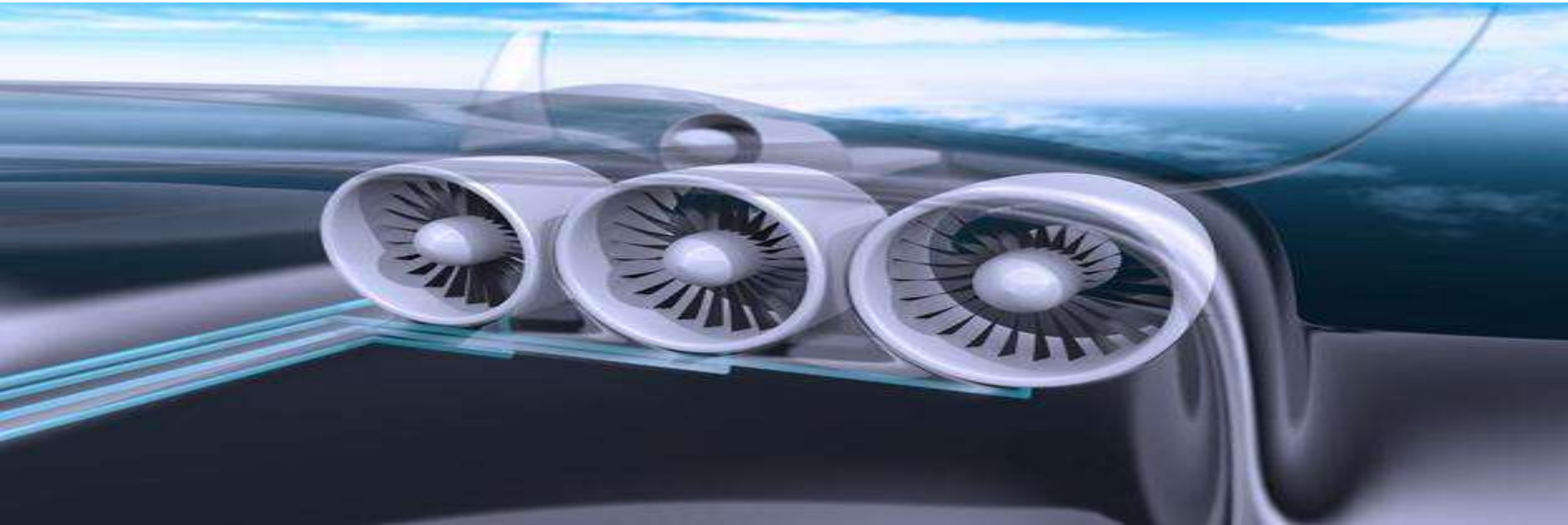
Dr. M.J. Benzakein
Director, Propulsion and Power Center

THE OHIO STATE UNIVERSITY

The Aero Engine:

Where we have been and where we are going. A look into the future.

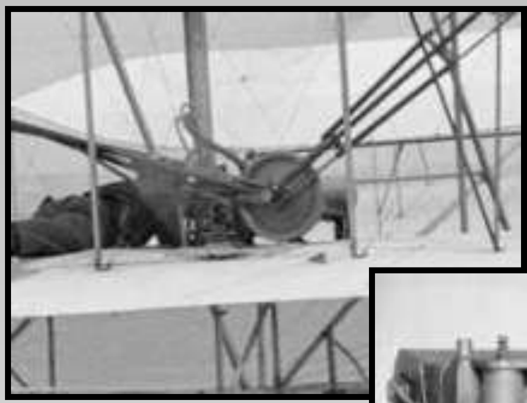


OUTLINE

- Introduction
- Commercial Airplane Markets for the next 20-30 years
- Customer Requirements and Propulsion needs
- What is coming NOW…2015-2030
- Going forward—NASA, Clean Sky
- What does it mean?
- The opportunities

Aviation … 100 years of powered flight has dramatically changed our world

Then …

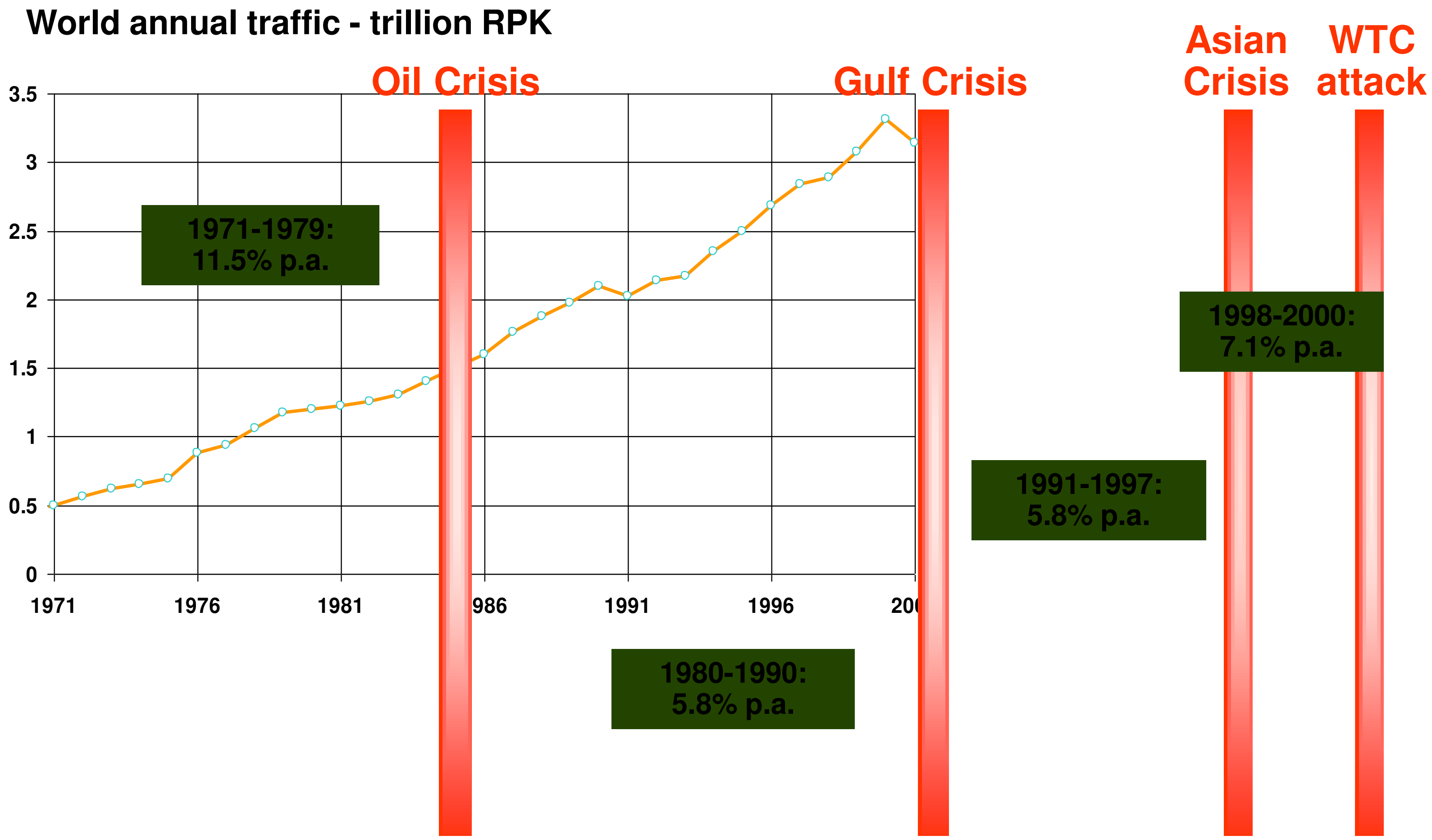


Wright Flyer
1 occupant
12 HP engine
4.7 pressure ratio
120 feet flight
12 second flight

Now …

B777-300ER
310 passengers
136,000 HP engines
42.2 pressure ratio
8000 mile range
16 hour flight

Air travel has grown more than six-fold during the past 30 years

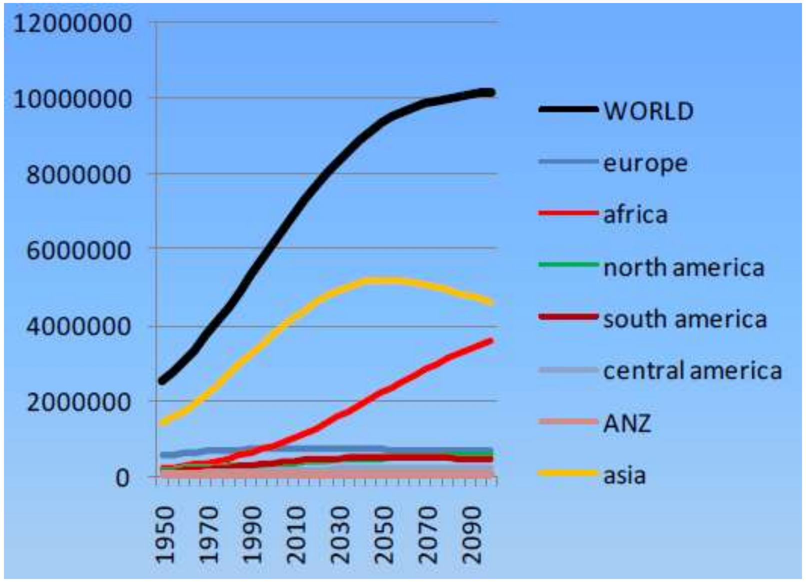


Source : ICAO

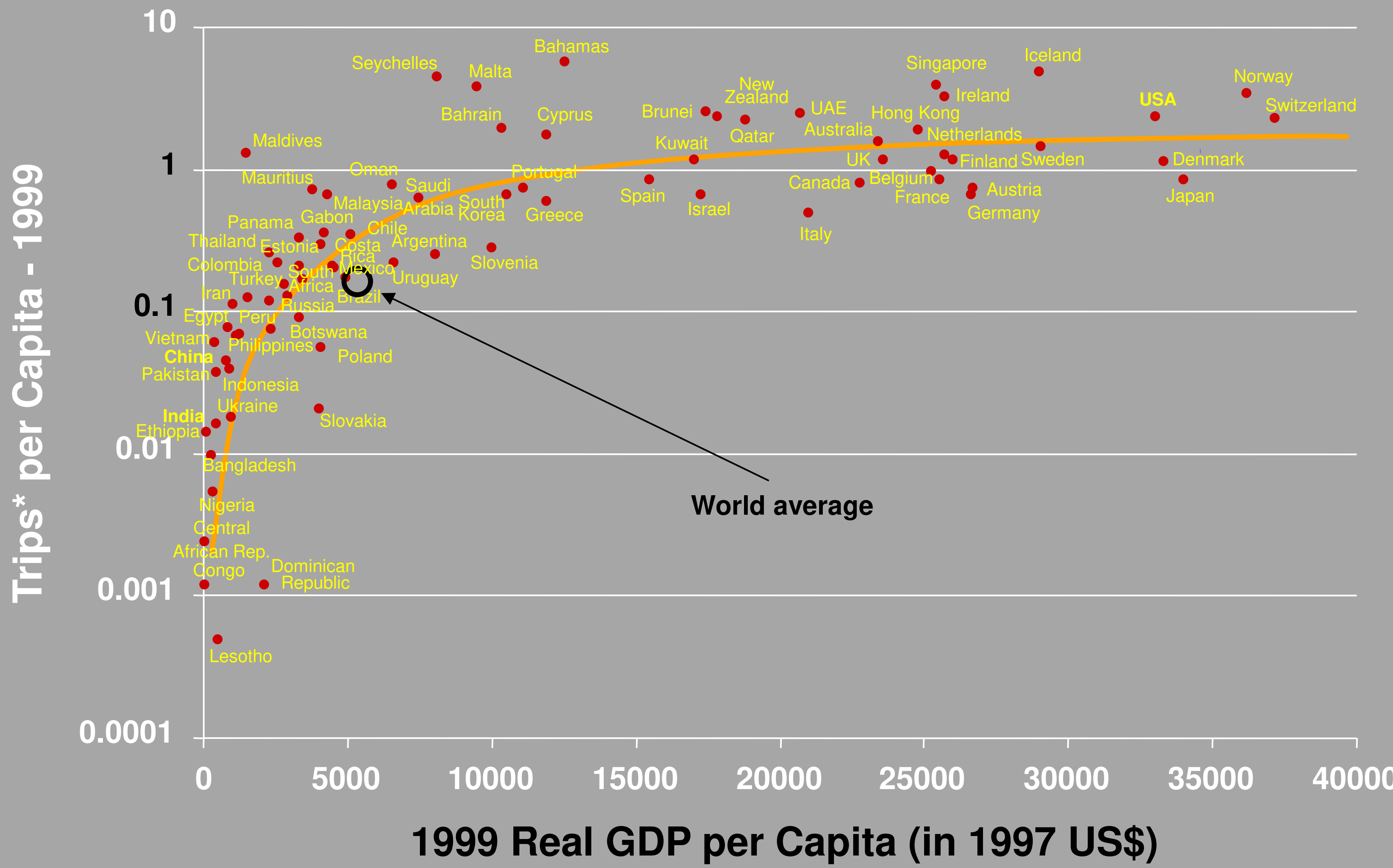
Demography

source: UN/ESA World Population Prospects

Populations
Now up to 2100: 10 billions
Europe decreasing after 2020
North America still growing
Asia decreasing after 2050
Africa towards1/3 of the world!



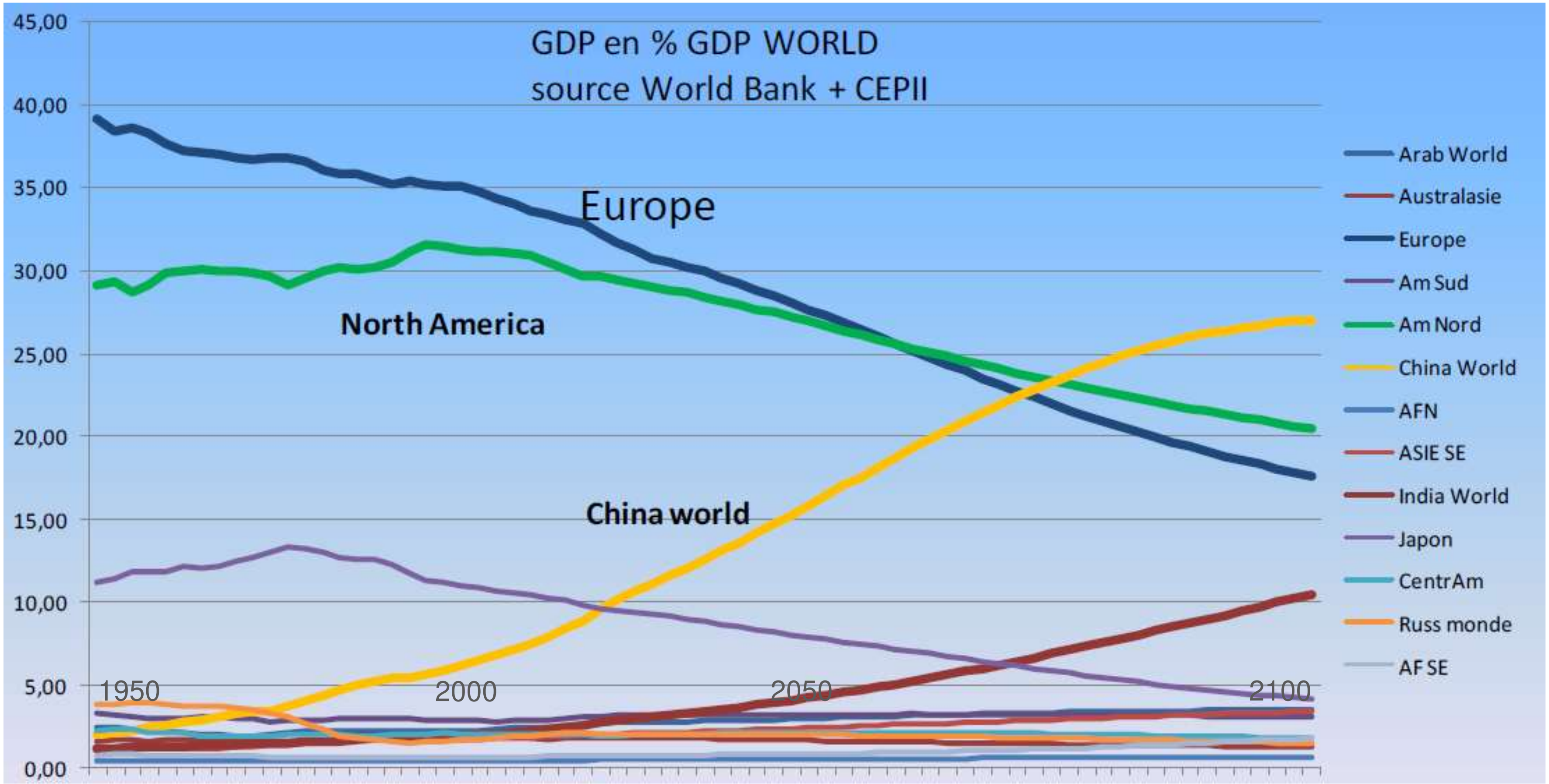
Huge potential exists for long-term growth in air travel



Sources : *ICAO, Global Insight*

* Passengers carried by airlines domiciled in the country

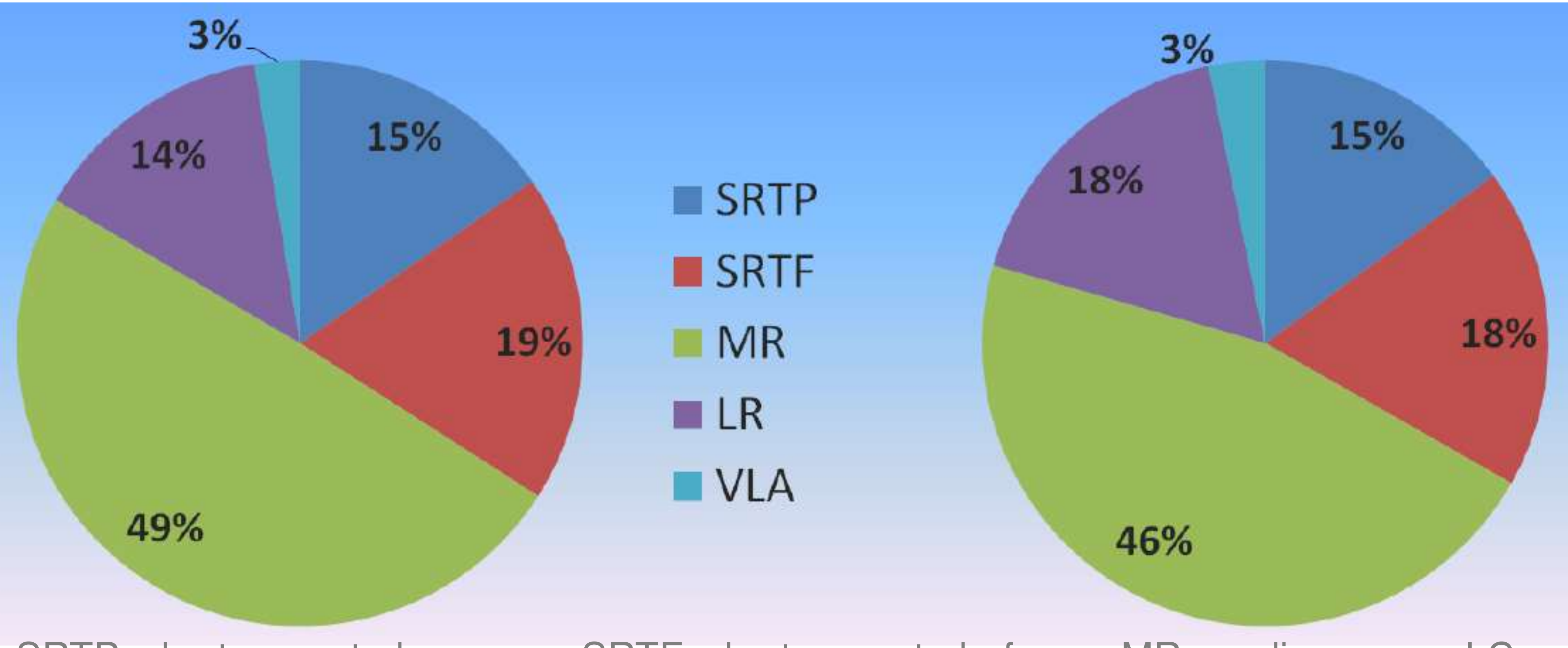
The Relative Weight of Different Zones is of Importance for the Traffic



