Gebhardt Lecture
Georgia Institute of Technology
January 23, 2014

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

THE OHIO STATE UNIVERSITY

What does the future bring?

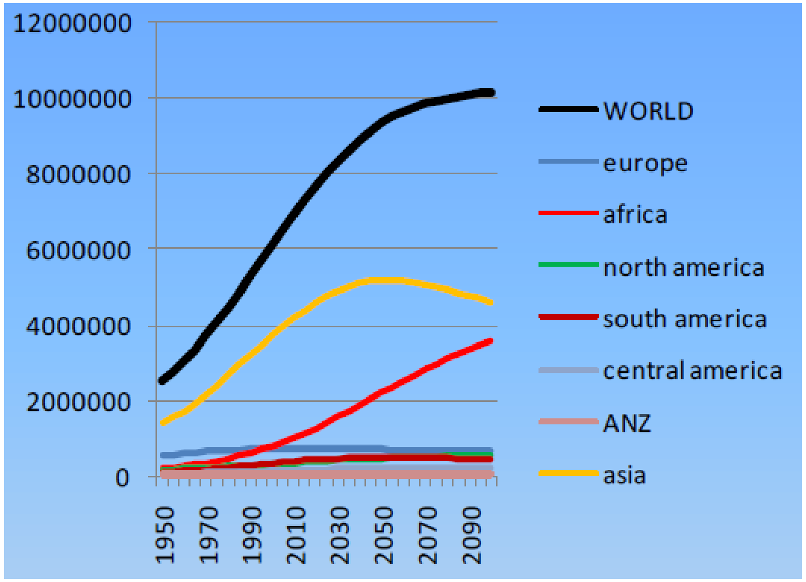
A look at Technologies for Commercial Aircraft in the years 2035-2050

OUTLINE

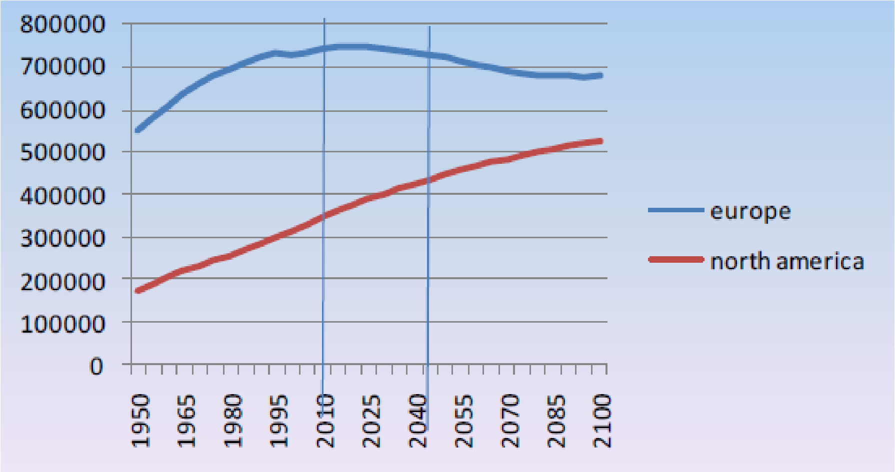
- Demographics and Economics
- The future…What does the customer want?
- The propulsion world going forward
- Airplane Aerodynamics
- Structures, Materials, and Manufacturing
- What does it all mean?
- The challenges and opportunities

Demography

source: UN/ESA World Population Prospects

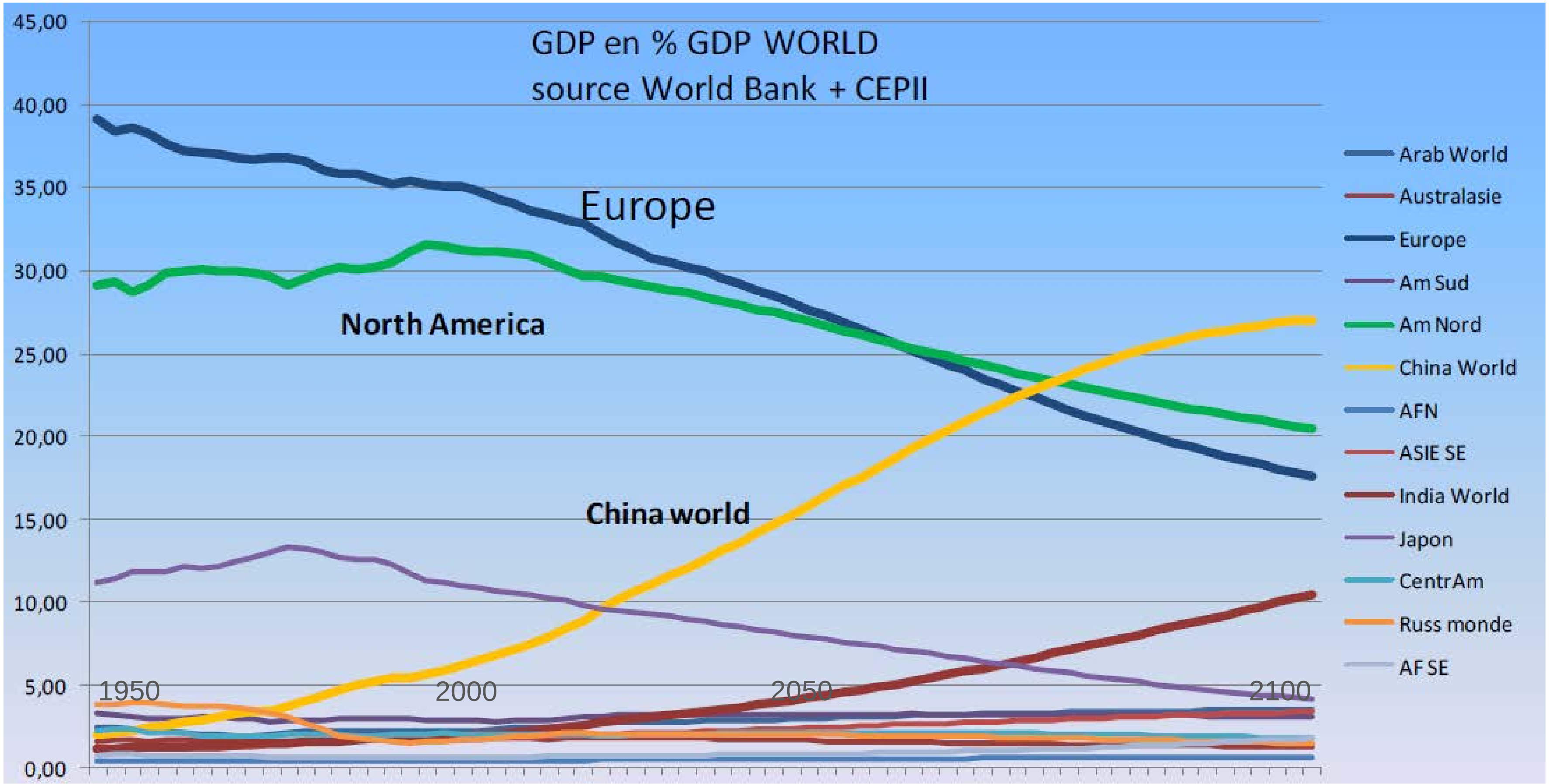


Populations
Now up to 2100: 10 billions
Europe decreasing after 2020
North America still growing
Asia decreasing after 2050
Africa towards1/3 of the world!

