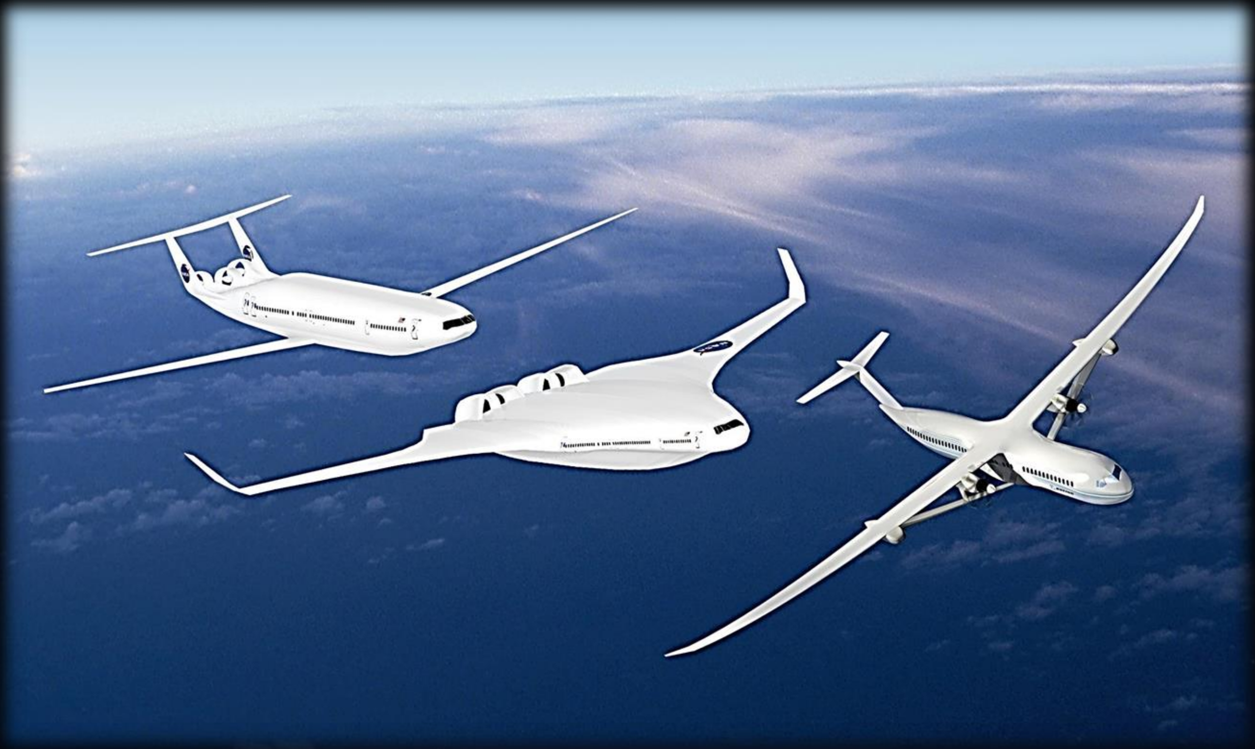
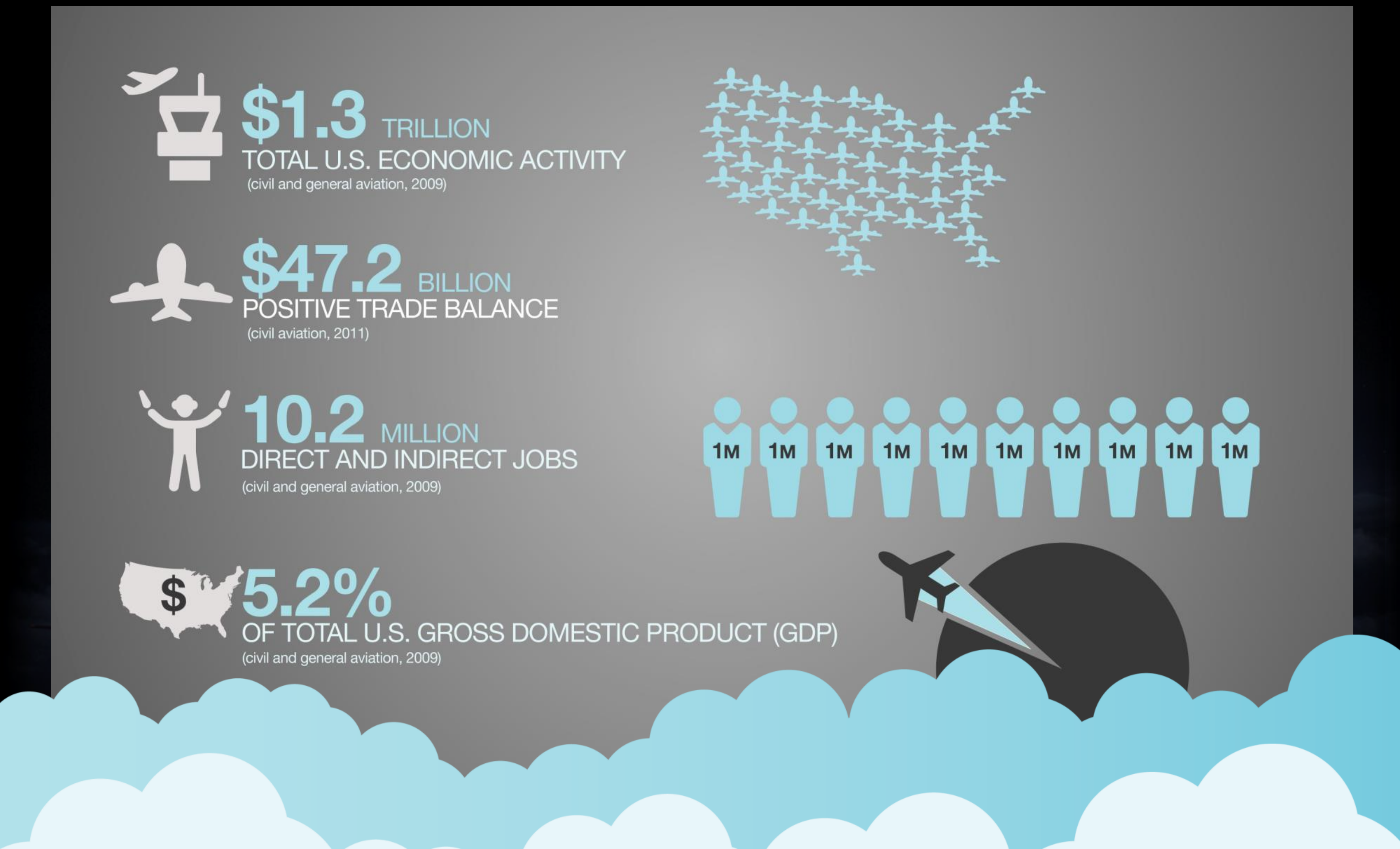
National Aeronautics and Space Administration



