Aviation Propulsion Technologies in the 21st Century

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07 November, 2013
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Our business units

Energy Management
5% / $7.4 B

Healthcare
12% / $18.3 B

Capital
31% / $46.0 B

Oil & Gas
10% / $15.2 B

Aviation
14% / $20.0 B

Home & Business Solutions
5% / $8.0 B

Power & Water
19% / $28.3 B

Transportation
4% / $5.6 B

~$147.4 Billion
Revenue in 2012

$16.1 B Operating Earnings
“Longitude”... Author - Dava Sobel

- Engineering crisis of the 18th century.
- Longitude committee formed, prize defined by parliament.
- John Harrison – by 1735 solves with an accurate ship-worthy clock.
- Not really in widespread use until roughly 1780 or later.
- Why?
Propulsion Challenge

Industry Revenue/Profits

Historical Fuel Prices

Airline Operating Costs

Regulatory Challenges
- CAEP/6 2008 / 2013
- CAEP/8 2014 / 2018
- EU Carbon Trading 2012
- ICAO CO₂ Standard 2016-2020
- FAR Stage 5 2020

Reduce commercial and military customer costs in an increasingly difficult environment
Technologies and Architectures
Energy Availability
For Every Unit of Fuel Chemical Energy...

Today’s Turbofan Is roughly 40% efficient
Energy Availability
converted into transfer efficiencies...

60% loss can be categorized as:

- **Thermal eff:** Thermodynamic loss due to the Brayton Cycle
- **Transfer efficiency:** Loss converting energy from the core to the bypass
- **Propulsive efficiency:** Loss of converting fan and core exhaust into usable thrust
Opportunities for the future...

\[ \text{Range} = \left( \frac{V_0}{SFC} \right) \times \left( \frac{L}{D} \right) \times \ln \left( \frac{W_{\text{initial}}}{W_{\text{final}}} \right) \]

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

- Highly Loaded Compressors
- High OPR Low Emissions Combustors
- Adaptive cycles
- Constant Volume Combustion
- Hybrid Electric Propulsion
- Low Loss Inlets
- Variable Low Loss Exhausts
- Distributed Power Transmission
- Very High BPR Turbofans
- Ultra High BPR Turbofans
- Open Rotors
- Distributed Propulsion
- Wake Ingestion
- Novel Alloys
- Non-metallics
- Advanced Engine Architectures

GE Aviation
imagination at work
Thermal Efficiency

Overall Pressure Ratio (OPR)

Thermal Efficiency

39k/0.8 (Mid-Cruise)

Rough Thermal Engine Efficiency Ceiling

Topping, Bottoming Cycles

Advanced Brayton (2025+)

Brayton (2015-2025)

Large Thermal Opportunity Beyond Conventional Brayton Cycle
PDE Technology

• unsteady shock wave + combustion zone
• pressure rise combustion
• more efficient conversion of energy in fuel

**Tube PDE**

1 Fuel fill → Intake Stroke
2 Initiation
3 Detonation
4 Blowdown
5 Purge Air

**IC Engine Analogy**

Compression and Power Stroke
Exhaust Stroke
Propulsive Efficiency

Drive to lower SFC’s and more integrated engine / aircraft designs
Open rotor tests with NASA

GE/NASA testing began in 2009

Test builds on 1985 demonstration

- Acoustics validation
- Aero model validation
- New blade concepts
- Installation effects
- Pitch change effects
- Pylon, sidewall interaction
Driving productivity through analytics

Fuel & carbon
- Flight operations data analysis
- Operations insights for fuel savings

Improving productivity of assets
1% fuel burn reduction\(^{-a}\)
= $10MM savings

IVHM
Integrated Vehicle Health Management
- Advanced prognostics & enterprise integration

Improving utilization of airplanes
1 hour increase in aircraft utilization per day
= $100MM+ annual benefit\(^{-c}\)

Digital workscope
- Optimize time on-wing

Improving service of our engines
5% annual productivity
= $50MM cost savings per year