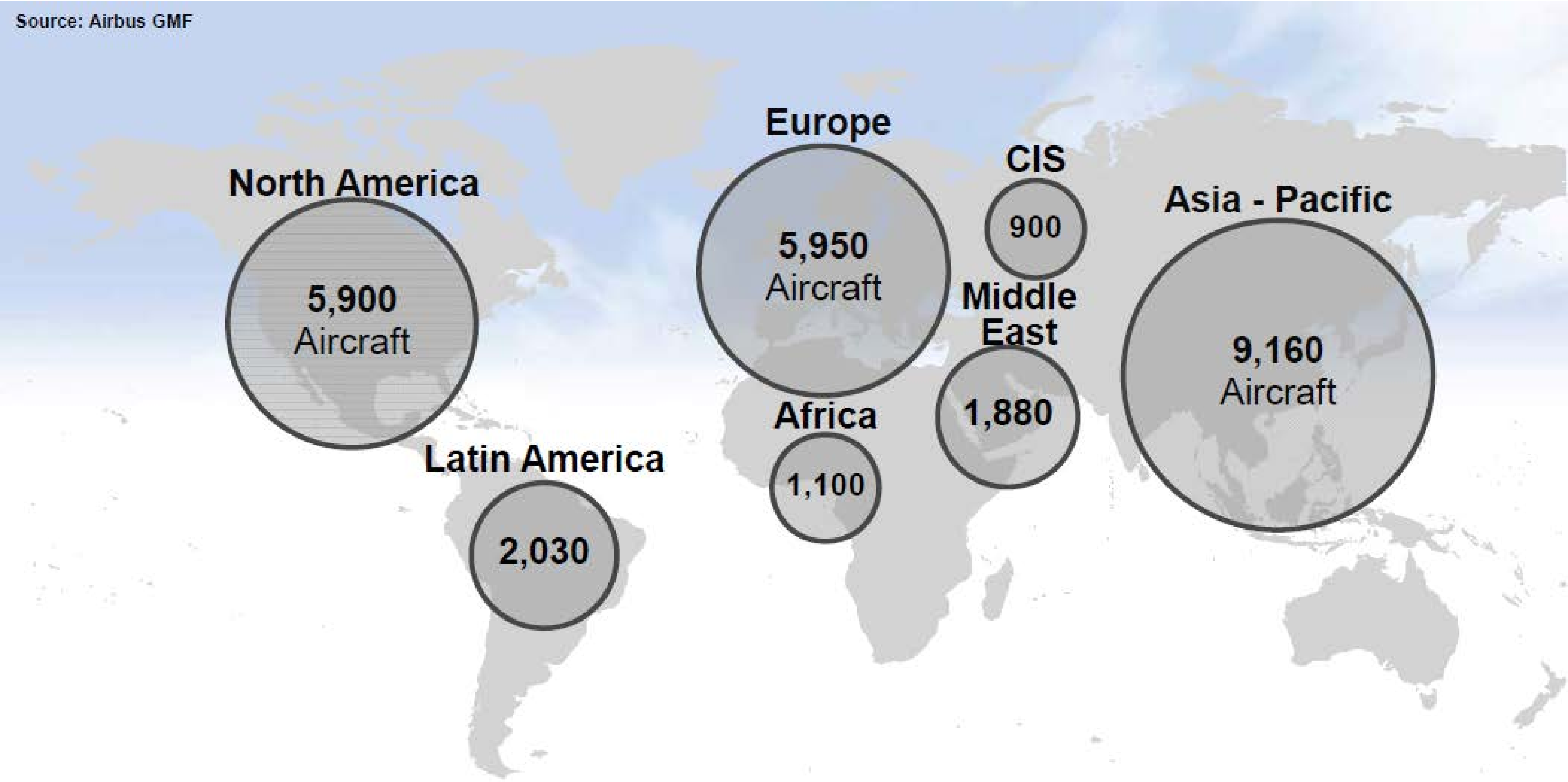


THE OHIO STATE UNIVERSITY

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



Geographical Demand

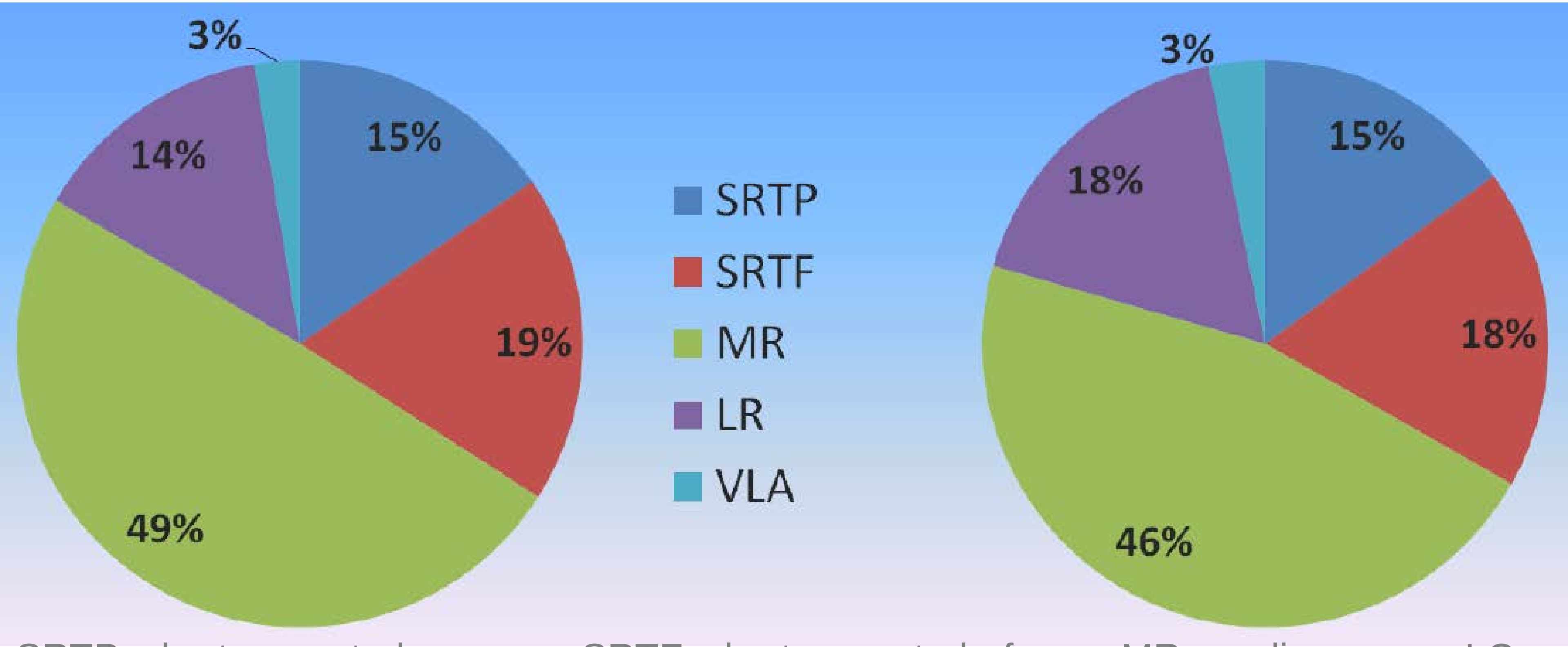


80% of the international demand over the next 20 years will be within Asia-Pacific, North America and Europe

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

The Future… What Priorities?

What does the customer want?

Speed?
Noise?
Fuel Burn?
Low Cost?
Environment… CO_2, NO_X, etc?

A delicate balance as we move forward

Competitive Business Environment

Business Case
- Development Cost
- Manufacturing Cost
- Revenue Stream
  - Unit Price
  - Sales Volume
  - Spares

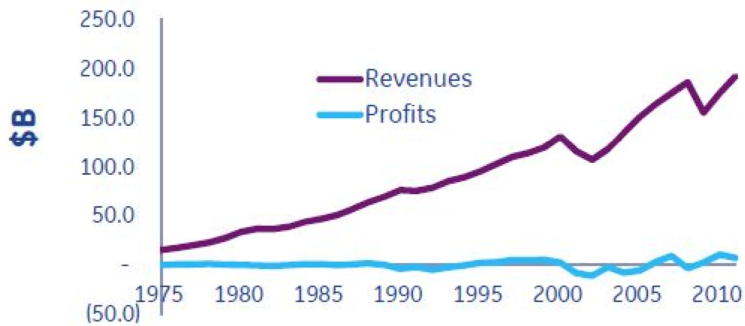
Customer Value
- Revenue
  - Payload
  - Range
- Cost of Ownership
  - Price
  - Fuel Burn
  - Maintenance Cost

Aircraft Requirements
- Passengers
- Cruise Speed & Insertion Altitude
- Balanced Field Length
- Power & Bleed Off-takes