Estimated Fleet Evolution by Aircraft Category

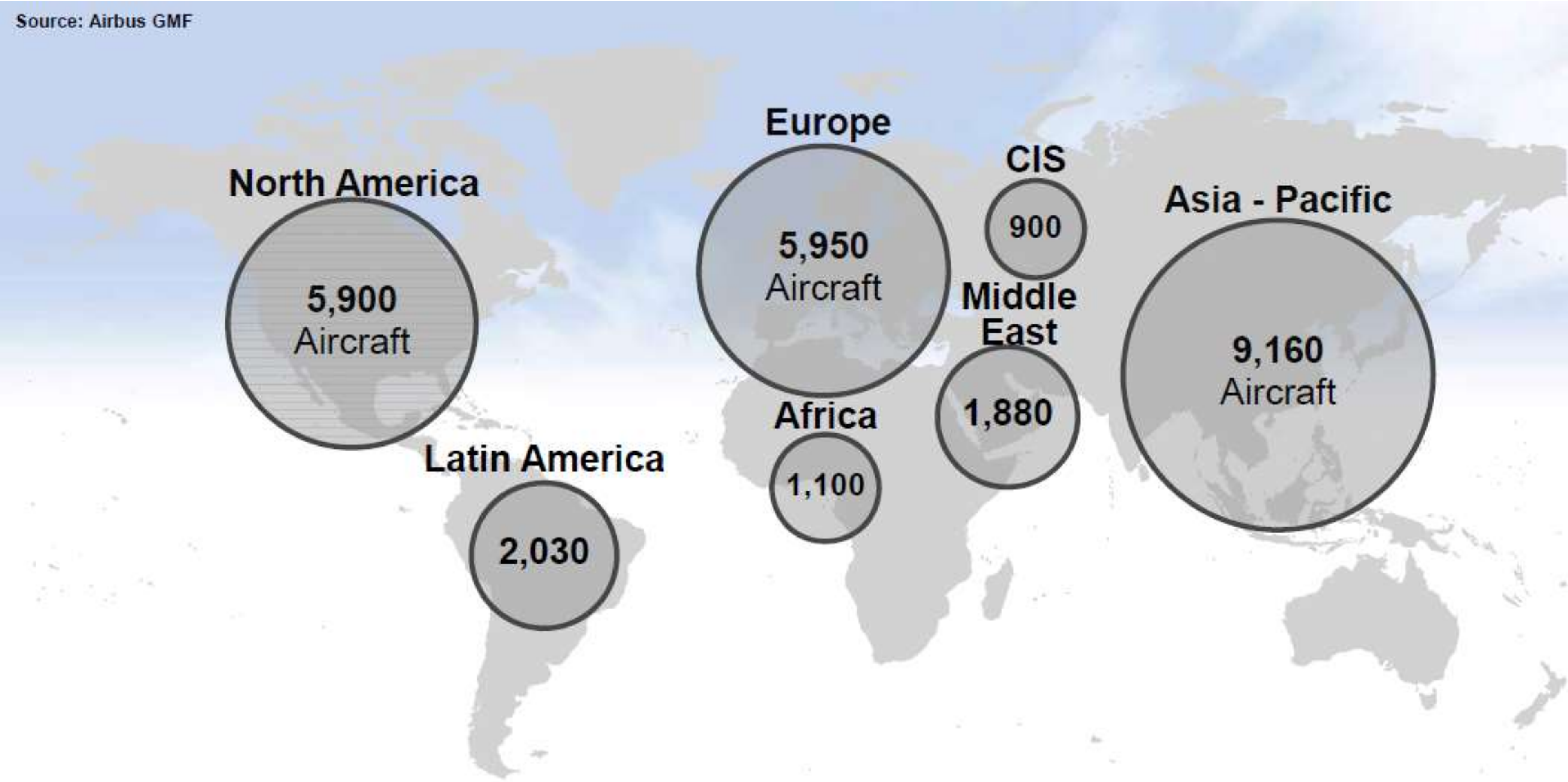
Total number of aircraft doubling between 2010 and 2050

2010: 20331 aircraft **2050: 40593 aircraft**



SRTP: short range turboprops – SRTF: short range turbofans – MR: medium range LC: long range – VLA: very large aircraft

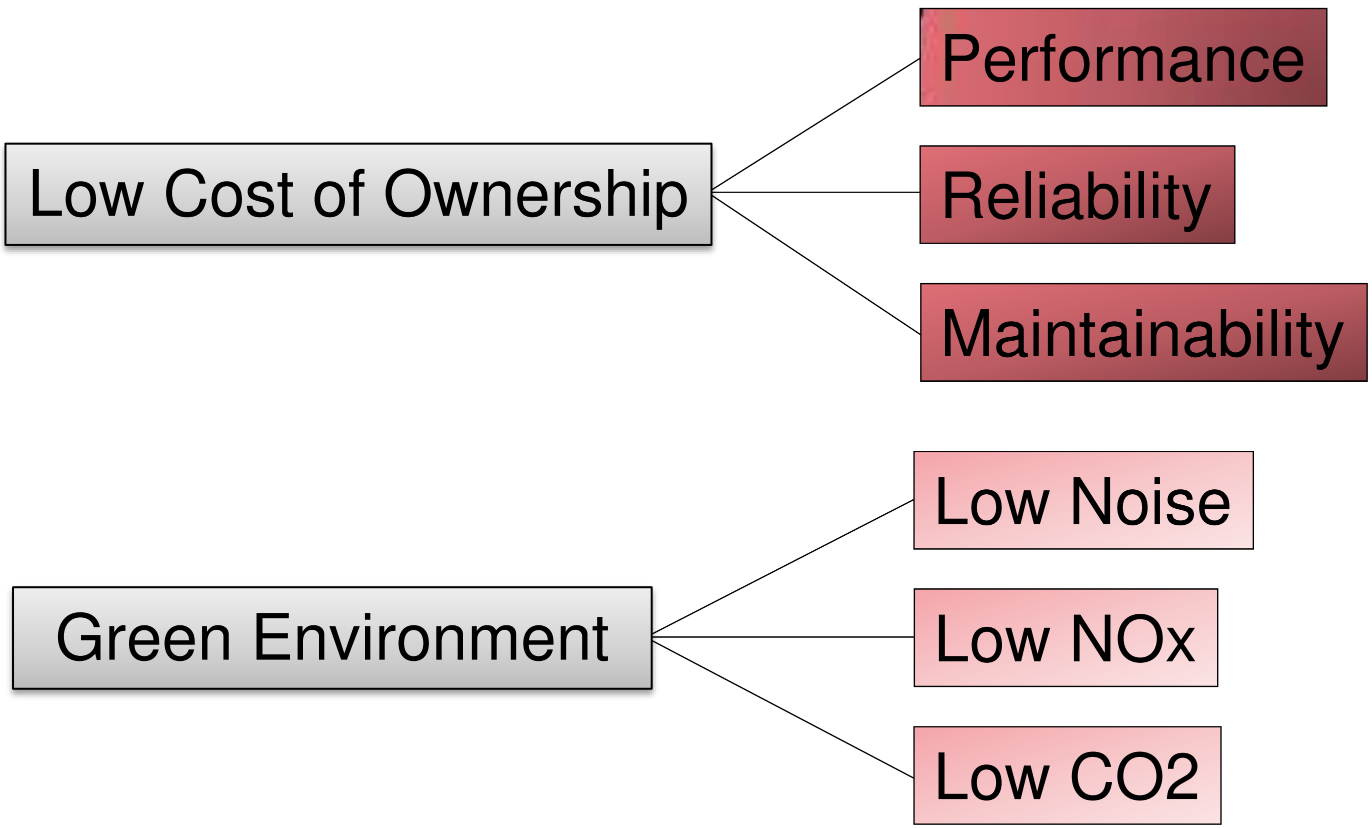
Geographical Demand



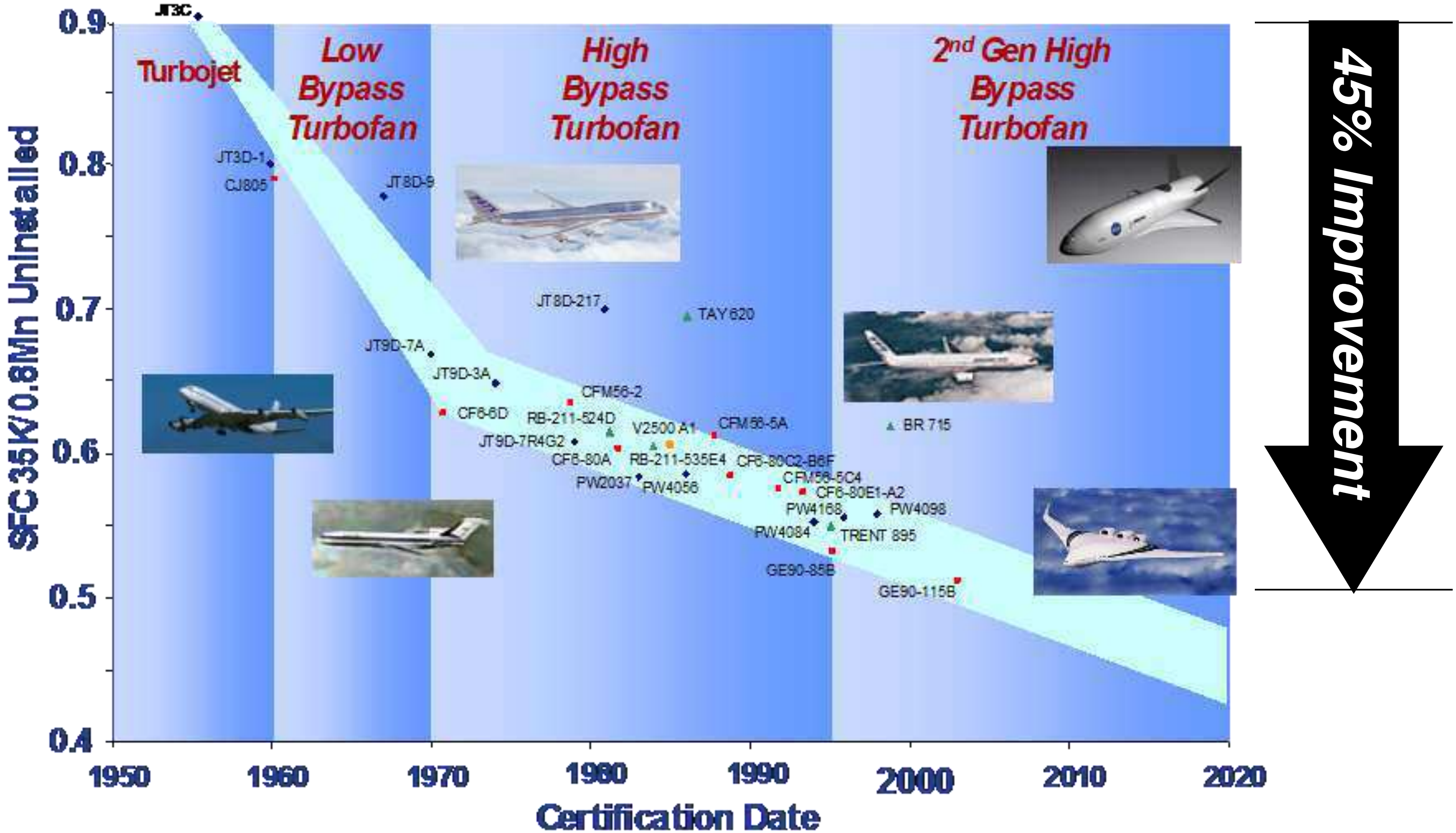
80% of the international demand over the next 20 years will be within Asia-Pacific, North America and Europe

Today and Tomorrow…

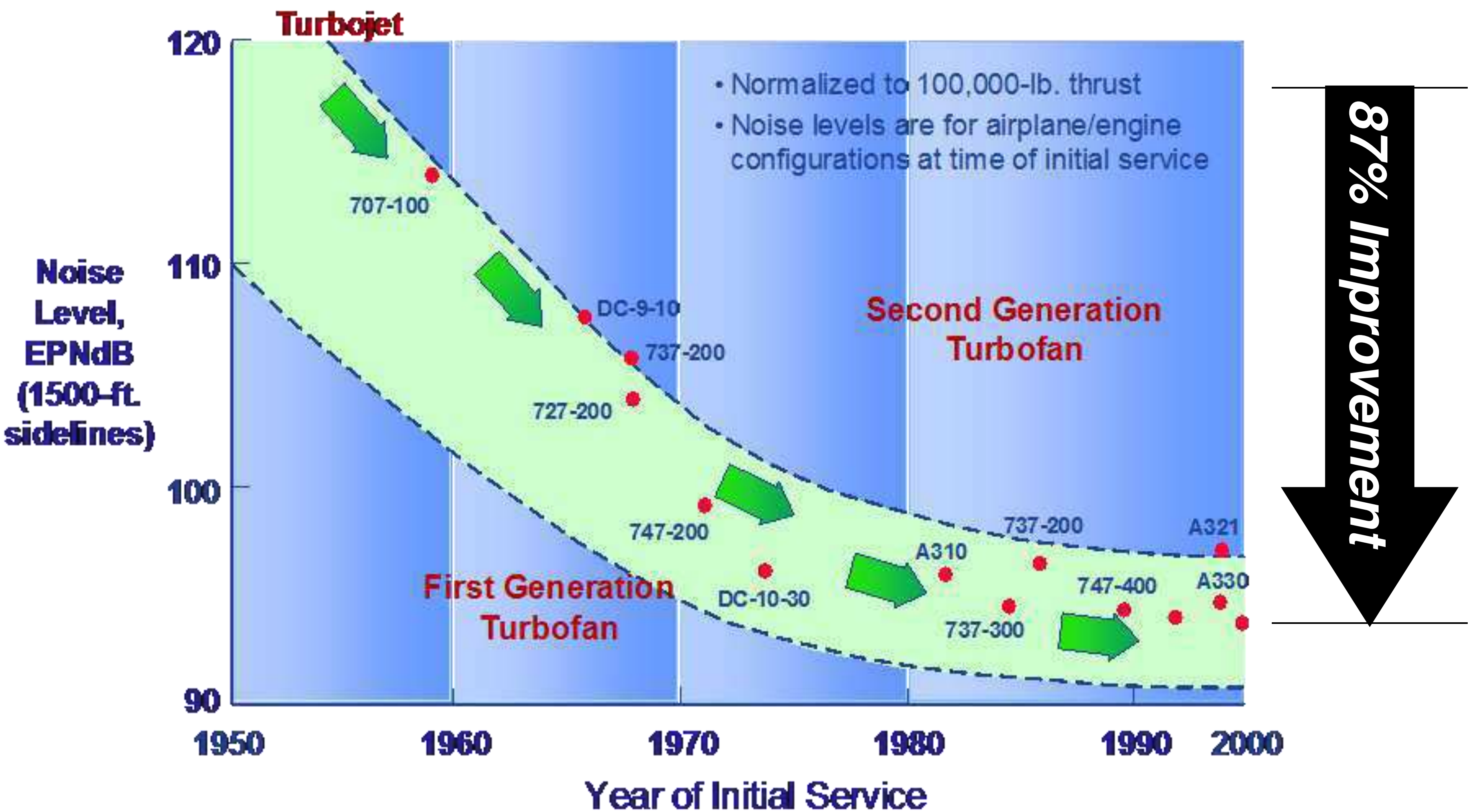
What Do the Customers Want?



