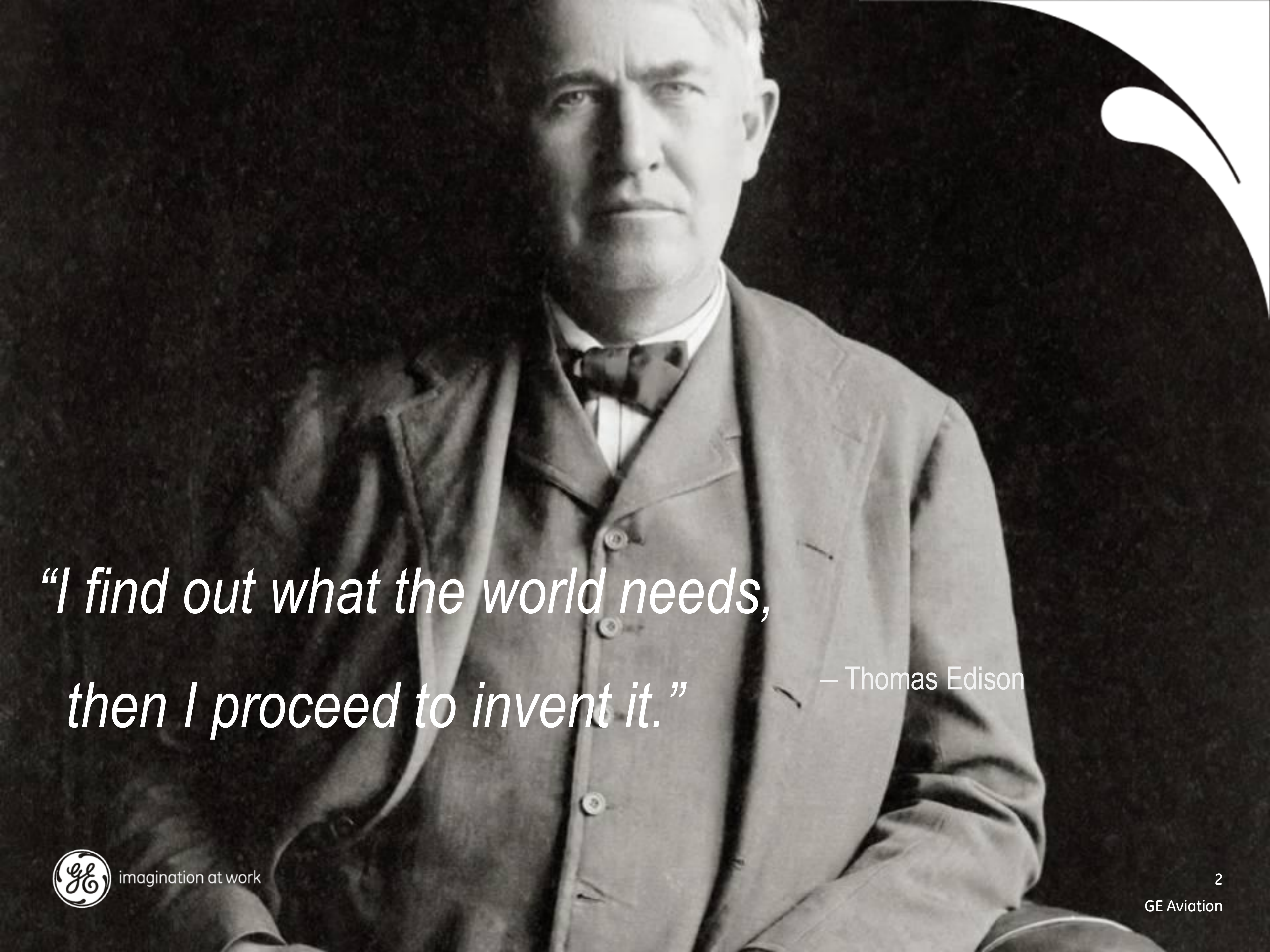
GE Aviation: Perspectives on Clean, Efficient Engines

Dr. Dale Carlson

May 7, 2013

imagination at work



“I find out what the world needs,

then I proceed to invent it.”

– Thomas Edison

Technical innovation …

Key to our past and future

First

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

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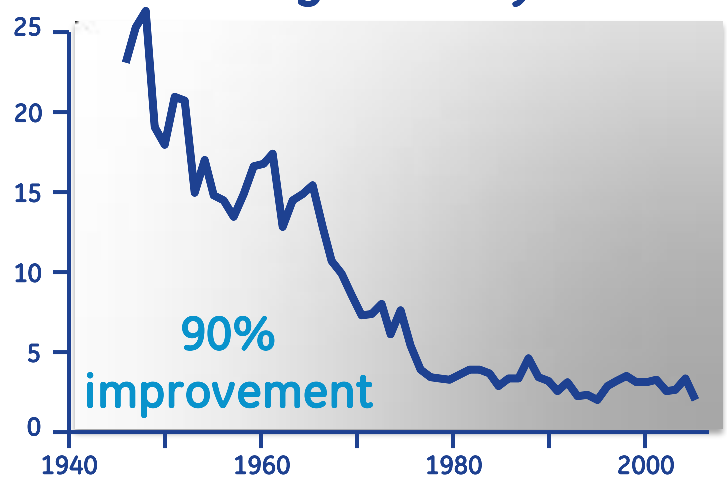
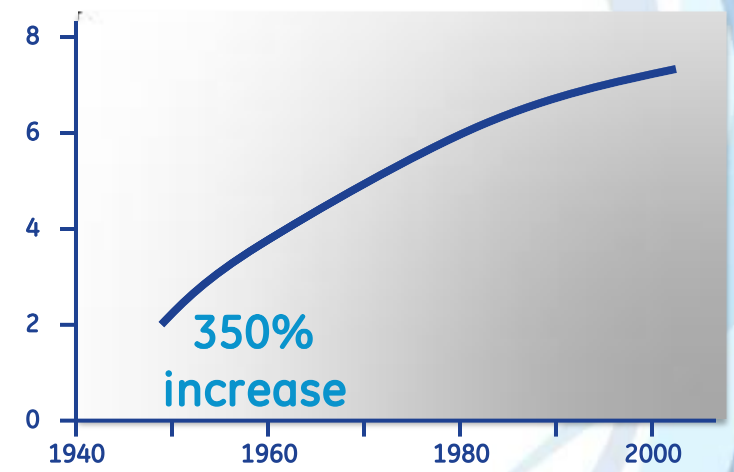
50 years of engine improvements