Regulatory Requirements
- Safety
- Noise
- Emissions

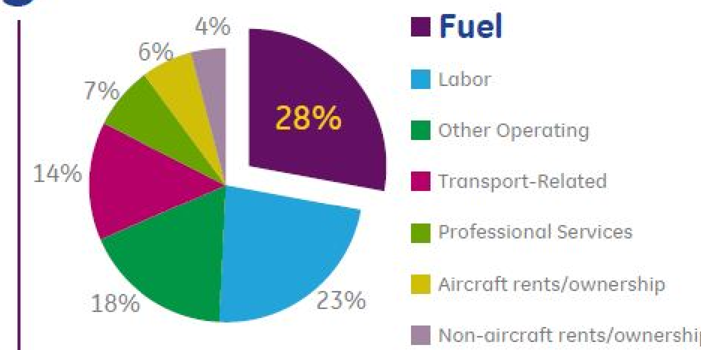
Propulsion Challenge

Industry Revenue/Profits



Sources: Air Transport Association/Bureau of Transportation Statistics

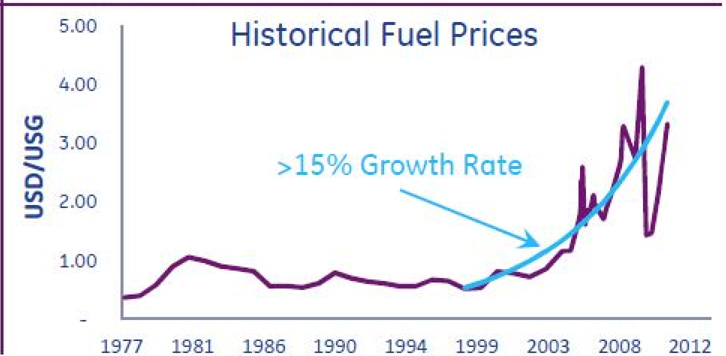
Airline Operating Costs



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

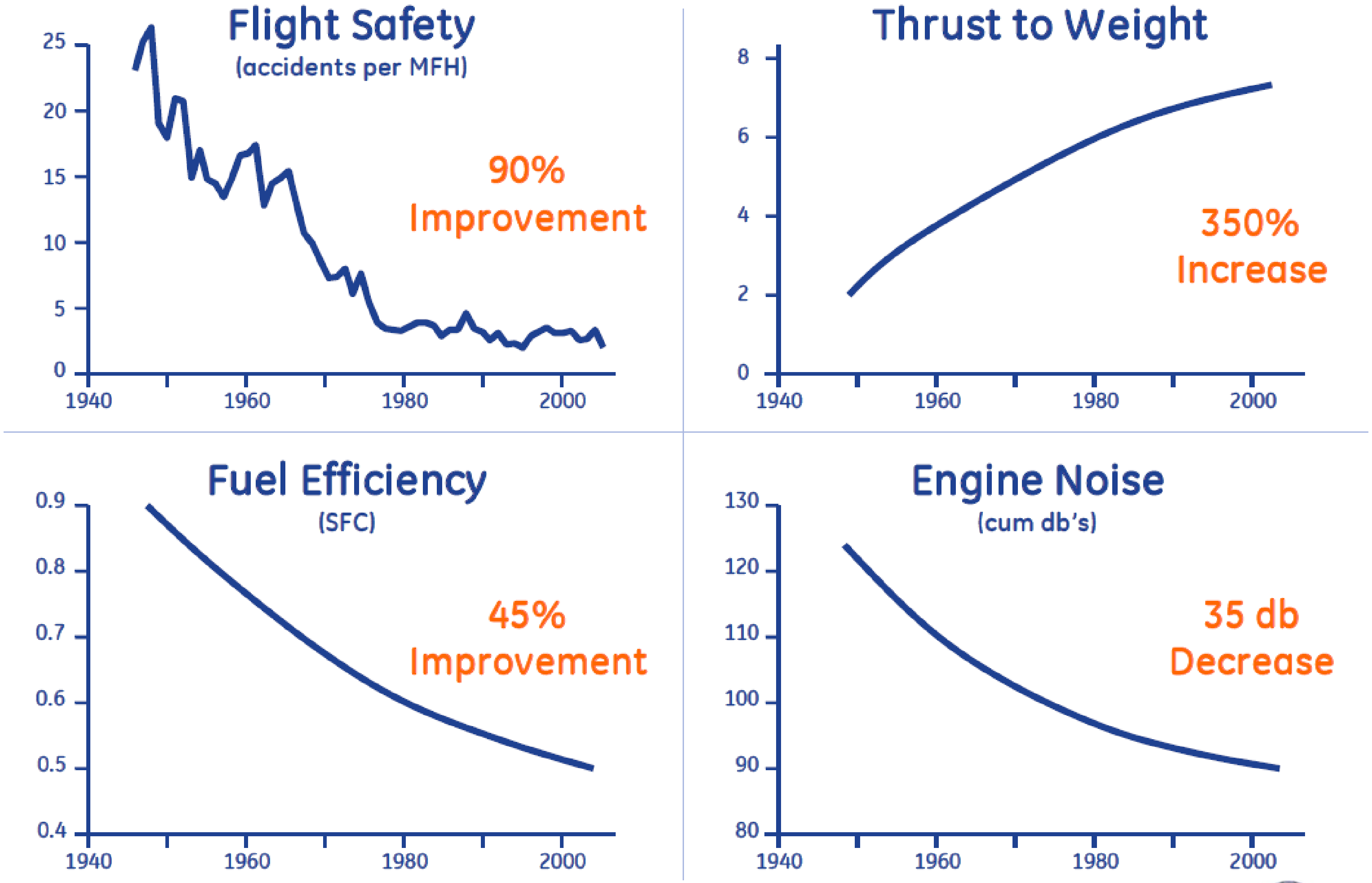


Sources: Air Transport Association, International Air Transport Association

Make airlines more profitable in an increasingly difficult environment

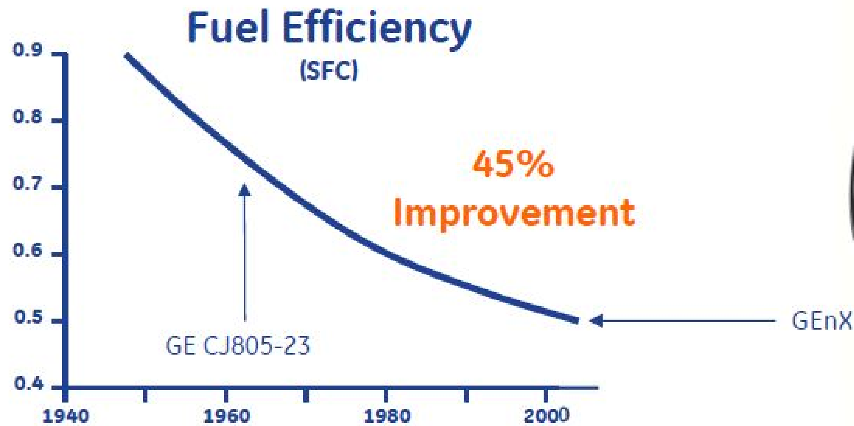
imagination at work

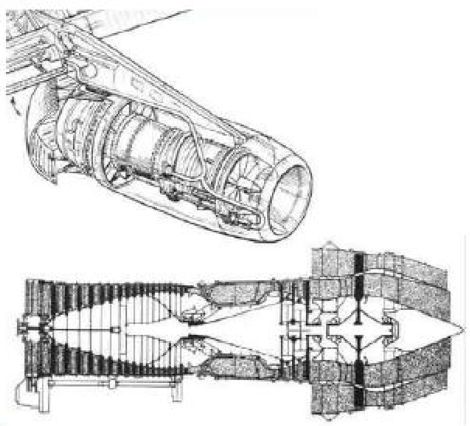
The History

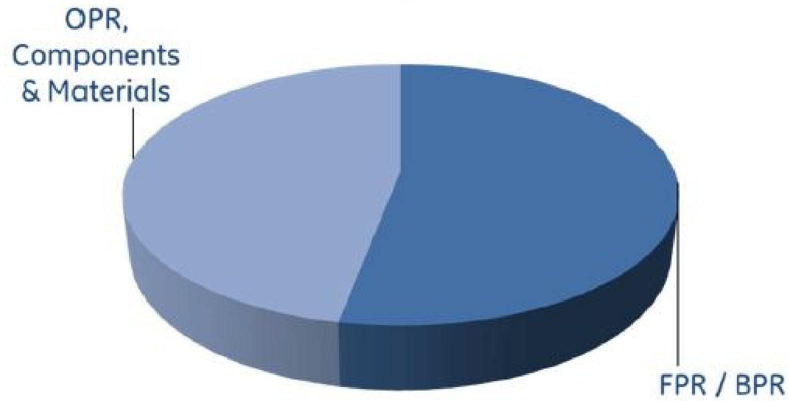


imagination at work

Historical Fuel Burn Improvements







imagination at work

Fuel consumption . . .