Gas Turbine powered flight … 50 years of technology has dramatically improved SFC



… and dramatically reduced noise

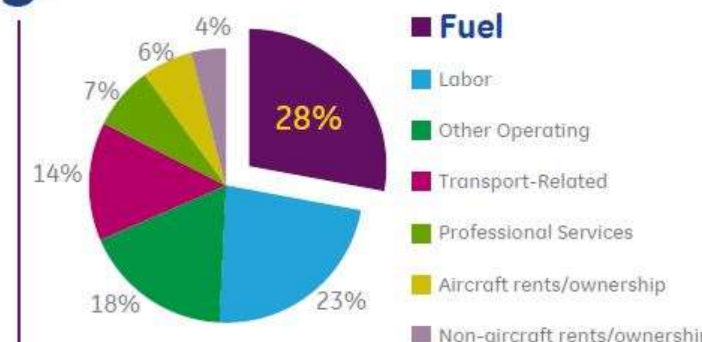


Propulsion Challenge

Industry Revenue/Profits

Sources: Air Transport Association/Bureau of Transportation Statistics

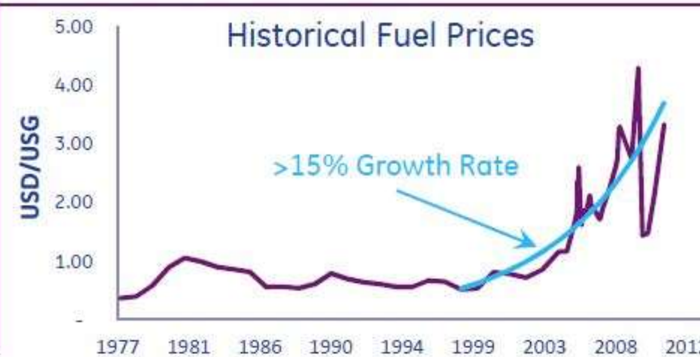
Airline Operating Costs



Source: A4A Quarterly Cost Index, US Airlines

Regulatory Challenges

CAEP/6	2008 / 2013
CAEP/8	2014 / 2018
EU Carbon Trading	2012
ICAO CO_2 Standard	TBD
FAR Stage 5	2020

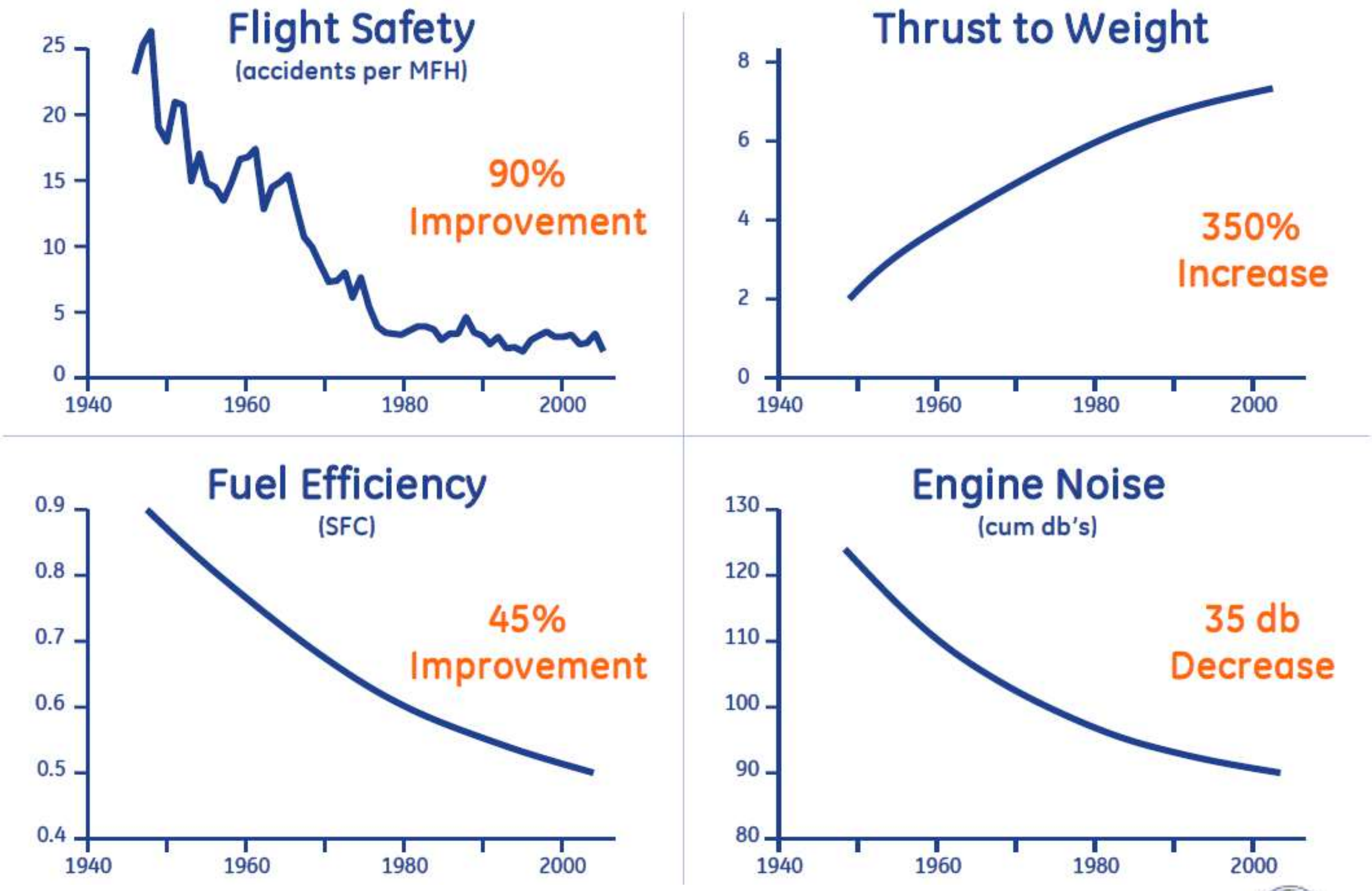


Sources: Air Transport Association, International Air Transport Association

Make airlines more profitable in an increasingly difficult environment

imagination at work

The History


Flight Safety
(accidents per MFH)
90%
Improvement
25
20
15
10
5
0
1940
1960
1980
2000
Thrust to Weight
350%
Increase
8
6
4
2
0
1940
1960
1980
2000
Fuel Efficiency
(SFC)
45%
Improvement
0.9
0.8
0.7
0.6
0.5
0.4
1940
1960
1980
2000
Engine Noise
(cum db's)
35 db
Decrease
130
120
110
100
90
80
1940
1960
1980
2000

Fuel consumption . . .
Addressing every aspect - sfc

$$\text{Fuel mileage} = \frac{V * L/D}{sfc * W}$$

$$SFC \approx \frac{v_0}{\eta_{overall} \cdot FHV} = \frac{v_0}{\eta_{thermal} \cdot \eta_{transfer} \cdot \eta_{propulsive} \cdot FHV}$$

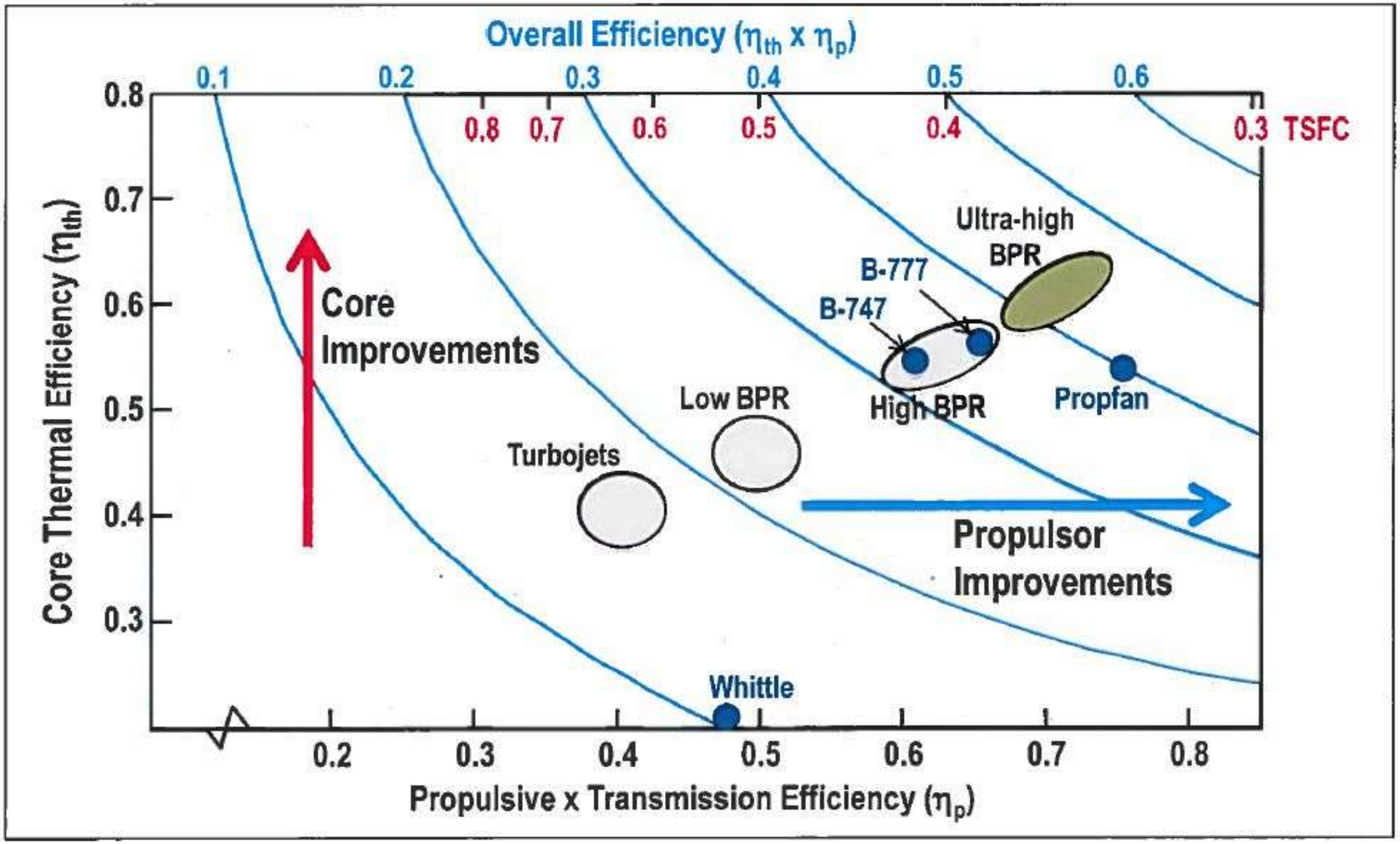
Core FPR

sfc . . . primary propulsion attribute

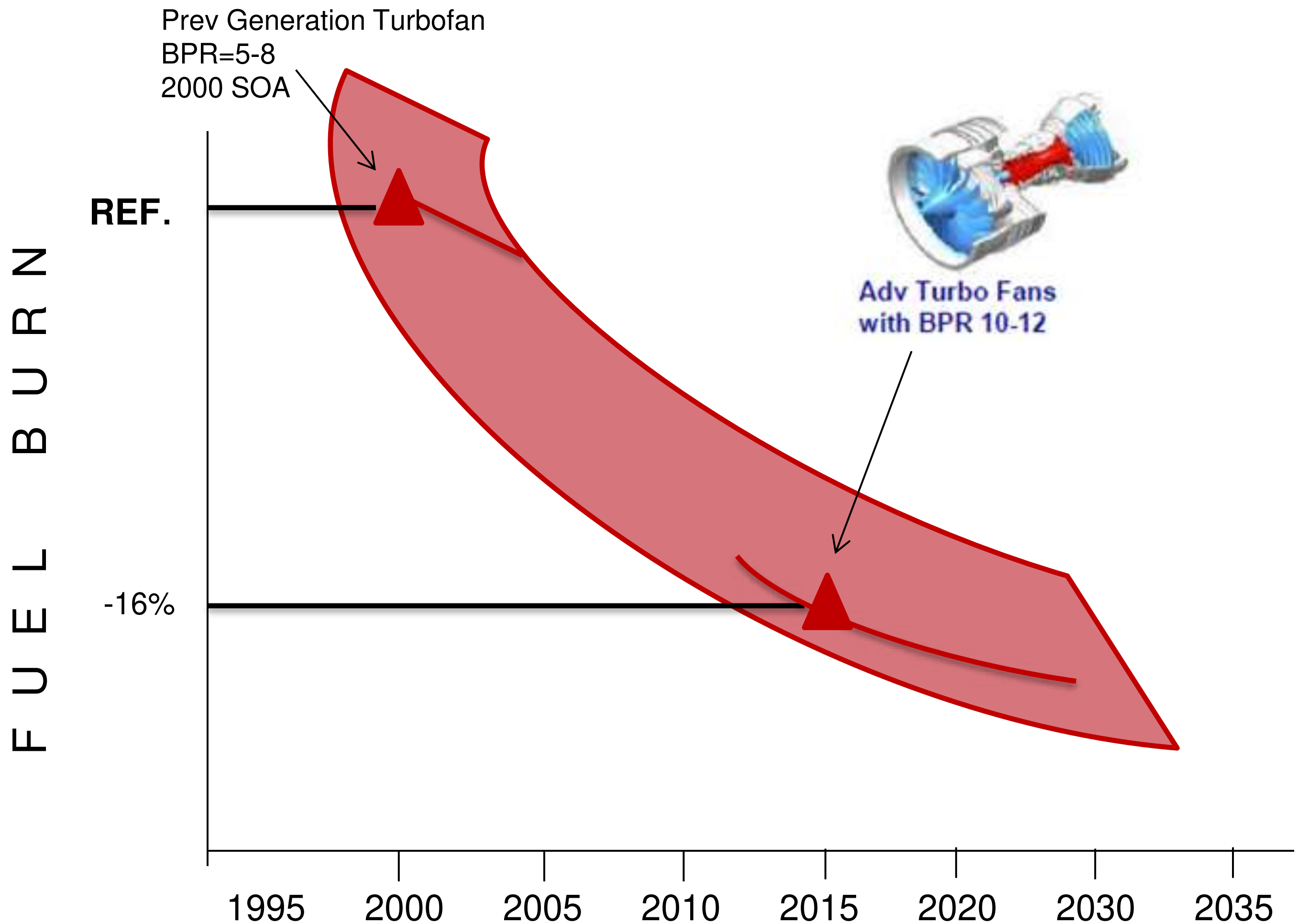
- Thermal efficiency - High OPR / high temp
  - Diminishing returns, but not at entitlement
  - Need cooled-cooling air or materials, or . . .
  - Component efficiencies and loss minimization
- Propulsive & Transfer efficiency - Low FPR, large fans & enablers
  - Unducted fans, propellers
- Or, new cycles
  - Adaptive or Non-Brayton cycles
  - Pulse detonation, constant volume

Efficiency Trends with Core and Propulsor Improvements

- Propulsion system improvements require advances in both propulsor and core technologies



Fuel Consumption Projections



What is coming NOW…2015-2020

Narrow Bodies—

- *Airplanes: A320 NEO, Boeing 737 MAX, COMAC 919*
- *Engines: Leaps, GTF's*

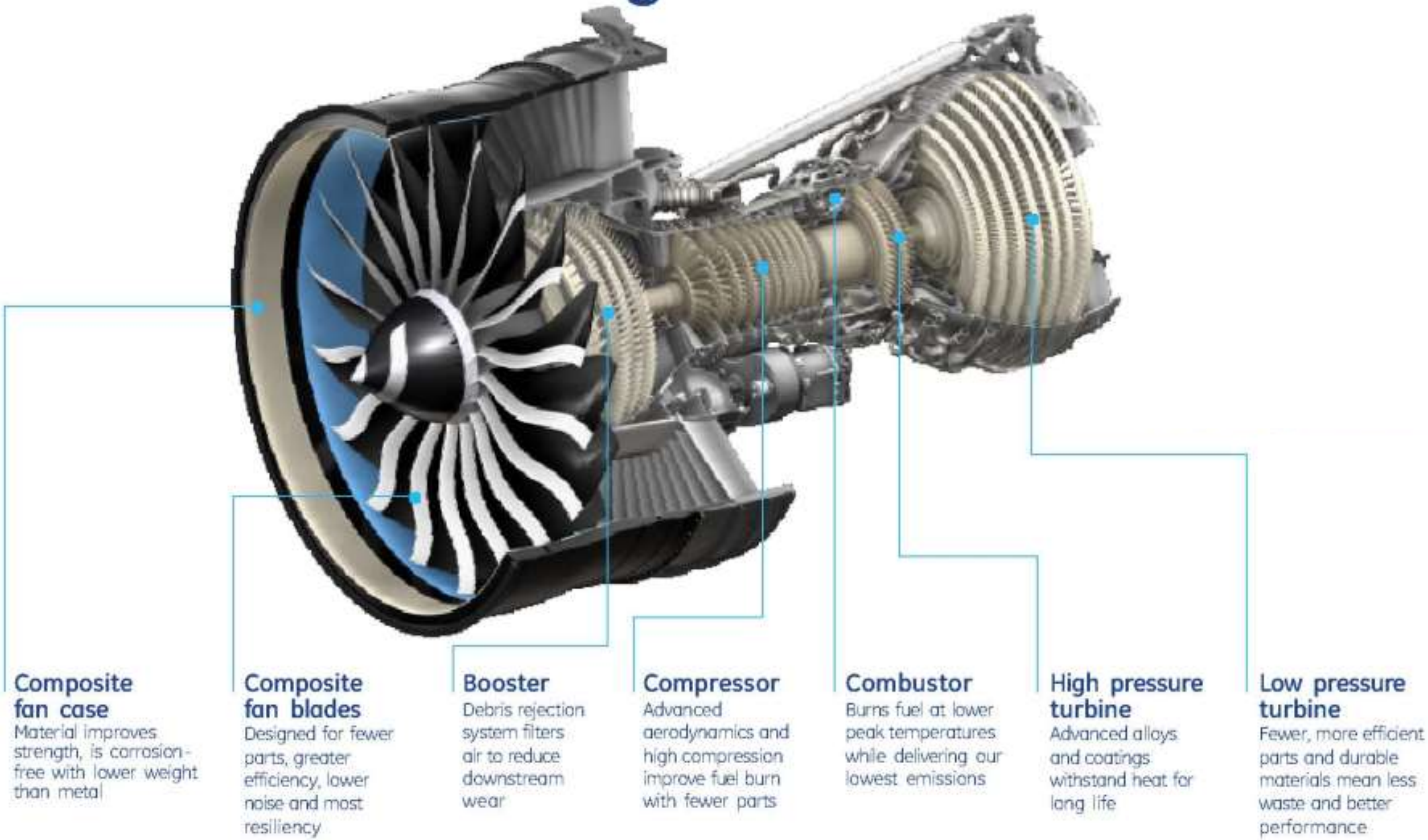
Wide Bodies—

- *Airplanes: A330 NEO, Boeing 787, Boeing 777x, A350, Genx*
- *Engines: RR 7000, RR 1000, GE9x*

Regional Jets—

- *Airplanes: Bombardier C Series, Mitsubishi MRJ, Embraer 190, Sukhoi Superjet*
- *Engines: Power Jet, GTFs*