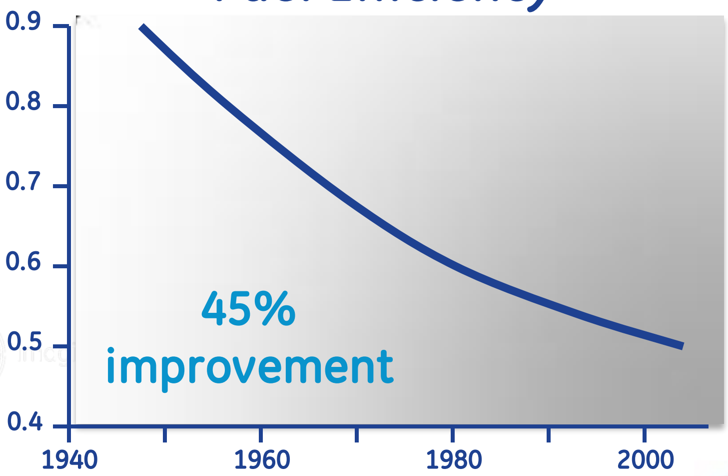
Flight Safety



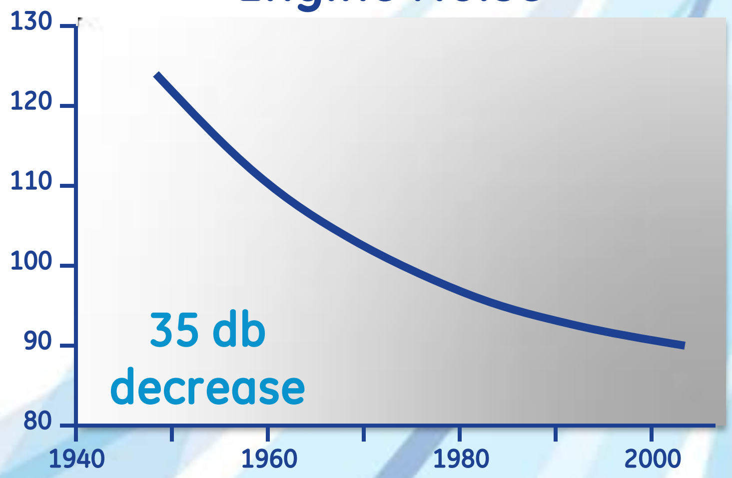
Thrust to Weight



Fuel Efficiency



Engine Noise



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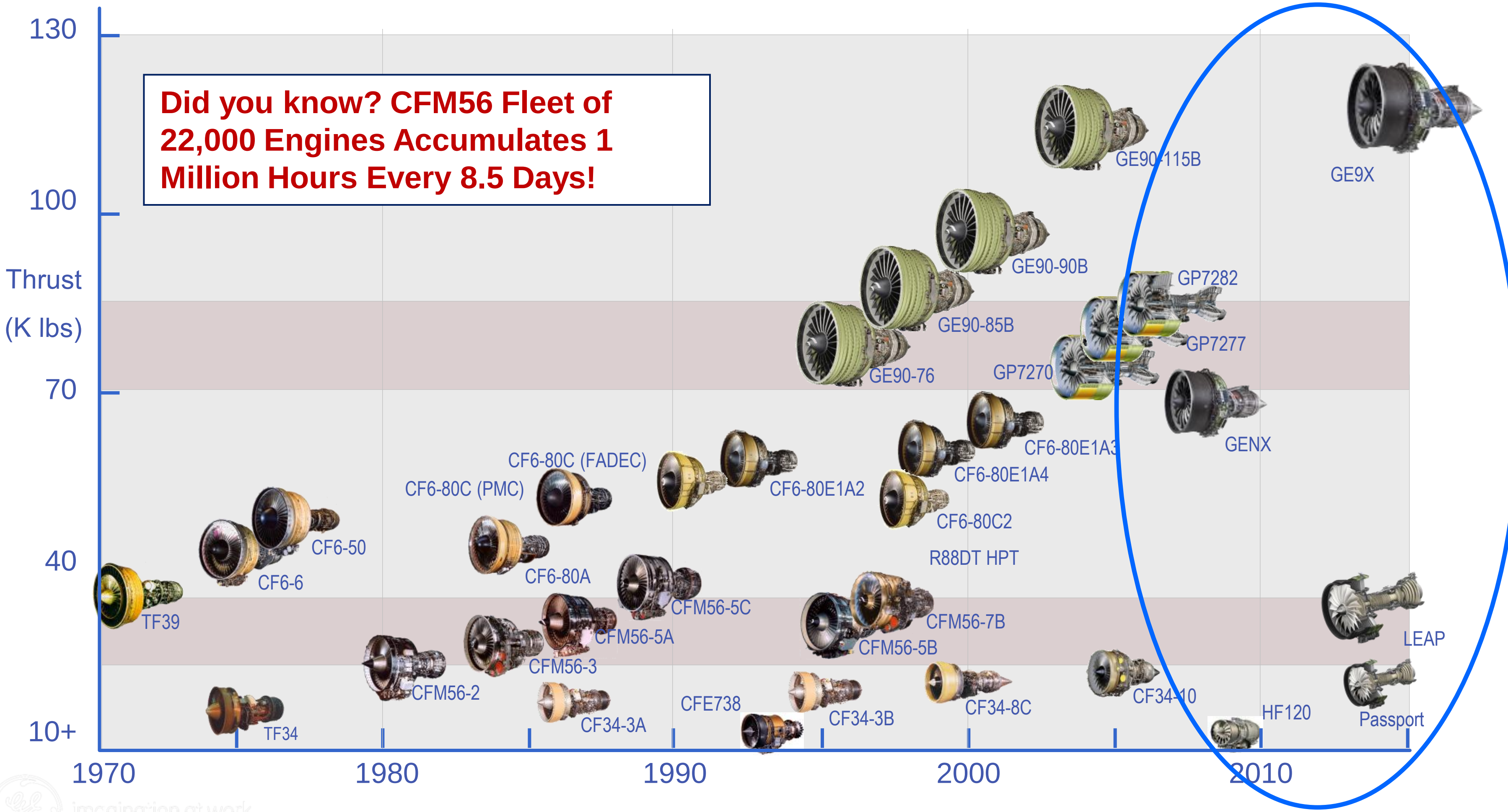
Commercial engines…by thrust rating

New Technology In Each Power Class



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

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The Future:

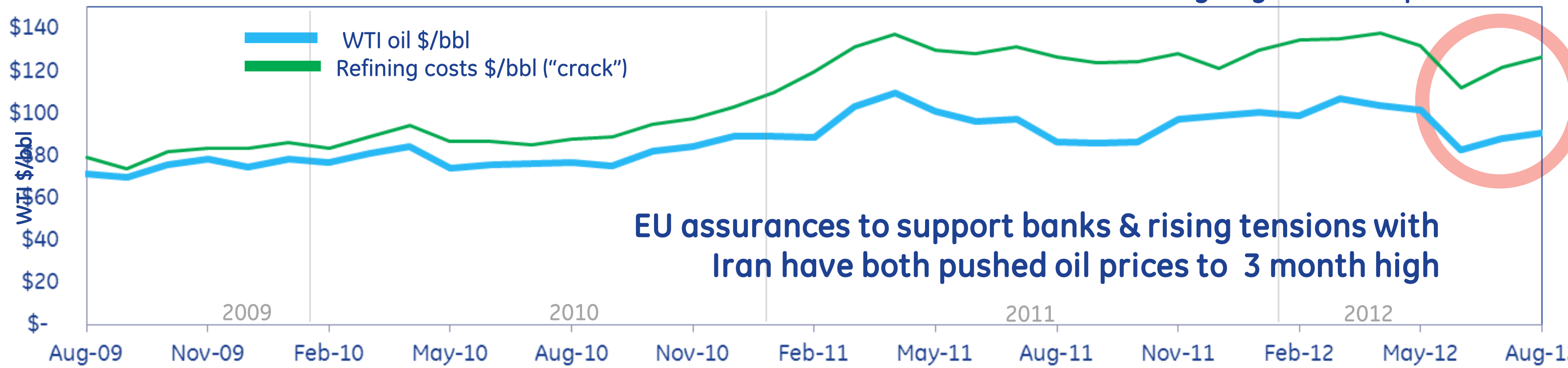
Global forces/environment

Industry drivers

Oil & crack spread

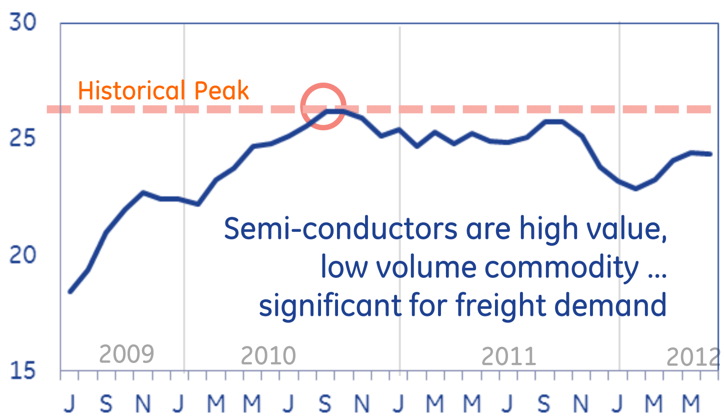
Energy Information Agency (EIA)

WTI ↑5.1% YoY … Avg August crack spread $36



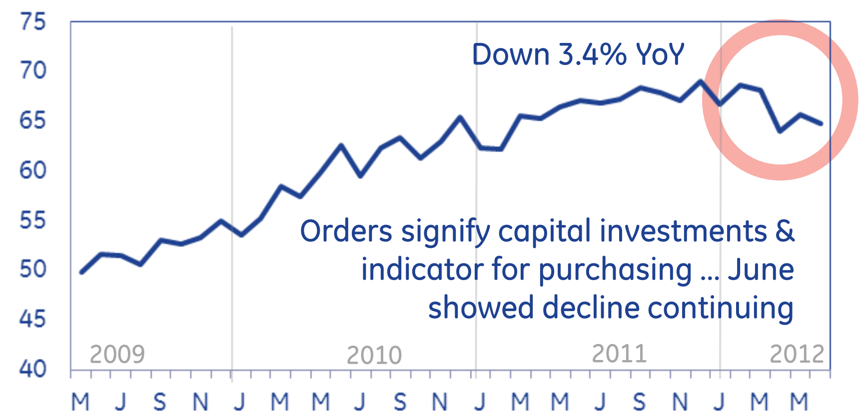
Global semi-conductor billings

SIA, 3 month moving average (Per MM)



U.S Non-defense capital goods orders

U.S Bureau of Labor Statistics (Orders, seasonally adjusted, $B)



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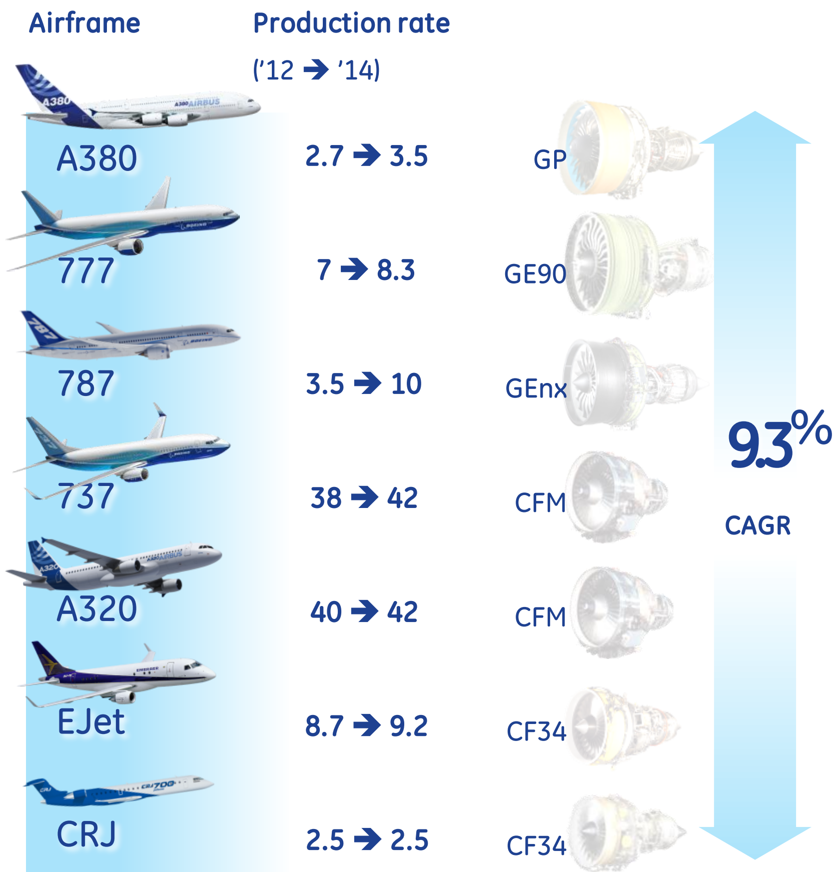
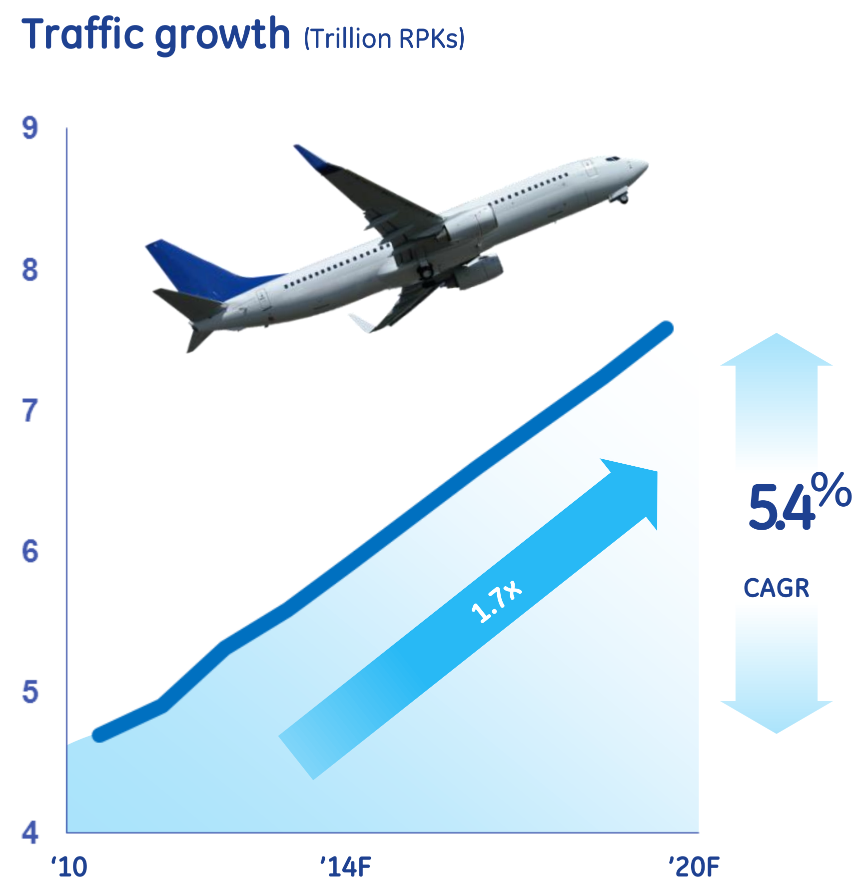
Commercial aviation growing steadily





