Overview
The Development of the Geared Turbofan™ Engine

• Some historical perspective
• A recurrent theme - conventional wisdom vs. reality
• The roles of architecture, design, and technology
• Speculation on the future
Why History?

“There is nothing new in the world except the history you do not know.”

Harry S. Truman
Pratt & Whitney – Dependable Engines

Wasp Engine
1925

Turbofan Engine
2015

Eras of Engine Architecture

OVERALL EFFICIENCY

1940 1960 1980 2000 2020

>10% STEPS IN EFFICIENCY

Single Spool
(1937)

Dual-Spool Turbojet
(1951)

High Bypass Turboprop
(1969)

Ultra-High Bypass Geared Turbofan
(2015)
Geared Turbofan Technology Demonstrators
Over 50 years of interest

Pratt & Whitney PW304, 1957

1960
1970
1980
1990

Hamilton Standard Q-Fan, 1972

General Electric QCSEE, 1977

Lycoming ALF502 1980

Turbomeca Astafan Variable Pitch Fan, 1969

Garrett TFE731 1970

Rolls Royce Dowty M455D-02, 1975

Pratt & Whitney ADP X-Engine, 1992

P&W Hydrogen Fueled Aircraft Engine
Project Suntan – Liquid H₂ engine circa 1957-58
Geared Turbofan Technology Demonstrators

Variable pitch fans

- Turbomeca Astafan Variable Pitch Fan, 1969
- Rolls Royce Dowty M45SD-02, 1975
- Pratt & Whitney ADP X-Engine, 1992

Turbofan Conversion Geared Engines

Turboprops/shaft transformed into high FPR turbofans

- Garrett TFE731 1970
- Lycoming ALF502 1980

FPR = fan pressure ratio

Image Credits
1 Johan Visschedijk Collection
3 Simon JP O'Riordan
4 NASA
$1B Technology Investment
25 years of research prior to product launch

Challenging Conventional Wisdom
Conventional wisdom - areas of general consensus

- Gears – too heavy, too much heat to reject, short-lived
GTF™ Engine
Architecture for the 21st Century

Conventional Engine

Higher Efficiency, Lower Noise

Turning Vision

Conventional Engine

Higher Efficiency, Lower Noise
**Conventional Engine**
Higher Efficiency, Lower Noise

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**Fan Drive Gear System**
25 years of technology development

- Efficient: >99.5%
- Simple: 13 major parts
- Reliable: 20 years before maintenance
Three Interlocking Enabling Technologies
Enable step change in propulsor performance

- Very Light Weight Reliable Gear
- Light Weight Extra Efficient Fan
- Advanced Nacelle

2 + 2 + 2 = 16% Improvement in Fuel Burn

Challenging Conventional Wisdom
Conventional wisdom - areas of general consensus

- Gears – too heavy, too much heat to reject, short lived
- Low FPR Fans – need variable pitch or variable nozzle
Low Fan Pressure Ratio Needs a Variable Area Nozzle

A widely accepted view

“Fan pressure ratios at cruise significantly lower than, say, 1.45 will probably have to wait until variable nozzles for the bypass stream become available or acceptable, a point that has been recognized in the industry for some time.

In other words, the variable area nozzle is an enabling technology for lower fan pressure ratio.” *

Challenging Conventional Wisdom

Conventional wisdom - areas of general consensus

- Gears – too heavy, too much heat to reject, short lived
- Low FPR Fans – need variable pitch or variable nozzle
- Nacelles – too large in diameter, too much drag
Low Noise Fans Enable Short Inlets
Less noise produced ➔ less acoustic treatment needed

Legacy
Inlet L/D ~ 1

GTF
Inlet L/D ~ 0.5-0.6

Engine Diameter Grows as Length Shrinks
35,000 lbs thrust (today) versus 47,000 lbs (1976)
A Challenge to Retrofit a Much Larger Engine

Challenging Conventional Wisdom

Conventional wisdom - areas of general consensus

• Gears – too heavy, too much heat to reject, short lived
• Low FPR Fans – need variable pitch or variable nozzle
• Nacelles – too large in diameter, too much drag
• **Composite blades are a superior, lighter solution**
Hybrid Metallic Fan Blade
Disciplined approach surprised conventional wisdom

Advanced Fan Blade
Very high efficiency, very low noise

Superior Aerodynamics
1% Better Fuel Burn
Challenging Conventional Wisdom

Conventional wisdom - areas of general consensus

- Gears – too heavy, too much heat to reject, short lived
- Low FPR Fans – need variable pitch or variable nozzle
- Nacelles – too large in diameter, too much drag
- Composite blades are a superior solution
- **Low emissions requires lean burn combustors**

TALON™ X Rich Burn Quick Quench Combustor

Best in class emissions and performance

- Blow out free 3rd Generation RQL aero
- World-class emissions and smoke levels
- Highly durable float wall construction
- 3rd Gen combustor alloys for oxidation
- Compact, lightweight configuration
- No complicated fuel nozzles or staging
- Optimized exit profile temperatures

>40% Margin to CAEP/8
Challenging Conventional Wisdom

Conventional wisdom - areas of general consensus

- Gears – too heavy, too much heat to reject, short lived
- Low FPR Fans – need variable pitch or variable nozzle
- Nacelles – too large in diameter, too much drag
- Modern fans must use composite blades
- Low emissions requires lean burn combustors
- **Higher pressure ratio core compressors are superior**