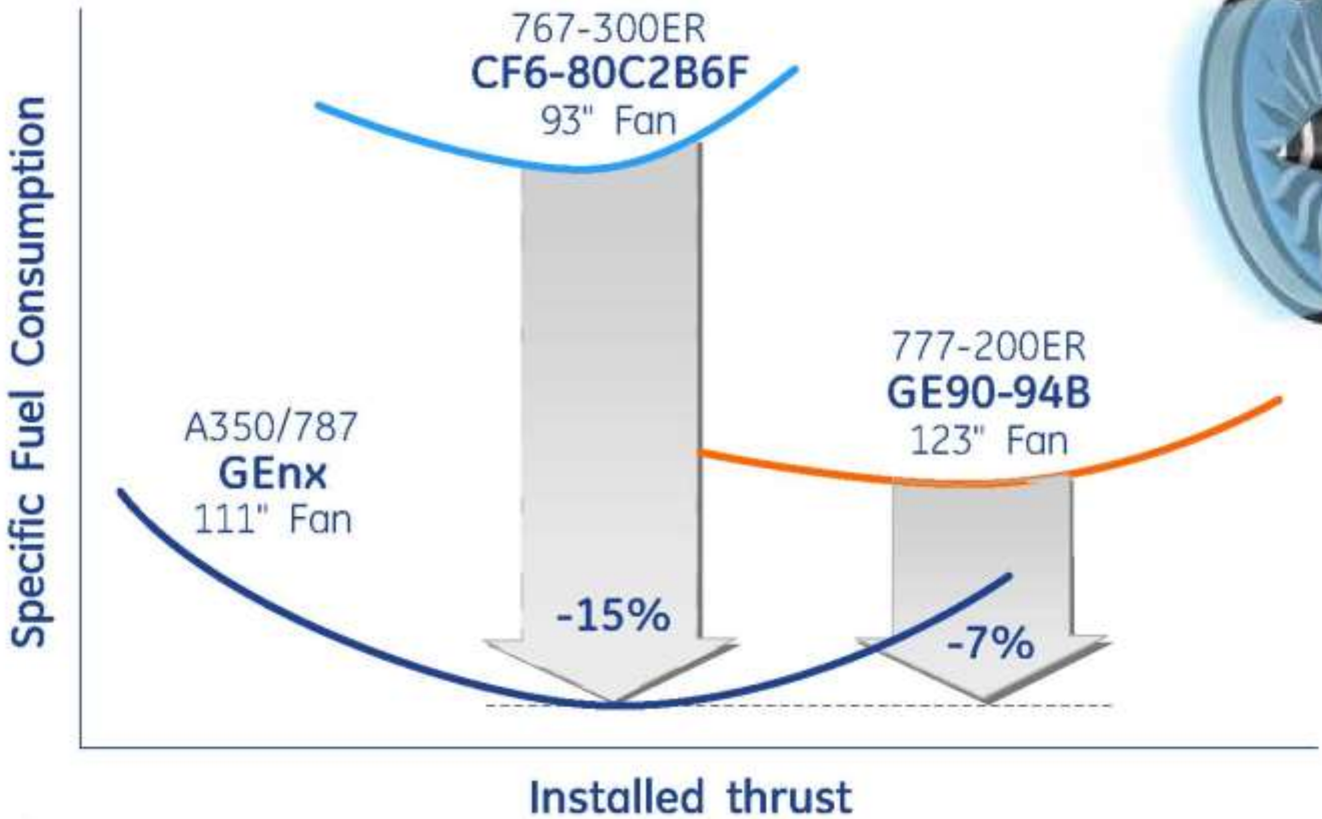
GEnx™ aircraft engine



imagination at work

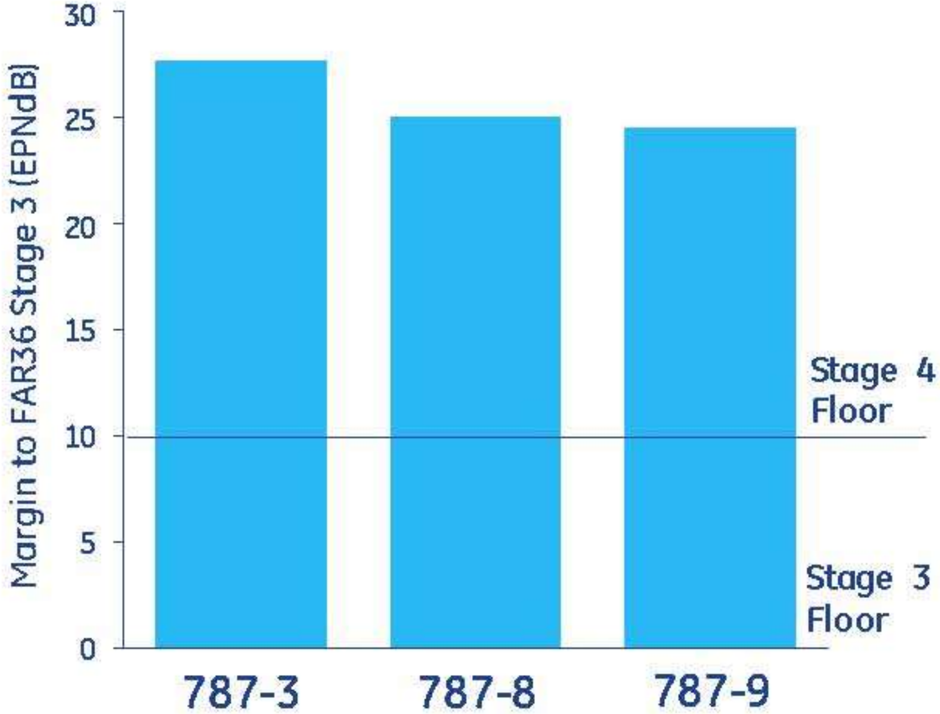
Balanced system design … SFC benefit

SFC comparison at cruise

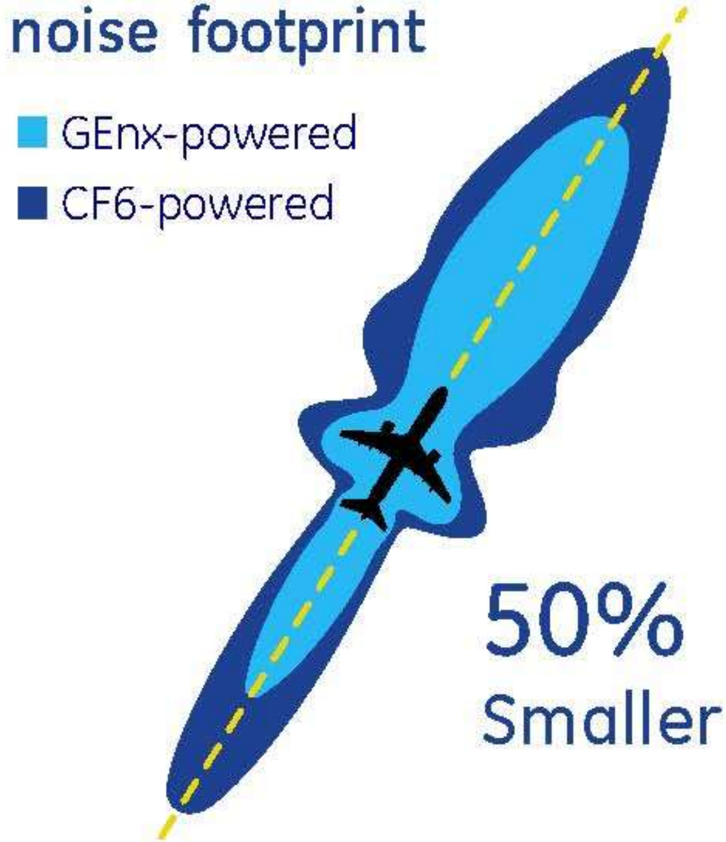


GEnx **quiet** with significant margin

Noise margin for Stage 3 and 4



Twin-engine aircraft noise footprint

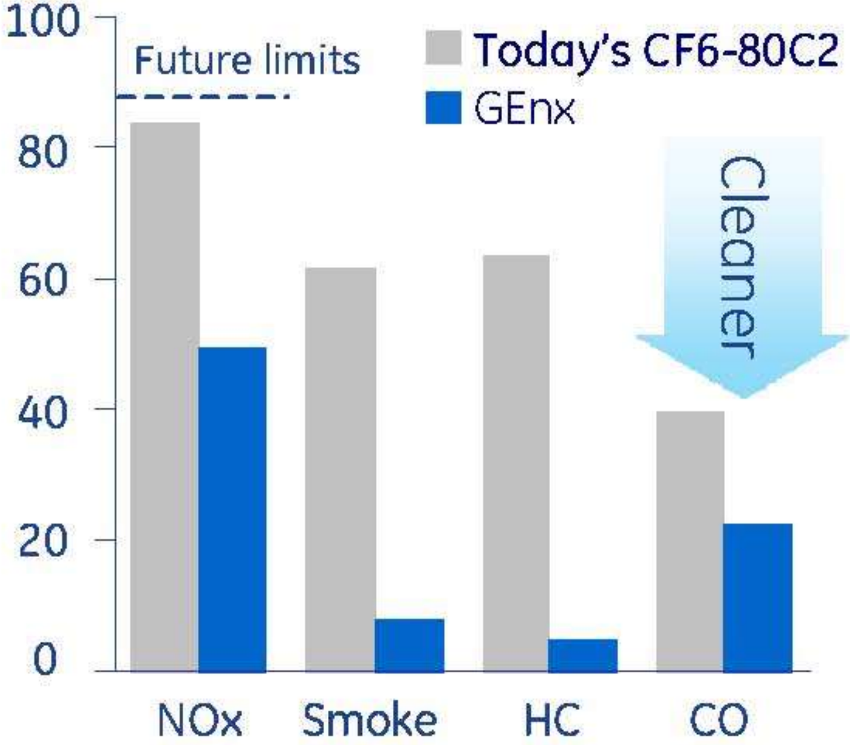


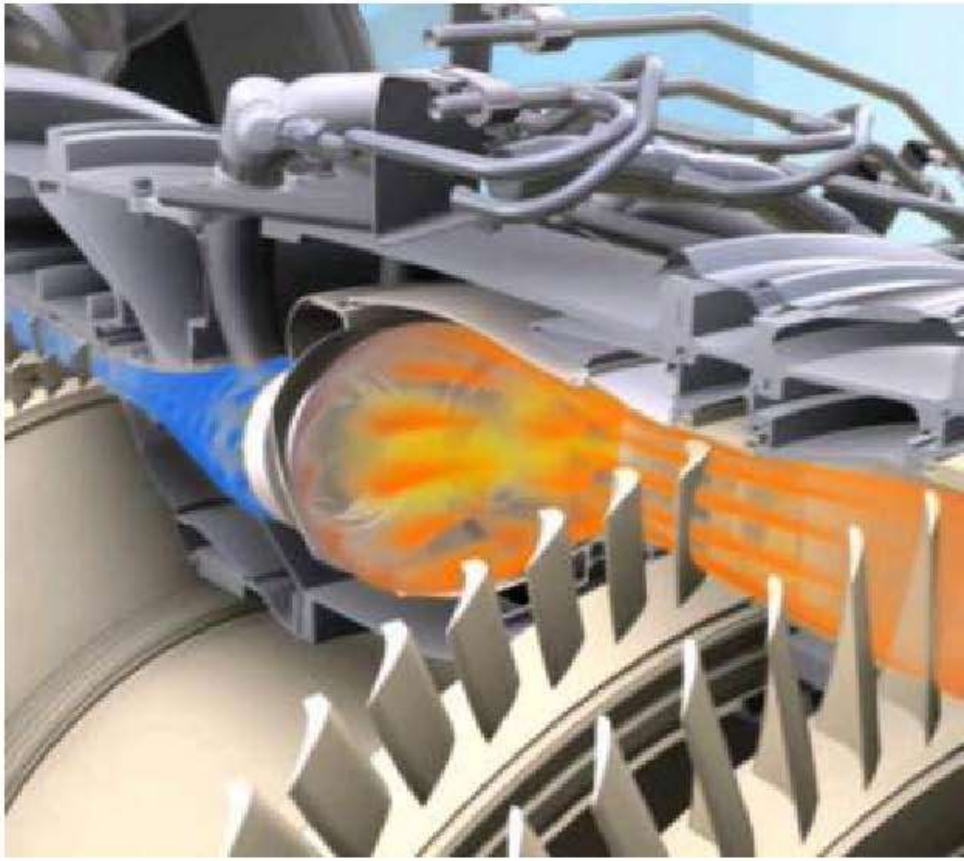
imagination at work

GEnx **cleanest** for the environment

Twin annular pre-swirl (TAPS) technology

Emissions as % of current limits

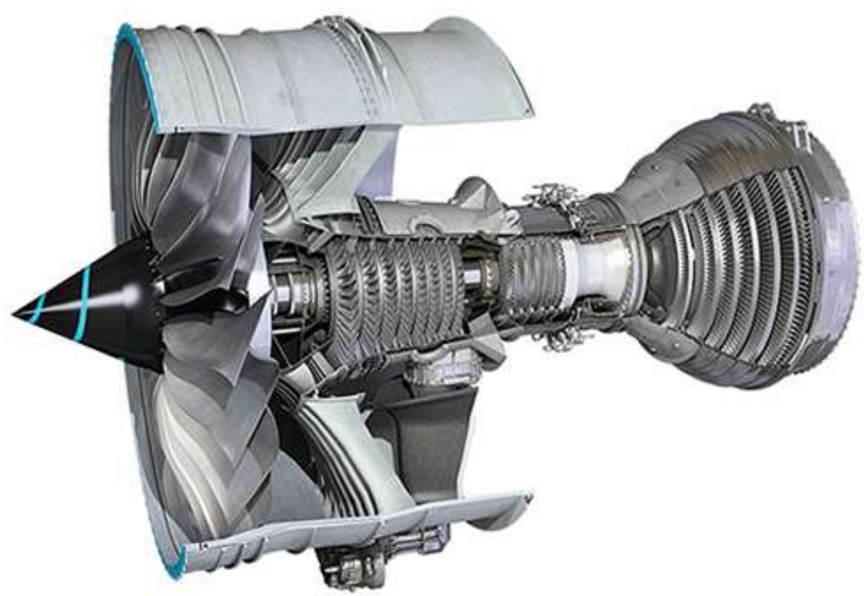




Rolls Royce Trent 7000 for A330 NEO

Trent 772 vs Trent 7000

	Trent 772	Trent 7000
Fan Diameter	97.5in	112in
Bypass Ratio	5:1	10:1
Core Pressure Ratio	36:1	50:1

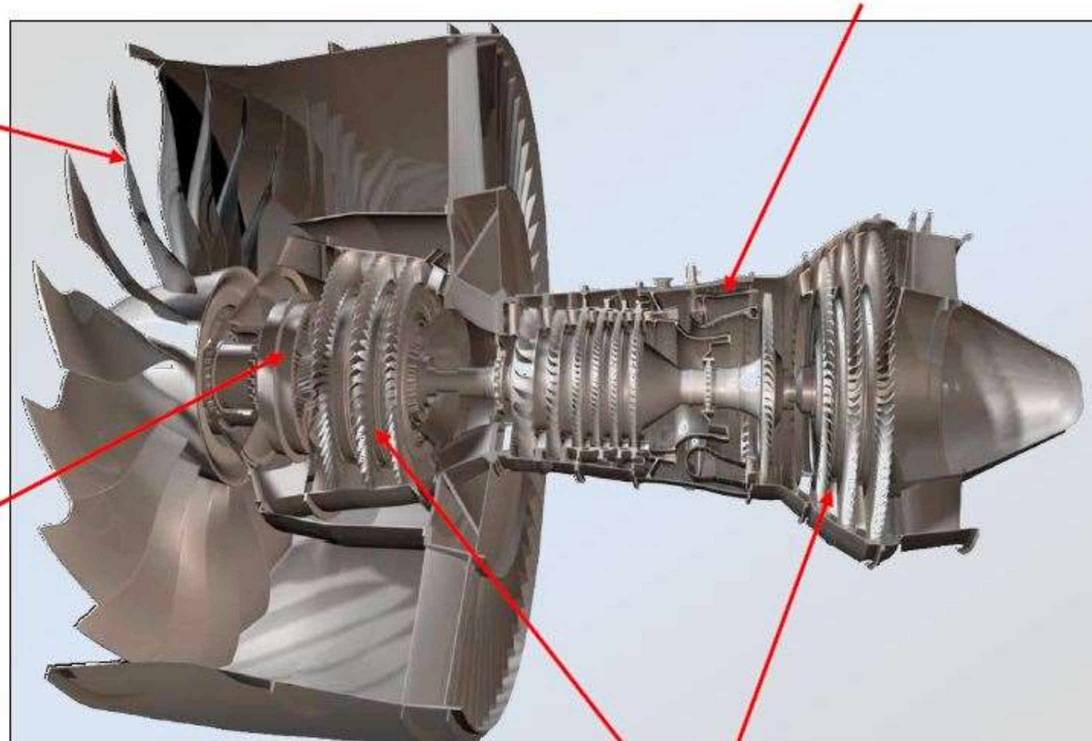


14% Lower Fuel Burn

Pratt & Whitney Geared TurboFan (GTF)

Low-Emissions Combustor

Low PR Fan
Low Tip Speed
BPR ~ 9 - 12

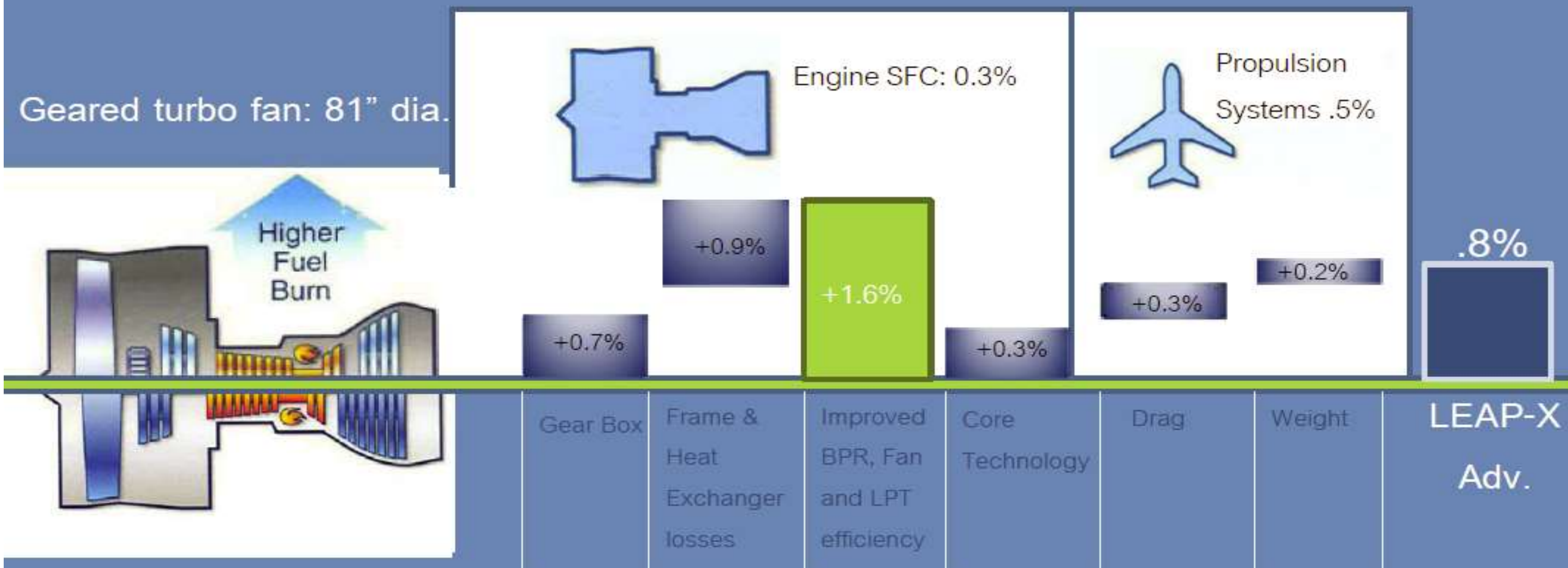


Fan Drive Gear System
5 Planets
Gear Ratio ~ 3

High-Speed Low Spool
Compact LPC, LPT

PW Geared V.S. LEAPx Fuel Burn Evaluation

Geared turbo fan: 81" dia.