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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EA is a 50/50 JV between GE and Pratt & Whitney

Technology success takes commitment and opportunity

Commitment … **$1-2 billion** continuous technology investment per year

GE90 core tests

GP7 core test

GEnx core tests

LEAP eCore tests

1995 **2000** **2005** **2010**

GE90

CF34-10E

CF34-8C

GEnx-1B

CFM56-5B

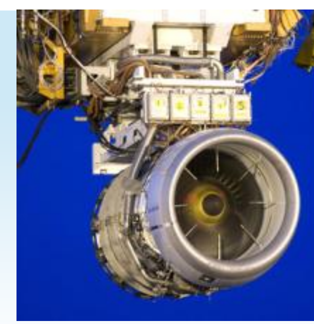
CFM56-7B

GE90-94B

GE90-115B

GP7200

GEnx-2B



Opportunity … **10 new engines** proving and maturing technology

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EA is a 50/50 JV between GE and Pratt & Whitney

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Our Industry-Specifically Propulsion

- 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 CO_2 commitment, other regs looming

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Technology Readiness to Serve

Today and Tomorrow

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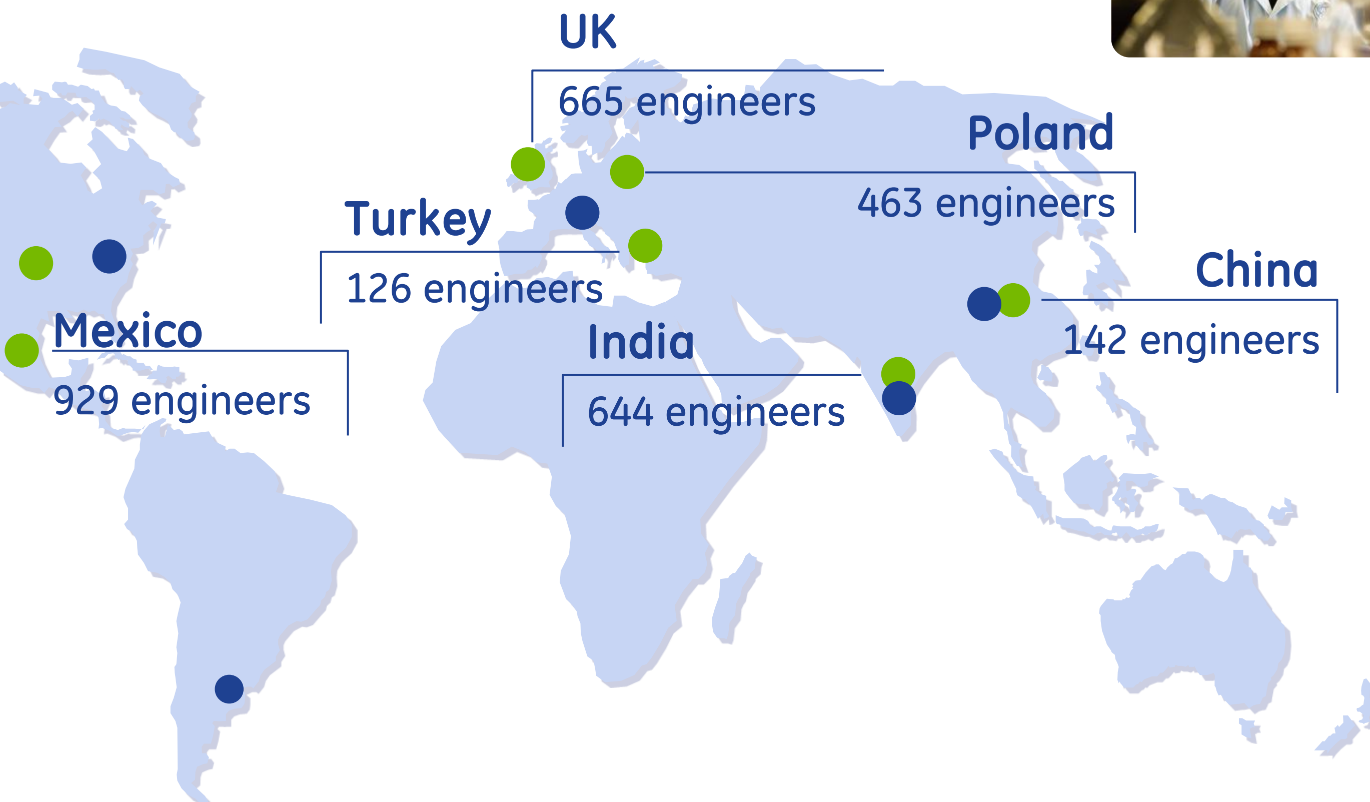
GE Aviation Engineering



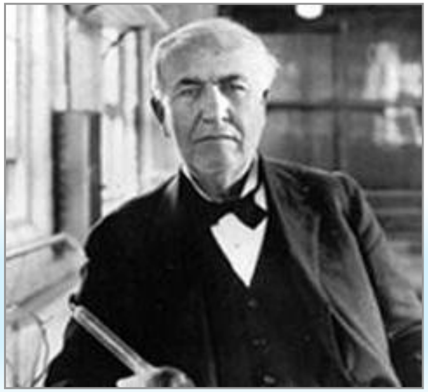
Over 8000 engineers around the globe
3000 technologists at 5 Global Research Sites

Practical innovation … GE's model

Global resources teamed to advance technology

Idea creation + **Technology maturation** = **Winning products**

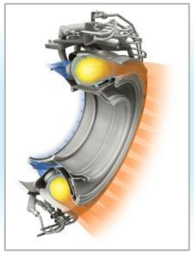
Idea creation
- Internal
- Customers
- Government
- Universities (300+ relationships)



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"

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

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

	$\eta_{thermal}$	$\eta_{transfer}$	$\eta_{propulsive}$	W_{empty}
Today	• Highly Loaded Compressors • High OPR Low Emissions Combustors	• Low Loss Inlets • Variable Low Loss Exhausts	• Very High BPR Turbofans • Ultra High BPR Turbofans	• Novel Alloys / MMC's • Non-metallics
2020-2050?	• Adaptive cycles • Constant Volume Combustion • Hybrid Electric Propulsion	• Distributed Power Transmission	• Open Rotors • Distributed Propulsion • Wake Ingestion	• Advanced Engine Architectures

