“I find out what the world needs, then I proceed to invent it.”

– Thomas Edison
Technical innovation ...
Key to our past and future

U.S. jet engine
U.S. turboprop engine
Mach 2 engine
High bypass engine
Variable cycle turbofan engine
Unducted fan engine
Composite fan blade in airline service
120,000+ lb thrust engine
4D trajectory flight in revenue service
Modular power tile
FMS-controlled Unmanned Aircraft System
50 years of engine improvements

**Flight Safety**
- 90% improvement

**Thrust to Weight**
- 350% increase

**Fuel Efficiency**
- 45% improvement

**Engine Noise**
- 35 db decrease
Did you know? CFM56 Fleet of 22,000 Engines Accumulates 1 Million Hours Every 8.5 Days!

World's Broadest, Most Modern Product Line

CFM, CFM56, LEAP and the CFM logo are trademarks of CFM International, a 50/50 joint company between Snecma and GE. EA (GP line) is a 50/50 JV between GE and Pratt & Whitney.
The Future:

Global forces/environment
Industry drivers

Oil & crack spread
Energy Information Agency (EIA)

EU assurances to support banks & rising tensions with Iran have both pushed oil prices to 3 month high

Global semi-conductor billings
SIA, 3 month moving average (Per MM)

Semi-conductors are high value, low volume commodity ... significant for freight demand

U.S Non-defense capital goods orders
U.S Bureau of Labor Statistics (Orders, seasonally adjusted, $B)

Orders signify capital investments & indicator for purchasing ... June showed decline continuing
### Commercial aviation growing steadily

<table>
<thead>
<tr>
<th>Airframe</th>
<th>Production rate ('12 → '14)</th>
<th>Engines</th>
</tr>
</thead>
<tbody>
<tr>
<td>A380</td>
<td>2.7 → 3.5</td>
<td>GP, GE90, GEnx, CFM, CF34</td>
</tr>
<tr>
<td>787</td>
<td>3.5 → 10</td>
<td></td>
</tr>
<tr>
<td>737</td>
<td>38 → 42</td>
<td>GE90</td>
</tr>
<tr>
<td>A320</td>
<td>40 → 42</td>
<td>GEnx</td>
</tr>
<tr>
<td>EJet</td>
<td>8.7 → 9.2</td>
<td>CFM</td>
</tr>
<tr>
<td>CRJ</td>
<td>2.5 → 2.5</td>
<td>CF34</td>
</tr>
</tbody>
</table>

**Traffic growth** (Trillion RPKs)

- 2010: 4 Trillion RPKs
- 2014F: 9 Trillion RPKs (9.3% CAGR)
- 2020F: 11 Trillion RPKs (5.4% CAGR)

**Highest production ramp rates in 3 decades ... inconsistent with demand growth**

Boeing and Airbus are increasing rates to ~40 / month. That means: 40 x 2 (Airbus & Boeing) x 11.5 mth / yr. = 920 / yr. or ~1,000 including the other new single aisles. 1,000 x 5 years = 5,000 / 10 yrs. = 10,000 / 20 yrs. = 20,000 aircraft.

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Technology success takes commitment and opportunity

Commitment ... $1-2 \text{ billion} \text{ continuous technology investment per year}

Opportunity ... 10 new engines proving and maturing technology

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Timescales of innovation long...safety demands technologies to be proven...strategic vision/commitment a must (Gamma TiAl, CMC, etc.)...multi-decade VISION

Almost every flying technology started as a USG funded (NASA, DoD, etc.) early TRL level study, many driven to TRL 5 or 6. Changing dynamics/players...WTO agreement, sequestration, emerging funding sources

Doubling of revenue miles every 13-15 years despite “shocks” such as 911

Question: How many “tube/wing” iterations are left?
- 15% campaign/campaign FB improvement a must
- ICAO 2050 CO₂ commitment, other regs looming
Technology Readiness to Serve Today and Tomorrow
GE Aviation Engineering

Over 8000 engineers around the globe
3000 technologists at 5 Global Research Sites
Practical innovation ... GE’s model