Addressing every aspect - sfc

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

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

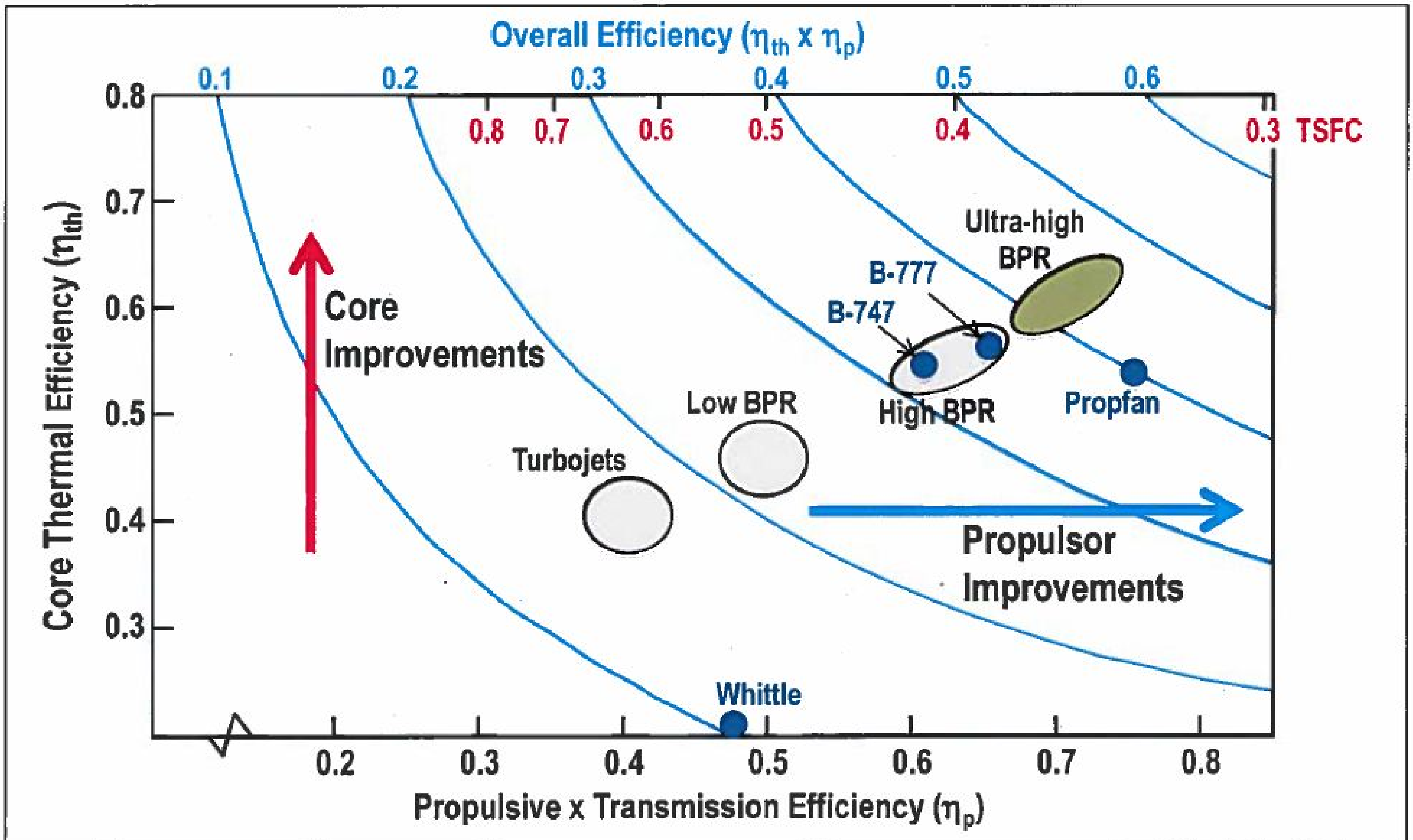
Core FPR

sfc . . . primary propulsion attribute

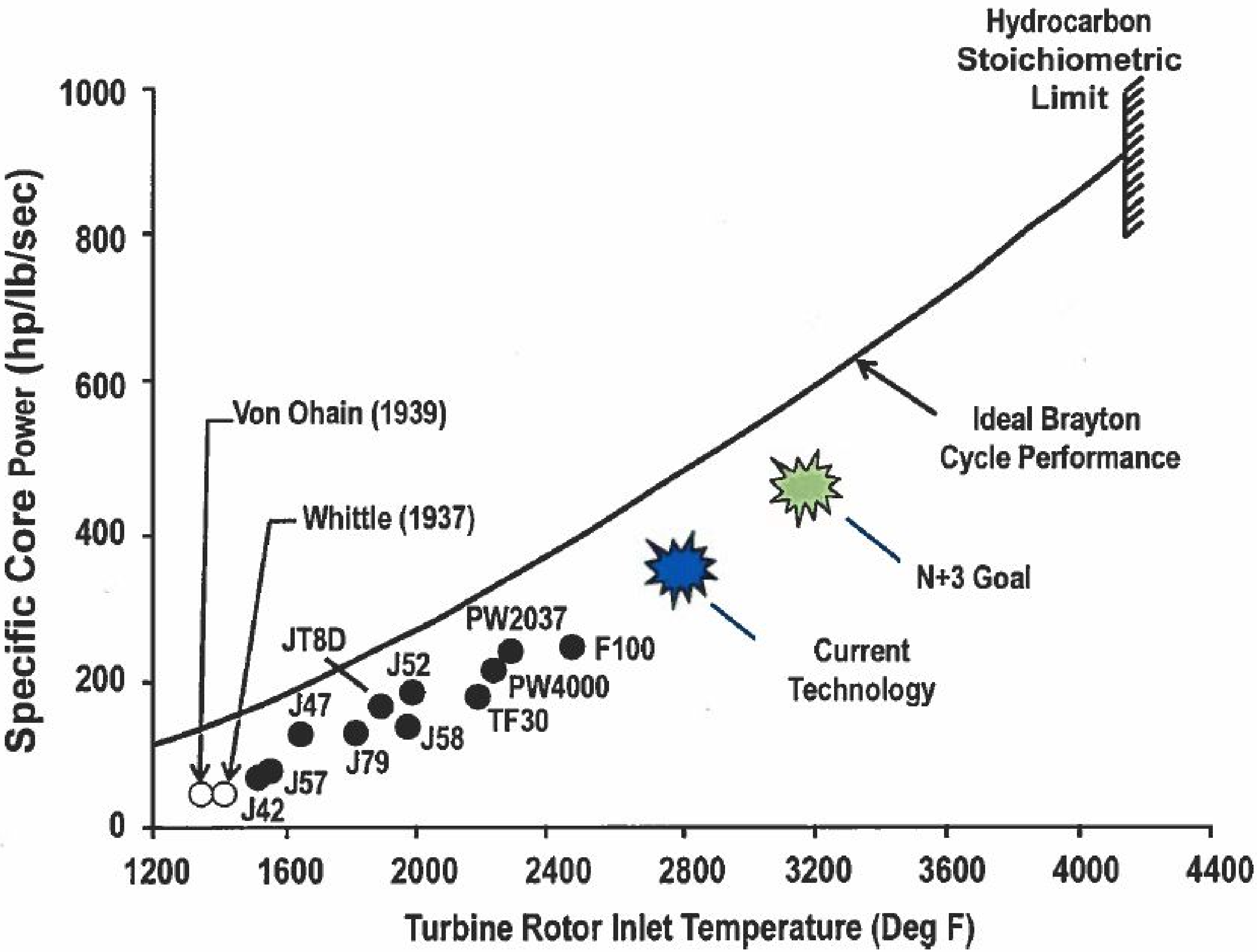
- Thermal efficiency - High OPR / high temp
  - Diminishing returns, but not at entitlement
  - Need cooled-cooling air or materials, or . . .
  - Component efficiencies and loss minimization
- Propulsive & Transfer efficiency - Low FPR, large fans & enablers
  - Unducted fans, propellers
- Or, new cycles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