Direct-drive turbofan: 78" dia.

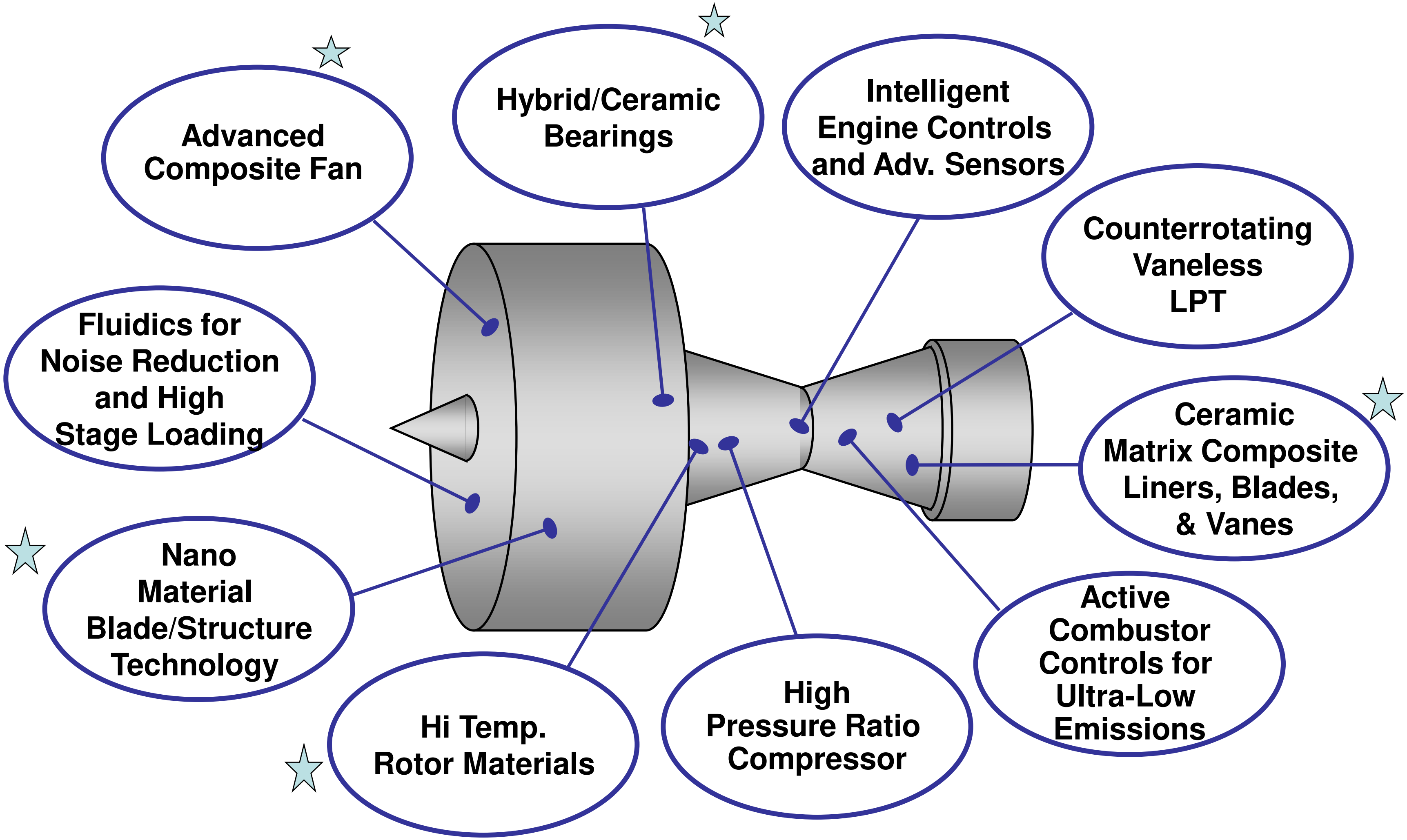
Architectures Within 1% Fuel Burn

Propulsion Systems that are arriving NOW 2015-2020

- Common Themes
  - Higher Pressure Ratio Core—30
  - Higher Bypass Ratio—10 to 12
- Some Differences
  - Direct Drives
  - Gear Boxes
- Benefits
  - 15% Reduction in Fuel Burn
  - More Green
  - More Quiet

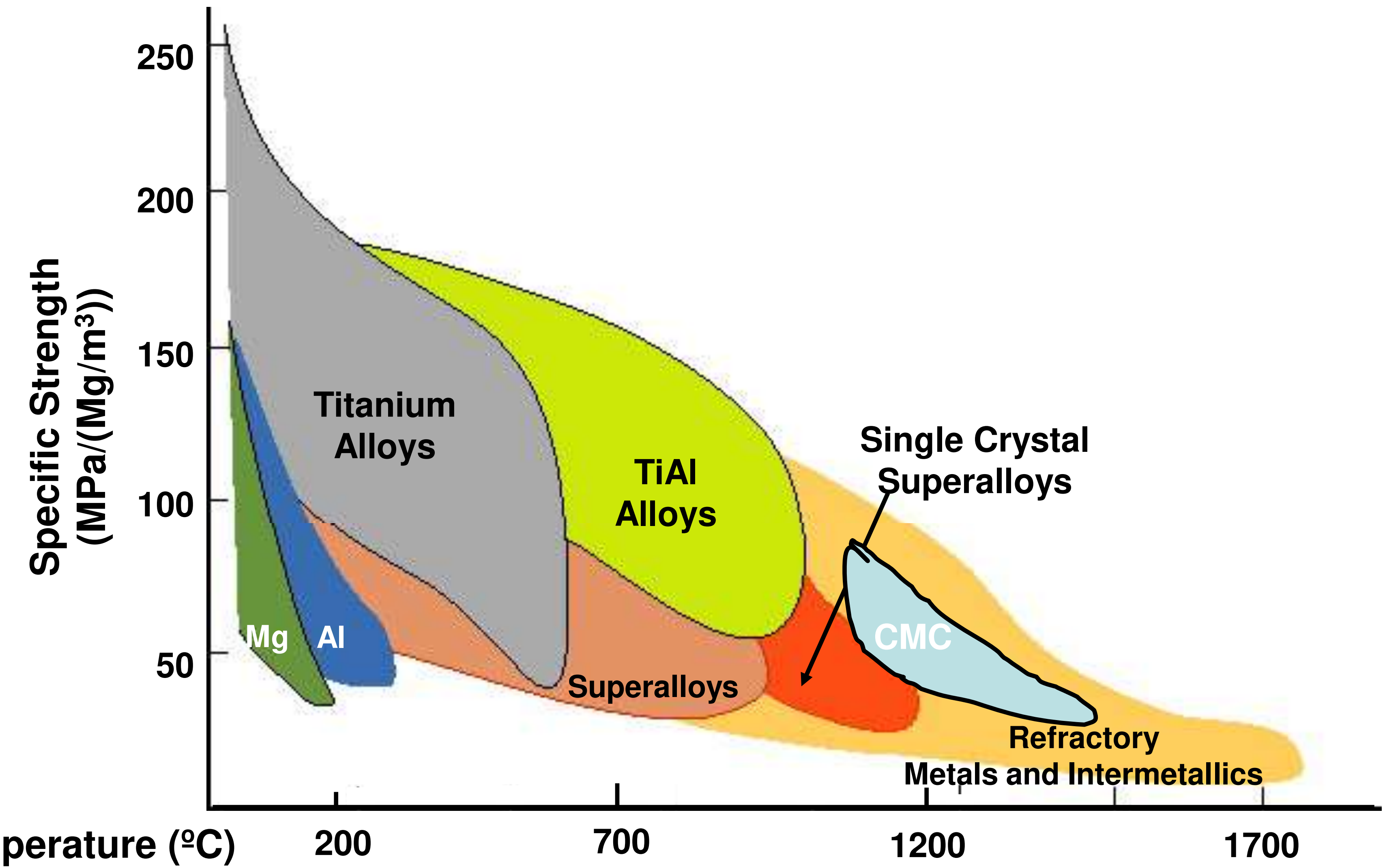
THE OHIO STATE UNIVERSITY

GENY Technologies



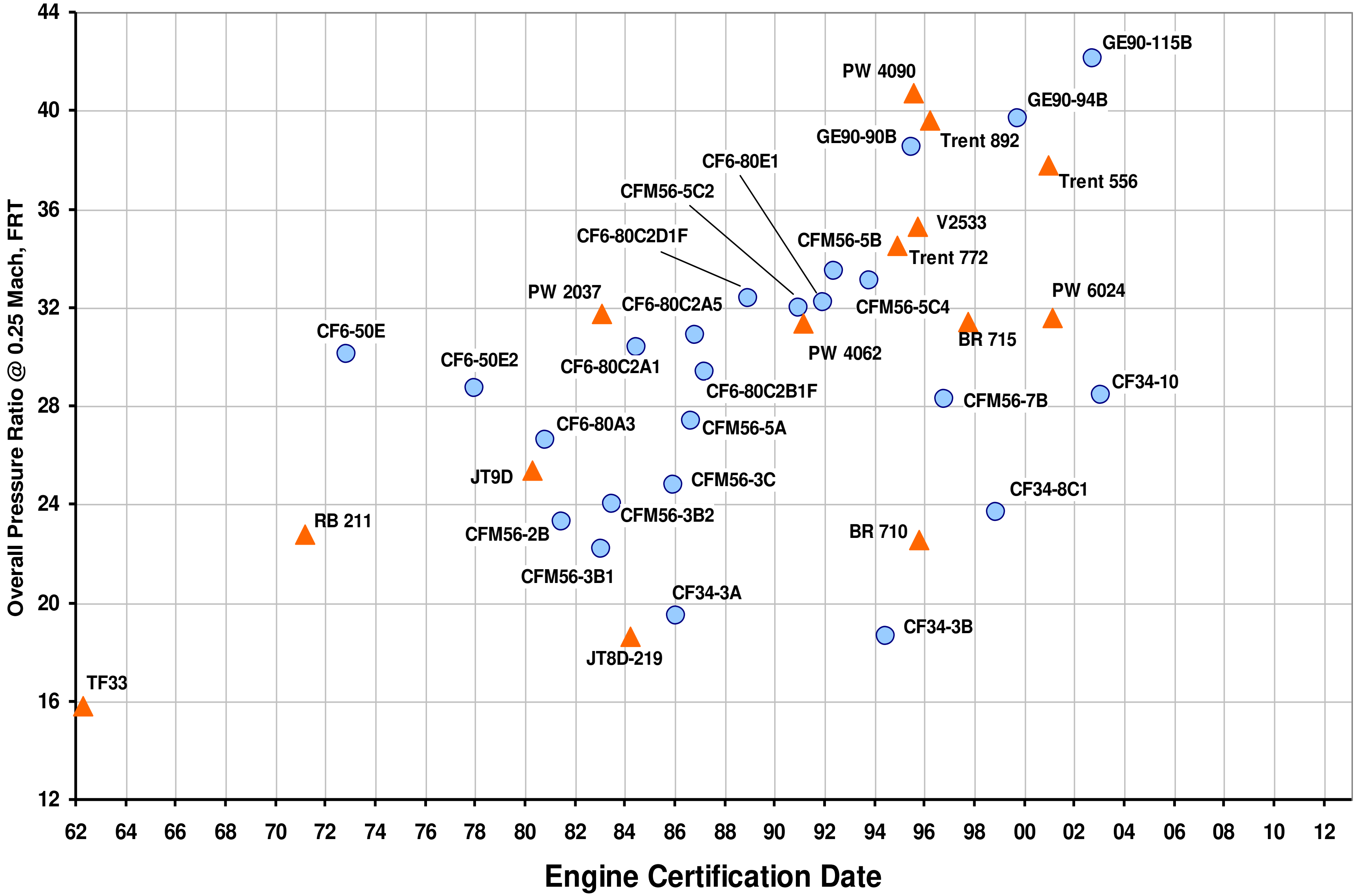
Technology to Revolutionize the State of the Art

