Technologies for the Next Engine Generation

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GE’s model ..... continuous innovation

Aviation needs
- Fuel efficiency
- Reliability
- Cost of ownership
- Emissions
- Noise

Targeted technology development
- Technology roadmaps
- Cross-disciplinary teams
- Ongoing R&D investment
- GE Global Research collaboration
- Sustained maturation

Differentiated products

GE Proprietary Information
Subject to restrictions on the cover or first page
Technology Demonstrator Programs
Strong history leading to commercial benefits today and beyond

CFM International is a 50/50 joint venture with Snecma (SAFRAN Group)
LEAP is a registered trademark of CFM International
Investing for growth...
Engineering as a strategic advantage

<table>
<thead>
<tr>
<th>Leadership</th>
<th>Innovation and execution</th>
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</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Right people, right time</td>
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<tr>
<td>Capability</td>
<td>Right skills to deliver</td>
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Over 8000 GE Aviation engineers around the globe

~3000 technologists at 5 Global Research Sites
Pioneering New Technologies
# GE’s multi generation technology plan

<table>
<thead>
<tr>
<th>LEAP</th>
<th>GE9X</th>
<th>2025+</th>
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<tbody>
<tr>
<td><strong>Advanced Materials</strong></td>
<td>• CMC Shroud</td>
<td>• Gen1 CMC HPT</td>
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<tr>
<td></td>
<td>• CMC Combustor</td>
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<td></td>
<td>• High Temp Disk</td>
<td>• High Temp Disk</td>
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<tr>
<td><strong>FAN &amp; LPT</strong></td>
<td>• Composite Fan</td>
<td>• Composite OGV</td>
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<tr>
<td></td>
<td>• 18 blades</td>
<td>• 16 blades</td>
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<tr>
<td></td>
<td>• Improved Aero</td>
<td>• Improved Aero</td>
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<tr>
<td><strong>Core</strong></td>
<td>• NG HPT Blade</td>
<td>• 27:1 Compressor</td>
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<td></td>
<td>• Additive mfg fuel nozzle</td>
<td>• TAPS III Combustor</td>
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<tr>
<td></td>
<td>• Adv cooling</td>
<td>• Adv. Seals</td>
</tr>
<tr>
<td><strong>Controls</strong></td>
<td>• Adv. FADEC</td>
<td>• Distributed Controls</td>
</tr>
<tr>
<td></td>
<td>• Lightweight externals</td>
<td>• Adv. Fuel Pump</td>
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- Gen2 CMC HPT
- Low Drag Installation
- Light weight adv. Components
- Unducted Fan

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Fan Technologies
Generational changes in technology

Lightweight
Durable
Efficient
Composite technology advancement
Improved performance and weight reduction

**GE90-94B**
777-200ER, 777F
- Wide chord design
- 22 blades

**GE90-115B**
777-200LR, -300ER
- Swept aero
- 22 blades

**GENx**
787, 747-8
- Improved efficiency
- Lower Radius Ratio
- 18 blades

**LEAP**
737 MAX, A320 neo
- 3D woven fiber and resin transfer mold
- Advanced camber
- 18 blades

**GE9X**
Next-Gen 777
- Improved fiber and resin system
- Thinner airfoils
- 16 blades

**Fan blade experience**
- **Today:** 30+ million flight hours
- **2019:** 150+ million flight hours

**Fan cases**
- Integrated structure
- Saves 700+ lbs/aircraft
High bypass turbofan challenges

Better Fan Efficiency while Reducing Noise
- Every fan blade design continues to improve efficiency
- GE9x fan rig tests maturing new acoustic technologies

Improved Aeromechanics
- GE relying on detailed analytical CFD and test experience
- GEnx fan design methodology improve flutter stability
- GE9X inlet and fan concepts reduce blade responses in distortion

Reducing the Weight the Fan System
- GE90 blade composite blades
- GEnx composite fan containment case (save up to 700+ lbs/aircraft)
- GE9X improves cost and weight with advanced manufacturing and new materials

Successful Field Experience that was Developed on Bird Strike and Blade Out Rigs
- 30+ million flight hours today and by 2019 over 150 million flight hours
Unsteady Coupled Inlet+Fan CFD in Crosswind