Global resources teamed to advance technology

Idea creation + Technology maturation = Winning products

Idea creation:
- Internal
- Customers
- Government
- Universities (300+ relationships)

Technology maturation:
- Cross-disciplinary teams
- Technology roadmaps
- TRL/MRL maturation plans
- Long-term growth strategies
- Tactical funding

Winning products:
- 30+ new technologies by 2020
The Physics of “Readiness to Serve”

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

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

- **Today**
  - 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

- **2020-2050?**
  - Very High BPR Turbofans
  - Ultra High BPR Turbofans
  - Open Rotors
  - Distributed Propulsion
  - Wake Ingestion

- Novel Alloys / MMC’s
- Non-metallics
- Advanced Engine Architectures
Essential technologies ... keeping the pipeline filled

Technology
- Composites
- Lean combustion
- Advanced cooling
- High-temp materials
- Flight Management

2010
- Advanced turbofan
- Integrated engine and aircraft systems

2020
- 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
Advanced materials
Carbon fiber fan blades have proven durability

**GE90 field experience ...**

No Airworthiness Directives (AD’s) or special inspections

No flight line lubrication

Incredibly durable ...  
... *almost maintenance free*

180+ bird ingestion events with only 1 blade not serviceable

SOURCE: GE90 in service record
Ceramic Matrix Composites ... future of performance

**EIS configuration**
- Stg1 Shroud CMC

**Enhancement**
- CMC HPT stage 2 airfoils
- Further CMC incorporation

**2016**
EIS performance

**Future**
- No cooling air losses
- 1/3 the weight
- Higher thermal capability

Engine fuel efficiency
GE ceramic-matrix composites (CMCs) development

1st GENERATION
2000s
Power Generation turbine shroud
• 15,000+ service hours

2nd GENERATION
2016
Aviation LEAP HPT shroud
• 1st FAA certification
• 10M+ service hours by ‘20

3rd GENERATION
2020
Aviation and Power Gen hot section airfoils and combustor

Game changing material technology ... reduced Fuel Burn through lower cooling flow and weight
CMC service introductions built on 20+ years of development
Gamma TiAl turbine blades
World’s first certified intermetallic application

Component Casting Trials
00s

Engine Testing of TiAl Components
05s

Complete Material Database
10s

Alloy Development
80s

TiAl LPTB weight reduction vs. Ni superalloys ... 100 lb./stage
Manufacturing Development

Turbine airfoils
Dayton

Rotating parts
Cincinnati

Manufacturing support
Cincinnati

Automation
Canada

PMC/Ox-Ox composites
Cincinnati

Structures
Cincinnati

Additive manufacturing
Cincinnati

CMC composites
Newark

Technology readiness ➔ research to production

Manufacturing readiness ➔ industrialization
Aerodynamics
Evolution of fan technology

1992 - CF6-80E
- Titanium blades
- Metal casing
- 34 airfoils
- Shrouded
- Radial aero

Today
- Compound swept aero
- Composite blades
- Composite casing
- 18 airfoils
- Unshrouded
- High eff / high flow

Significant fuel burn reduction
eCore technology...delivers thermal efficiency and retention

Performance efficiency
- Next generation 3D Aero
- 22:1 PR in 10 stages ... best in industry

Performance retention
- Short, stiff core retains performance
- Rigid aft case maintains clearances
- Blisks minimize dovetail leakage

Operability
- Stall-free performance
Compressor aerodynamics for LEAP

Efficiency, performance retention, maintenance costs

3rd generation 3-D aerodynamic design

- Advanced sweep
- End wall contouring... tip and root
- Balanced stage loading

Bowed stators

Integral bladed disks

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Advanced turbine cooling & efficiency

Film Effectiveness

Cooling Flows

Purge, Leakage Flows

HPT S1B Hgas

HPT S1B Ttb

Htc

All Streamlines

LE

PS SS
Lean-burn combustion ... over 25 million hours of experience

Cruise NOx improvement versus typical rich-quench-lean combustor (NOx emission per lb of fuel*)