Material Options



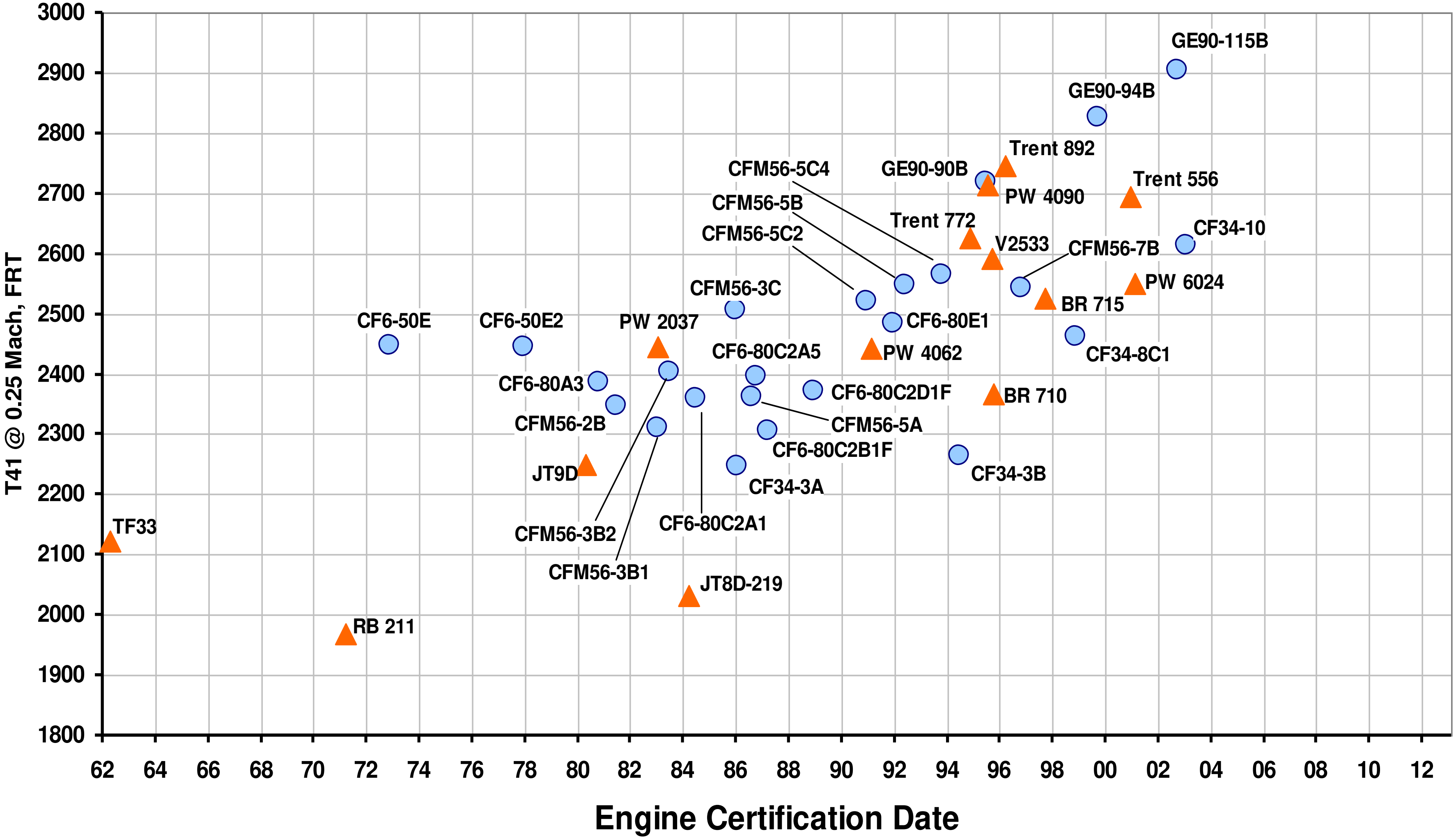
THE OHIO STATE UNIVERSITY

Engine Pressure Ratio Trend



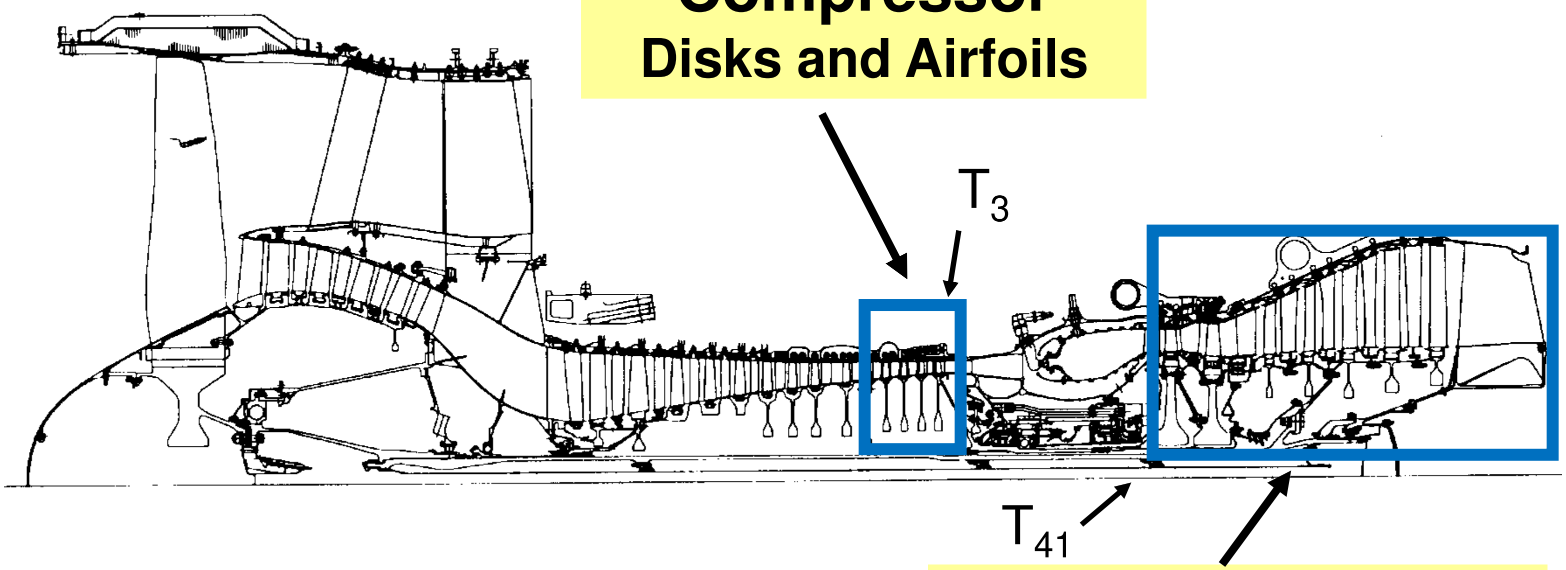
THE OHIO STATE UNIVERSITY

Engine Temperature Trend



High Temperature Structural Material Applications

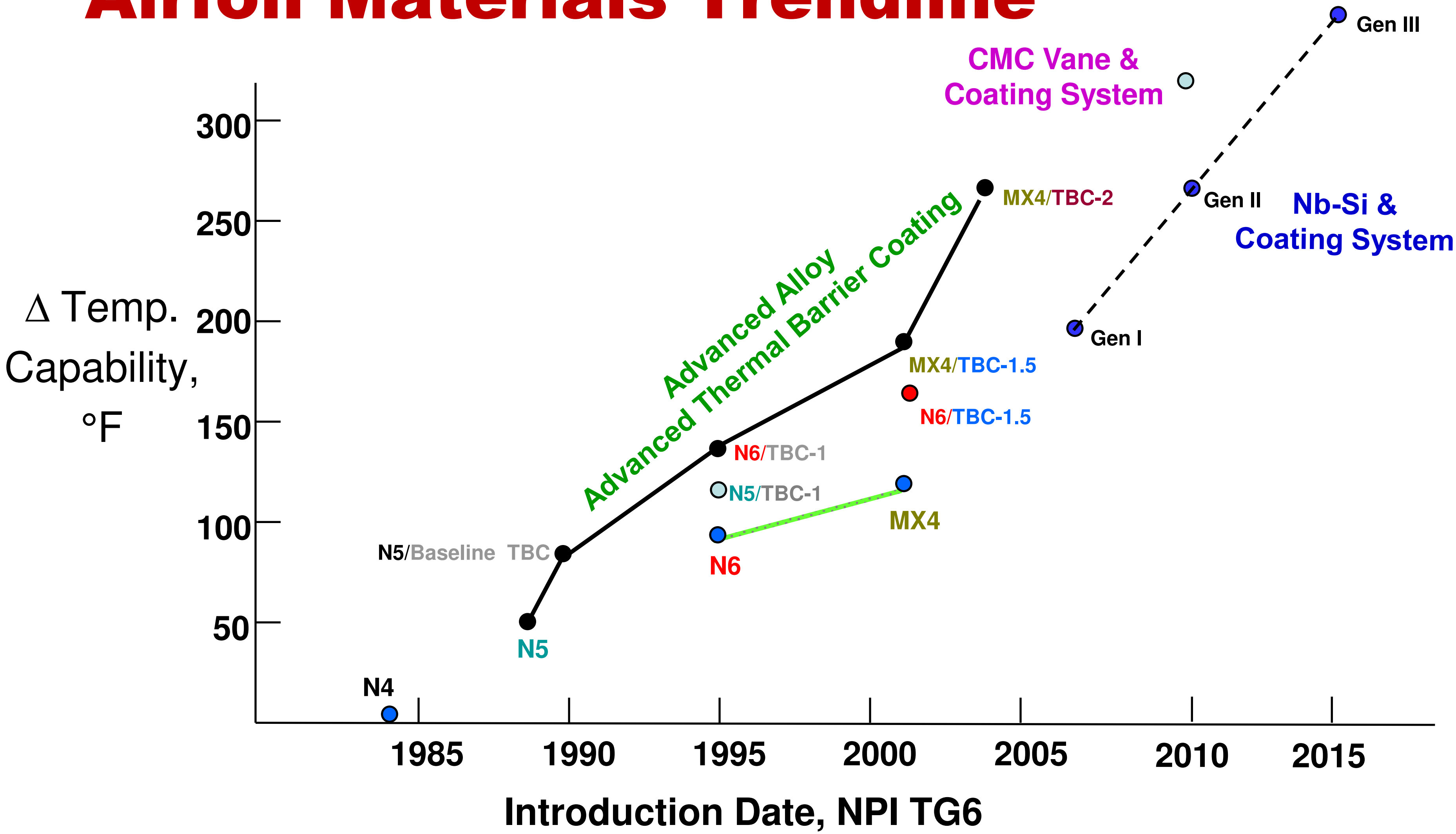
High Pressure Compressor
Disks and Airfoils



HP and LP Turbine
Disks, Airfoils and Structures

THE OHIO STATE UNIVERSITY

Airfoil Materials Trendline



Turbine Airfoil Material Advancements Pushing the Envelope

Coming soon to an engine near you …

advanced materials technologies

Structural Composite Case

R104

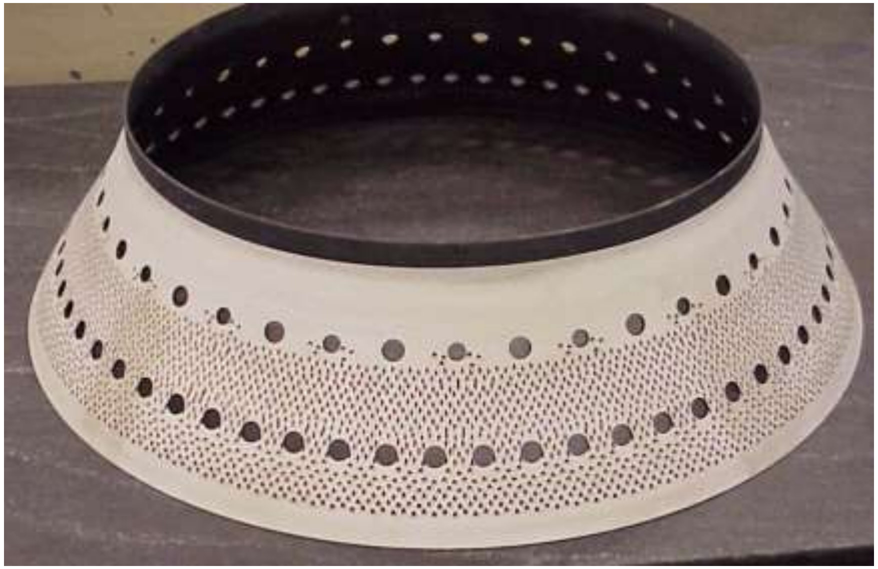
Advanced Superalloy Structural Alloy

Advanced Turbine Airfoil System

Mid-Fan Shaft– GE1014

TiAl LPT Blade

Ceramic Matrix Composites (CMC)



CMC Combustor Liner

CMC Vane

CMC Blade

2200°F Capability
50% Cooling Air Reduction
50% Weight Reduction
20% NOx Reduction

2200°F Capability
70% Weight Reduction
Reduced Cooling Air
Increased Efficiency

CMC's Reduce Weight and Improve Performance

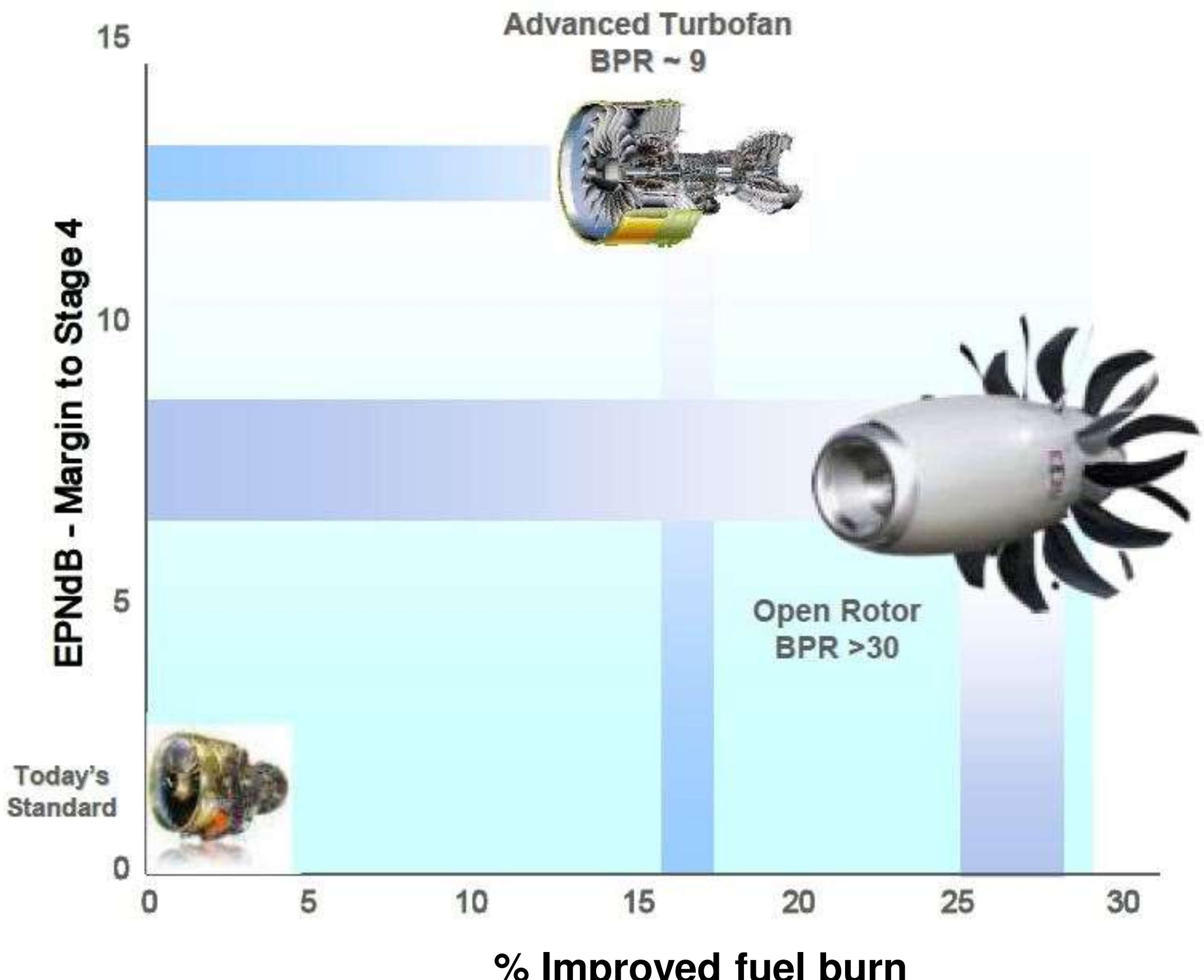
What is NEXT?

- Let us now look at the future:
  - More Bypass
  - Higher Pressure Ratio Cores
  - New Architecture
  - Drivers
    - ✓ NASA N+3 Goals
    - ✓ Clean Sky 2

NASA N+3 Subsonic Fixed Wing Goals

Corners of the Trade Space	N=1 (2015) Technology Benefits Relative to a Single Aisle Reference Configuration	N+2 (2020) Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 (2025) Technology Benefits
Noise (cum below Stage 4)	- 32 dB	- 42 dB	- 71 dB
LTO NOx Emissions (below CAEP 6)	- 60%	- 75%	Better than –75%
Performance Aircraft Fuel Burn	- 33%	- 50%	Better than -70%
Performance Field Length	- 33%	- 50%	Exploit metroplex concepts

Open Rotor Technology has potential for significant performance improvement, but with noise goal challenges

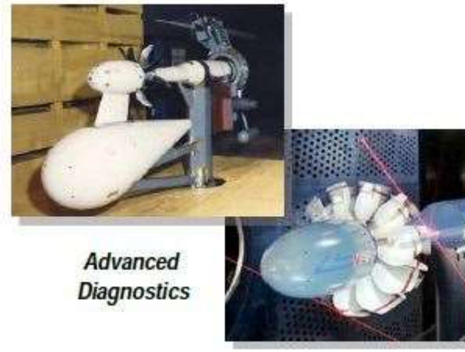


Leveraging the NASA/GE UDF Experience and UHB Partnership

Climb/Cruise in Glenn 8′x6′ Wind Tunnel

Approach/Takeoff in Glenn 9′x15′ Wind Tunnel

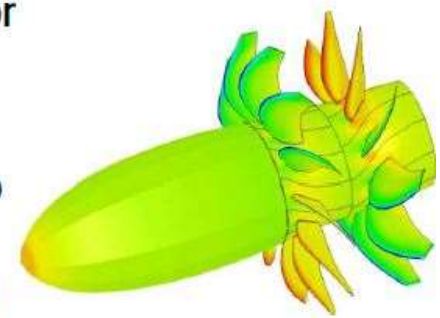
Installation Effects



Advanced Diagnostics

Counter-rotation Blade Profiles

- Extensive 1980s collaborative testing experience of counter-rotation, open rotor concepts by NASA and GE, resulting in substantial experimental database to guide new activity
- Improved Computational Aeroacoustics developed by NASA/GE/Universities to evaluate new open rotor concepts
- Improved design and system analysis tools to screen potential candidates and minimize scale model test configurations
- Utilize proven NASA test facilities, improved diagnostic testing techniques and existing scale model test articles
- Build on GE expertise in composite construction and advanced core technology to achieve full Open Rotor potential



Opportunities for the Future

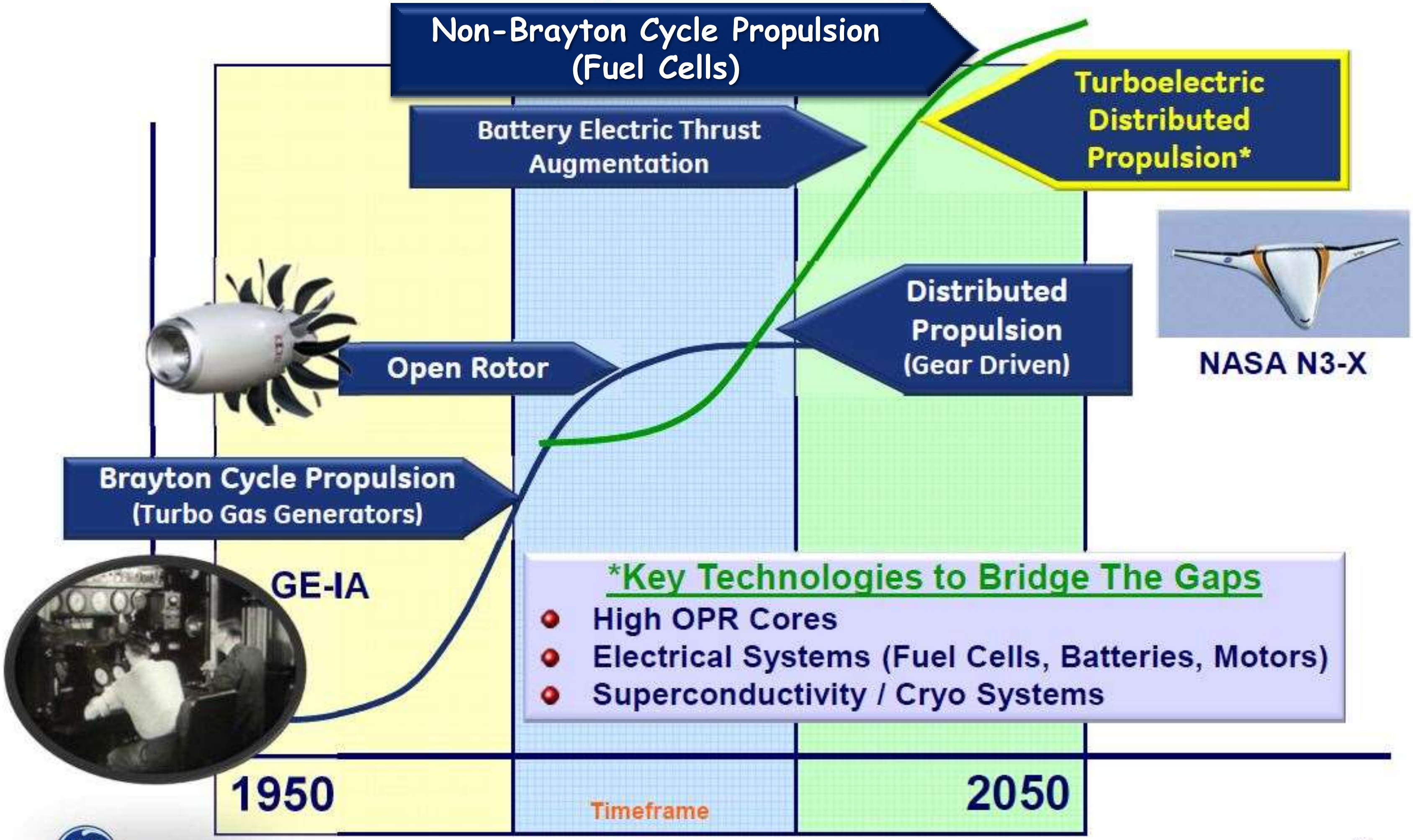
$$Range = \left(\frac{V_0}{SFC}\right) * \left(\frac{L}{D}\right) * \ln\left(\frac{W_{initial}}{W_{final}}\right)$$

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

	$\eta_{thermal}$	$\eta_{transfer}$	$\eta_{propulsive}$	W_{empty}
N+1	• Highly Loaded Compressors • High OPR Low Emissions Combustors	• Low Loss Inlets • Variable Low Loss Exhausts	• Very High BPR Turbofans	• Novel Alloys / MMC's • Non-metallics
N+2	• Adaptive cycles		• Ultra High BPR Turbofans • Open Rotors	• Advanced Engine Architectures
N+3	• Constant Volume Combustion • Hybrid Electric Propulsion	• Distributed Power Transmission	• Distributed Propulsion • Wake Ingestion	

imagination at work

2030 – 2050 Propulsion System Vision



Distributed Propulsion Options

- Two gas generators
- Multiple electrically powered embedded fans with boundary layer ingestion capabilities

NASA N3-X Concept

- Multiple gas generators (2-3)
- Multiple gear driven fans for each generator with boundary layer ingestion capabilities

Boeing/NASA N2B

- Liquid hydrogen cooled superconducting TeDP
- Embedded fans

ESAero/NASA Concept

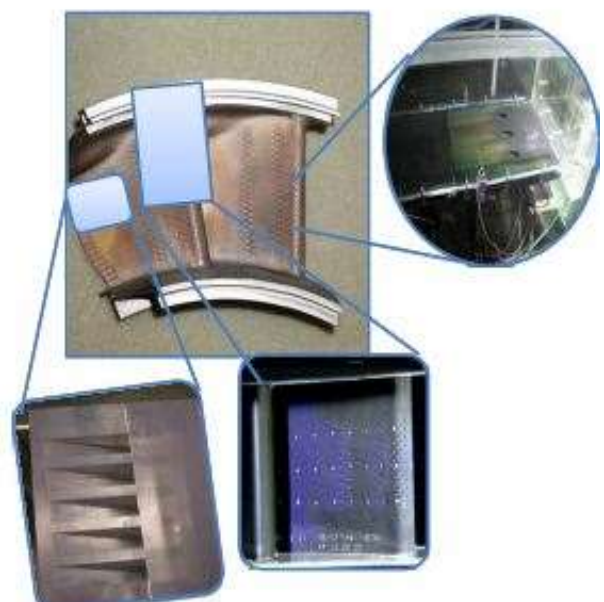
NASA Concept

- Two or more gas generators
- Multiple distributed open rotor fans for each generator