Validation Program
- Modeling nacelle, fan, OGV, & nozzle and ground plane
- Utilizing model and engine test data for validation

Improved Fan-Inlet Design Tool
- Allows computation of Fan pumping effect on inlet
- Captures all fan – inlet interactions
- Improved tool for nacelle and distortion-tolerant fan design

Improved Fan response and distortion transfer assessments
- Fan forced response analyses & assessment
- Fan response to inlet distortion & distortion transfer to core
- Fan operability assessment via numerical throttling

High Bypass Fan Simulation

Impact of Fan Design on Inlet Separation
Design 1
Design 2
Open Rotor Designs for Low Noise and High Efficiency

GE: designs, acoustic predictions, test planning/execution

NASA: rig fabrication, facilities, data acquisition, personnel

FAA: feedback, reviews, sponsorship under Continuous Lower Energy, Emissions, and Noise (CLEEN) program

Goals:
- 26% fuel burn reduction relative to CFM56-7B powered narrow body aircraft
- 15-17 EPNdB cumulative margin to Chapter 4
Computational aero-acoustics (CAA)

Prediction process

Multi-step Acoustic Prediction Process

Wakes/Gusts → Unsteady R2 Surface Pressure → Radiated Acoustics

Predicted experimentally observed trends between 2 Gen1 designs. Used for Gen2 design guidance.
Open rotor technology progress

- Goal for 26% fuel burn benefit rel. to CFM56-7B
- Full Scale Max Climb Net Efficiency
- Historical Aero-only
- GE36 (1989)
- Gen1A+B +5% clip, MC/L
- Gen2A+B

- Goal: 15-17 EPNdB
- Cum Margin Re: Ch4 (EPNdB)
- Historical Aero-only
- GE36 (1989)
- Gen1A+B +5% clip, TO/M
- Gen2A+B*

• Adjusted rig efficiency by +0.8 pt for full scale Re No.
• Assessments incl. measured effects of AoA & pylon blowing
• Pitch and pylon blowing not necessarily optimized
• Gen2A+B* = measured Gen2A + assessment of “+B” tech (based on measured Gen1A+B vs. Gen1A)

- 1980’s designs were marginally satisfactory for either performance or acoustics
- Gen2 demonstrated technology effectively meets CLEEN open rotor goals
Booster Technologies
Core Stream Ice and Sand Particle Extraction

- VBV doors open at part power. Bleed air from Booster exit to control Booster operating line.
- Can be effective in extracting ice and sand particles from entering core engine.
- GE90 & GEnx use inward-opening VBV doors.

**Improved extraction reduces core performance deterioration & improves HPC operability**

- Improved particle trajectory CFD fidelity provides better understanding of particle tracking through Fan, Booster and Goose Neck Duct into HPC.

**Sand Transport Analyses**
Improved Particle Trajectory Modeling Benefits

More effective sand & ice shed particle extraction prior to HPC by optimizing Booster & GND flowpath, and VBV configuration designs.

- Improved Inclement Weather Operability - simplify Engine Control Systems
- reduced HP spool performance deterioration
- without adversely affecting Booster and GND aerodynamic performance

Ice Particle Shed Trajectory Analyses

Next Generation Engines will benefit from Improved Ice and Sand/Dirt Extraction
HP Compressor Technologies
Advanced compression technology

**GE90-115B**
777-200LR, -300ER

- 1995-2004
- 9-10 stages
- Compressor Pressure Ratio 19
- Overall pressure ratio ~40

**GE9X and LEAP**
787, 747-8, C919, 737 MAX, A320neo,

- 2011
- 10 stages
- Compressor Pressure Ratio 23
- Overall pressure ratio ~50

**GE9X**
Next-Gen 777

- 2018 Cert
- 11 stages
- Compressor Pressure Ratio 27
- Overall pressure ratio ~60

It all begins with a world-class compression system for GE9X... testing begins in 2013!
High Pressure Ratio Compressor

Technology Driver:
• Increased Thermal Efficiency from High OPR

Technology Play:
• 11 stage, 27:1 pressure ratio with advanced 3D aero
• Improved clearances from TCF engine mount

Benefit: ~2% SFC benefit

Technology Maturation Program for High OPR HPC

Front stage rig
Improved front stage efficiency

LSRC rig
Improved rear stage efficiency & clearances

HPC 11-stage rig
• Leverage GE O&G Massa facility
• Validates efficiency and operability goals