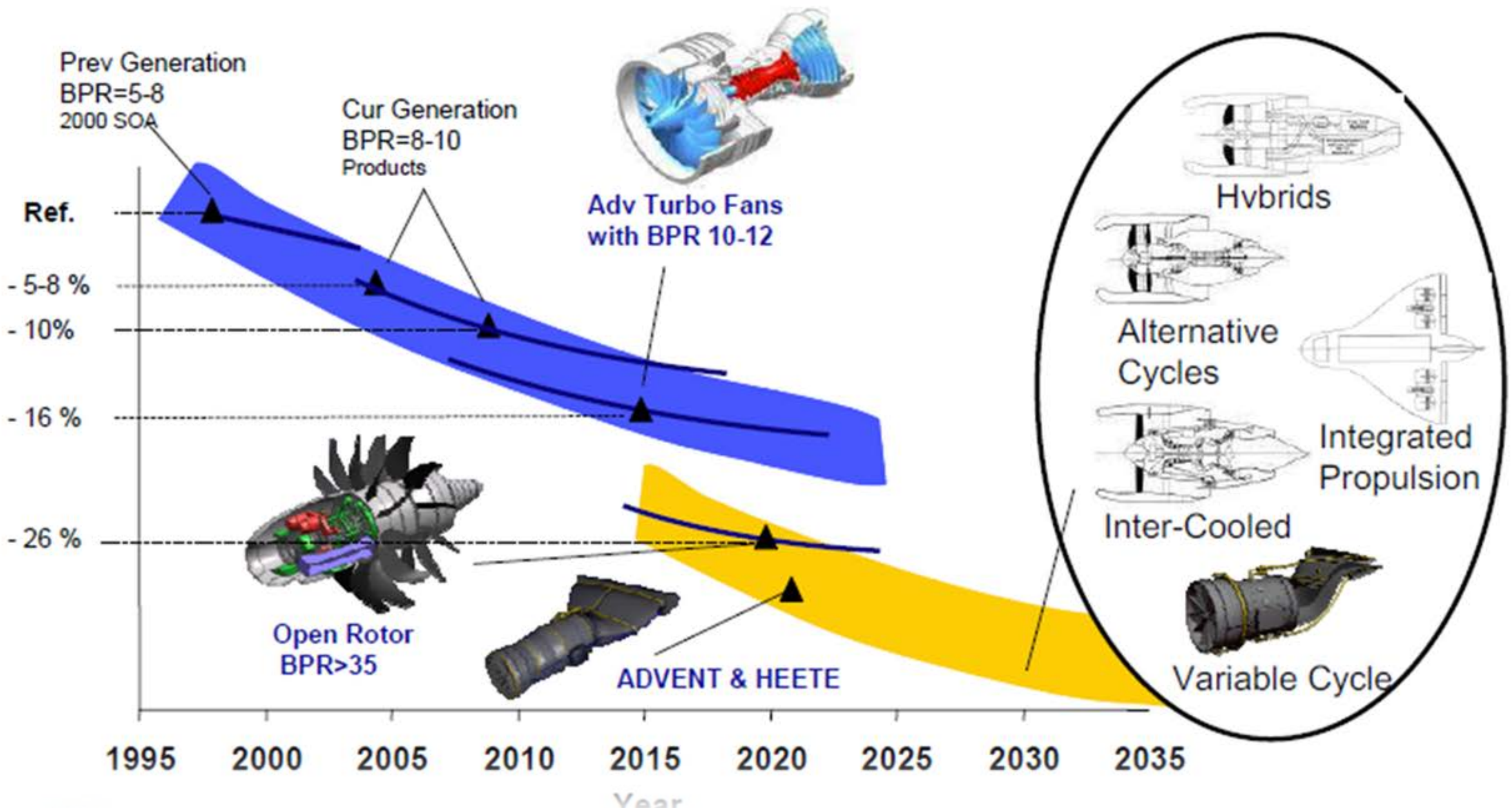


Variation in Core Power with Turbine Inlet Temperature



Fuel consumption projections

A step-change is coming soon



New Engine Architectures and New Challenges

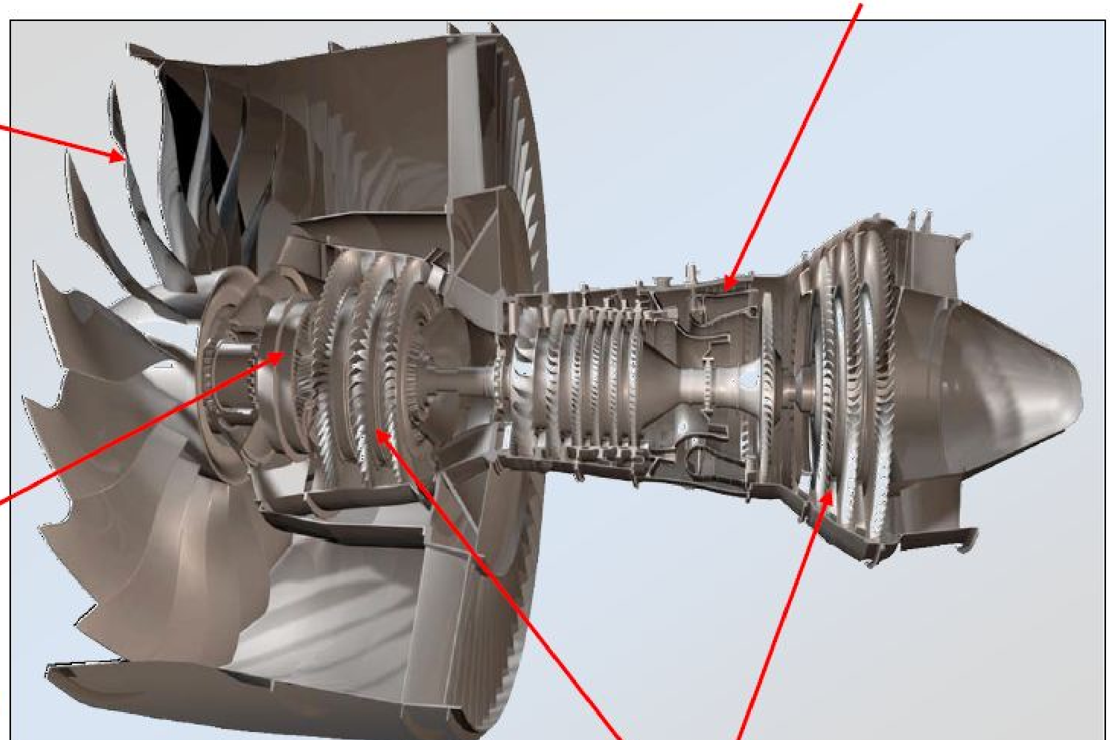
- **Geared Turbofan (P&W)**
- *Small, high density engine core*–required to achieve higher fan bypass ratio without significantly increasing fan diameter
- *Aerodynamic performance*–larger fan diameter means larger nacelle and higher drag
- *Installation*–increasingly larger diameter engines means limited application for current, low wing aircraft designs

- **Open Rotor (GE)**
- *Noise*–rotor blade noise radiates unobstructed to the environment, well above current aircraft noise regulation limits
- *Installation*–very large blade diameters mean significant aircraft installation problems, perhaps requiring all new aircraft design
- *Power* –slow, counter-rotating rotors requires novel turbine power distribution designs to optimize turbomachinery efficiency

Pratt & Whitney Geared TurboFan (GTF)

