Technologies for the Next Engine Generation

Dr. A. R. Wadia
Chief Consulting Engineer - Aerodynamics
GE Aviation
Cincinnati, Ohio

September, 2014

imagination at work

GE's model ….. continuous innovation

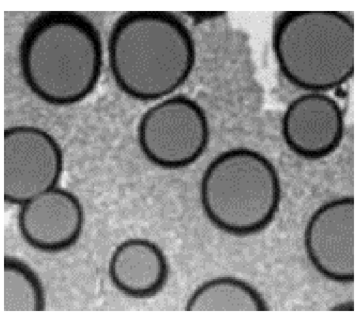
Aviation needs +

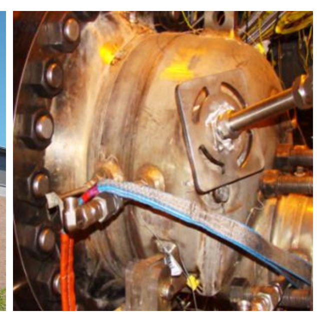
- Fuel efficiency
- Reliability
- Cost of ownership
- Emissions
- Noise

Targeted technology development =

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

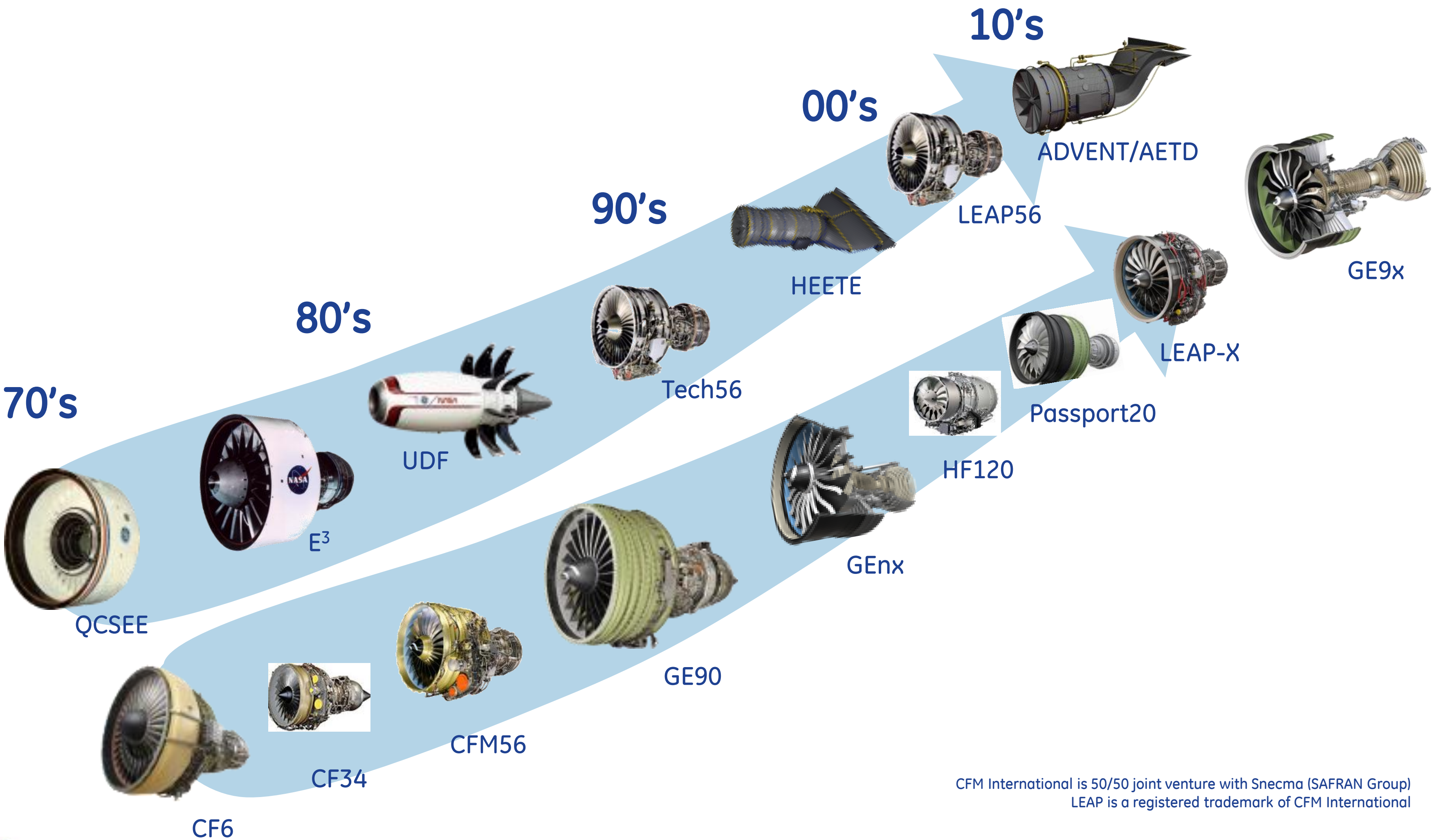
Differentiated products





Technology Demonstrator Programs

Strong history leading to commercial benefits today and beyond



CFM International is 50/50 joint venture with Snecma (SAFRAN Group)
LEAP is a registered trademark of CFM International