Essential technologies … keeping the pipeline filled

Technology


Composites


Lean combustion


Advanced cooling


High-temp materials


Flight Management

2010

Advanced turbofan

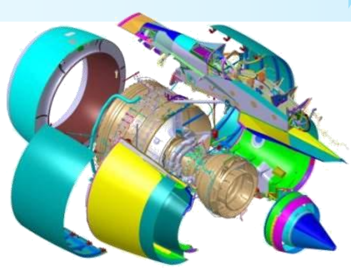
Integrated engine and aircraft systems

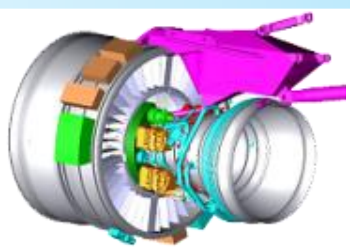
Adaptive cycles

Advanced architectures

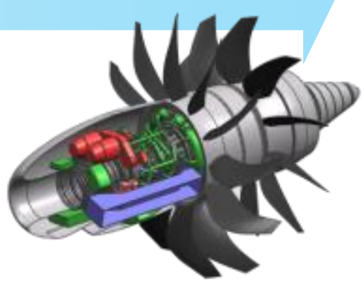
2020

Architecture


Integrated propulsion


Integrated power generation


Core efficiency


New designs

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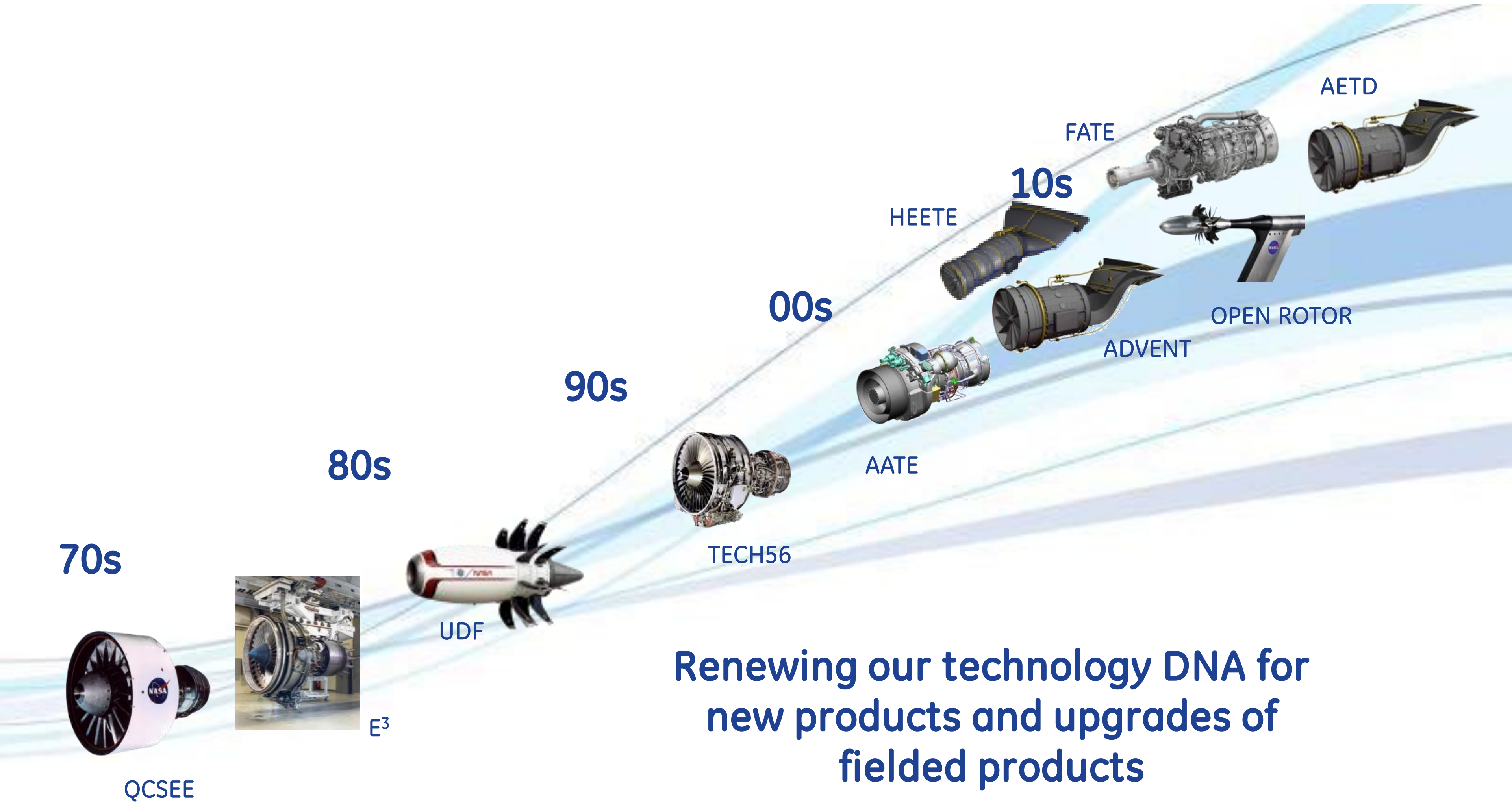
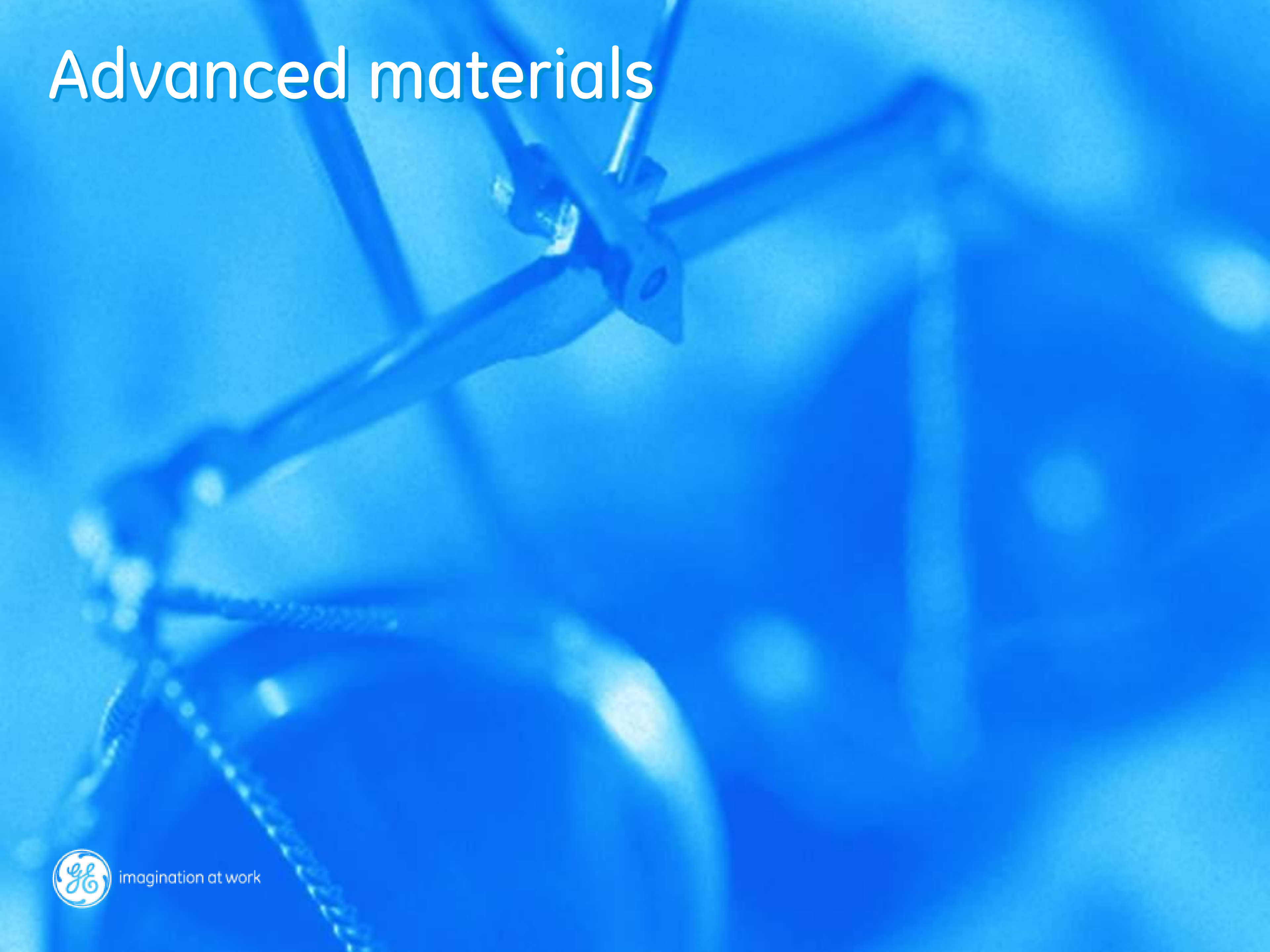
Technology demonstrator programs



Renewing our technology DNA for new products and upgrades of fielded products

Advanced materials



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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

16+ YEARS in service

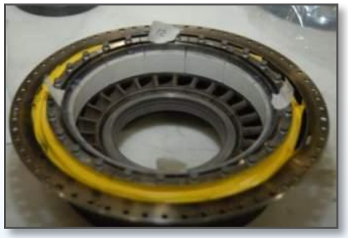
30+ MILLION flight hours

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

No cooling air losses

1/3 the weight

Higher thermal capability

Engine fuel efficiency

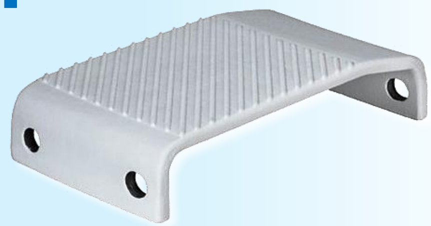
1st commercial application

2016
EIS performance

Future

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

TiAl turbine blade

10s

Complete Material Database

05s

Engine Testing of TiAl Components

00s

Component Casting Trials

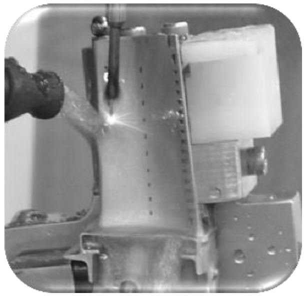
90s

Alloy Development

80s

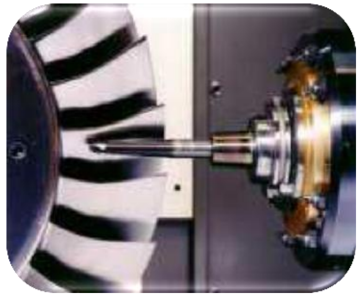
TiAl LPTB weight reduction vs. Ni superalloys … 100 lb./stage