Low-Emissions Combustor

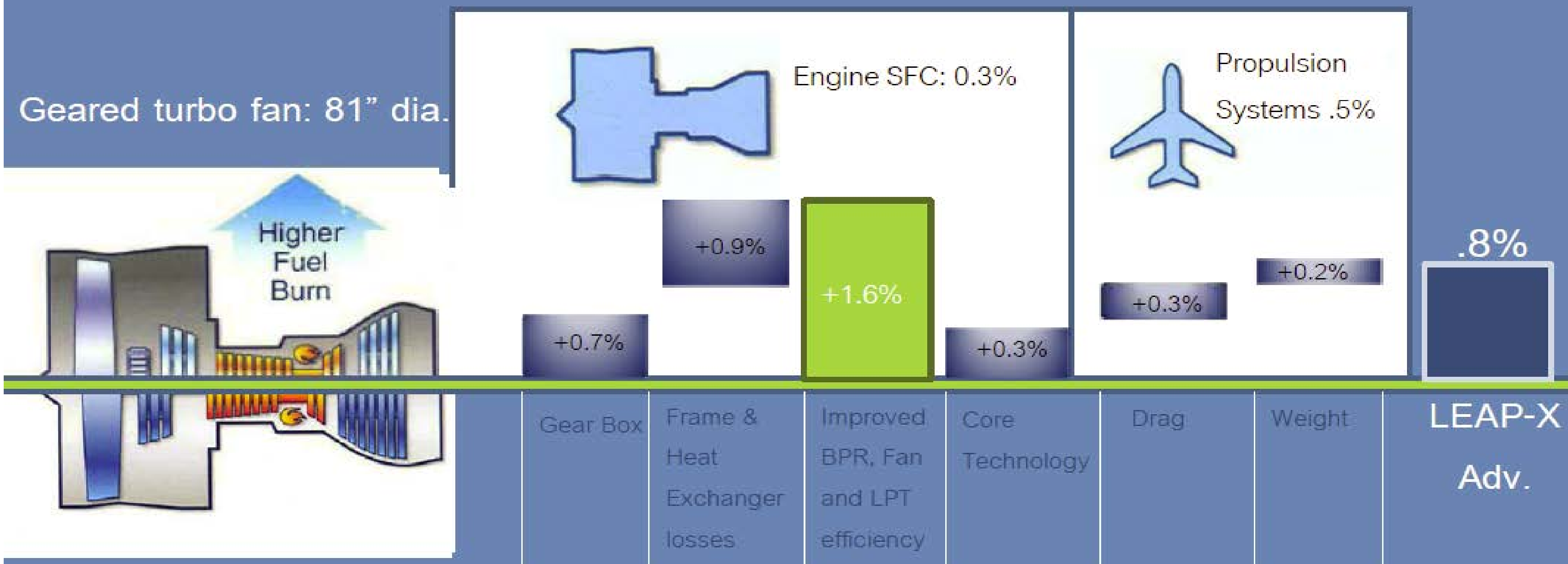
Low PR Fan
Low Tip Speed
BPR ~ 9 - 12



Fan Drive Gear System
5 Planets
Gear Ratio ~ 3

High-Speed Low Spool
Compact LPC, LPT

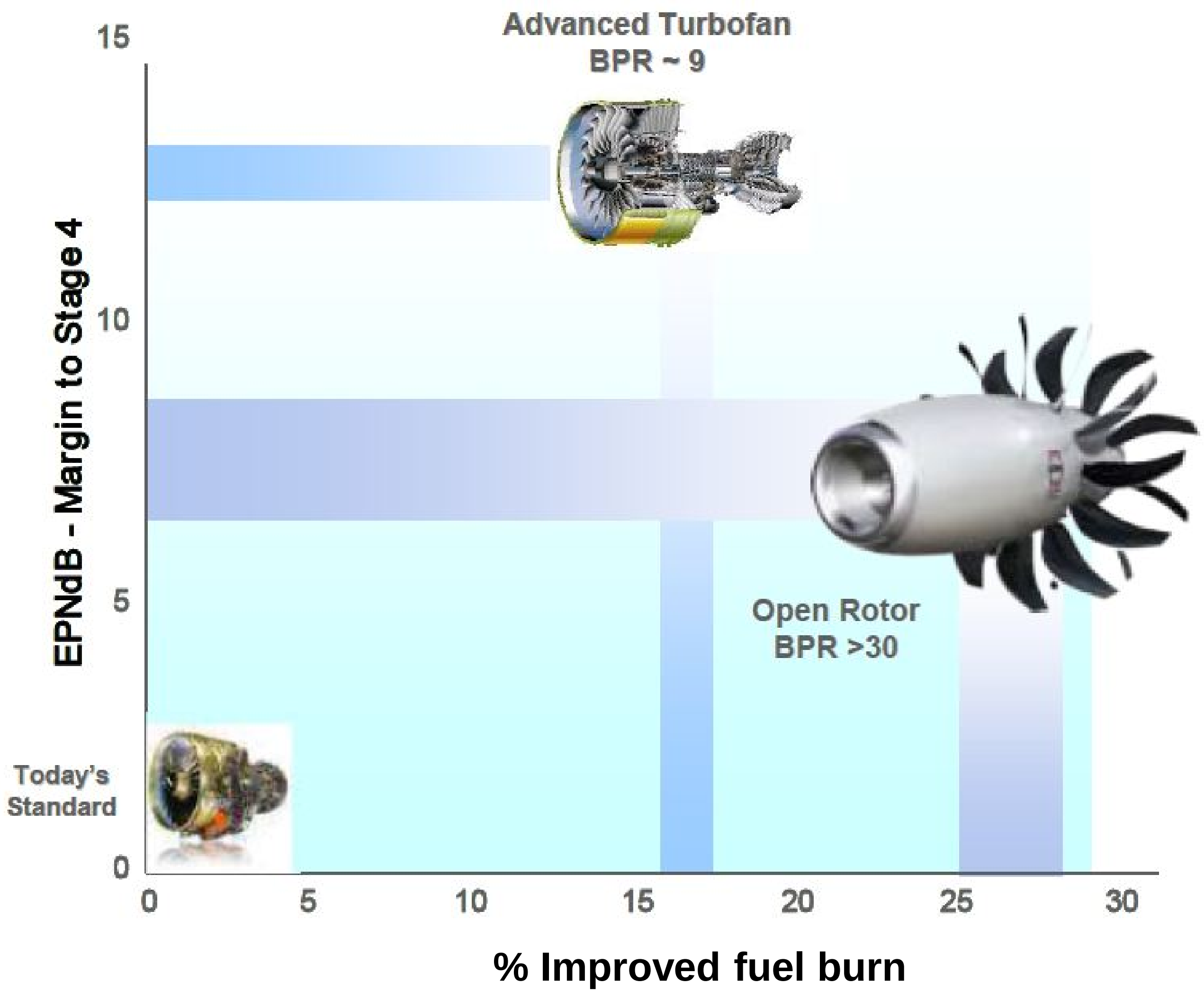
PW Geared V.S. LEAPx Fuel Burn Evaluation



Direct-drive turbofan: 78" dia.

Architectures Within 1% Fuel Burn

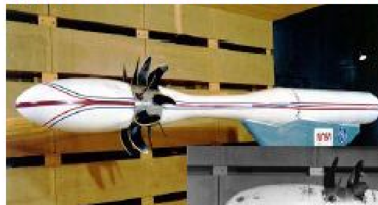
Open Rotor Technology has potential for significant performance improvement, but with noise goal challenges



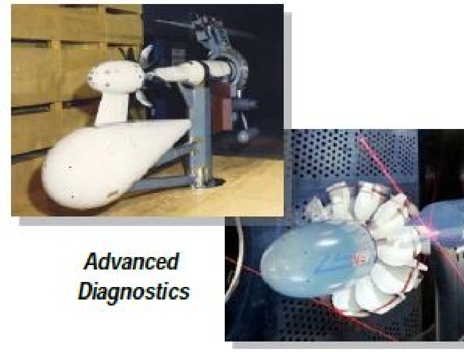
Leveraging the NASA/GE UDF Experience and UHB Partnership

Climb/Cruise in Glenn 8′x6′ Wind Tunnel

Approach/Takeoff in Glenn 9′x15′ Wind Tunnel



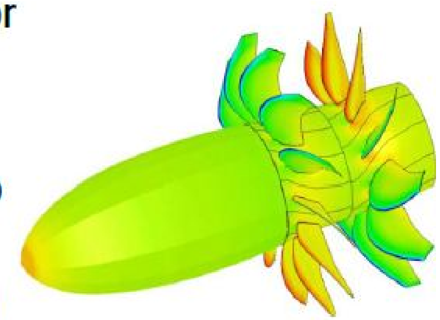
Installation Effects



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



GEnx

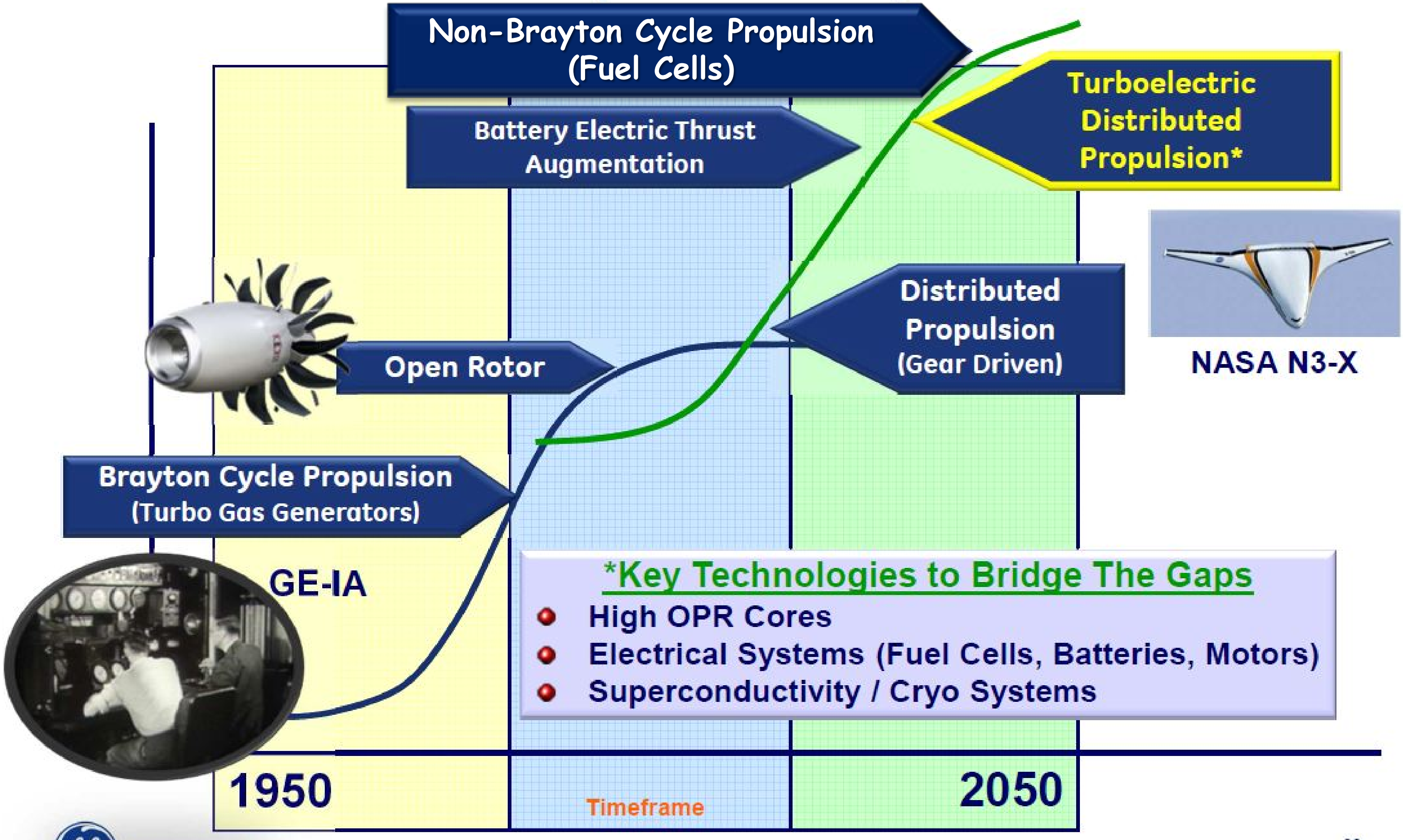
Opportunities for the Future

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

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

	$\eta_{thermal}$	$\eta_{transfer}$	$\eta_{propulsive}$	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	

