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 towards 1/3 of the world!
Huge potential exists for long-term growth in air travel

![Graph showing the relationship between 1999 Real GDP per Capita (in 1997 US$) and Trips per Capita - 1999. Countries are plotted on a scatter plot, with GDP per capita on the x-axis and trips per capita on the y-axis. Countries like the USA, Norway, and Switzerland are highlighted.]

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

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?

- Performance
- Reliability
- Maintainability
- Low Cost of Ownership
- Green Environment
  - Low Noise
  - Low NOx
  - Low CO2
Gas Turbine powered flight ... 50 years of technology has dramatically improved SFC

45% Improvement
... and dramatically reduced noise

- Normalized to 100,000-lb. thrust
- Noise levels are for airplane/engine configurations at time of initial service

87% Improvement
Propulsion Challenge

Graph: Industry Revenue/Profits
- Revenues
- Profits

Airline Operating Costs
- Fuel: 28%
- Labor: 23%
- Other Operating: 18%
- Professional Services: 14%
- Transport-Related: 14%
- Other: 6%

Regulatory Challenges
- CAEP/6: 2008 / 2013
- CAEP/8: 2014 / 2018
- EU Carbon Trading: 2012
- ICAO CO₂ Standard: TBD
- FAR Stage 5: 2020

Historical Fuel Prices
- >15% Growth Rate

Make airlines more profitable in an increasingly difficult environment
The History

Flight Safety
(accidents per MFH)

90% Improvement

Thrust to Weight

350% Increase

Fuel Efficiency
(SFC)

45% Improvement

Engine Noise
(cum db's)

35 db Decrease
Fuel consumption . . .
Addressing every aspect - sfc

\[ \text{Fuel mileage} = \frac{V \cdot L/D}{sfc \cdot W} \]

\[ SFC \approx \frac{\frac{v_0}{\eta_{overall} \cdot FHV}}{\text{Core} \cdot FPR} = \frac{v_0}{\eta_{thermal} \cdot \eta_{transfer} \cdot \eta_{propulsive} \cdot FHV} \]

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

Prev Generation Turbofan
BPR=5-8
2000 SOA

Adv Turbo Fans
with BPR 10-12

REF.

-16%
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**

- **Composite fan case**: Material improves strength, is corrosion-free with lower weight than metal.
- **Composite fan blades**: Designed for fewer parts, greater efficiency, lower noise and most resiliency.
- **Booster**: Debris rejection system filters air to reduce downstream wear.
- **Compressor**: Advanced aerodynamics and high compression improve fuel burn with fewer parts.
- **Combustor**: Burns fuel at lower peak temperatures while delivering our lowest emissions.
- **High pressure turbine**: Advanced alloys and coatings withstand heat for long life.
- **Low pressure turbine**: Fewer, more efficient parts and durable materials mean less waste and better performance.

*Imagination at work*
Balanced system design ... SFC benefit

SFC comparison at cruise

- 767-300ER CF6-80C2B6F
  93" Fan
  -15%

- 777-200ER GE90-94B
  123" Fan
  -7%

A350/787 GEnx
111" Fan
GE nx quiet with significant margin

Noise margin for Stage 3 and 4

<table>
<thead>
<tr>
<th>Margin to FAR36 Stage 3 (EPNdB)</th>
<th>787-3</th>
<th>787-8</th>
<th>787-9</th>
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<tbody>
<tr>
<td>0</td>
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<td>30</td>
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</table>

Twin-engine aircraft noise footprint

- GEnx-powered
- CF6-powered

50% Smaller
GEnx cleanest for the environment

Twin annular pre-swirl (TAPS) technology

Emissions as % of current limits

Future limits

Today’s CF6-80C2

GEnx

Cleaner

NOx  Smoke  HC  CO
Rolls Royce Trent 7000 for A330 NEO

Trent 772 vs 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 PR Fan
- Low Tip Speed
- BPR ~ 9 - 12

- Fan Drive Gear System
- 5 Planets
- Gear Ratio ~ 3

- High-Speed Low Spool
- Compact LPC, LPT

- Low-Emissions Combustor
PW Geared V.S. LEAPx Fuel Burn Evaluation

Geared turbo fan: 81” dia.

Engine SFC: 0.3%

Propulsion Systems: 0.5%

+0.7% +0.9% +1.6% +0.3% +0.3% +0.2%

LEAP-X Adv.