Investing for growth…

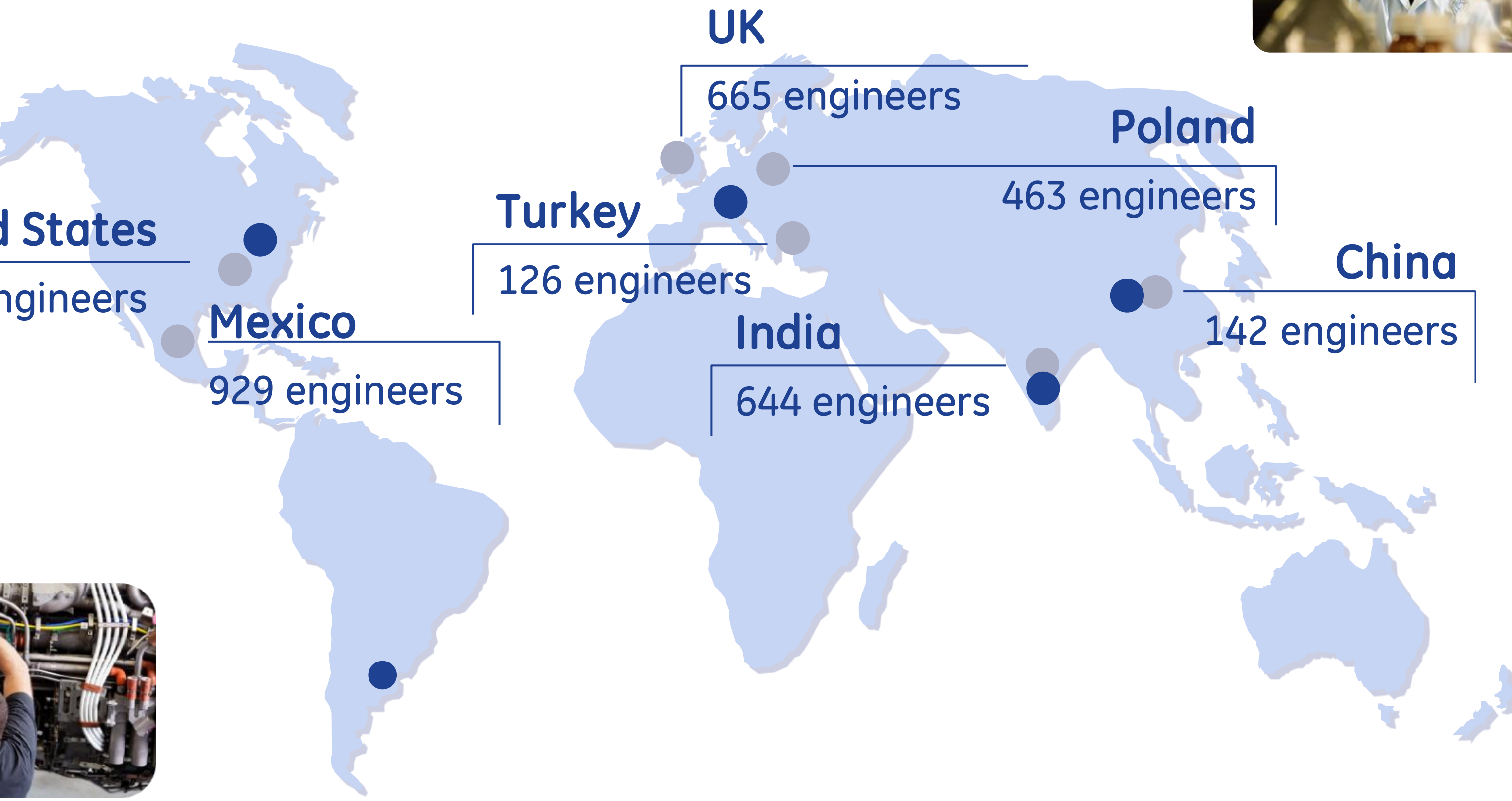
Engineering as a strategic advantage

Leadership — Innovation and execution

Capacity — Right people, right time

Capability — Right skills to deliver

GE Aviation Engineering



- Over 8000 GE Aviation engineers around the globe
- ~3000 technologists at 5 Global Research Sites

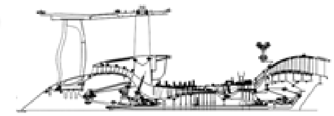
Pioneering New Technologies

GE's multi generation technology plan

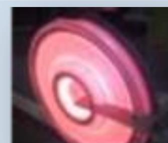
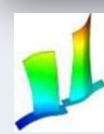
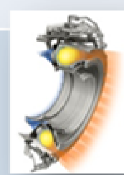
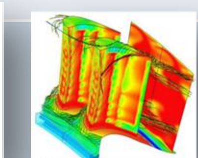
GEnx
2011

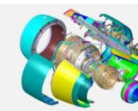
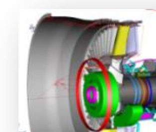
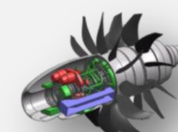
LEAP
2016

GE9X
2019



2025+ Engine

	LEAP	GE9X	
Advanced Materials	• CMC Shroud	• Gen1 CMC HPT • CMC Combustor • High Temp Disk	 
FAN & LPT	• Composite Fan • 18 blades • Improved Aero	• Composite OGV • 16 blades • Improved Aero	 
Core	• NG HPT Blade • Additive mfg fuel nozzle • Adv cooling	• 27:1 Compressor • TAPS III Combustor • Adv. Seals	 
Controls	• Adv. FADEC • Lightweight externals	• Distributed Controls • Adv. Fuel Pump	 

2025+	
Gen2 CMC HPT	
Low Drag Installation	
Light weight adv. Components	
Beyond 2025+	
Unducted Fan	

Fan Technologies

Generational changes in technology

Lightweight
Durable
Efficient

Composite technology advancement

Improved performance and weight reduction

GE90-94B
777-200ER, 777F

1995

- Wide chord design
- 22 blades

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

2004

- Swept aero
- 22 blades

GEnx
787, 747-8

2011

- Improved efficiency
- Lower Radius Ratio
- 18 blades

LEAP
737 MAX, A320 neo

2015 cert

- 3D woven fiber and resin transfer mold
- Advanced camber
- 18 blades

GE9X
Next-Gen 777

2018 cert

- 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

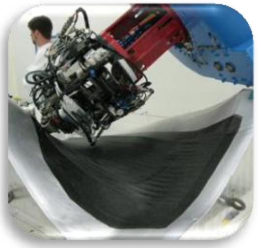
Successful Field Experience that was Developed on Bird Strike and Blade Out Rigs

- 30+ million flight hours today and by 2019 over 150 million flight hours

Crosswind

Subscale Rigs

Bird-strike/FBO rigs



Manufacturing

Unsteady Coupled Inlet+Fan CFD in Crosswind

Validation Program

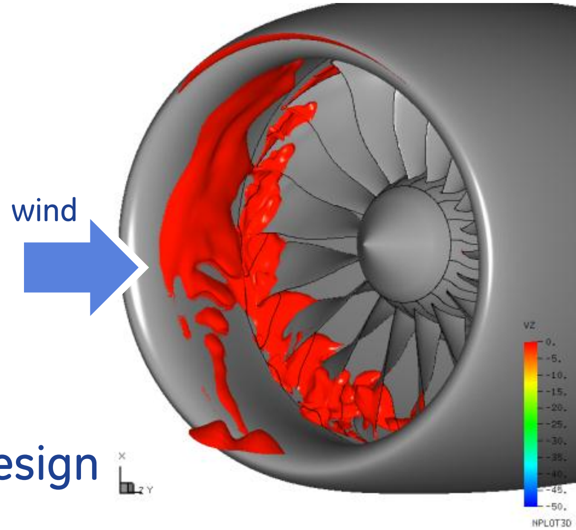
- Modeling nacelle, fan, OGV, & nozzle and ground plane
- Utilizing model and engine test data for validation