NASA's Vision for Potential Energy Reduction from Future Generations of Propulsion Technology

Bill Haller
NASA Glenn Research Center
Cleveland, Ohio

Air Transportation System Critical to Economic Vitality



NASA Aeronautics Research Strategic Thrusts

Safe, Efficient Growth in Global Operations

- Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

Innovation in Commercial Supersonic Aircraft

- Achieve a low-boom standard

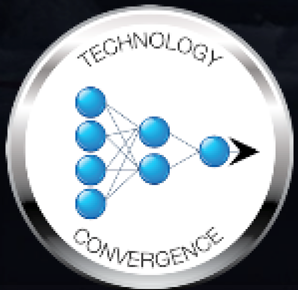
Ultra-Efficient Commercial Vehicles

- Pioneer technologies for big leaps in efficiency and environmental performance

Transition to Low-Carbon Propulsion

- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Primary Interest



Real-Time System-Wide Safety Assurance

- Develop an integrated prototype of a real-time safety monitoring and assurance system

Assured Autonomy for Aviation Transformation

- Develop high impact aviation autonomy applications

NASA Subsonic Transport System Level Metrics

v2013.1

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-52 dB
LTO NO_X Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NO_X Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines. N+2 values are referenced to a 777-200 with GE90 engines.

** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO_2 emission benefits dependent on life-cycle CO_{2e} per MJ for fuel and/or energy source used

Research addressing revolutionary far-term goals with opportunities for near-term impact

Key Government Efforts Supporting Commercial Transport Technology Development

Continuous Lower Energy, Emission and Noise (CLEEN)

- Focused on accelerating development & commercial deployment of promising, near-term aircraft technologies and alternative fuels
- 5-yr agreements signed with 5 companies (FY11-FY15)
- CLEEN II Solicitation released in Sept '14

Environmentally Responsible Aviation (ERA)

- Goal to mature promising technology and advanced aircraft configurations that meet mid-term (N+2) goals
- 6-yr program (Phase I: FY10-12, Phase II: FY13-15)
- Phase I investigated wide array of technologies to identify critical, high-payoff areas to focus Phase II work
- Phase II focused on 8 key engine, airframe and PAI technology areas

Advanced Air Transport Technology (AATT)

- Goal to explore/develop technologies for improved energy efficiency for N+3 (and later portion of N+2) fixed-wing subsonic transports
- Strong emphasis on investigating the benefits/potential of hybrid-electric & distributed propulsion systems

“N+3” Advanced Vehicle Concept Studies

Boeing, GE, GA Tech

NG, RR, Tufts, Sensis, Spirit

GE, Cessna, GA Tech

MIT, Aurora, P&W, Aerodyne

NASA, VA Tech, GT

NASA

Trends:

- Tailored/multifunctional structures
- High aspect ratio/laminar/active structural control
- Highly integrated propulsion systems
- Ultra-high bypass ratio (20+ with small cores)
- Alternative fuels and emerging hybrid electric concepts
- Noise reduction by component, configuration, and operations improvements

Advances required on multiple fronts…

Small Core Size Design Challenge - High OPR Engine

Problem

Enable high OPR gas generator core for improved thermal efficiency and fuel burn reduction. Need to mitigate decrements in efficiencies due to tip clearance and seal cavity gaps associated with small core size.