Architecture and Spool Pressure Ratio

Engine architecture sets optimum low-high split
Same Overall Pressure Ratio (OPR)
Geared vs. direct drive different split among spools

45% fewer airfoils – 6 fewer stages

High Speed Low Pressure Turbine
Higher speed improves efficiency and drops weights

Gear Enables High Speed LPT

- Higher Efficiency
- Lower Stage Count
- >1700 fewer Airfoils
- Lower Weight
- Smaller Diameter and Length
- Better installation, lower airframe weight
- Lower Maintenance Cost

LPT efficiency trades 1:1 for fuel efficiency (fuel burn)
Cores Shrink as Efficiency Improves

For similar missions

**JT8D**
- 1964/1980: 14,000/21,700 lbf

**V2524**
- 1995: 24,800 lbf

**PW1524G**
- 2016: 24,000 lbf
PurePower® Geared Turbofan™ Engine
New technologies realized

Challenging Conventional Wisdom
Conventional wisdom - areas of general consensus

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- Nacelles – too large in diameter, too much drag
- Modern fans must use composite blades
- Low emissions requires lean burn combustors
- Higher pressure ratio core compressors are superior
- Larger diameter, low FPR geared engines may have lower TSFC but will have higher fuel burn due to weight & drag penalties
Conventional Propulsion System Fundamentals
Trading fuel burn against noise

![Diagram showing the trade-off between fuel burn and noise for different bypass ratios and fan diameters.]

Dramatic Reduction in Community Noise
73% reduction in noise footprint – Paris CDG

![Comparison of noise footprints for existing turbofan and PurePower PW1000G Engine.]

Source: Wyle Labs
Existing turbofan: 75 dB contour = 106.4 sq km
PW1000G engine: 75 dB contour = 28.7 sq km
Evolution of Turbofan Engine Noise

Jet noise no longer predominates

1960's engine
1:1 BPR

1990's engine
6~8:1 BPR

2015 engine
12:1 BPR

Engine Models

<table>
<thead>
<tr>
<th>Engine Model</th>
<th>PW1100G-JM</th>
<th>PW1200G</th>
<th>PW1400G</th>
<th>PW1500G</th>
<th>PW1700G / PW1900G</th>
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</thead>
<tbody>
<tr>
<td>Airbus A320neo</td>
<td>A319neo PW1124G-JM</td>
<td>MRJ90 PW1215G</td>
<td>MC-21-200 PW1428G</td>
<td>CS100 PW1519G</td>
<td>E175-E2 PW1700G</td>
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<tr>
<td></td>
<td>24,000 lbs</td>
<td>15,000 lbs</td>
<td>28,000 lbs</td>
<td>19,000 lbs</td>
<td>up to 17,000 lbs</td>
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<td>PW1127G-JM</td>
<td>27,000 lbs</td>
<td>PW1217G</td>
<td>PW1431G</td>
<td>PW1521G</td>
<td>E190/195-E2 PW1900G</td>
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<tr>
<td></td>
<td>A320neo PW1133G-JM</td>
<td></td>
<td></td>
<td></td>
<td>up to 22,000 lbs</td>
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<tr>
<td></td>
<td>33,000 lbs</td>
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</table>
7,000 Orders & Commitments

- Embraer E-Jets E2
- Mitsubishi Regional Jet
- Irkut MC-21
- Rosteknologii
- SaudiGulf
- Airbus A320neo

Successfully Completing Milestones

- Bombardier C Series
  - FETT
  - First Flight
  - EIS
- Mitsubishi Regional Jet
  - FETT
  - First Flight
  - EIS
- Airbus A320neo
  - FETT
  - First Flight
  - EIS
- Irkut MC-21
  - FETT
  - First Flight
  - EIS
- Embraer E-Jets E2
  - FETT
  - First Flight
  - EIS
The Future
Semi-informed speculation

• What will be future engine requirements?
• What will the engines of the future look like?
• What technologies are needed?

Evolution of Jet Engine Efficiency
### Change in Bypass Ratio, Efficiency

<table>
<thead>
<tr>
<th>In Service</th>
<th>2013-16</th>
<th>Longer Term</th>
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<tbody>
<tr>
<td>BPR 5</td>
<td>BPR ~12</td>
<td>BPR 15~18</td>
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<tr>
<td>Fuel Burn Reference</td>
<td>-15%</td>
<td>-20~30%</td>
</tr>
</tbody>
</table>

### Fan Pressure Ratios Must Drop

So inlets must shorten

*Image credit: NASA*
One Advanced Concept, the LRU Core
Solving design challenges, reducing maintenance

Airplanes of the Future?
Future airplane is unclear, future motor is not

Source: ATAG
1:11 Scale D8 Aircraft

Innovation in Energy – Solar Powered Airplanes
Sustainable Drop-In Biofuels for Reduced CO₂

Conventional Fuel

Bio Fuel
Summary
The future of commercial aviation

• Gas turbines are the future of commercial aviation
  – Most efficient engines on the planet
  – Most reliable
  – Lowest emissions
  – Lowest cost of ownership

• Geared, Ultra-high bypass ratio will dominate

• Conventional wisdom vs. technical reality
  – Conventional wisdom based on “all else being equal”
  – History suggests that it rarely is