Leverage Cost Workout
• Grit Blast finish on HPC case
• Robotic vane assembly
Compressor test facility, Massa, Italy
Combustor Technologies
Combustion technology evolution

**DAC (GE90-94B)**
777-200ER, 777F
- 2 Nozzle lean burn
- 10M+ flight hours

**TAPS I (GEnx)**
787, 747-8
- World-class emissions

**TAPS II (LEAP)**
737 MAX, A320 neo
- Improved durability
- 30% lower emissions

**TAPS III (GE9X)**
Next-Gen 777
- Higher pressure
- Reduced cooling flow
- NextGen Mixer
- 60% lower emissions

GE leading in lean combustion in service experience and technology
HP Turbine Technologies
CMCs ... long-term commitment to execute and unlock potential

Material temp. capability

<table>
<thead>
<tr>
<th>80's</th>
<th>90's</th>
<th>00's</th>
<th>10's</th>
<th>20°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
<td>CMCs</td>
<td>CMCs</td>
<td>CMCs</td>
<td>CMCs</td>
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</tbody>
</table>

1/3 weight
20% Greater
thermal capability

Application growth

Product development and revenue service

Research and proof of concept


Combustion test rig Demo engine test Mixer Turbine nozzles

LEAP ADVENT GE9X
LP Turbine Technologies
Advanced LP Turbine

Technology Driver:
• Minimize fuel burn through increased efficiency and decreased weight

Technology Play:
• Increased LP speed, advanced aerodynamics and mechanical design, overhung LPT with aerodynamic OGV

Benefit:
• 0.6pts fuel burn reduction vs SOA

Technology Maturation Program for Adv LPT

Technology Development
Single and dual spool test validation

Cascade rig
Steady flow & unsteady to confirm loading optimization

Rotating rigs
Validate improvements with low & high speed rigs

Low Cost Mfg
TiAl Near-Net-Shape Spin Casting Facilities
Bringing it all together
CFM LEAP-1A/B/C

Fan
- 18 Blades
- 3D Woven Composite Blade
- Composite Case

Booster
- Inward Opening VBV Doors
- Inlet Lip Anti Ice

Program:
Core 2&3 complete
FETT Sept. 2013

TAPS II Combustor with Dual Orifice Nozzles

LPT
- R65 Rotor
- TiAl Blades

HPT
- Advanced Cooling
- Next Gen Blade
- CMC shroud
- Modulated Turbine Cooling

HPC
- 10 stages
- PR=23
- Start Bleed
- Transient Bleed
GE9X Product Overview

<table>
<thead>
<tr>
<th>Bypass Ratio</th>
<th>115B</th>
<th>GE9x</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPC Pressure Ratio</td>
<td>18:1</td>
<td>27:1</td>
</tr>
<tr>
<td>Overall Pressure Ratio</td>
<td>46:1</td>
<td>64:1</td>
</tr>
<tr>
<td>T3 Redline</td>
<td>1300°F</td>
<td>1400°F</td>
</tr>
<tr>
<td>Thrust</td>
<td>115k Ib</td>
<td>100k Ib</td>
</tr>
<tr>
<td>Fan Diameter</td>
<td>128”</td>
<td>132”</td>
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~100,000 pound takeoff thrust class

**Fan, booster**
- 132” fan diameter
- 4th generation fan blade technologies
- Improved fan/booster aero ... higher tip speed
- Composite structures
- Acoustic technologies

**Nacelle, installation, controls**
- Integrated nacelle and exhaust system for reduced weight and improved aerodynamics
- Acoustic optimization
- Performance-enhancing, lightweight controls, externals

**Core**
- Next-gen HPC aero
- 27:1 HPC pressure ratio
- Next-gen high-temp disk alloy and coating
- TAPS III combustor
- Next-gen HPT blade
- CMCs beyond LEAP
- Advanced seals

**Low pressure turbine**
- Increased efficiency
- Next-gen materials
Learning from our past and designing for the future

Proven track record... executes on new products

Innovation ... creates product value across the lifecycle

Investment ... solutions for severe environmental challenges

Support ... technology insertion and new digital services

48,000 engines
8,000 engineers
7 locations
35 test sites