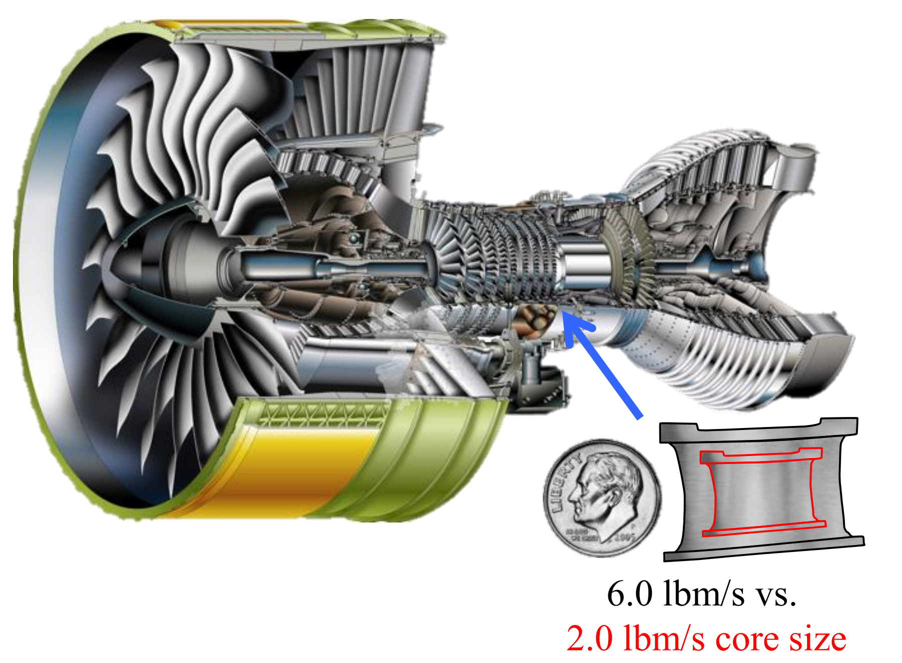
Status of Small Core Design Challenge

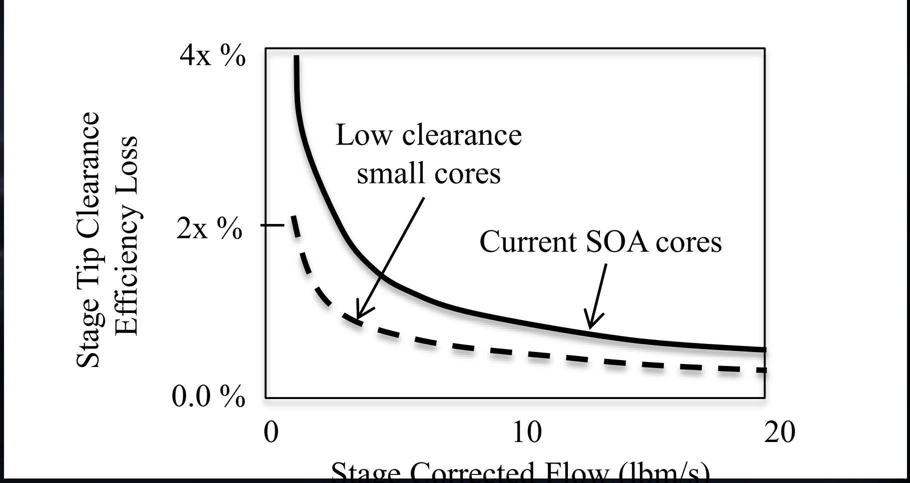
Performed N+3 system studies to assess benefits and develop concepts, approaches, and roadmaps to substantiate potential performance and fuel burn benefits and down-select concept(s) for testing.

Significance

N+3 relevant system studies combined with future testing to confirm benefits of high OPR small core engine concepts will enable significantly higher engine BPRs due to smaller/compact cores.

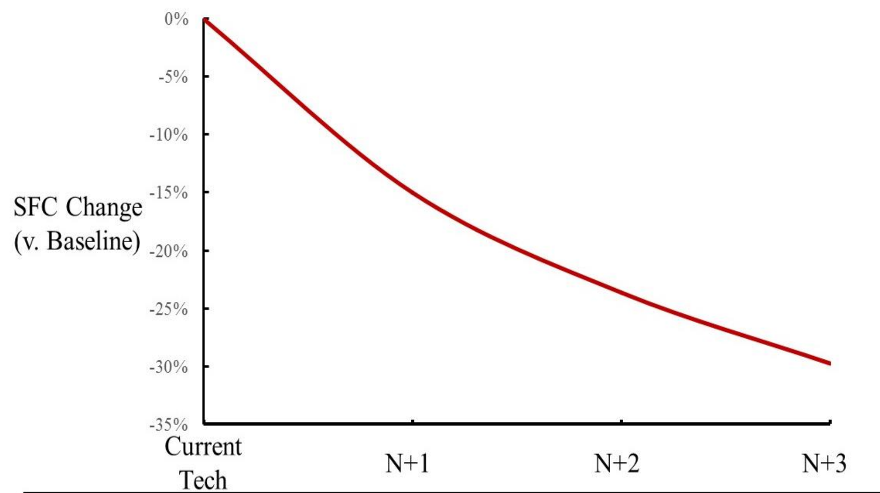
Next step: Recently awarded contracts to P&W and GE to investigate the small core challenge