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

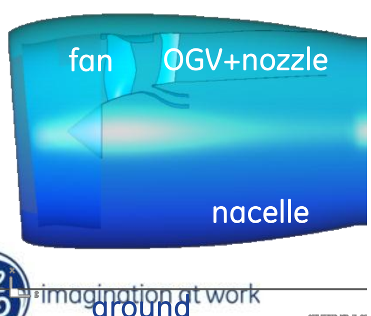
Improved Fan response and distortion transfer assessments

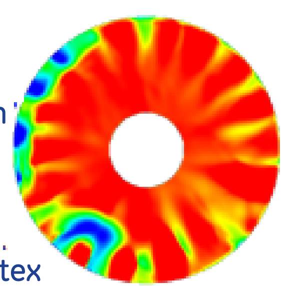
- Fan forced response analyses & assessment
- Fan response to inlet distortion & distortion transfer to core
- Fan operability assessment via numerical throttling



Nacelle Separation bubble

High Bypass Fan Simulation

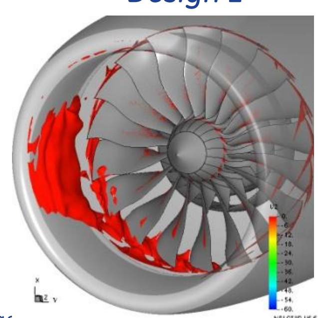




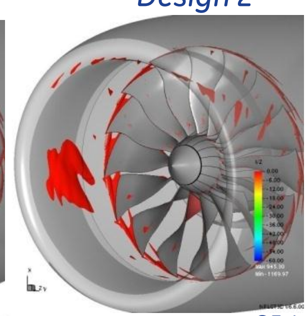
Fan face Stagnation Pressure

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

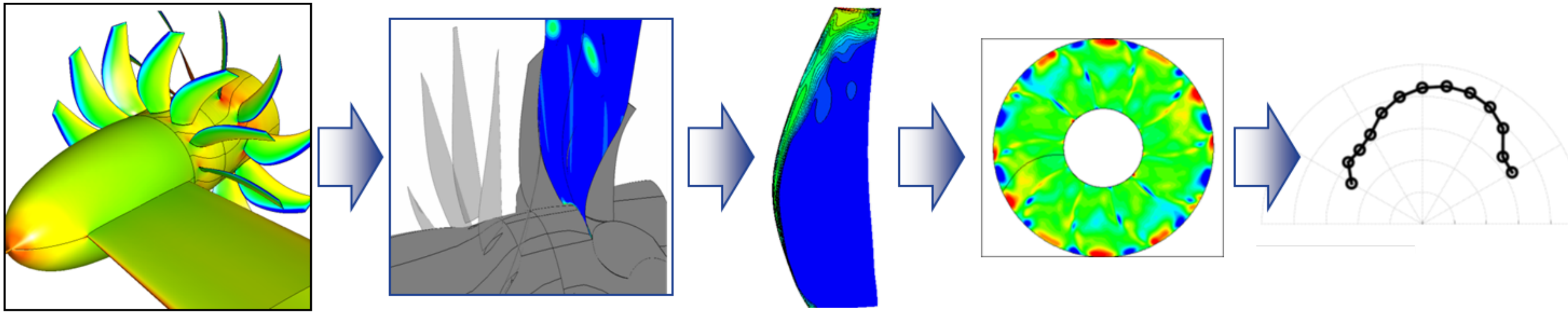
FAA: feedback, reviews, sponsorship under Continuous Lower Energy, Emissions, and Noise (CLEEN) program

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



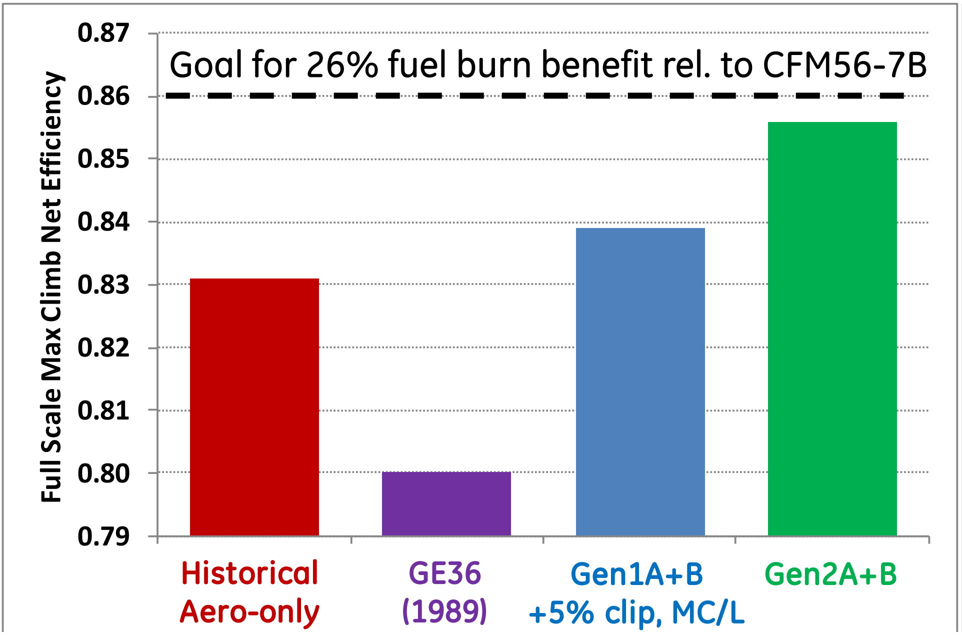
Sources | Gust / Forcing | Blade Response | Nearfield Acoustics | Farfield Acoustics