% RQL NOx emissions

0 25 50 75 100


Dry Low Emissions (Aeroderivative)
- 15M+ industrial hours

Dual Annular (CFM)
- 10M+ flight hours
- 2-nozzle lean burn mode

Twin Annular Premixing Swirler (TAPS)
- Compact staging
- Certified on GEnx

Next-gen TAPS
- LEAP engine

Potential TAPS evolution ...
- maintenance cost reductions

Continued emissions reductions while meeting the increased turbofan cycle demands

*On ground, 1000F combustor inlet temperature
Comparison with DLE made assuming equivalent operating pressures and liquid fuel

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Lean combustion lowers NOx

Traditional Combustor

Lean burning TAPS Combustor

(Fuel / Air Ratio)

(Fuel / Air Ratio)

Temperature Rise Curve

NOx production zone

Stoichiometric Temperature

Excess Fuel

Excess Air

Rich → Lean
Lean-burn combustion ... lowers HPT distress & improves thermal efficiency

TAPS lean combustor

• Lean flame reduces local hot spots
• Improves turbine part life for better TOW and HPT maintenance cost
• Reduced NOx, achieves CAEP/10 limits

*Twin Annular Pre-mixing Swirler
Technology readiness for EIS and growth

Continuous investment produces multiple technologies & innovations

**Composites**
Lighter, durable blades & case
... maintenance free fan

**Core efficiency**
3rd generation 3D aero & debris rejection
High Press. Ratio HPCs

**Combustor**
Low temp. profile and lean burning
... durable combustor

**CMC’s / TiAl / Cooling / Coatings**
Better efficiency with same metal temp.
... durable HPT & LPT
GE Aviation

Integrating new technologies throughout the engine

**COMPOSITE CASE & FAN BLADES**
- 1000 lbs./aircraft

**CONTROLS**
- Model based
- Distributed
- High temp packaging

**HPT**
- 15% reduction in cooling flow
- Next gen disk materials

**LPT**
- TiAl spin casting

**COMBUSTOR**
- 50% NOx margin
- TAPS

**FAN BLADE AERO & ACOUSTICS**
- Improved SFC
- Adv. noise prediction

**COMPRESSOR**
- Performance retention
- Adv. aero and stability modeling

**Entry Into Service in 2011**
- 787
- 747-8
LEAP
The next generation of technology

STRUCTURES
- Rigid structures
- 360° double wall HPC case

DIRECT-DRIVE
- High bypass ratio

COMBUSTOR
- Lean-burn

COMPRESSOR
- Integral bladed disks
- Advanced 3D aero

COMPOSITES
- Fan blades & fan case

HPT
- Proven materials
- 3D aero
- Adv. Cooling

Entry Into Service ~2016

A320 NEO
COMAC C919
737 MAX
The Future: Open rotor tests

GE/FAA/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
No Tube & Wing? BLI / Wake Propulsion

Reenergizing aircraft wake via distributed propulsion

Aircraft Installation and integration Critical

> 10% Fuel Burn Savings Potential
Hybrid Turbo/Electric Engine Concepts

Multiple potential configurations

- Power transfer between shafts
- Back-up power, eliminate APU, EPU
- Aircraft systems synergy
- Electric idle / taxi operation
- Reduced energy costs
Superconducting Turbo-Electric Propulsion

Fuel Burn Reduction* (%)

Conventional Turbofan (FPR~1.6)
Turbo-Electric Fan (FPR~1.35)
Turbo-Electric Distributed Fan (FPR~1.25)
Turbo-Electric Distributed Wake Fan (FPR~1.25)
Turbo-FC-Electric Distributed Wake Fan (FPR~1.25)
Battery Turbo-Electric Distributed Wake Fan (FPR=1.25)

* Relative to 2000 SOA TF

A “Work in Progress”
GE’s commitment ...

- Technology innovation for customer value
- Learning from the world’s largest installed fleet
- Focusing on people, processes, and tools
- To be prepared for, and shape, the future of flight