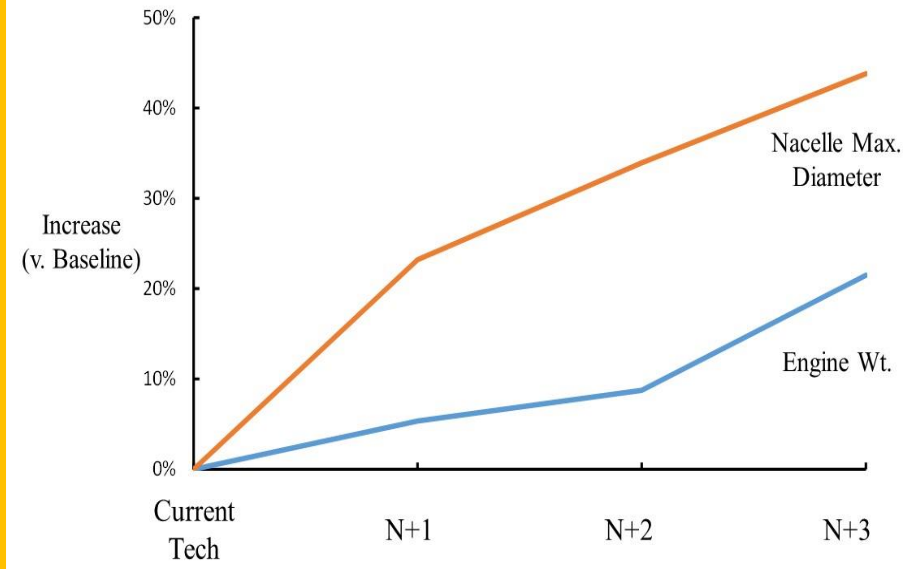


Propulsion System Trends for Single-Aisle Thrust Class

(Results From NASA In-house Benefit Assessments)



	Current Tech	N+1	N+2	N+3
BPR_{DES}	5	14	19	24
$HPC\ Wc_{exit}$	~7	5.4	3.7	~3



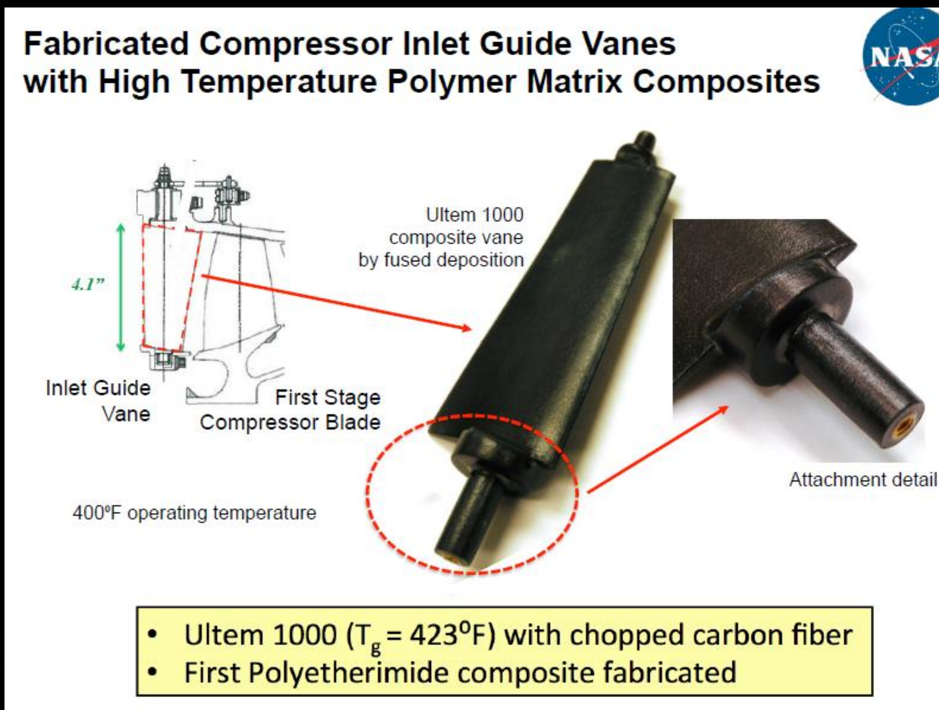
(Engines Sized for Approximately Same Thrust)