Multi-step Acoustic Prediction Process

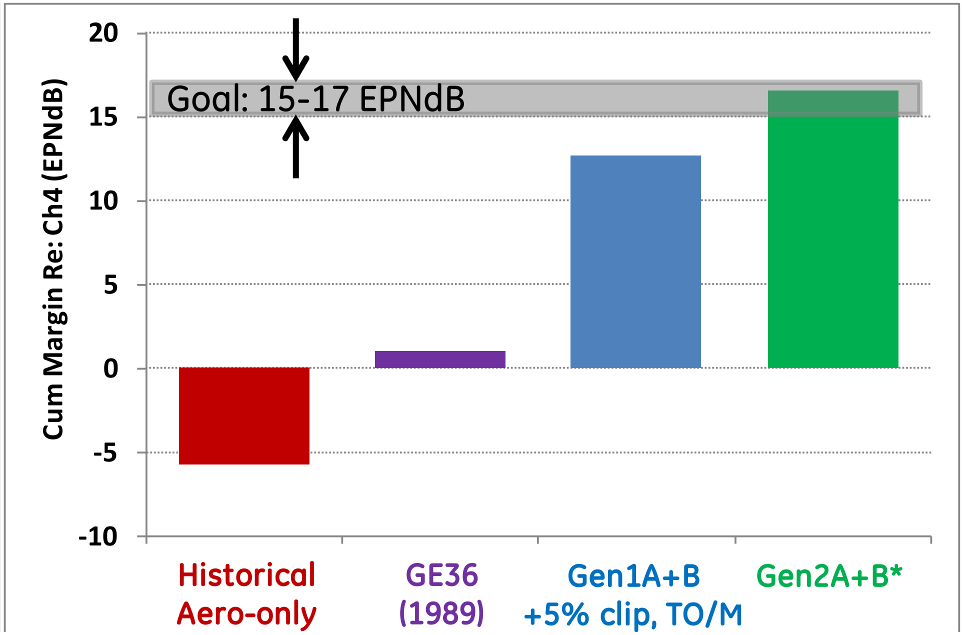
$$\underbrace{\text{Wakes/Gusts} \rightarrow \text{Unsteady R2 Surface Pressure}}_{\text{CFD}} \rightarrow \underbrace{\text{Radiated Acoustics}}_{\text{CAA}}$$

Predicted experimentally observed trends between 2 Gen1 designs. Used for Gen2 design guidance.

Open rotor technology progress



- 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)*

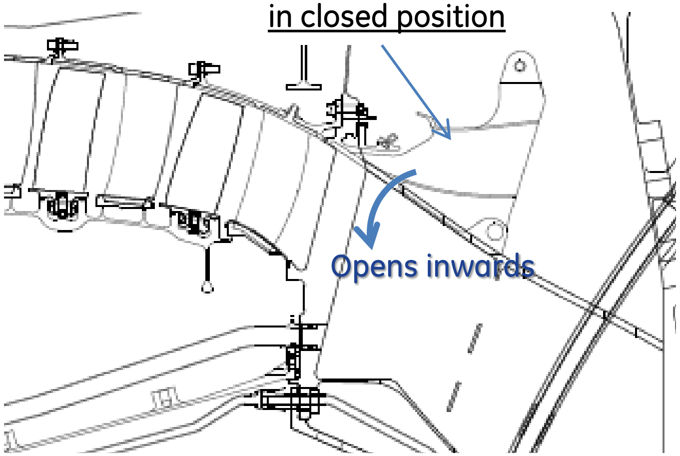
- 1980's designs were *marginally* satisfactory for either performance or acoustics
- Gen2 demonstrated technology effectively meets CLEEN open rotor goals

Booster Technologies

Core Stream Ice and Sand Particle Extraction

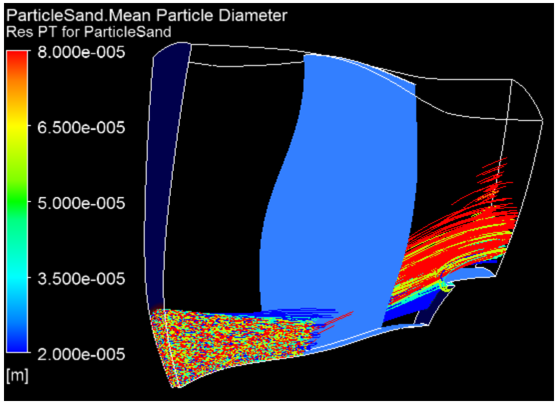
- VBV doors open at part power. Bleed air from Booster exit to control Booster operating line.
- Can be effective in extracting ice and sand particles from entering core engine.
- GE90 & GEnx use inward-opening VBV doors.

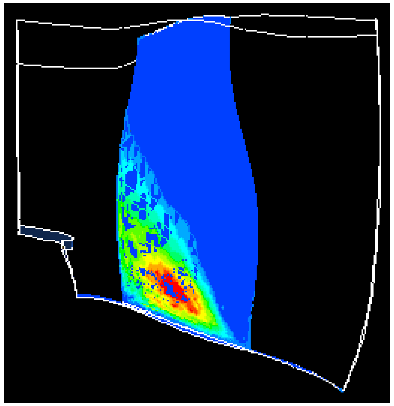
Improved extraction reduces core performance deterioration & improves HPC operability

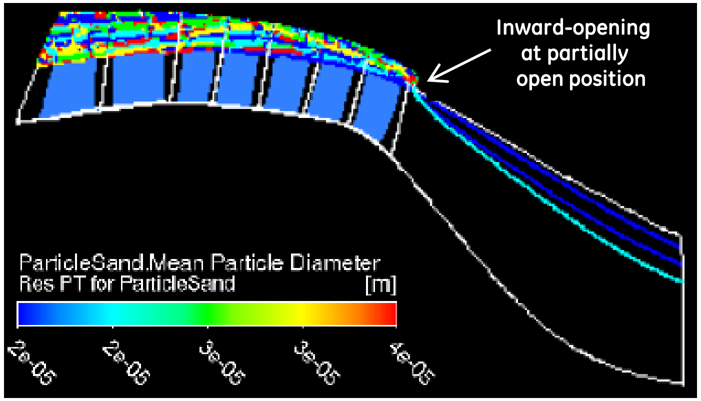


- Improved particle trajectory CFD fidelity provides better understanding of particle tracking through Fan, Booster and Goose Neck Duct into HPC.

Sand Transport Analyses





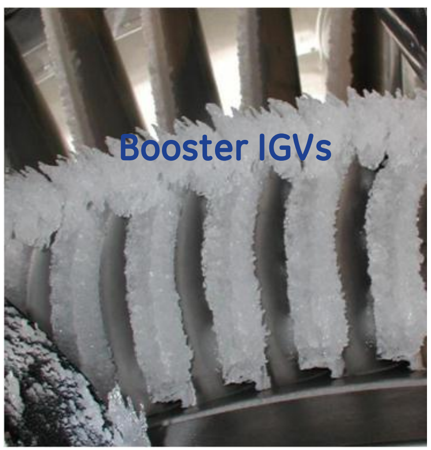


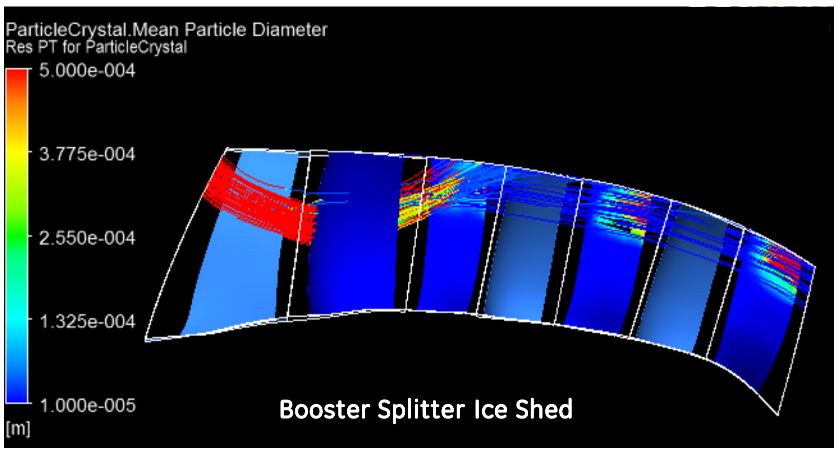
Improved Particle Trajectory Modeling Benefits