Over 25,000\(^{-b}\) engines monitored
... and growing

- Fuel efficiency
- Asset utilization
- Operations efficiency

\(a\)- Assumes a typical 70 aircraft, $1B fuel bill, fuel cost is $3.25 per gallon
\(b\)- Includes CFM, GE & EA engines
\(c\)- Assumes fleet > 50 aircraft
Global challenges
Temperature, dust, pollution, gravel, sand, construction debris

Illustration of particulate matter concentration (Source: NASA)
Technology integration thru 2020
Keeping the pipeline filled

Technology
- Composites
- Lean Combustion
- CMCs
- Adv. Cooling
- High-Temp Materials
- Flight Mgmt

2010
- Advanced turbofan
- Integrated engine and aircraft systems
- Adaptive cycles
- Advanced architectures

Architecture
- Integrated propulsion
- Integrated power generation
- Core efficiency
- New designs
Technology demonstrator programs

Renewing our technology DNA for new products and upgrades of fielded products. Mostly USG funded, what comes next?
Adaptive Engine Technology Development

- AETD...new class of engines with up to 25% better fuel efficiency
- Variable cycle technology
- Technology demonstration that builds on ADVENT
- Foundation for future generation of combat propulsion
New Products and Services
GEnx build-up, acceptance & flight test...
New Product Introduction (NPI)
Taking our products from design to manufacturing

Test types
- Performance
- Ingestion – water, hail, ice, dust, birds
- Acoustic
- Fan blade-out
- Emissions
- Vibration
- Endurance
- Flight
New Product Introduction (NPI)

Lean labs

Turbine Airfoils  | Rotating Parts
Composites       | Special Products
Structures       | Automation
Castings         | Additive Manuf.

Explore, develop and industrialize Advanced Manufacturing Technologies and transition to Supply Chain.

Process development

Demo production

Full scale production

Industrialization for cost, quality & delivery
New military and commercial pipeline...

• F414 Gripen
• F414 INS6
• CT7, T700 derivatives
• LEAP
• GE9X
• GE38
Alternative Fuels
Aviation

Alternative Fuels...

- Drop in
- Near Drop-in
- Non Drop-in
## The Cost Of Fuel...

### Wholesale price per Jet-A gallon equivalent $

<table>
<thead>
<tr>
<th></th>
<th>Huge reserves</th>
<th>Limited volumes</th>
<th>Oil or equivalent based distillates – narrow price range</th>
<th>Heavy ends. Freeze pt and emissions</th>
<th>Conversion costs</th>
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</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>C1</td>
<td>C3-C4</td>
<td>C6-C10</td>
<td>C12</td>
<td>C16</td>
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<tr>
<td>LNG</td>
<td>C1</td>
<td></td>
<td>C12</td>
<td>C16</td>
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<tr>
<td>NGL's, LPG</td>
<td>C1</td>
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<tr>
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<td>C16</td>
<td>C20-40</td>
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<tr>
<td>Kerosene, Jet</td>
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<td>C16</td>
<td>C80</td>
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<td>C20-40</td>
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<tr>
<td>Heavy gas oil</td>
<td>C1</td>
<td></td>
<td>C80</td>
<td>C100++</td>
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<tr>
<td>Residuals</td>
<td>C1</td>
<td></td>
<td>C80</td>
<td>C100++</td>
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<tr>
<td>Coal</td>
<td>C1</td>
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<td>C80</td>
<td>C100++</td>
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</tbody>
</table>

- **C1**: Wholesale price per Jet
- **C1**: A gallon equivalent $
Summary

Traditional fuel burn reduction strategies are beginning to yield diminishing returns – innovative technologies are required

- Light weight, high propulsive efficiency
- Advanced materials
- Highly integrated
- Big data, prognostics, IVHM
- Non-Brayton cycles

New products are the lifeblood of the business

- Roadmaps near term to 2050+
- Maintenance concept selection can have multi billion dollar impact to the bottom line.

Aviation alternative fuels may play a significant role in our energy future