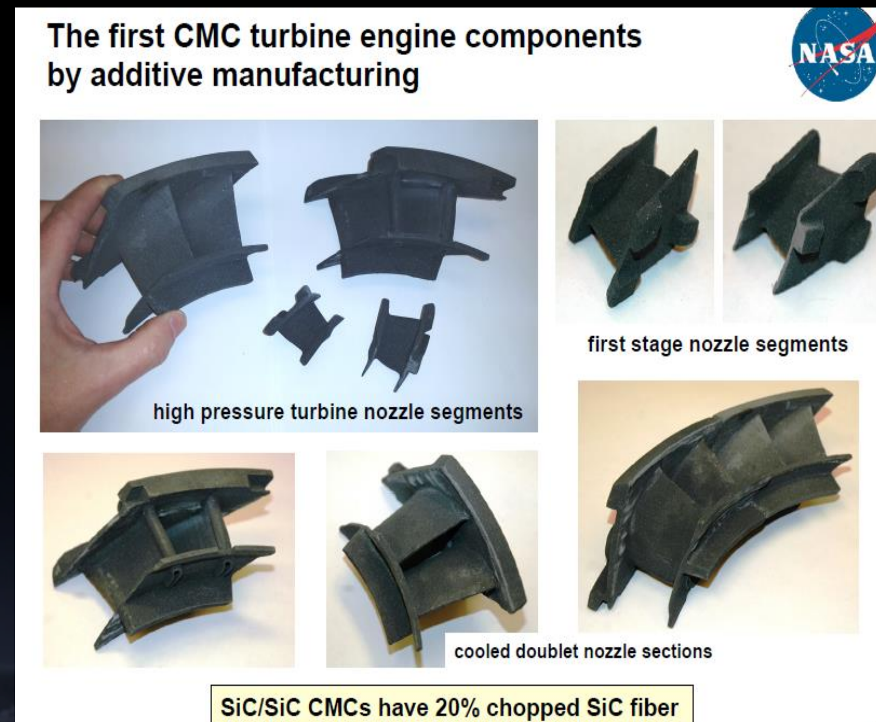
- SFC reductions possible through higher OPRs, turbomachinery eff. gains, advanced cooling schemes and increased propulsive efficiency (i.e., lower FPR)
- Challenge to maintain high component efficiencies at smaller engine core size
- Engine weight/diameter increases will mitigate some fuel burn savings

Potential for Additive Manufacturing

- NASA Seedling Fund study (1-yr effort) conducted to investigate additive manufacturing opportunities
  - Partnership between NASA, Honeywell, RP+M and Ohio Aerospace Institute
- First comprehensive evaluation of emerging materials and manufacturing technologies that could ultimately enable fully non-metallic gas turbine engines
- Assessed feasibility of using additive manufacturing technologies to fabricate turbine engine components from polymer matrix composites (PMCs) and ceramic matrix composites (CMCs)
- Fabricated and tested prototype components in engine operating conditions
- Conducted engine system study to estimate benefits of inserting PMCs & CMCs into regional-jet engine

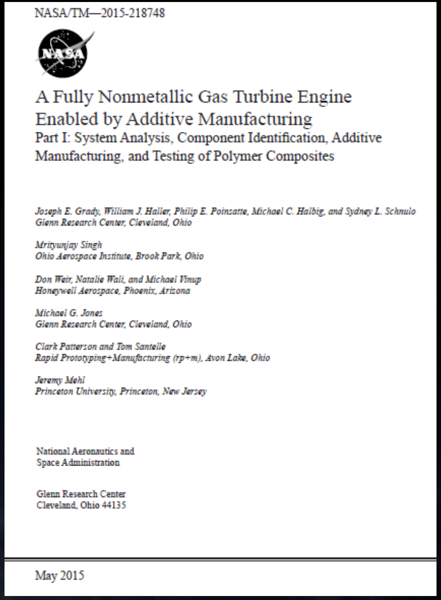
Component Manufacturing Results





Additive Manufacturing Benefit Assessment

- Systems analysis assessment performed to estimate potential benefits of PMC/CMC engine components (produced via additive manufacturing) on a RJ-class system
- Weight reductions from PMC materials utilized in inlet acoustic liner, fan stator and initial (“low temp”)HPC stator rows
- Weight and turbine cooling reductions from CMC materials utilized in combustor liner, HPT/LPT and core nozzle
- Assumed no change to engine OPR (no adv. HPC technology)
- Resize airplane to take advantage of “advanced” engine
- Results show a **4.9% reduction in aircraft fuel burn** and a corresponding **8.3% reduction in NO_X emissions** due to the use of advanced materials & manufacturing processes



NASA/TM—2015-218748

A Fully Nonmetallic Gas Turbine Engine Enabled by Additive Manufacturing
Part I: System Analysis, Component Identification, Additive Manufacturing, and Testing of Polymer Composites

Joseph E. Grady, William J. Haller, Philip E. Poinsatte, Michael C. Halbig, and Sydney L. Schnulo
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Mrityunjay Singh
Ohio Aerospace Institute, Brook Park, Ohio

Don Weir, Natalie Wali, and Michael Vinup
Honeywell Aerospace, Phoenix, Arizona

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Glenn Research Center, Cleveland, Ohio

Clark Patterson and Tom Santelle
Rapid Prototyping+Manufacturing (rp+m), Avon Lake, Ohio

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Princeton University, Princeton, New Jersey

National Aeronautics and
Space Administration

Glenn Research Center
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May 2015

Hybrid Electric Propulsion for Large Aircraft

Develop and demonstrate technologies that will revolutionize large commercial transport aircraft propulsion and accelerate development of all-electric aircraft architectures

- Why electric?
  - Less emissions (cleaner skies)
  - Less atmospheric heat release (less global warming)
  - Quieter flight (community and passenger comfort)
  - Better energy conservation (less dependence on fossil fuels)
  - More reliable systems (more efficiency, less delays)
- Considerable success in development of “all-electric” light GA aircraft and UAVs
- Creative ideas and technology advances needed to exploit full potential
- NASA can help accelerate key technologies in collaboration with OGAs, industry and academia