Manufacturing Development



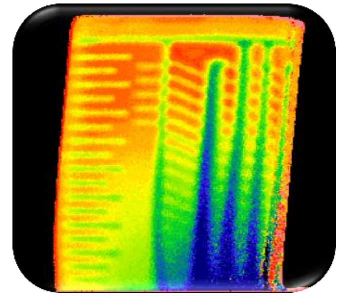
Turbine airfoils

Dayton



Rotating parts

Cincinnati



Manufacturing support

Cincinnati

Automation

Canada

PMC/Ox-Ox composites

Cincinnati

Structures

Cincinnati

Additive manufacturing

Cincinnati

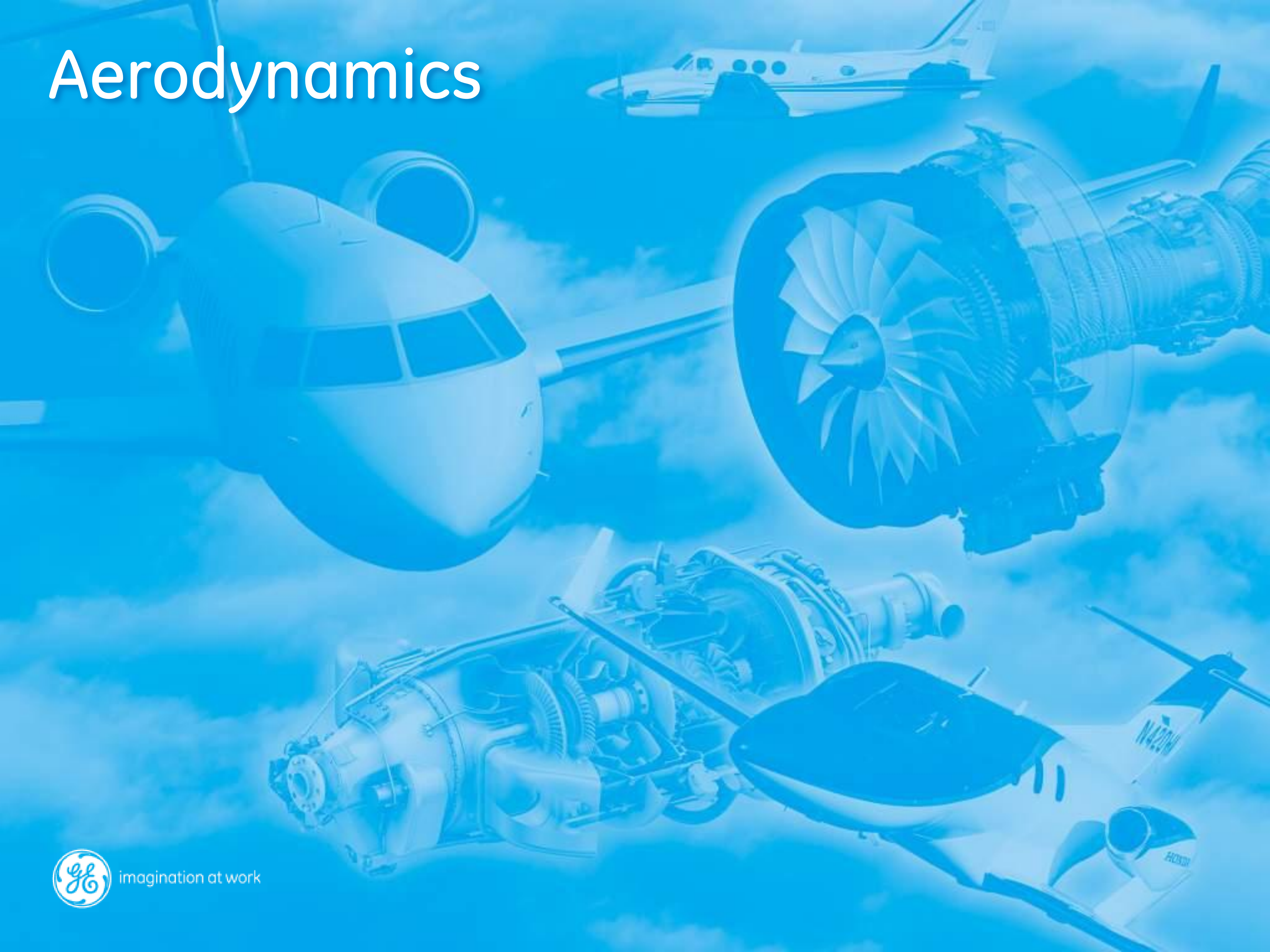
CMC composites

Newark

Technology readiness → research to production

Manufacturing readiness → industrialization

Aerodynamics



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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

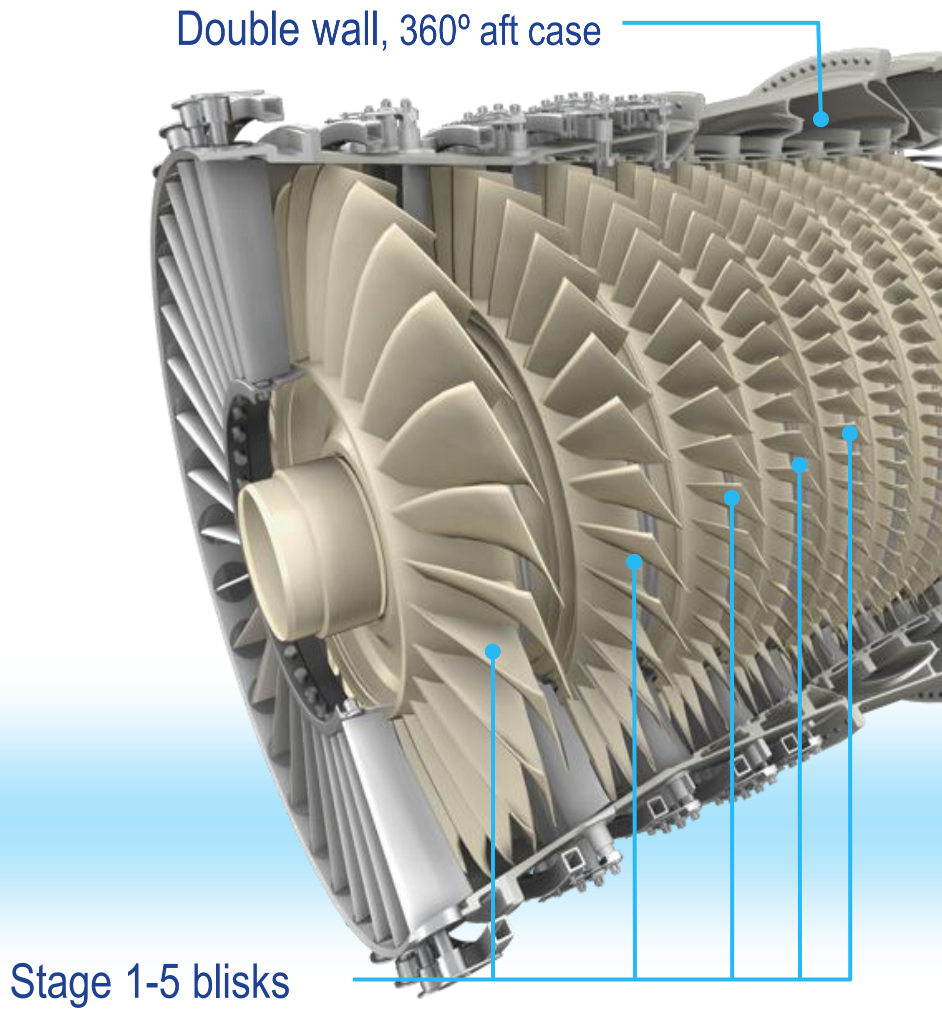
- Next generation 3D Aero
- 22:1 PR in 10 stages … best in industry

Performance retention

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

Operability

- Stall-free performance



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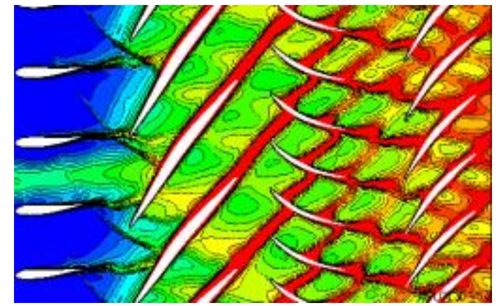
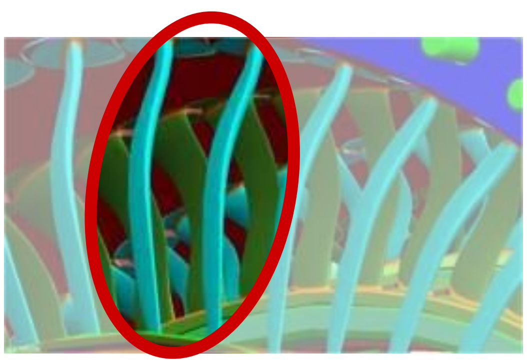
Compressor aerodynamics for LEAP