2030 – 2050 Propulsion System Vision



***Key Technologies to Bridge The Gaps**

- High OPR Cores
- Electrical Systems (Fuel Cells, Batteries, Motors)
- Superconductivity / Cryo Systems

imagination at work

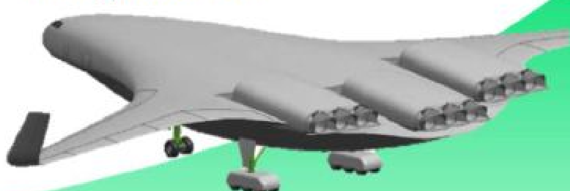
Distributed Propulsion Options

- 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

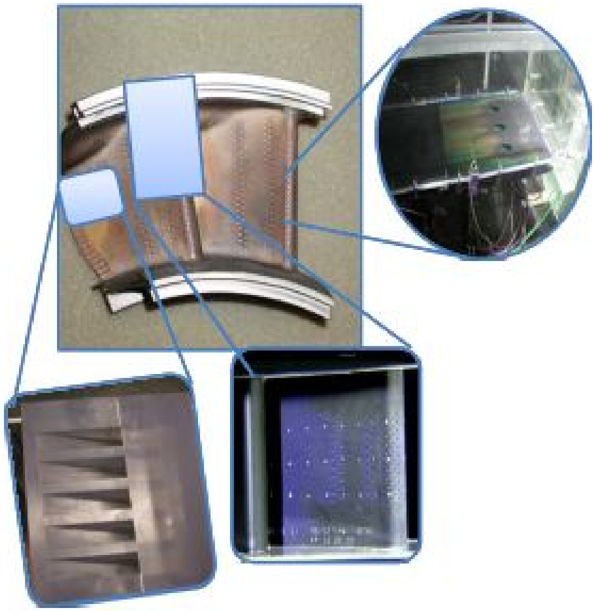
NASA Concept

- 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
- 1500^{o}F HP Compressor
- 3000^{o}F HP Turbine blades/vanes

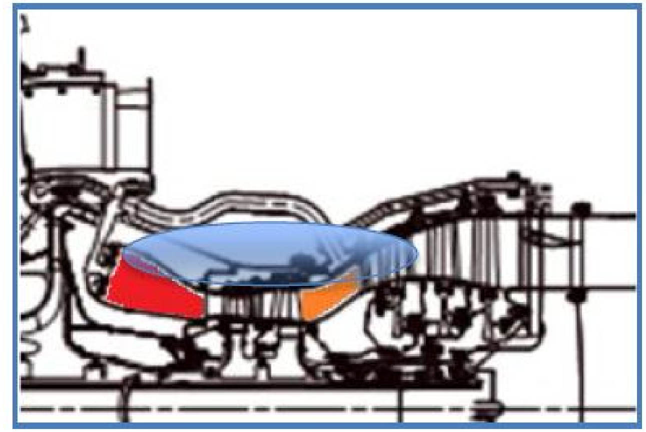
TECH 56 six stage Compressor

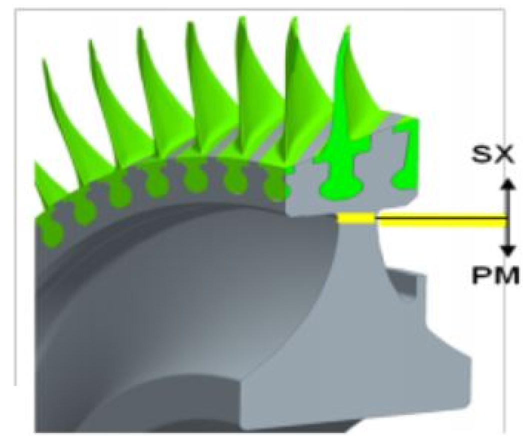


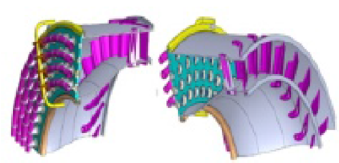
THE OHIO STATE UNIVERSITY

High Efficiency High OPR Gas Generators

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







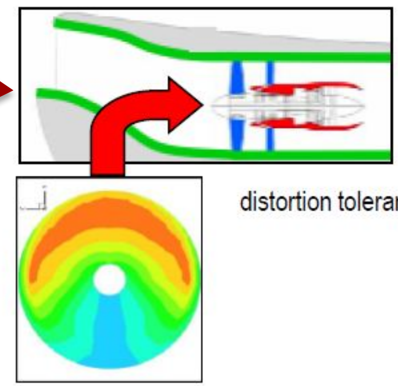
Advanced fuel stage injector concepts

THE OHIO STATE UNIVERSITY

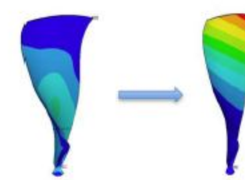
Propulsion Airframe Integration

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

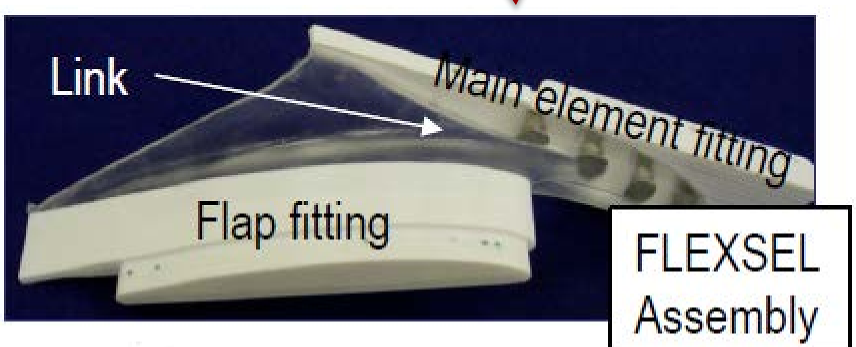
boundary-layer ingesting concepts
thrust vectoring



distortion tolerance



adaptive fan blades



Airplane Aerodynamic Improvements

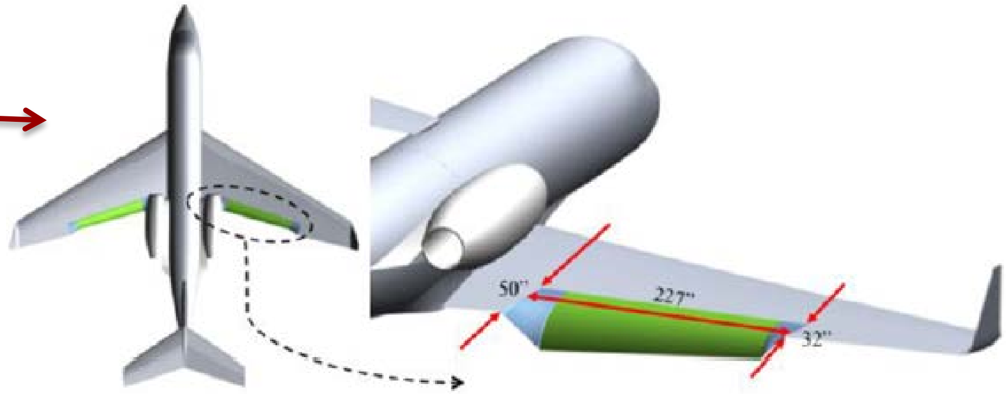
- Laminar flow nacelles
- Laminar flow on wings
- Low friction paint coating
- Improved aero-transonic design
- Wingtip technology
- Variable camber

passive/active
advanced aerodynamics

The Ohio State University

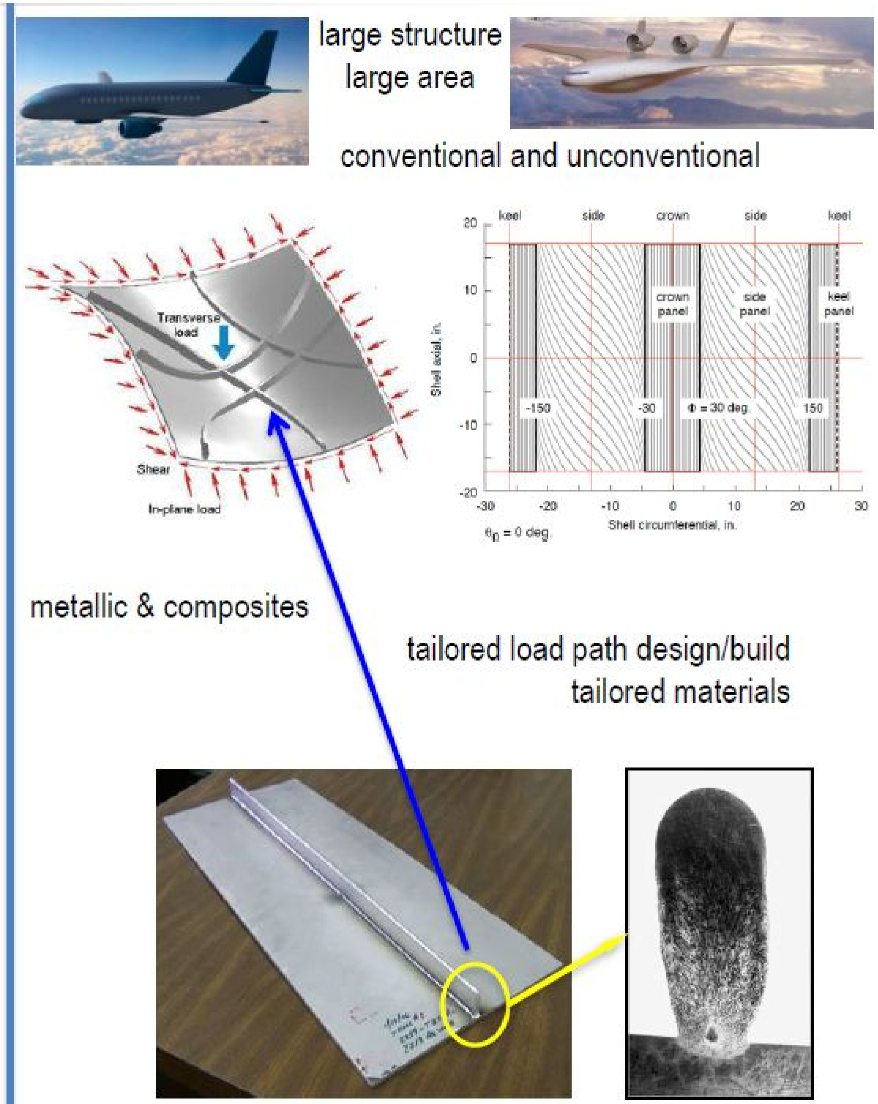
Airplane Aerodynamic Improvements

- Adaptive compliant trailing edge
- Active stability control
- Increased wing span
- Enhanced Vertical Tail