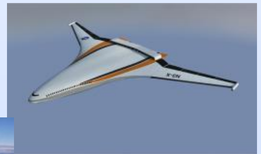
Hybrid/Turbo-Electric Propulsion Vision

Projected Timeframe for Achieving Technology Readiness Level (TRL) 6

- Envision gradual development/ improvement in critical hybrid/ turbo-electric technologies
- Initial infusion of technology will most likely come in smaller vehicle classes





Power Level for Electrical Propulsion System

kW class

1 to 2 MW class

2 to 5 MW class

5 to 10 MW

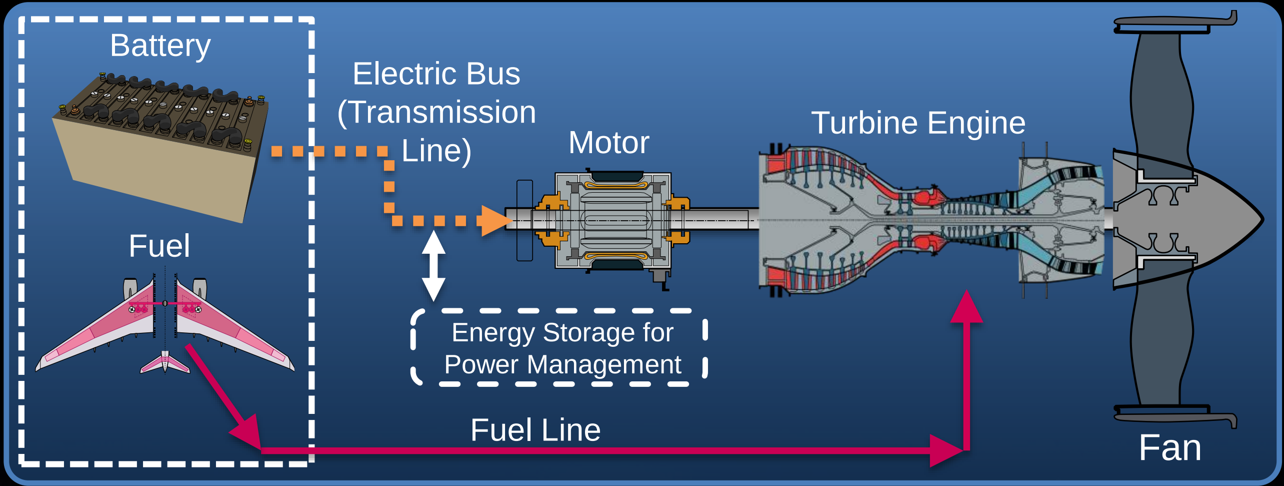
>10 MW

Spinoff Technologies Benefit of More/All Electric Architectures:
- High-power density electric motors replacing hydraulic actuation
- Electrical component and transmission system weight reduction