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
GENY Technologies

Advanced Composite Fan

Fluidics for Noise Reduction and High Stage Loading

Nano Material Blade/Structure Technology

Hybrid/Ceramic Bearings

Intelligent Engine Controls and Adv. Sensors

Counterrotating Vaneless LPT

Ceramic Matrix Composite Liners, Blades, & Vanes

Active Combustor Controls for Ultra-Low Emissions

Hi Temp. Rotor Materials

High Pressure Ratio Compressor

Technology to Revolutionize the State of the Art
Material Options

Specific Strength (MPa/(Mg/m³))

Temperature (°C)

Titanium Alloys

TiAl Alloys

Superalloys

Mg Al

Single Crystal Superalloys

CMC

Refractory Metals and Intermetallics
Engine Temperature Trend

Engine Certification Date

T41@0.25 Mach, FRT
High Temperature Structural Material Applications

High Pressure Compressor Disks and Airfoils

HP and LP Turbine Disks, Airfoils and Structures
Airfoil Materials Trendline

Δ Temp. Capability, °F

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

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

CMC Vane

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

CMC Blade

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

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Noise (cum below Stage 4)</td>
<td>- 32 dB</td>
<td>- 42 dB</td>
<td>- 71 dB</td>
</tr>
<tr>
<td>LTO NOx Emissions (below CAEP 6)</td>
<td>- 60%</td>
<td>- 75%</td>
<td>Better than –75%</td>
</tr>
<tr>
<td>Performance Aircraft Fuel Burn</td>
<td>- 33%</td>
<td>- 50%</td>
<td>Better than -70%</td>
</tr>
<tr>
<td>Performance Field Length</td>
<td>- 33%</td>
<td>- 50%</td>
<td>Exploit metroplex concepts</td>
</tr>
</tbody>
</table>
Open Rotor Technology has potential for significant performance improvement, but with noise goal challenges
Leveraging the NASA/GE UDF Experience and UHB Partnership

- 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

\[ \text{Range} = \left( \frac{V_0}{SFC} \right) \times \left( \frac{L}{D} \right) \times \ln \left( \frac{W_{\text{initial}}}{W_{\text{final}}} \right) \]

\[ = (FHV \times \eta_{\text{thermal}}) \times \eta_{\text{transfer}} \times \eta_{\text{propulsive}} \times \left( \frac{L}{D} \right) \times \ln \left( 1 + \frac{W_{\text{fuel}}}{W_{\text{payload}} + W_{\text{empty}}} \right) \]

- N+1
  - Highly Loaded Compressors
  - High OPR Low Emissions Combustors
  - Adaptive cycles
  - Constant Volume Combustion
  - Hybrid Electric Propulsion

- N+2
  - Low Loss Inlets
  - Variable Low Loss Exhausts
  - Distributed Power Transmission

- N+3
  - Very High BPR Turbofans
  - Ultra High BPR Turbofans
  - Open Rotors
  - Distributed Propulsion
  - Wake Ingestion

- Novel Alloys / MMC’s
- Non-metallics
- Advanced Engine Architectures
2030 – 2050 Propulsion System Vision

Key Technologies to Bridge The Gaps
- High OPR Cores
- Electrical Systems (Fuel Cells, Batteries, Motors)
- Superconductivity / Cryo Systems
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

ESAs/NASA Concept

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

NASA Concept

Advanced Concept Design and Challenges for Future Commercial Aircraft Propulsion
11 October 2013
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°F HP Compressor
- 3000°F HP Turbine blades/vanes
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

Conventional Propulsion

$$\eta_p = \frac{2U_0}{(U_j + U_0)}$$

BLI Propulsion

$$\eta_p = \frac{2U_0}{(U_j + U_{in})}$$
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
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

- **Year:** 1975
- **Share of Composite Components:** 0%
- **Year:** 1980
- **Share of Composite Components:** 0%
- **Year:** 1985
- **Share of Composite Components:** 10%
- **Year:** 1990
- **Share of Composite Components:** 20%
- **Year:** 1995
- **Share of Composite Components:** 30%
- **Year:** 2000
- **Share of Composite Components:** 40%
- **Year:** 2005
- **Share of Composite Components:** 50%
- **Year:** 2010
- **Share of Composite Components:** 50%
Relative Weights

- Electric Motors
- Advanced Combustors
- Alternative Fuels
- Boundary Layer Ingestion
- Composites
- Distributed Propulsion
- Gearbox
- Acoustic Liners
- Computational Tools
- Variable Geometry
- Sensors
- Clearance Control
- Smart Materials
- Batteries
- Fuel Cells

Relative Benefits of Technologies Relative to N+3 Goals
# Energy Transfer Options for Powering Remote Fans