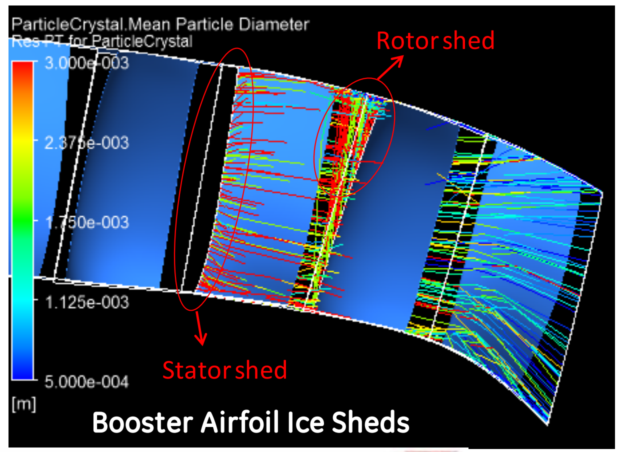
More effective sand & ice shed particle extraction prior to HPC by optimizing Booster & GND flowpath, and VBV configuration designs.

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

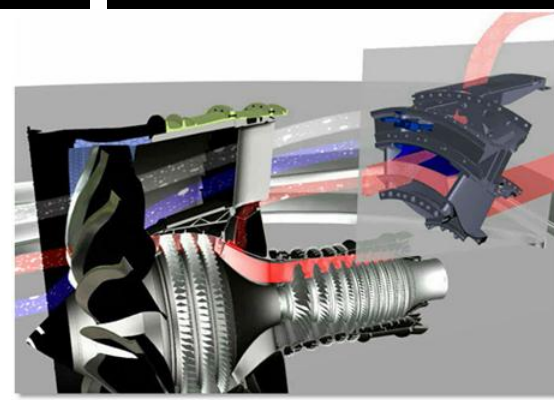
Ice Particle Shed Trajectory Analyses







Next Generation Engines will benefit from Improved Ice and Sand/Dirt Extraction



HP Compressor Technologies

imagination at work

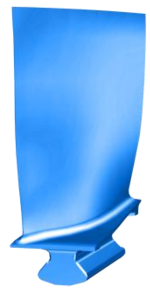
Advanced compression technology

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

1995-2004

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

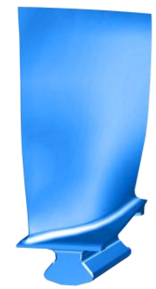
GEnx and LEAP
787, 747-8, C919,
737 MAX, A320neo,



2011

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

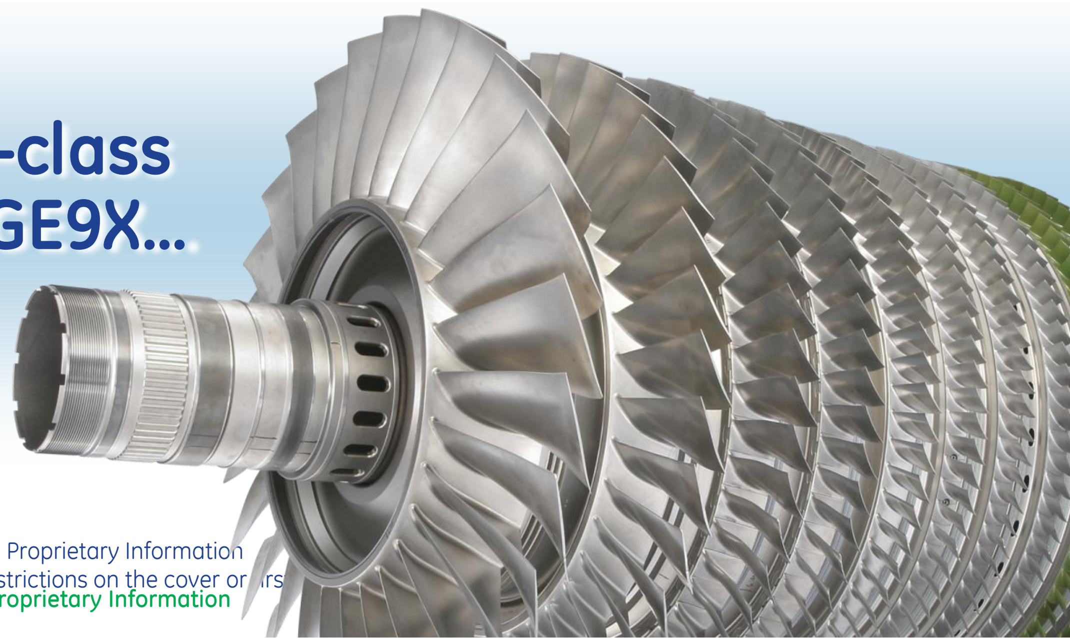
GE9X
Next-Gen 777



2018 Cert

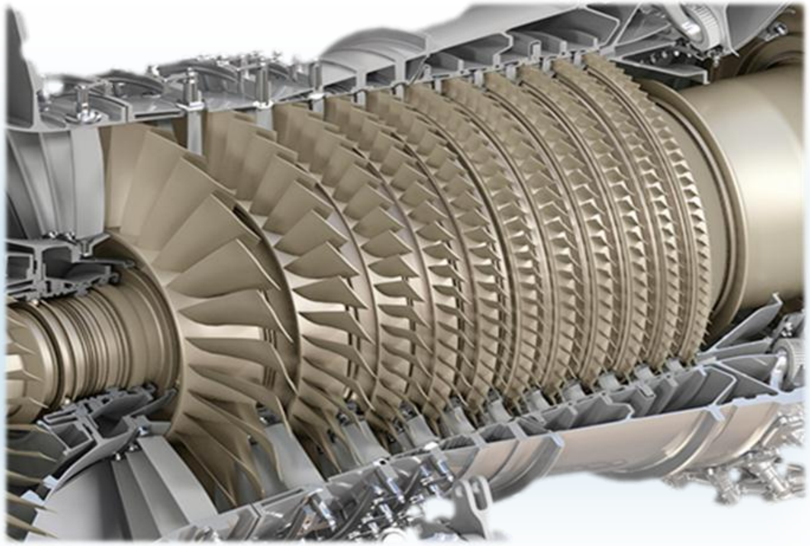
- 11 stages
- Compressor Pressure Ratio **27**
- Overall pressure ratio ~**60**

It all begins with a world-class compression system for GE9X… testing begins in 2013!