Today | 10 Year | 20 Year | 30 Year | 40 Year

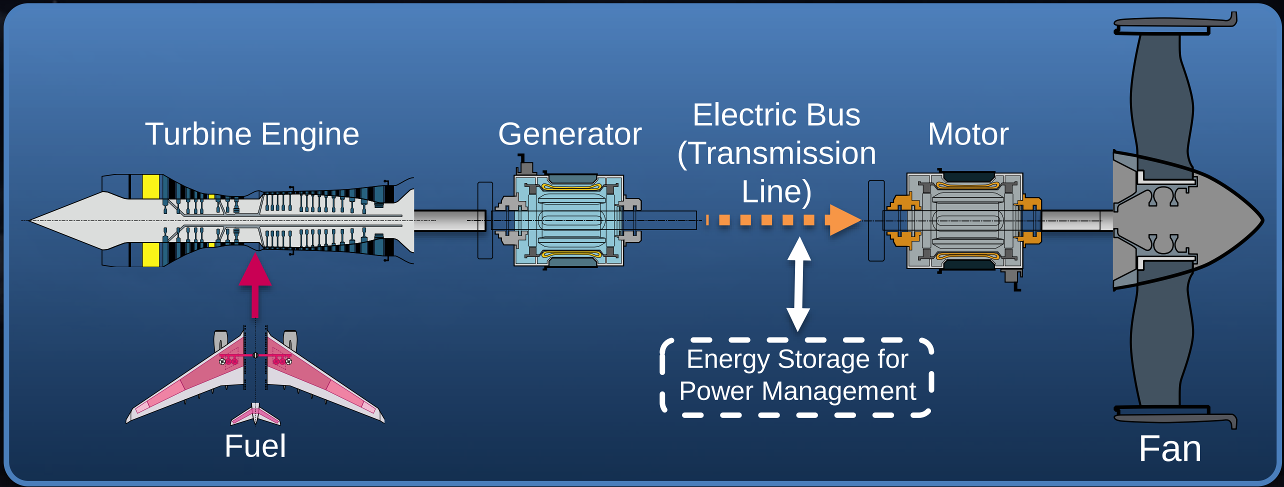
Types of Electric Propulsion

Hybrid Electric



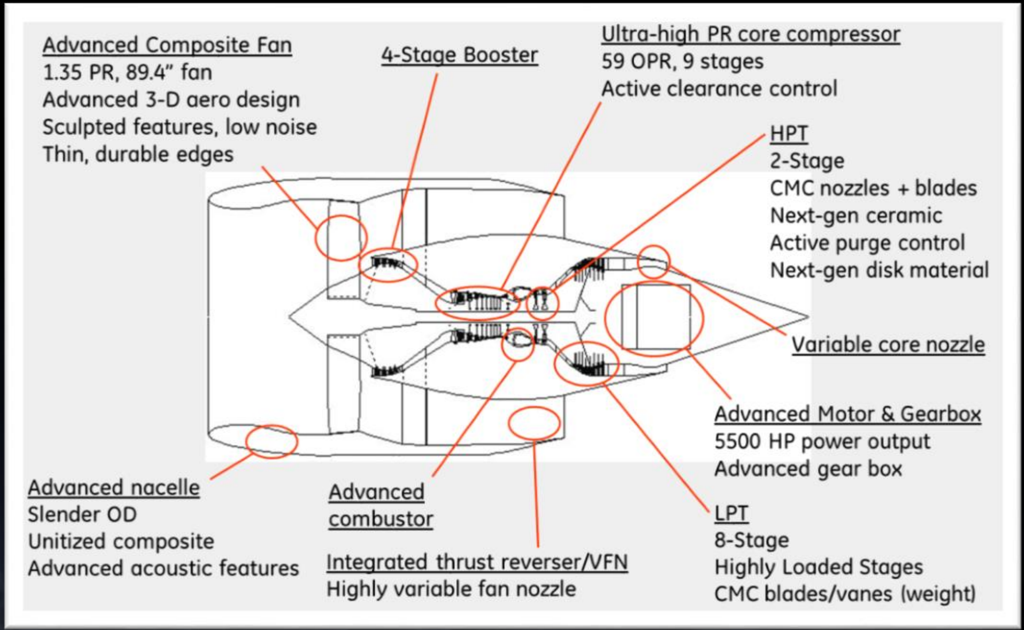
Both concepts can use either non-cryogenic motors or cryogenic superconducting motors.

Turbo Electric



Boeing-GE "SUGAR Volt" Hybrid Electric Propulsion

Truss-Braced Wing Airframe (Boeing)



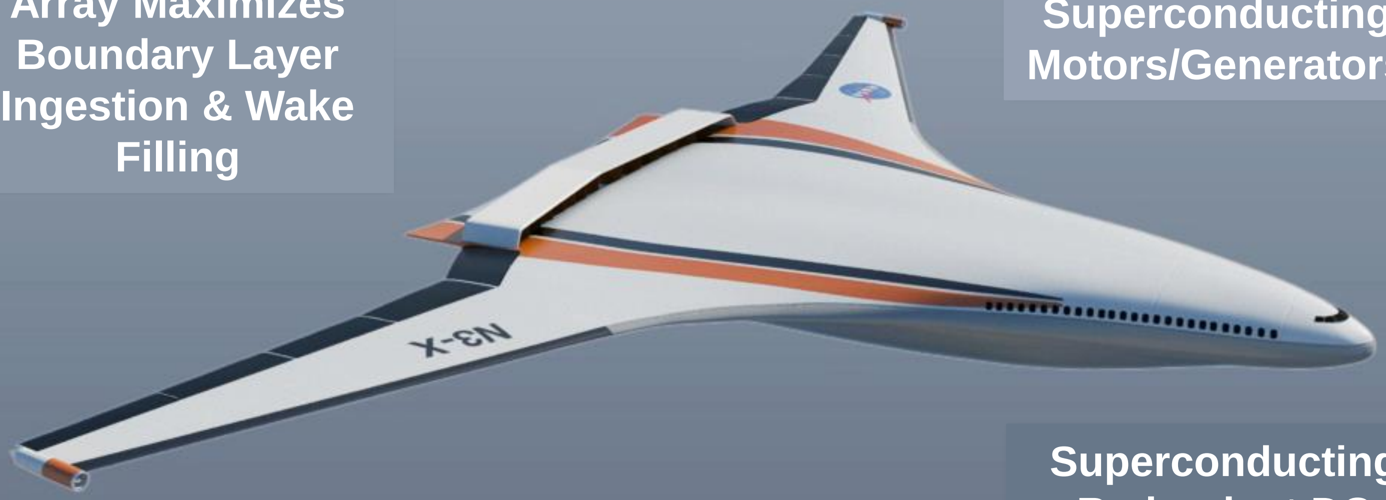
hFan Engine "Walkaround" (GE)

N3-X Turbo-Electric Distributed Propulsion Concept

Many Small, Distortion-Tolerant Fans Yields Large Total Area and High Effective Bypass Ratio

Wide Propulsor Array Maximizes Boundary Layer Ingestion & Wake Filling

Superconducting Motors/Generators



Superconducting Redundant DC microGrid

Highly Efficient Gas Generator

Forward and Aft Fan Noise Shielding by Airframe

Key N3-X Propulsion Design Assumptions

Propulsor

- Fan Pressure Ratio = 1.3
- Fan Efficiency = 94.3%
- (1% embedded distortion eff. penalty)
- Inlet Total Pressure Loss = 0.2%