Efficiency, performance retention, maintenance costs

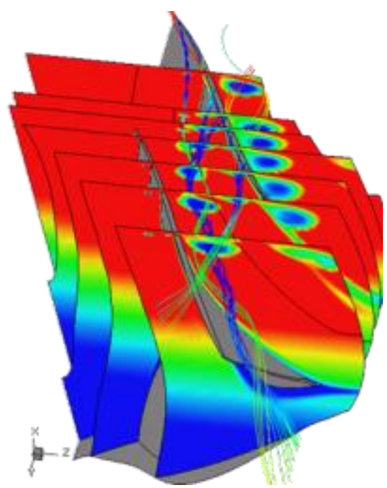


3rd generation 3-D aerodynamic design

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

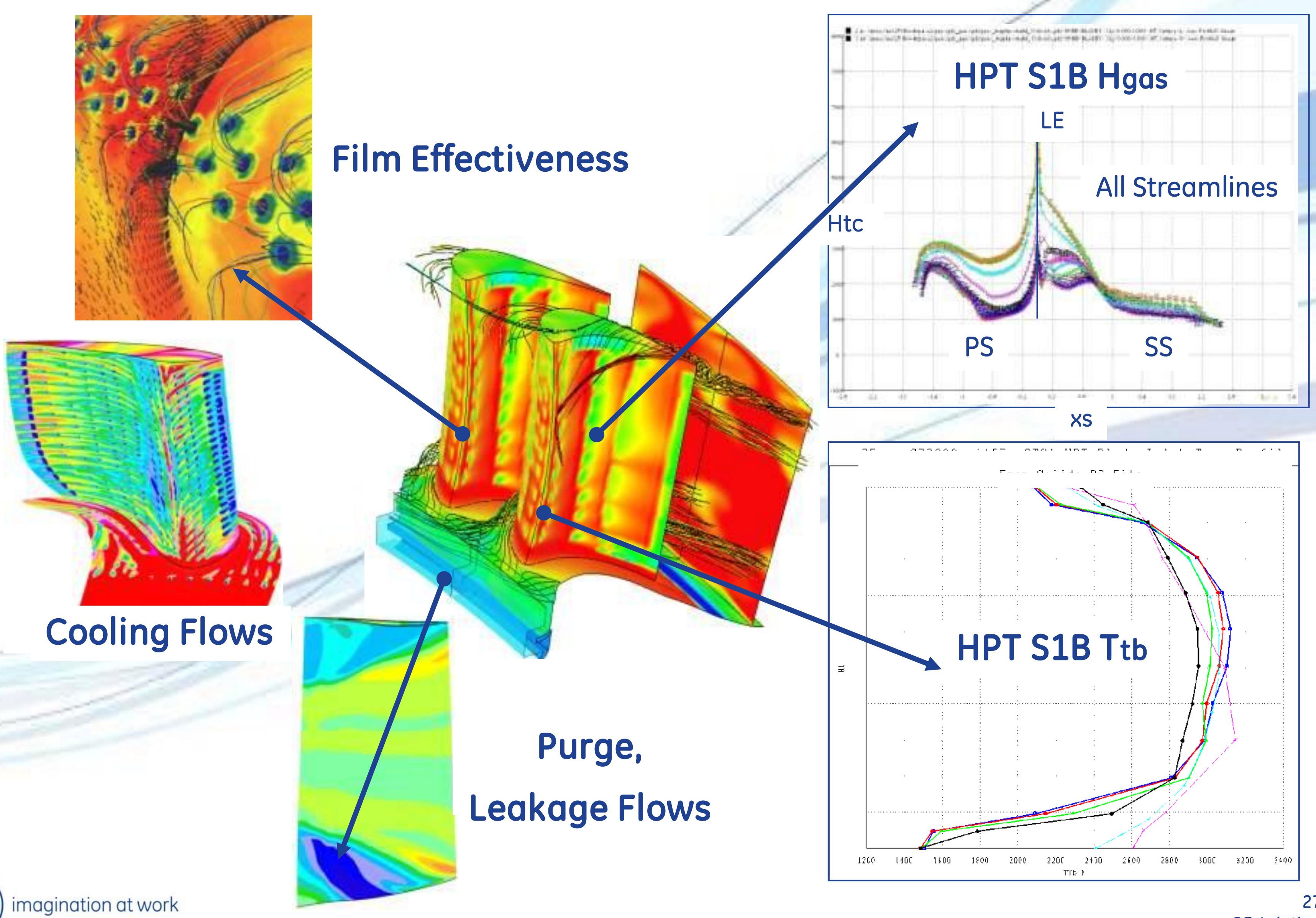


Bowed stators



Integral bladed disks

Advanced turbine cooling & efficiency



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Combustion

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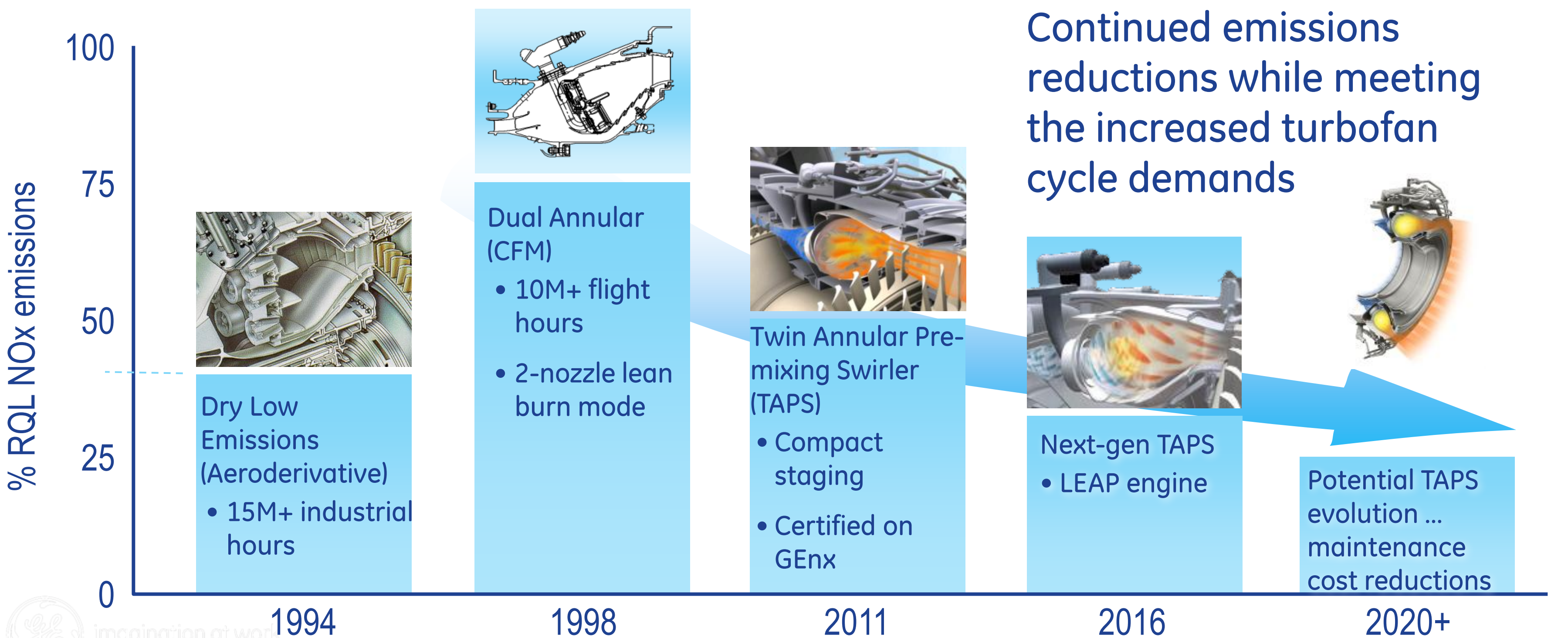
Lean-burn combustion …
over 25 million hours of experience

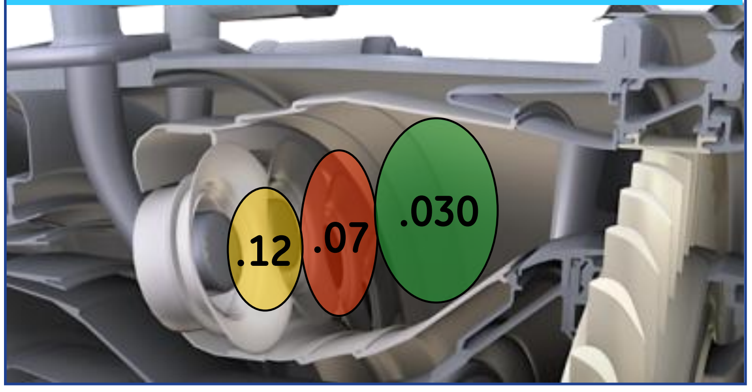
Cruise NOx improvement versus typical rich-quench-lean combustor
(NOx emission per lb of fuel*)



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

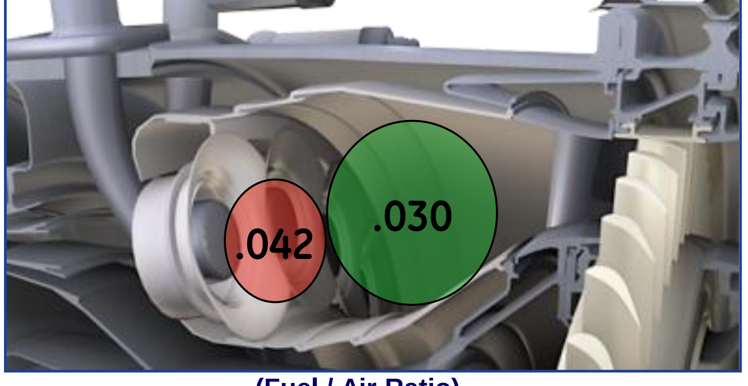
Lean combustion lowers NOx

Traditional Combustor



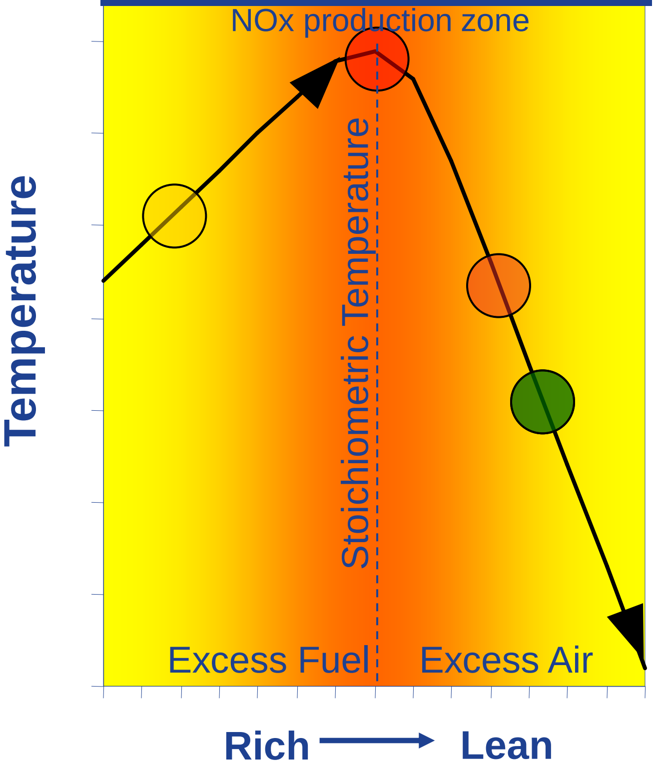
(Fuel / Air Ratio)

Lean burning TAPS Combustor



(Fuel / Air Ratio)

