 ER

Fuel Burn Improvements  2035+

Aerodynamics  15%
Engine  17%
Structures  11%

43%

Noise: Will meet Stage 4 with 70dB margin
NOX: Will meet Cap 6 with 80% margin
What does it all mean?

Projections for Regional Jets

Baseline  Embraer E190AR

Fuel Burn Improvements 2035+

Aerodynamics  12%
Engine        28%
Structures    5%
               45%

Noise: Will meet Stage 4 with 70dB margin
NOX: Will meet Cap 6 with 80% margin
Looking Forward…The Challenges and Opportunities

- The market is global and is growing
  - This is good…big markets
- More players want to play
  - They bring technology competition…which is good
  - They bring financial competition…which is not necessarily good
- Governments play a role
  - United States Air Force, Navy and Army Research Labs—still strong on the military side
  - NASA going down significantly
  - European Union—strong and growing with the Clean Sky Program
  - Others
Next Gen portfolio
Military/Commercial Technology Synergies

<table>
<thead>
<tr>
<th>Program goals</th>
<th>Technologies</th>
<th>Segments</th>
</tr>
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<tbody>
<tr>
<td>US Army</td>
<td>25% better SFC 65% ↑ hp/wt</td>
<td>Attack/utility Helicopters</td>
</tr>
<tr>
<td>US Army</td>
<td>35% better SFC 80% ↑ hp/wt</td>
<td>Heavy lift Helicopters</td>
</tr>
<tr>
<td>US Navy/US Air Force</td>
<td>20-200+% better SFC</td>
<td>Combat aircraft</td>
</tr>
<tr>
<td>US Air Force</td>
<td>35% better SFC</td>
<td>Tanker/Transport</td>
</tr>
</tbody>
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- **AATE** (Advanced Affordable Turbine Engine)
- **FATE** (Future Affordable Turbine Engine)
- **ADVENT** (Adaptive Versatile Engine Technology)
- **HEETE** (Highly Efficient, Embedded Turbine Engine)
Technology Demonstrator Programs
Strong History Leading to Commercial Benefits Today and Beyond

Versatile Affordable Advanced Turbine Engine (VAATE) programs leveraged SOA commercial compression technology

NASA E³ program enabled latest generation of large GE engines

CFM International is 50/50 joint venture with Snecma (SAFRAN Group)
LEAP is a registered trademark of CFM International
There will be a stronger need for partnerships
  - Between Companies
  - Between Industry and Universities
Will have to work smarter
  - Rely on component tests as opposed to demonstrators
Technology roadmaps will be essential to success in a very competitive world…competitive in terms of technology opportunities as well as funding streams
The opportunity for our young engineers are immense as new innovative products will be needed and will flourish in this industry
Thank you for your time!