GE Proprietary Information

High Pressure Ratio Compressor



Technology Driver:

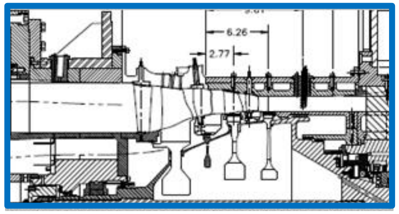
- Increased Thermal Efficiency from High OPR

Technology Play:

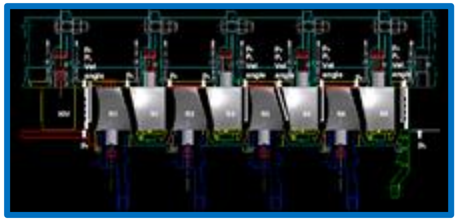
- 11 stage, 27:1 pressure ratio with advanced 3D aero
- Improved clearances from TCF engine mount

Benefit: ~2% SFC benefit

Technology Maturation Program for High OPR HPC

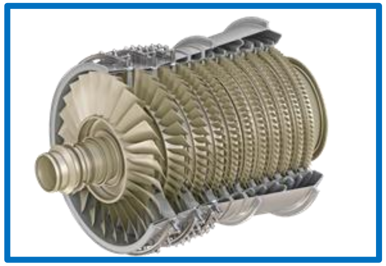


Front stage rig
Improved front stage efficiency



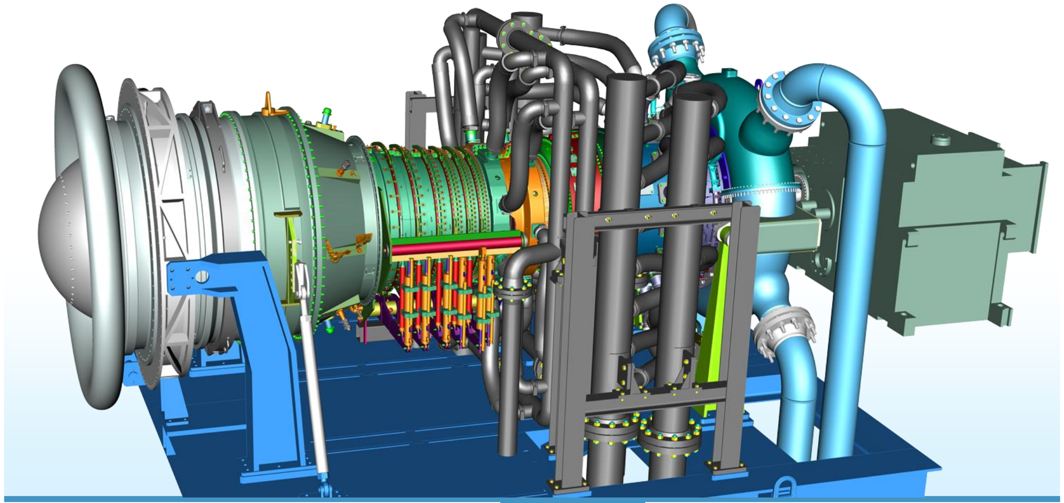
LSRC rig
Improved rear stage efficiency & clearances