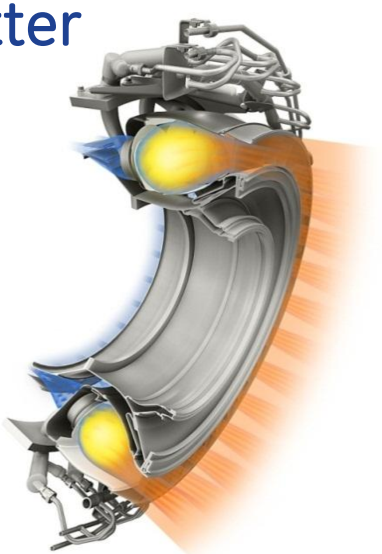
Temperature Rise Curve



Lean-burn combustion … lowers HPT distress & improves thermal efficiency

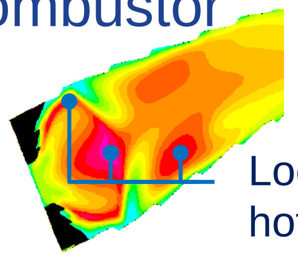
TAPS lean combustor

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

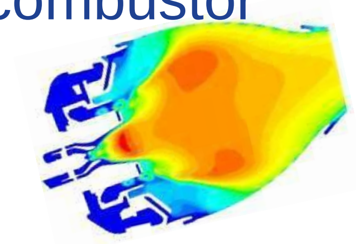


*Twin Annular Pre-mixing Swirler

Typical **rich burn** combustor



TAPS **lean burn** combustor



Bringing it all together

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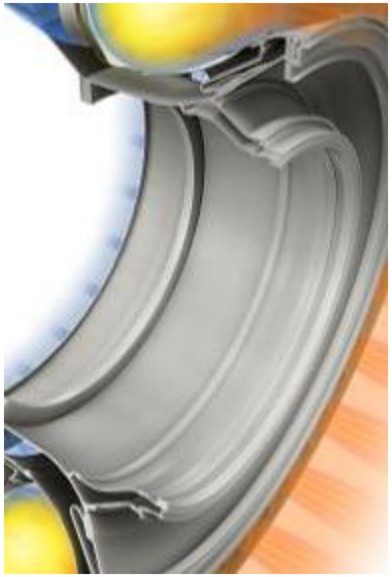
Technology readiness for EIS and growth

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

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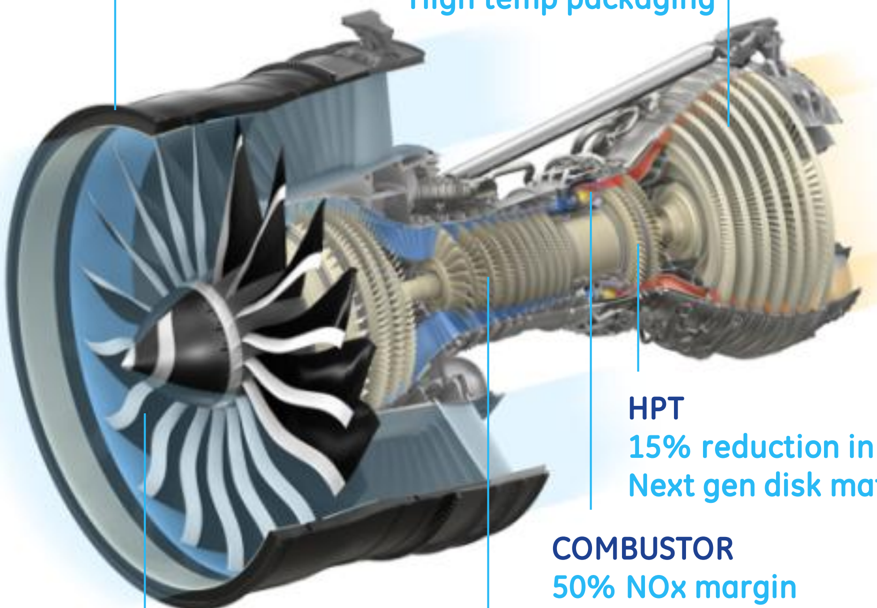
GEnx

Integrating new technologies throughout the engine

COMPOSITE CASE & FAN BLADES
1000 lbs./ aircraft

CONTROLS
Model based
Distributed
High temp packaging

LPT
TiAl spin casting



HPT
15% reduction in cooling flow
Next gen disk materials

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

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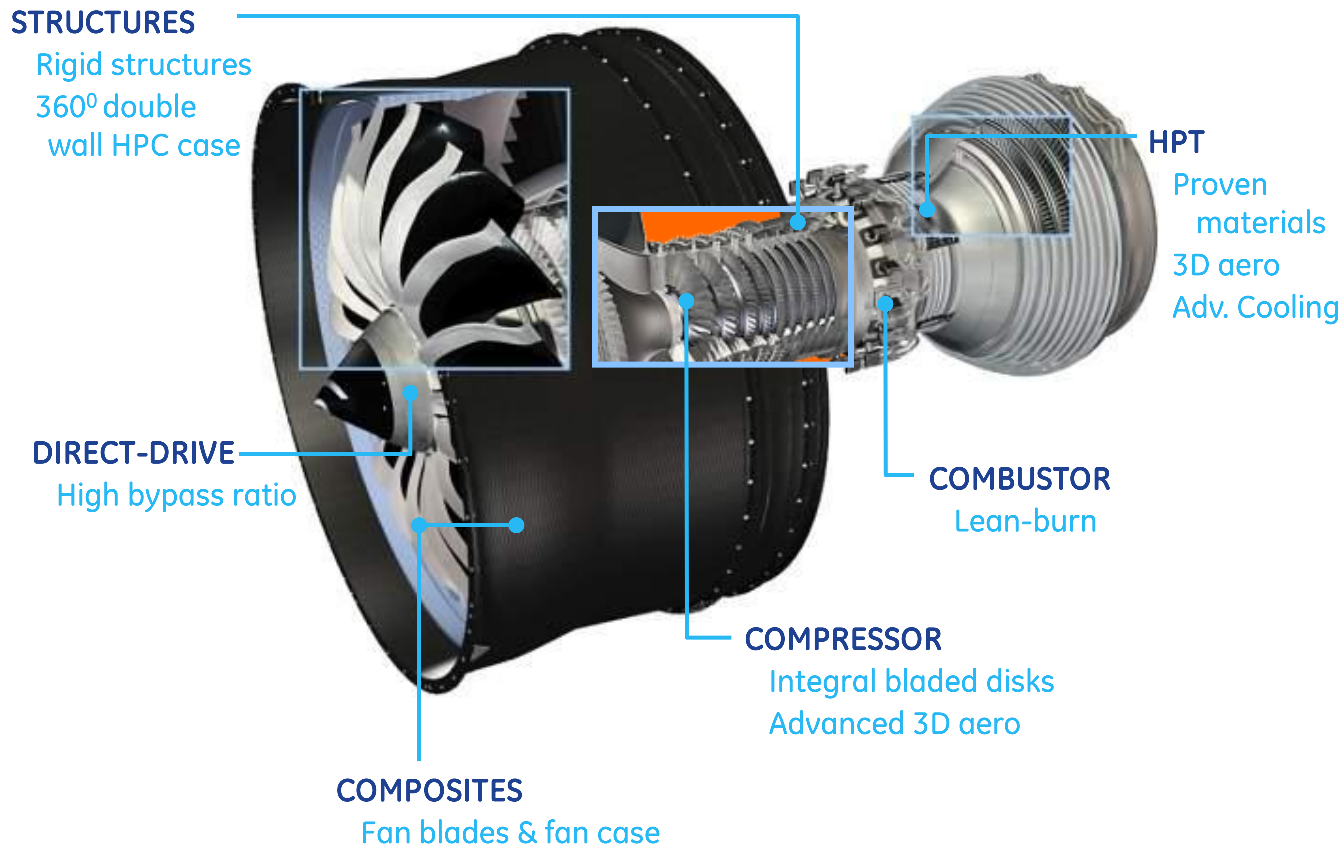
LEAP

The next generation of technology



Entry Into Service ~2016

A320 NEO

COMAC C919

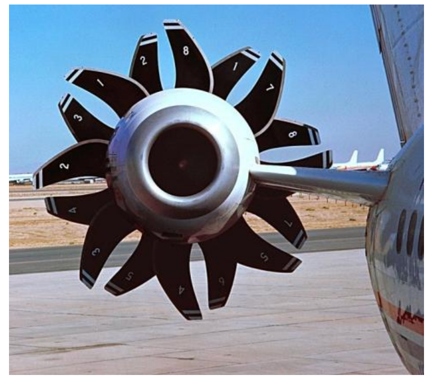
737 MAX

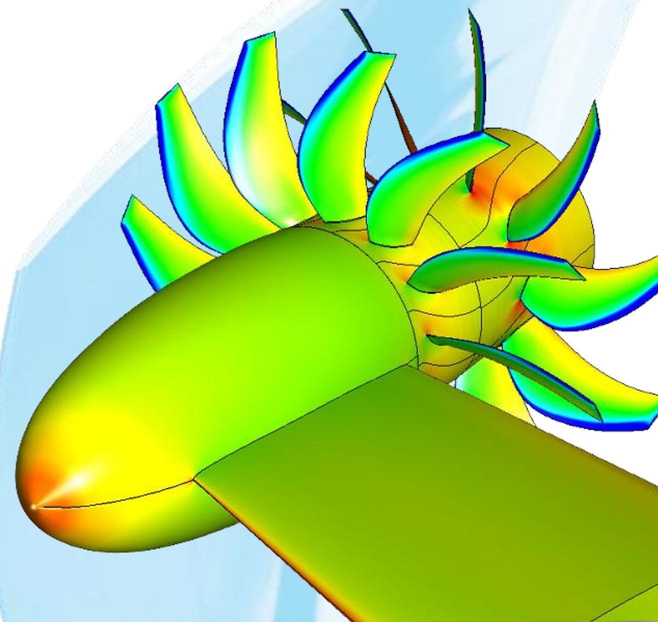
The Future: Open rotor tests

GE/FAA/NASA testing began in 2009

Test builds on 1985 demonstration

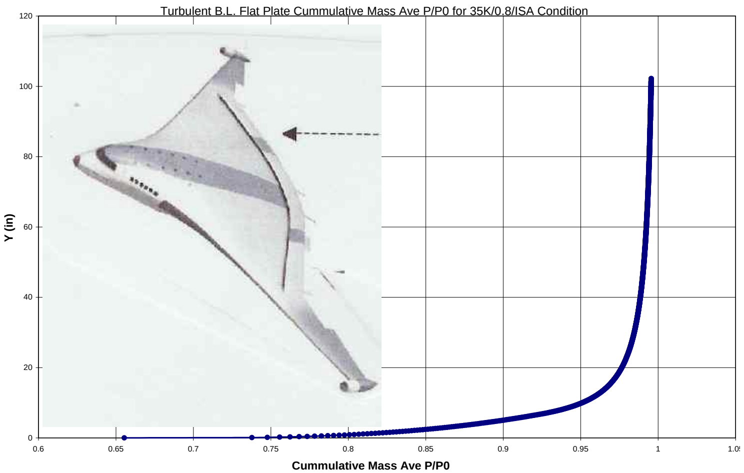
- Acoustics validation
- Aero model validation
- New blade concepts
- Installation effects
- Pitch change effects
- Pylon, sidewall interaction