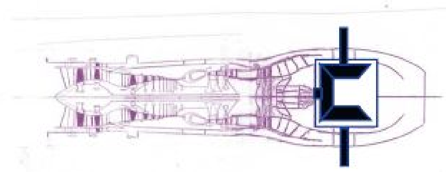


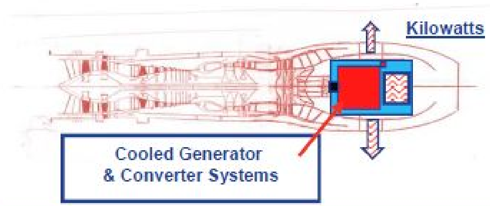
Structure, Materials, and Manufacturing

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



Energy Transfer Options for Powering Remote Fans





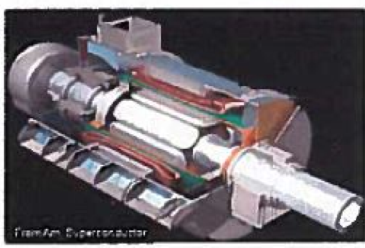
	Shafting/Gearing Horsepower	Electrical Power to Motors
Benefits	• Lower FPR for a given packaging constraint • High temperature gas contained to core stream	• Lower FPR for a given packaging constraint • Fan functionality after failure of one generator • High temperature gas contained to core stream • 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

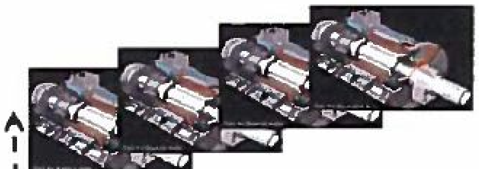
Light, Efficient Components Must Be Cryogenic or Superconducting

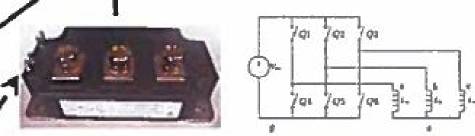
Technical challenges are <u>soluble</u> and being pursued:

Superconducting transmission lines between generators and motors
Utilities & Air Force are working this



Superconducting motors drive propulsive fan array





Turbine engine driven superconducting generator/motors
1/10th SOA weight &
low AC losses
NRA Advanced Magnet Lab

Cryocooler(s) for cryogenic components
1/5th SOA weight
Phase 1 SBIR @ Creare, Inc.

Cryogenic Inverter for variable speed fans
Weight ½ SOA & ~1/10th SOA loss
Phase 2 SBIR @ MTECH Labs
In-House Cryo-inverter Tests

Total electric system
Distribute ~50 MW in a stable & responsive grid
RTAPS Contract @ Liberty Works
In-House Subscale System Model

What does it all mean?

Projections for Single Aisle Aircraft

<u>Baseline</u> A320-200

<u>Fuel Burn Improvements</u> 2035+

Aerodynamics	14%
Engine	23%
Structures	<u>8%</u>
	45%

Noise: Will meet Stage 4 with 70dB margin
NOX: Will meet Cap 6 with 80% margin

What does it all mean?

Projections for Twin Aisle Aircraft

Baseline B777-200 ER

Fuel Burn Improvements 2035+

Aerodynamics	15%
Engine	17%
Structures	11%
	43%

Noise: Will meet Stage 4 with 70dB margin

NOX: Will meet Cap 6 with 80% margin

What does it all mean?

Projections for Regional Jets

Baseline Embraer EI90AR

Fuel Burn Improvements 2035+

Aerodynamics	12%
Engine	28%
Structures	5%
	45%

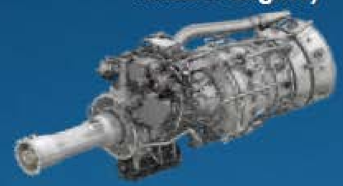
Noise: Will meet Stage 4 with 70dB margin

NOX: Will meet Cap 6 with 80% margin

Looking Forward…The Challenges and Opportunities

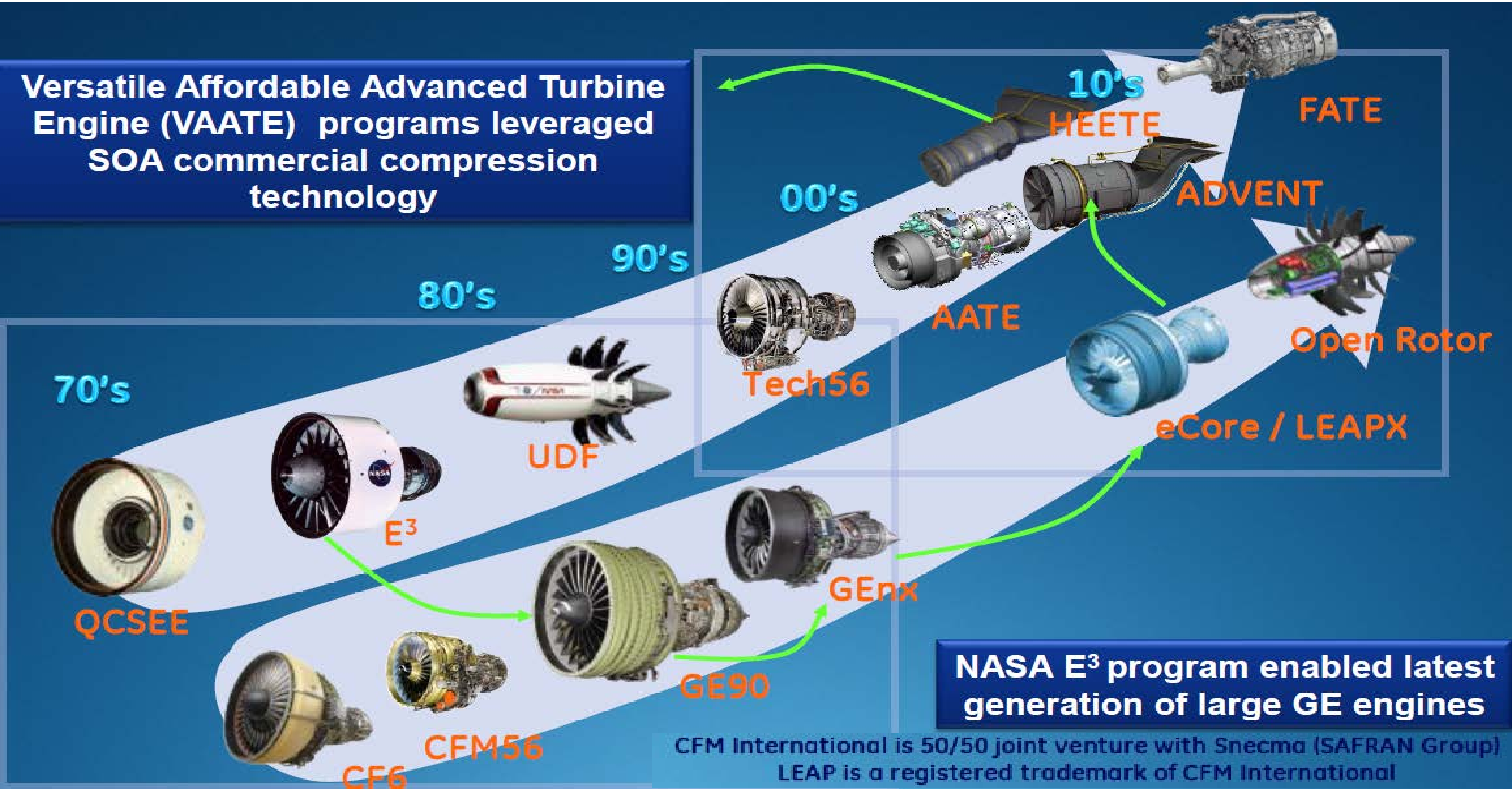
- The market is global and is growing
  - This is good…big markets
- More players want to play
  - They bring technology competition…which is good
  - They bring financial competition…which is not necessarily good
- Governments play a role
  - United States Air Force, Navy and Army Research Labs—still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

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—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