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

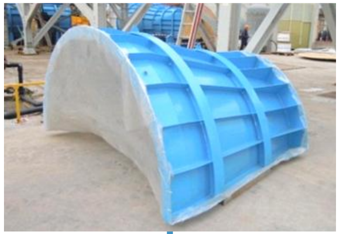
Compressor test facility, Massa, Italy



Inlet piping

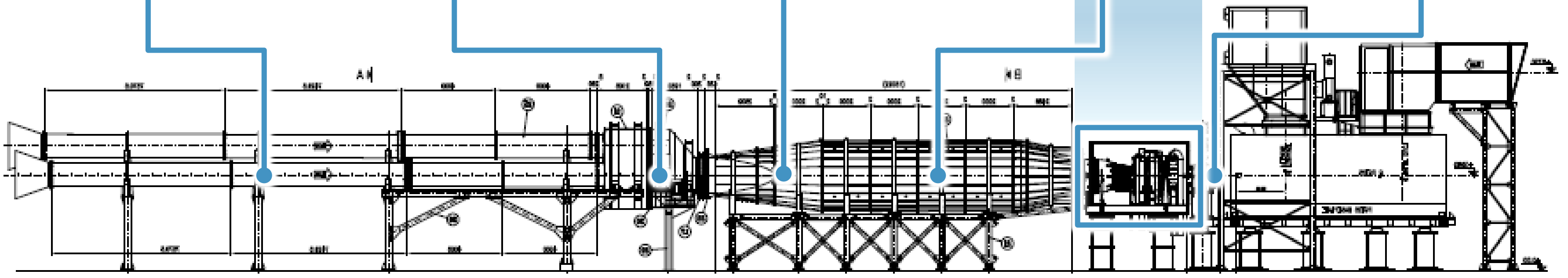
Inlet filtration

Reducer section



Flow straightener

Gearbox



Combustor Technologies

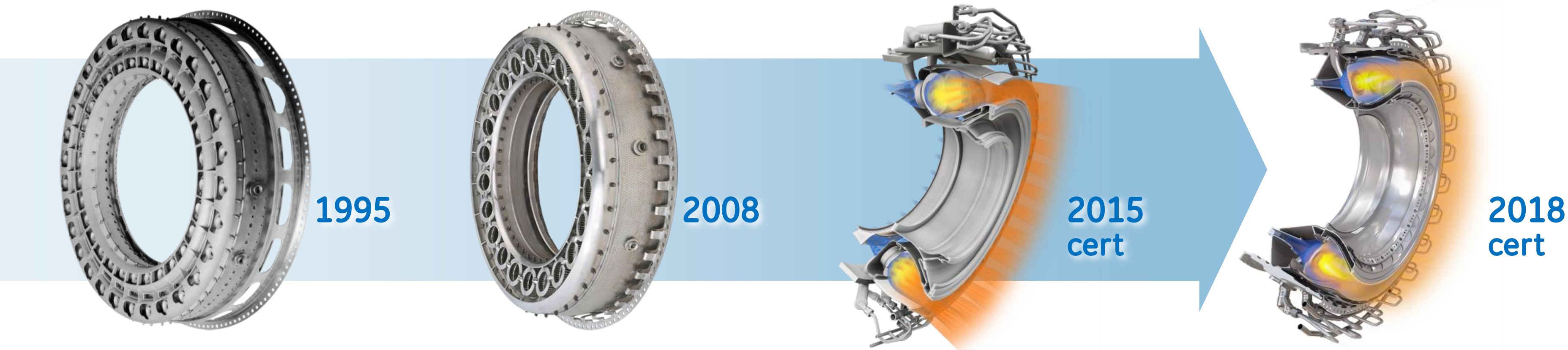
Combustion technology evolution

DAC (GE90-94B)
777-200ER, 777F

TAPS I (GEnx)
787, 747-8

TAPS II (LEAP)
737 MAX, A320 neo

TAPS III (GE9X)
Next-Gen 777



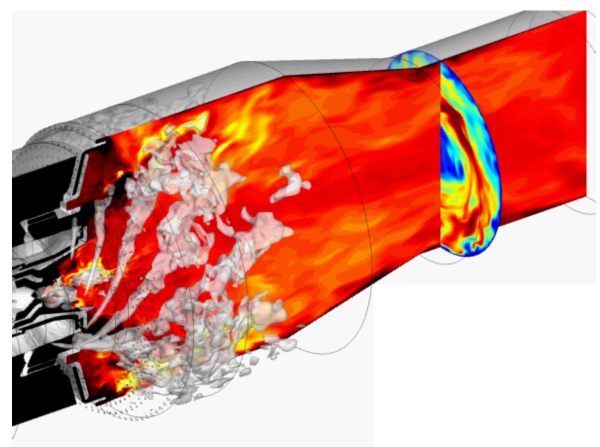
DAC
- 2 Nozzle lean burn
- 10M+ flight hours

TAPS I
- World-class emissions

TAPS II
- Improved durability
- 30% lower emissions

TAPS III
- Higher pressure
- Reduced cooling flow
- NextGen Mixer
- 60% lower emissions

GE leading in lean combustion in service experience and technology



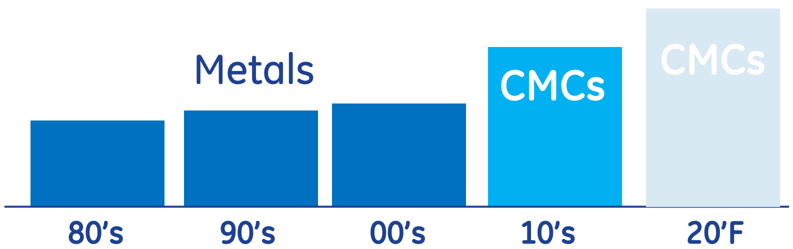
GE Proprietary Information

HP Turbine Technologies

imagination at work

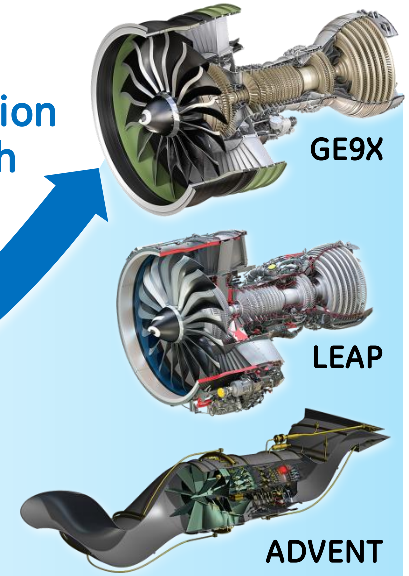
CMCs … long-term commitment to execute and unlock potential

Material temp. capability



1/3 weight
20% Greater
thermal capability

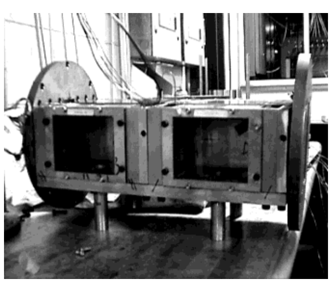
Application
growth



Product development
and revenue service

Research and proof of concept

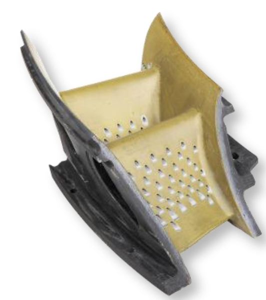
1980 1990 2000 2010 2020+



Combustion test rig

Demo engine test

Mixer



Turbine nozzles

GE Proprietary Information

LP Turbine Technologies

imagination at work

Advanced LP Turbine

Technology Driver:

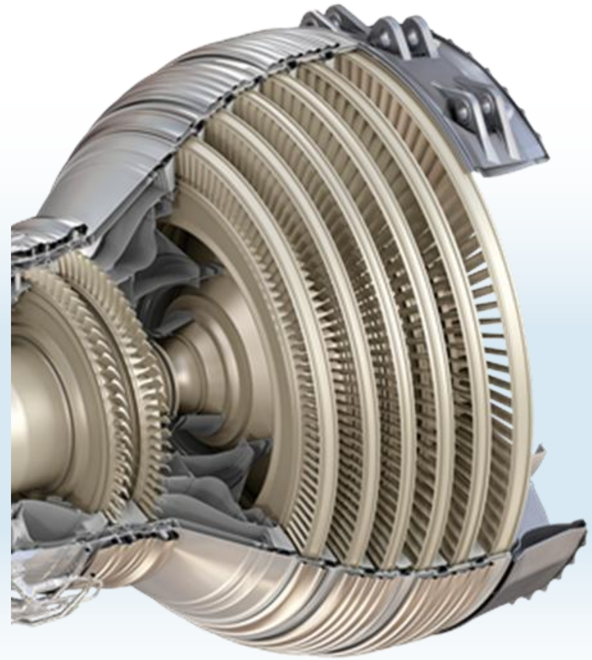
- Minimize fuel burn through increased efficiency and decreased weight

Technology Play:

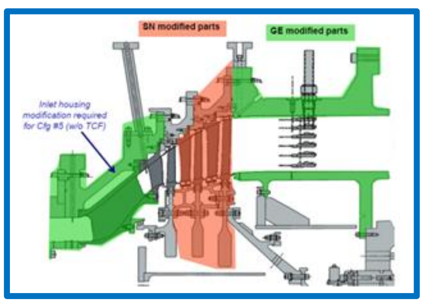
- Increased LP speed, advanced aerodynamics and mechanical design, overhung LPT with aerodynamic OGV