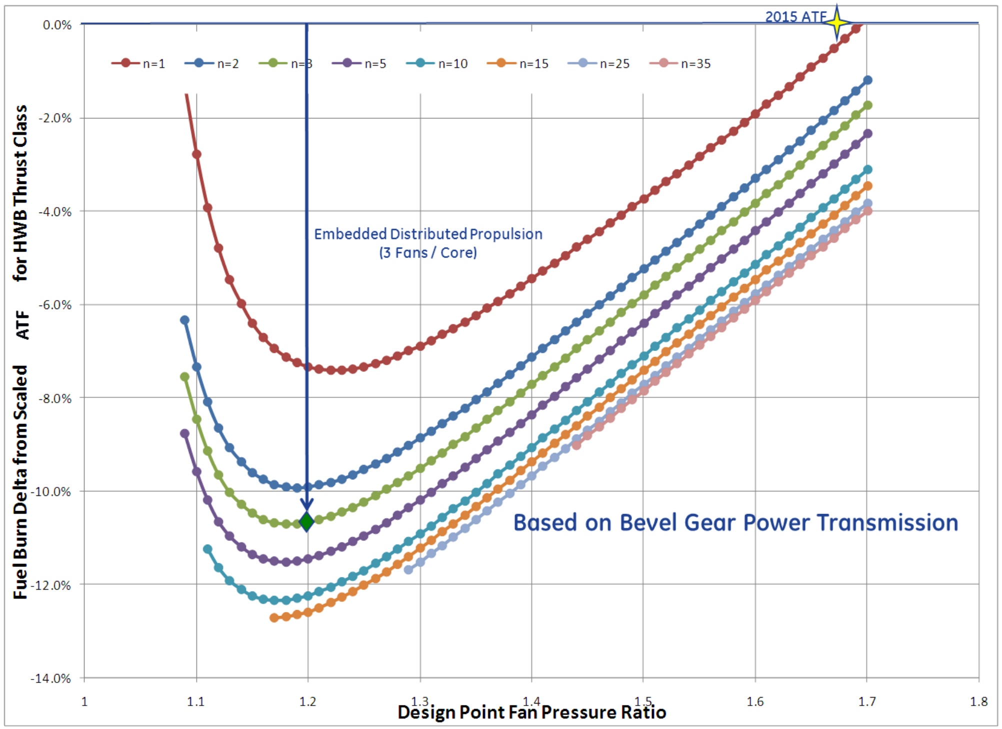




No Tube & Wing? BLI / Wake Propulsion

Reenergizing aircraft wake via distributed propulsion

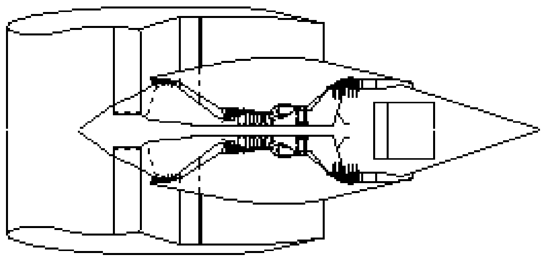




Aircraft Installation and integration Critical

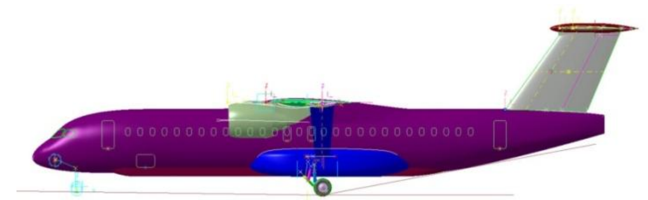
> 10% Fuel Burn Savings Potential

Hybrid Turbo/Electric Engine Concepts



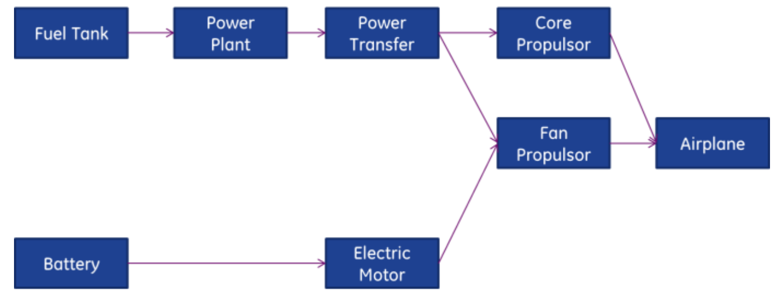
N+3 SUGAR GE hFan

Hybrid Turbo/Electric Engine



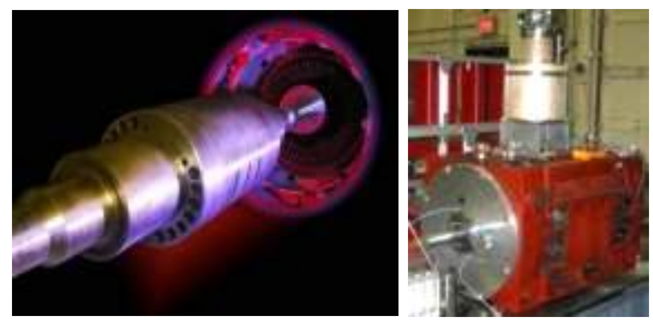
NASA N+3 Boeing-GE SUGAR Volt

Hybrid Fuel/Battery Airplane



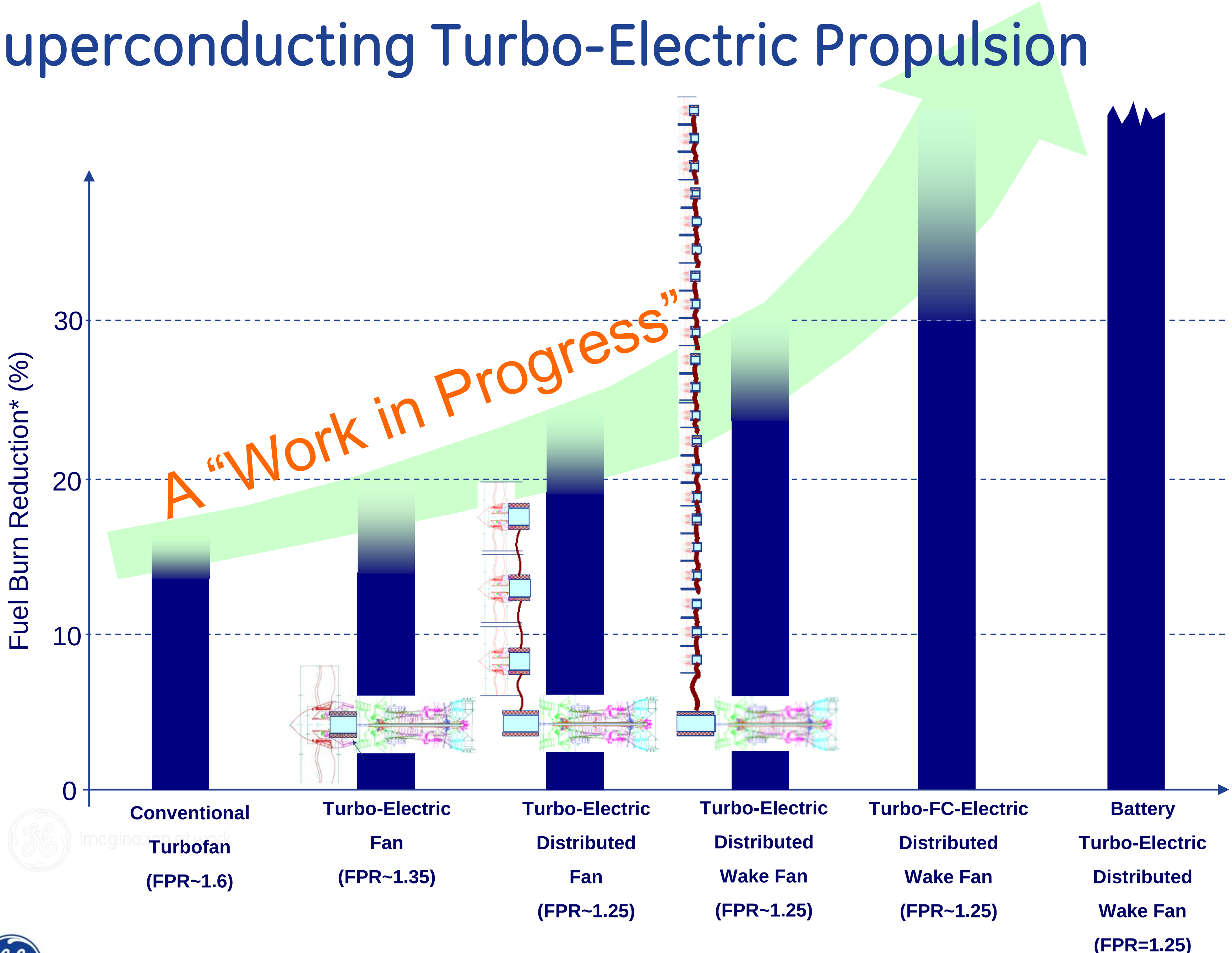
Multiple potential configurations

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



Superconducting Machines

Superconducting Turbo-Electric Propulsion



* Relative to 2000 SOA TF

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

imagination at work

imagination at work