High Efficiency High OPR Gas Generators

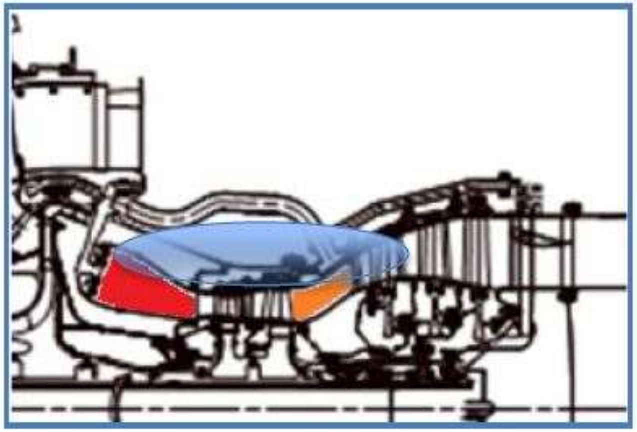
- Now driving to Bypass Ratios of 20+
- Highly loaded front block Compressor
- Minimizing the core size
- Hot section materials
- 1500ºF HP Compressor
- 3000ºF HP Turbine blades/vanes

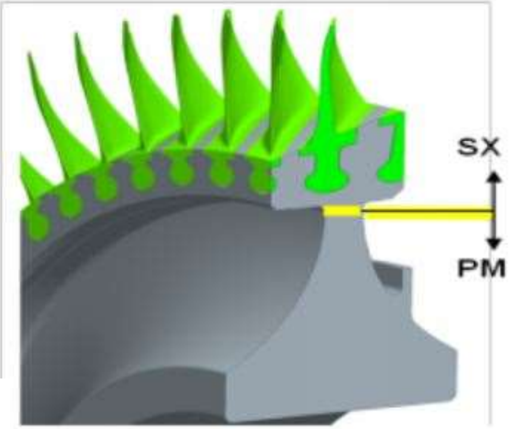
TECH 56 six stage Compressor

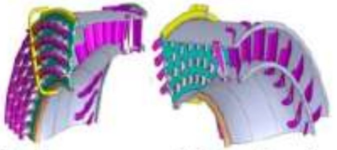


High Efficiency High OPR Gas Generators

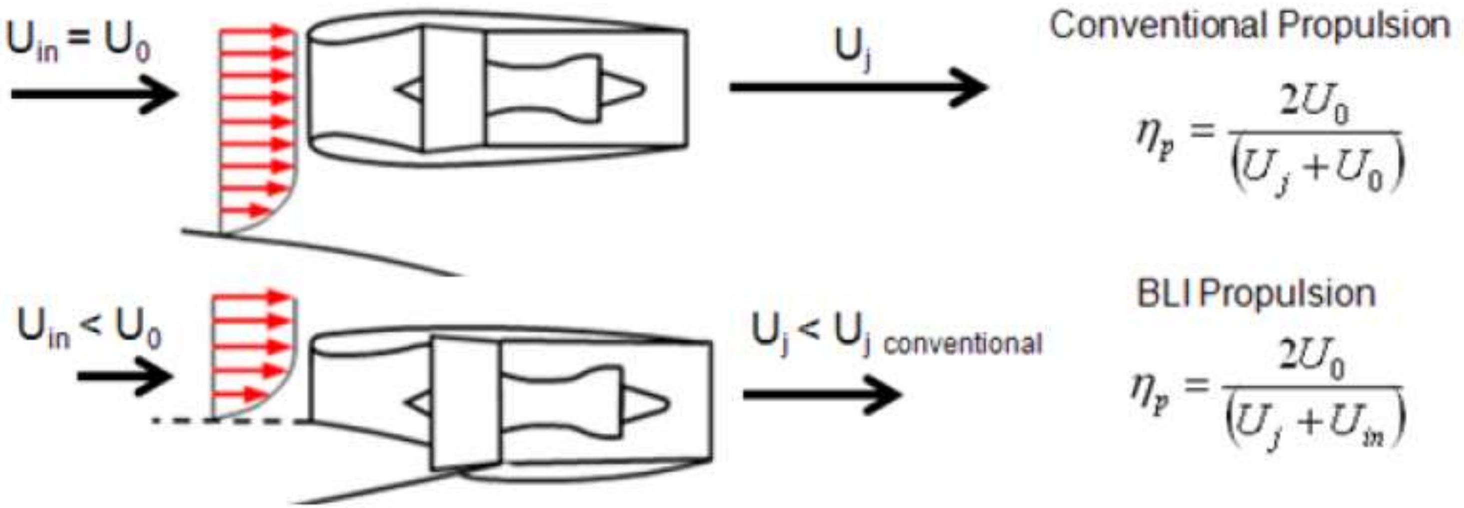
- Ceramic Matrix Composites
- NextGen disk material
- Tip/End Wall Aerodynamics
- Turbine Clearance Controls
- Low NOx Combustors
- Core Noise







Advanced fuel stage injector concepts

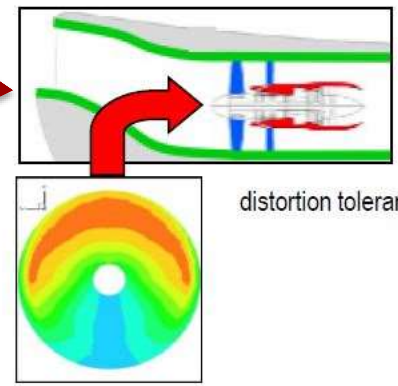


Boundary Layer Ingestion

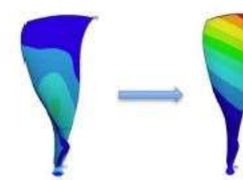
Propulsion Airframe Integration

- High Bypass Installations
- Slim Line Nacelles
- Adaptive Lightweight Fan Blade
- Distortion Tolerant Fans
- Multi-Degree of Freedom Acoustic Liners
- Low Jet Flap Acoustic Interactions

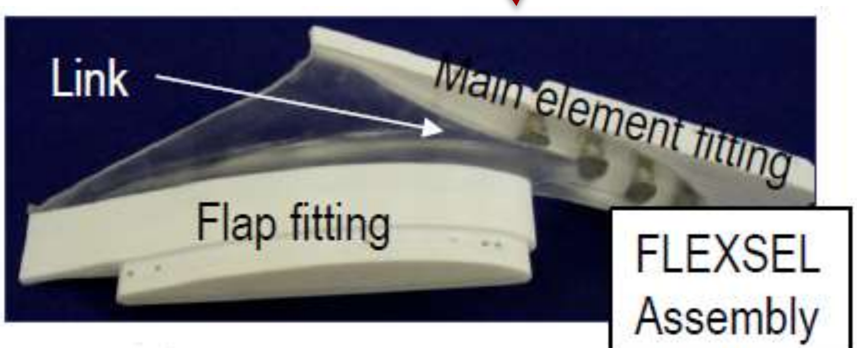
boundary-layer ingesting concepts
thrust vectoring



distortion tolerance



adaptive fan blades

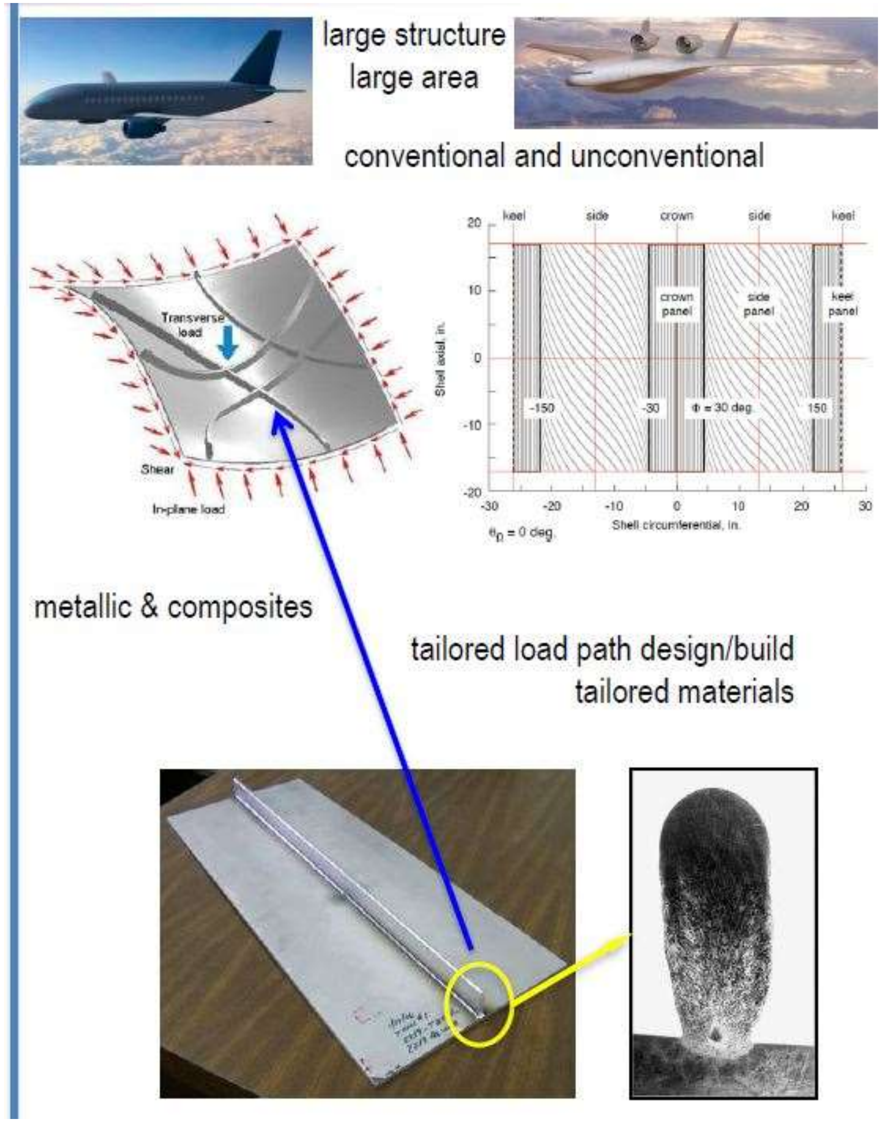


Airplane Aerodynamic Improvements

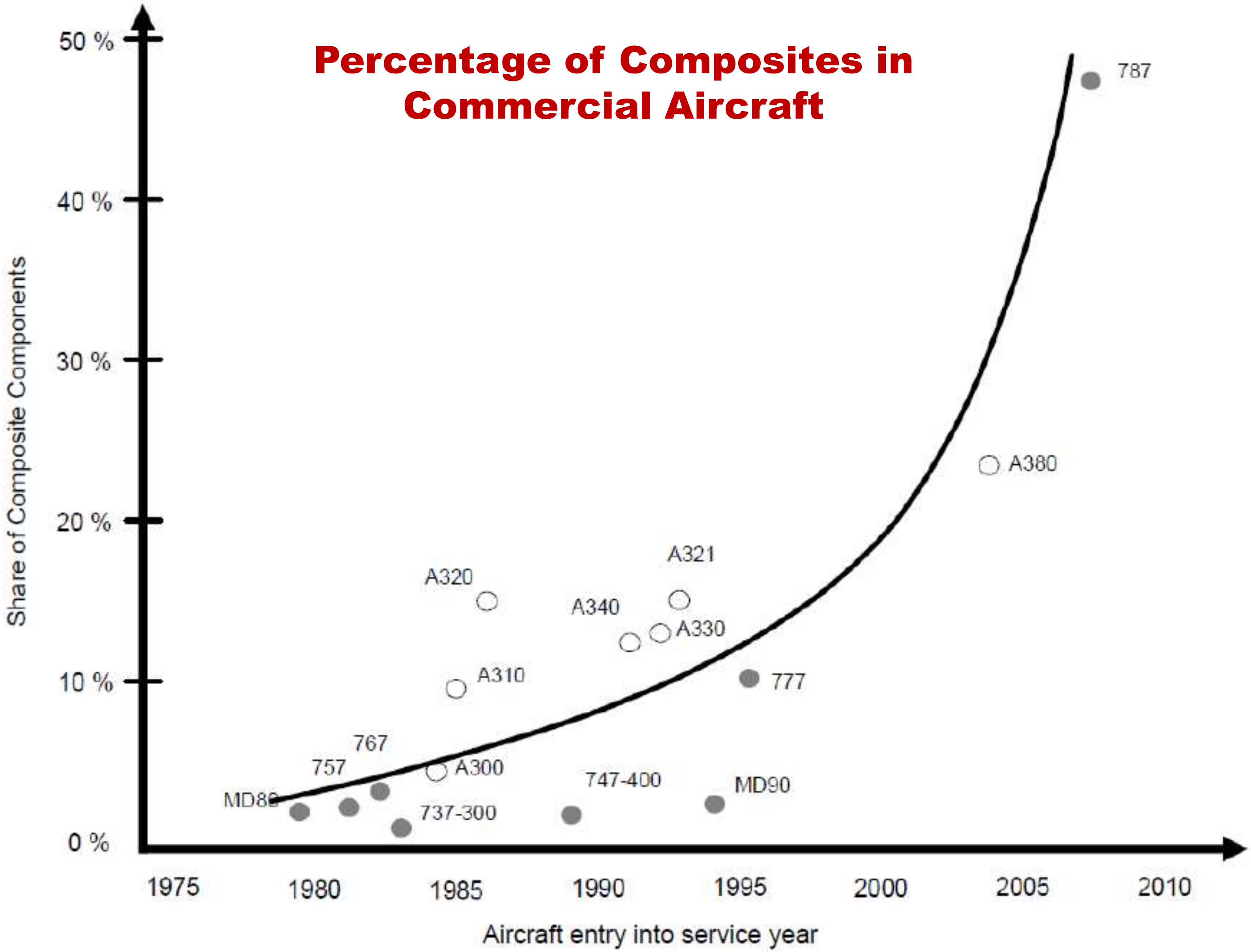
- Laminar flow nacelles
- Laminar flow on wings
- Low friction paint coating
- Improved aero-transonic design
- Wingtip technology
- Variable camber

Structure, Materials, and Manufacturing

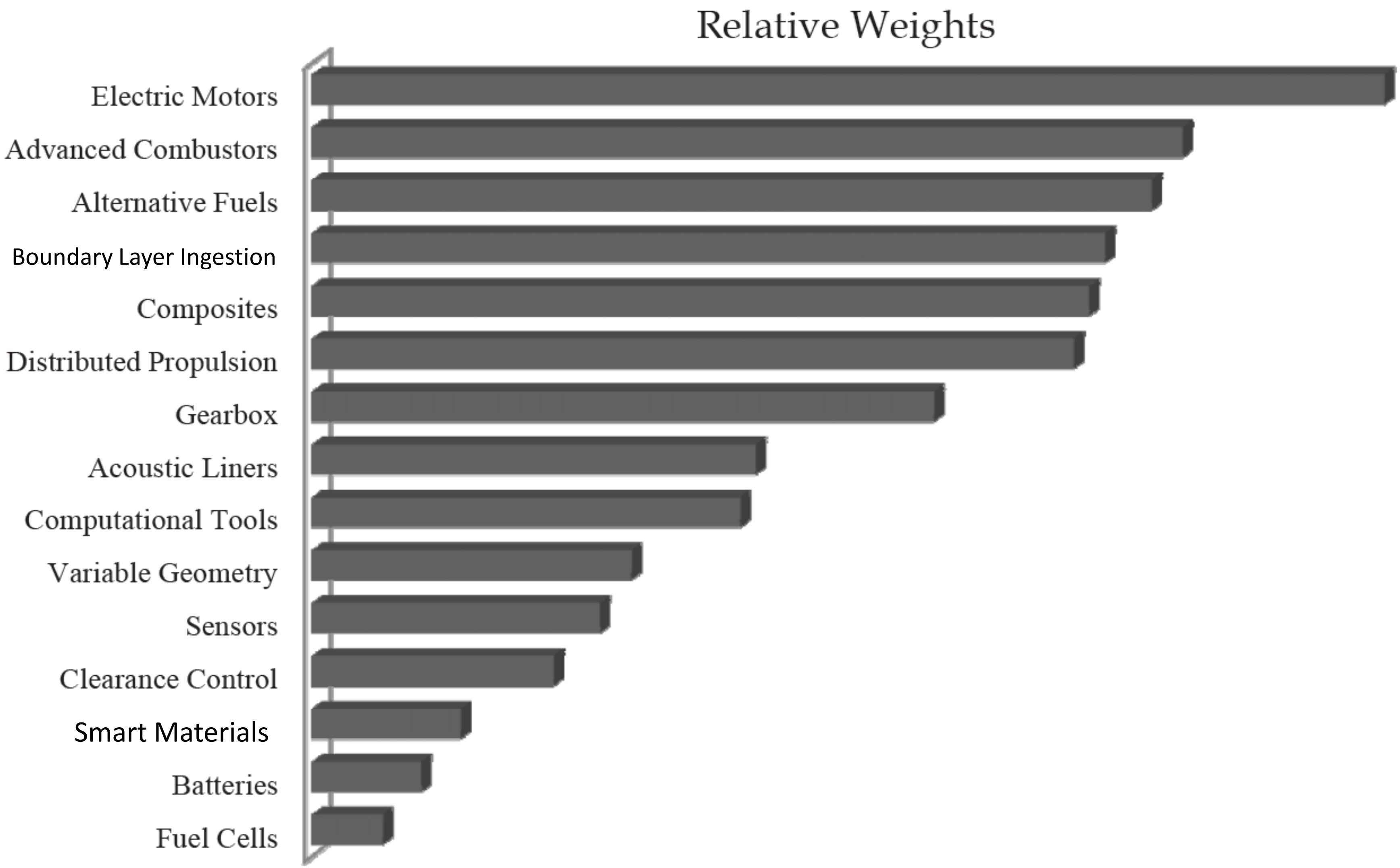
- All composite aircraft
- Integrated structural health monitoring
- Advanced manufacturing technology