Benefit:

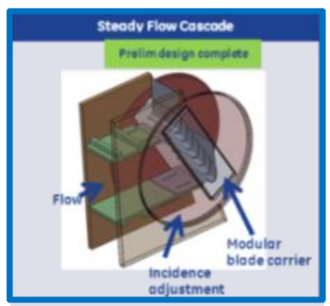
- 0.6pts fuel burn reduction vs SOA



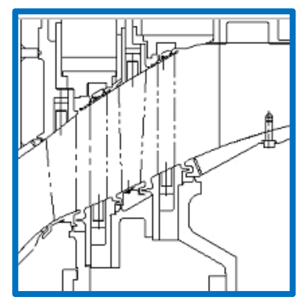
Technology Maturation Program for Adv LPT



Technology Development
Single and dual spool test validation



Cascade rig
Steady flow & unsteady to confirm loading optimization

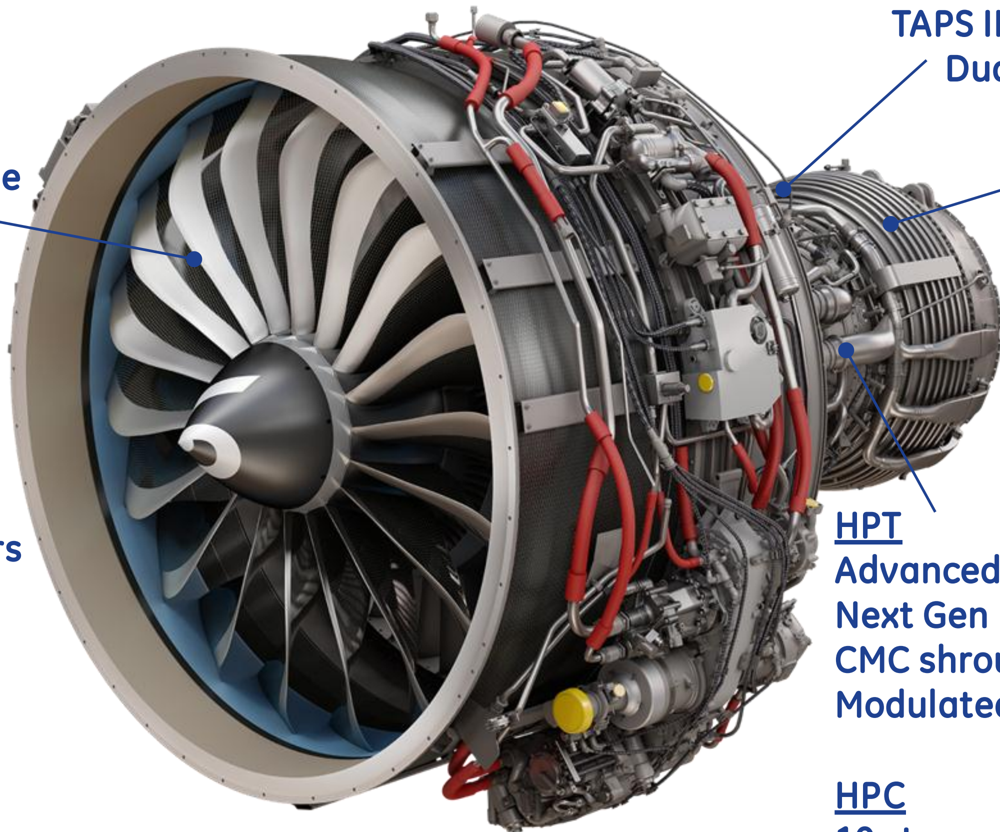


Rotating rigs
Validate improvements with low & high speed rigs

Low Cost Mfg
TiAl Near-Net-Shape Spin Casting Facilities

Bringing it all together

CFM LEAP-1A/B/C



TAPS II Combustor with
Dual Orifice Nozzles

Fan
18 Blades
3D Woven Composite Blade
Composite Case

LPT
R65 Rotor
TiAl Blades

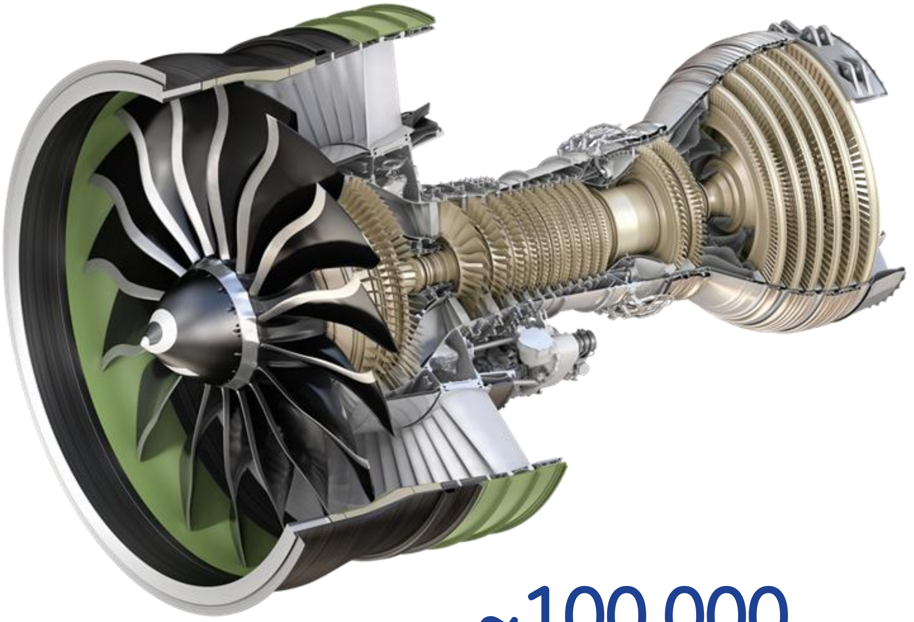
Booster
Inward Opening VBV Doors
Inlet Lip Anti Ice

HPT
Advanced Cooling
Next Gen Blade
CMC shroud
Modulated Turbine Cooling

Program:
Core 2&3 complete
FETT Sept. 2013

HPC
10 stages
PR=23
Start Bleed
Transient Bleed

GE9X Product Overview



	115B	GE9x
Bypass Ratio	8:1	10:1
HPC Pressure Ratio	18:1	27:1
Overall Pressure Ratio	46:1	64:1
T3 Redline	1300°F	1400°F
Thrust	115klb	100klb
Fan Diameter	128”	132”

~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

imagination at work