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

Each Transfer Technology has Pros/Cons Depending on Specific Application
Light, Efficient Components Must Be Cryogenic or Superconducting

Technical challenges are soluble 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 1/4 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
<table>
<thead>
<tr>
<th>Technology</th>
<th>Challenges</th>
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<tbody>
<tr>
<td>Electric Motor</td>
<td>• Power to Weight Ratio</td>
</tr>
<tr>
<td></td>
<td>• Decrease AC Losses</td>
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<tr>
<td>Advanced Combustor</td>
<td>• Fuel Mixing</td>
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<tr>
<td></td>
<td>• Combustion Instability</td>
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<td></td>
<td>• Linear Material</td>
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<tr>
<td>Boundary Layer Ingestion</td>
<td>• Fan/Inlet Losses</td>
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<tr>
<td></td>
<td>• Acoustic and Aeromechanical Issues</td>
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<tr>
<td></td>
<td>• Off Design Operation</td>
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<tr>
<td>Composites</td>
<td>• Material Composition/Properties</td>
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<tr>
<td></td>
<td>• Design Architecture</td>
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<tr>
<td>Distributed Propulsion</td>
<td>• Integration Complexity</td>
</tr>
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<td></td>
<td>• Maintenance Cost</td>
</tr>
<tr>
<td></td>
<td>• Minimal Loss Power Distribution</td>
</tr>
<tr>
<td>Acoustic Liners</td>
<td>• Determine Location and Applicability</td>
</tr>
<tr>
<td></td>
<td>• Higher Bandwidth Attenuation</td>
</tr>
<tr>
<td>Computational Tools</td>
<td>• Setup Times</td>
</tr>
<tr>
<td></td>
<td>• Validation</td>
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<td></td>
<td>• Greater MDAO</td>
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<tr>
<td>Active Tip Clearance Control</td>
<td>• Sensor Capabilities</td>
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<td></td>
<td>• Dynamic Modeling Accuracy</td>
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<td>• System Complexity</td>
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<tr>
<td>Shape Memory Alloys</td>
<td>• Dimensional Stability</td>
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<td></td>
<td>• Fatigue/Durability</td>
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<td>• Higher Temperature Capabilities</td>
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<tr>
<td>Batteries</td>
<td>• Energy Density</td>
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<td>• Lifecycle</td>
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<tr>
<td>Fuel Cells</td>
<td>• Power to Weight Ratio</td>
</tr>
<tr>
<td></td>
<td>• Fuel Leakage/Processing</td>
</tr>
<tr>
<td></td>
<td>• Deterioration/Lifecycle</td>
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</table>
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

<table>
<thead>
<tr>
<th></th>
<th>Clean Sky 2</th>
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<tbody>
<tr>
<td>CO₂ and Fuel Burn</td>
<td>-20% to -30% (2025/2035)</td>
</tr>
<tr>
<td>NOₓ</td>
<td>-20% to -40% (2025/2035)</td>
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<tr>
<td>Population exposed to noise/Noise footprint impact</td>
<td>Up to -75% (2035)</td>
</tr>
</tbody>
</table>

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
- Turboshift Engine Demonstrator
- Lean Burn Program
What does it all mean?
Projections for Aircraft 2035+

<table>
<thead>
<tr>
<th></th>
<th>Single Aisle Aircraft Baseline A320-200</th>
<th>Twin Aisle Aircraft Baseline 777-200 ER</th>
<th>Regional Jets Baseline Embraer E190</th>
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<tbody>
<tr>
<td>FUEL BURN</td>
<td>45%</td>
<td>43%</td>
<td>45%</td>
</tr>
<tr>
<td>NOISE</td>
<td>Stage 4 with 70 dB margin</td>
<td>Stage 4 with 70 dB margin</td>
<td>Stage 4 with 70 dB margin</td>
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<tr>
<td>NOx</td>
<td>Cap 6 with 80% margin</td>
<td>Cap 6 with 80% margin</td>
<td>Cap 6 with 80% margin</td>
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TREMENDOUS OPPORTUNITIES IN ECONOMICS AND THE ENVIRONMENT
Technology Demonstrator Programs
Strong History Leading to Commercial Benefits Today and Beyond

Versatile Affordable Advanced Turbine Engine (VAATE) programs leveraged SOA commercial compression technology

NASA E³ program enabled latest generation of large GE engines

CFM International is 50/50 joint venture with Sncma (SAFRAN Group)
LEAP is a registered trademark of CFM International
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
Thank you for your time!