Percentage of Composites in Commercial Aircraft

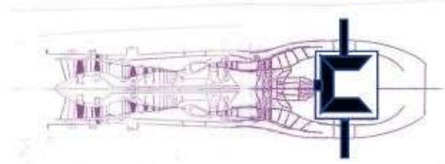


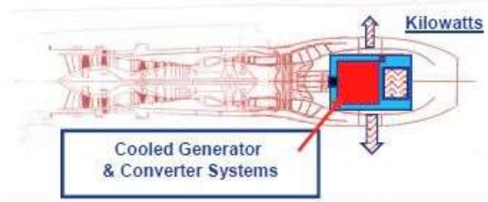
THE OHIO STATE UNIVERSITY



Relative Benefits of Technologies Relative to N+3 Goals

Energy Transfer Options for Powering Remote Fans



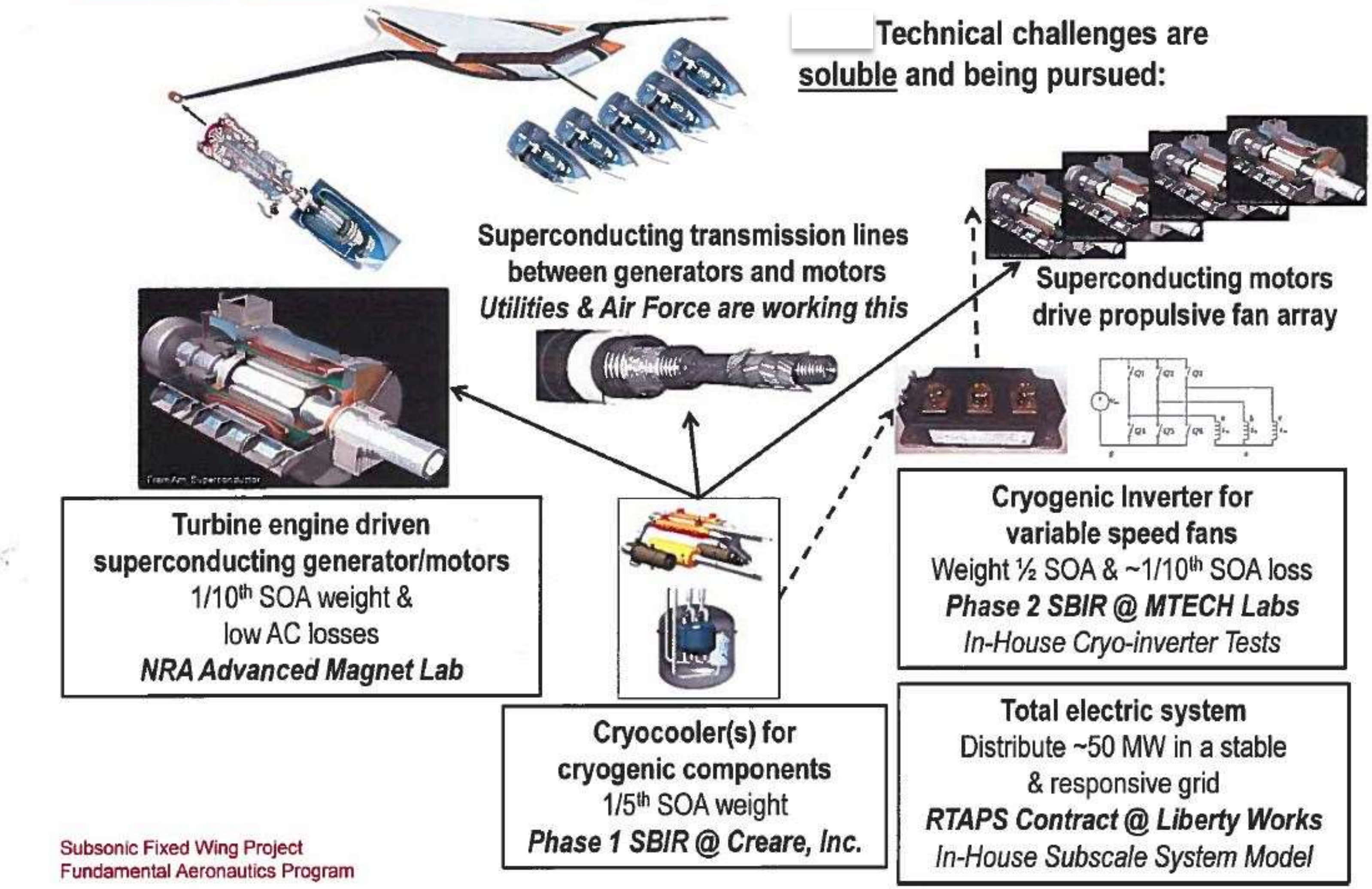


	Shafting/Gearing Horsepower	Electrical Power to Motors
Benefits	• Lower FPR for a given packaging constraint • High temperature gas contained to core stream	• Lower FPR for a given packaging constraint • Fan functionality after failure of one generator • High temperature gas contained to core stream • Offers most flexibility in fan placement and number of fans
Drawbacks	• Distance is restricted between gas generator and fans • Limited to ~3 fans	• Need for development of superconductivity technologies

Each Transfer Technology has Pros/Cons Depending on Specific Application

THE OHIO STATE UNIVERSITY

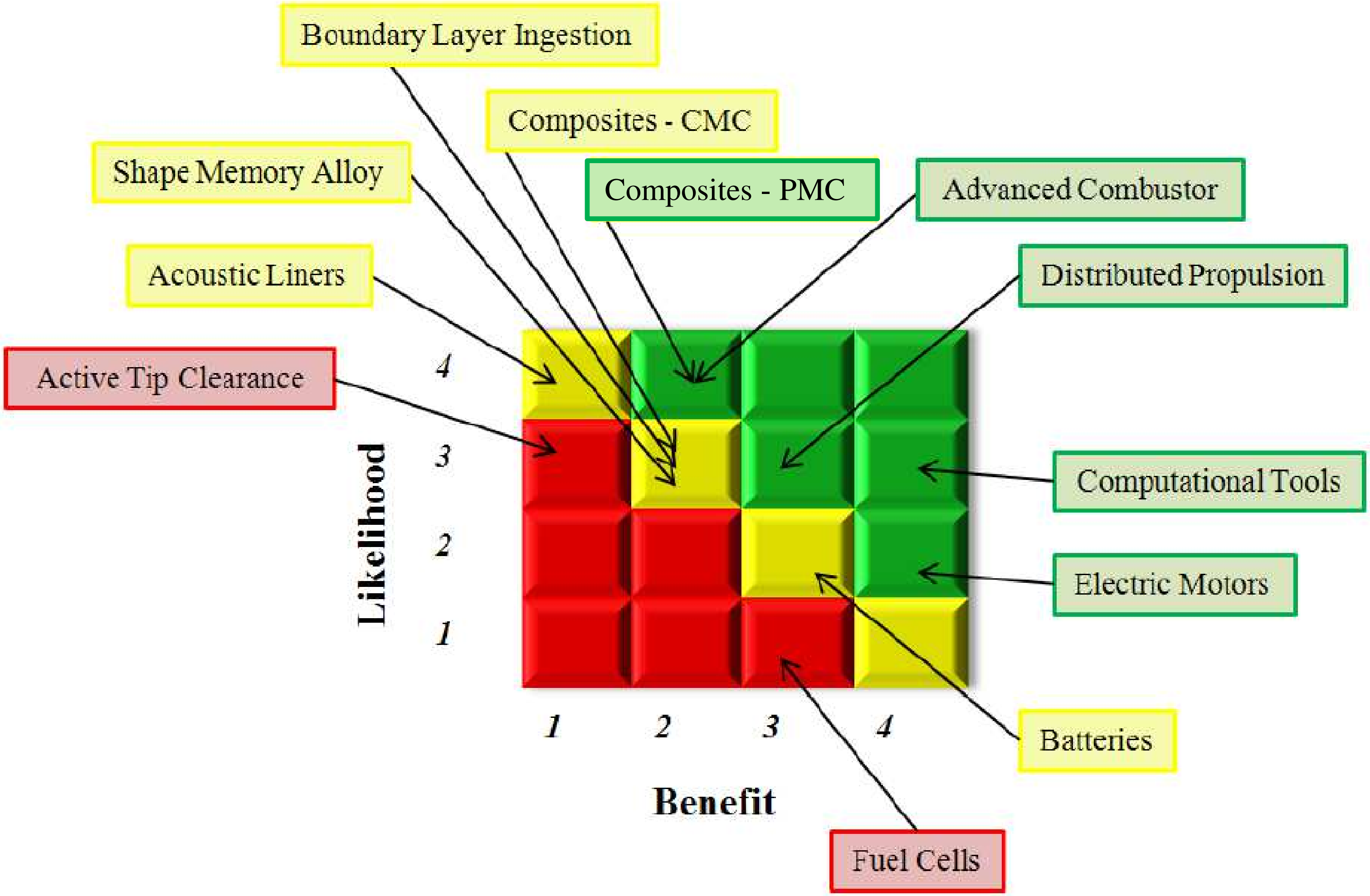
Light, Efficient Components Must Be Cryogenic or Superconducting



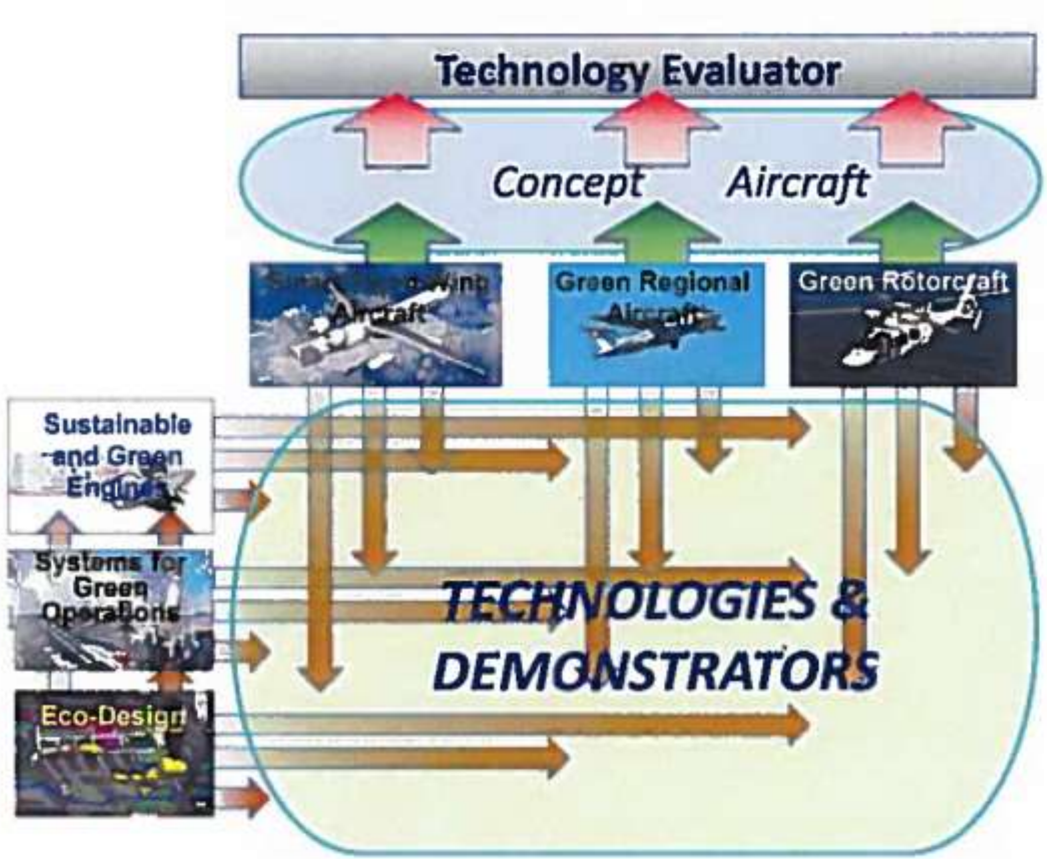
Technology	Challenges
Electric Motor	• Power to Weight Ratio • Decrease AC Losses
Advanced Combustor	• Fuel Mixing • Combustion Instability • Linear Material
Boundary Layer Ingestion	• Fan/Inlet Losses • Acoustic and Aeromechanical Issues • Off Design Operation
Composites	• Material Composition/Properties • Design Architecture
Distributed Propulsion	• Integration Complexity • Maintenance Cost • Minimal Loss Power Distribution
Acoustic Liners	• Determine Location and Applicability • Higher Bandwidth Attenuation
Computational Tools	• Setup Times • Validation • Greater MDAO
Active Tip Clearance Control	• Sensor Capabilities • Dynamic Modeling Accuracy • System Complexity
Shape Memory Alloys	• Dimensional Stability • Fatigue/Durability • Higher Temperature Capabilities
Batteries	• Energy Density • Lifecycle
Fuel Cells	• Power to Weight Ratio • Fuel Leakage/Processing • Deterioration/Lifecycle

THE OHIO STATE UNIVERSITY

Technology Assessment Matrix



Clean Sky 2



European Commission (EC) Budget of €3.6B (approx. $5B) with 50% cost share from EC over 6 years (2015-2021)

VERY DYNAMIC PROGRAM

Clean Sky 2 Goals

	Clean Sky 2
CO_2 and Fuel Burn	-20% to -30% (2025/2035)
NO_x	-20% to -40% (2025/2035)
Population exposed to noise/Noise footprint impact	Up to -75% (2035)

Baseline for these figures is best available performance in 2014

Clean Sky 2

- R&D leading to Demonstrators
- 3 Integrated Aircraft Demonstrator Platforms (IADP's)
  - Large passenger
  - Regional
  - Fast Rotorcraft
- 3 Integrated Technology Demonstrators (ITD's) for Airframe, Engines and Systems
- Eco Designs and Small General Aviation/Commuter Aircraft

Sustainable and Green Engines

- *Open Rotor*
- *Geared Open Rotor*
- *Large 3 Shaft Turbofan*
- *Geared Turbofan*
- *Turboshaft Engine Demonstrator*
- *Lean Burn Program*

THE OHIO STATE UNIVERSITY

What does is all mean?
Projections for Aircraft 2035+

	Single Aisle Aircraft Baseline A320-200	Twin Aisle Aircraft Baseline 777-200 ER	Regional Jets Baseline Embraer EI90
FUEL BURN	45%	43%	45%
NOISE	Stage 4 with 70 dB margin	Stage 4 with 70 dB margin	Stage 4 with 70 dB margin
NOx	Cap 6 with 80% margin	Cap 6 with 80% margin	Cap 6 with 80% margin

TREMENDOUS OPPORTUNITIES IN ECONOMICS AND THE ENVIROMENT

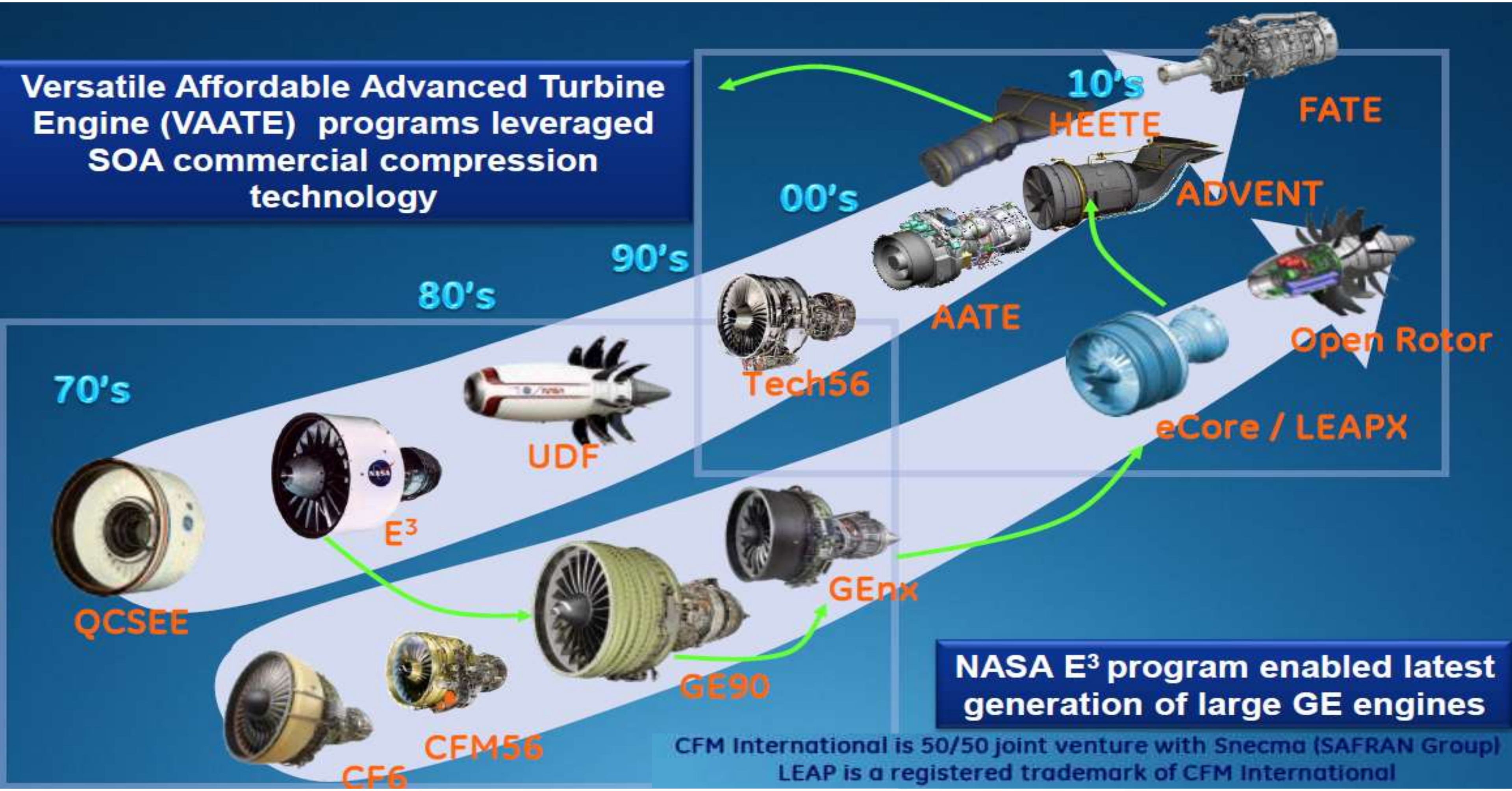
Next Gen portfolio
Military/ Commercial Technology Synergies

	AATE (Advanced Affordable Turbine Engine)	FATE (Future Affordable Turbine Engine)	ADVENT (Adaptive Versatile Engine Technology)	HEETE (Highly Efficient, Embedded Turbine Engine)
Customer	US Army	US Army	US Navy/ US Air Force	US Air Force
Program goals	25% better SFC 65% ↑hp/wt	35% better SFC 80% ↑hp/wt	20-200+% better SFC	35% better SFC
Technologies	3D aero, materials	3D aero, efficiency	Variable cycle, 3D aero, FLADE™	3D aero, efficiency
Segments	Attack/utility Helicopters	Heavy lift Helicopters	Combat aircraft	Tanker/Transport

Blackhawk NextGen heavy lift 6th Generation KC-135

Technology Demonstrator Programs

Strong History Leading to Commercial Benefits Today and Beyond



Looking Forward…The Challenges and Opportunities

- The market is global and is growing
  - This is good…big markets
- More players want to play
  - They bring technology competition…which is good
  - They bring financial competition…which is not necessarily good
- Governments play a role
  - United States Air Force, Navy and Army Research Labs—still strong on the military side
  - NASA going down significantly
  - European Union—strong and growing with the Clean Sky Program
  - Others

Looking Forward—Challenges and Opportunities (cont.)

- There will be a stronger need for partnerships
  - Between Companies
  - Between Industry and Universities
- Will have to work smarter
  - Rely on component tests as opposed to demonstrators
- Technology roadmaps will be essential to success in a very competitive world…competitive in terms of technology opportunities as well as funding streams
- The opportunity for our young engineers are immense as new innovative products will be needed and will flourish in this industry

THE OHIO STATE UNIVERSITY

Thank you for your time!

Dr. M.J. Benzakein
Director, Propulsion and Power Center