Turboshaft Engine

- Polytropic Efficiencies:
  - LPC/HPC = 0.93
  - LPT/HPT = 0.93
  - PT = 0.92
- Temperature Limits:
  - T3 = 1810 R (1006 K)
  - T4 = 3360 R (1867 K)
- Cooling *(Uncooled CMC rotors/stators)*:
  - HPT = 4% (nonchargeable)
  - LPT = 2% (nonchargeable)
  - PT = 1% (chargeable)

Electrical System (N3-X/TeDP)

BSCCO	Motor Eff	=	99.94%
	Generator Eff	=	99.93%
	T_{MAX}	=	50 K
MgB_2	Motor Eff	=	99.97%
	Generator Eff	=	99.98%
	T_{MAX}	=	30 K
Inverter	Efficiency	=	99.93%
	T_{MAX}	=	100 K
Cryocooler	% of Carnot Eff	=	30%
	T_{sink}	=	T_{amb}
Tank Wt / LH_2 Wt		=	0.50

N3- X Cycle Performance

	RTO		TOC	
	BSCCO	MgB_2	BSCCO	MgB_2
Total Vehicle Thrust - lbf	94,200	85,800	35,500	33,400
Specific Fuel Consumption - lbm/hr/lbf	0.236	0.217	0.341	0.313
Specific Energy Consumption - BTU/s/lbf	1.22	1.19	1.76	1.73
Effective bypass ratio	35	36	29	30
Overall pressure ratio	57	57	84	84
Max compressor exit temperature -°R	1,800	1,800	1,680	1,680
Maximum turbine inlet temperature - °R	3,360	3,360	3,260	3,260
Fan nozzle exit velocity - ft/s	610	600	990	990
Turboshaft nozzle exit velocity - ft/s	760	750	1,370	1,360

RTO (sea level, M0.24, ISA+27 °R) *TOC (34,000 ft, M0.84, ISA)*

N3-X Electrical System Details

		BSCCO	MgB_2
Generator (x2)	Power – hp (MW)	41080 (30.6)	37840 (27.9)
	Power/Weight – hp/lb (kw/kg)	35 (57)	35 (57)
	Weight – lbs (kg)	1180 (535)	1090 (495)
Motor (x14)	Power – hp (MW)	5920 (4.4)	5280 (3.95)
	Power/Weight – hp/lb (kw/kg)	14 (23)	14 (23)
	Weight – lbs (kg)	410 (186)	365 (166)
Inverter (x14)	Power/Weight – hp/lb (kw/kg)	18 (30)	18 (30)
	Weight – lbs (kg)	325 (147)	300 (136)
Cooling System	Total Cryocooler Wt – lbs (kg)	5130 (2327)	
	LH_2 Tank Wt – lbs (kg)		1510 (685)
Grid	Cable + Protection – lbs (kg)	3570 (1619)	3290 (1492)

N3-X Propulsion System Weight

		BSCCO	MgB_2
Turbogenerator	Turboshaft Engine & Nacelle – lbs (kg)	4310 (1955)	4070 (1846)
	Generator – lbs (kg)	1180 (535)	1090 (494)
	One Turbogenerator – lbs (kg)	5490 (2491)	5160 (2339)
Propulsor	Fan + Nacelle – lbs (kg)	1560 (709)	1425 (646)
	Motor + Inverter – lbs (kg)	735 (332)	665 (301)
	One Propulsor – lbs (kg)	2295 (1041)	2090 (947)
Cooling System	Total Cryocooler Wt – lbs (kg)	5130 (2327)	
	LH_2 Tank Wt – lbs (kg)		1510 (685)
Grid	Cable + Protection – lbs (kg)	3570 (1619)	3290 (1492)
Total System	2 TurboGen + 14 Props + Cooling + Grid – lbs (kg)	51,810 (23,505)	44,380 (20,110)
777-200LR	2 GE90-115 "Dry" + Nacelle + Pylon	47,300 (21,455)	

Estimated Benefits From Systems Studies

SUGAR Volt (baseline Boeing 737-800)

- ~60% fuel burn reduction
- 50-55% energy use reduction
- 75-85% reduction in NO_X
- 24-31 EPNdB cum noise reduction

N3-X (baseline Boeing 777-200)

- ~70% energy use reduction
- ~85% reduction in NO_X
- 32-64 EPNdB cum noise reduction

MIT D8 (Boeing 737–800 like baseline)

- ~65% fuel burn reduction

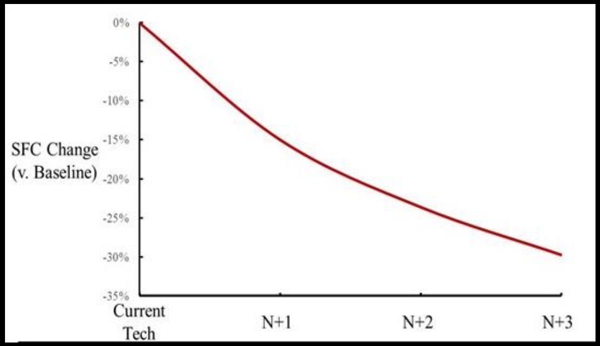
The Future……..

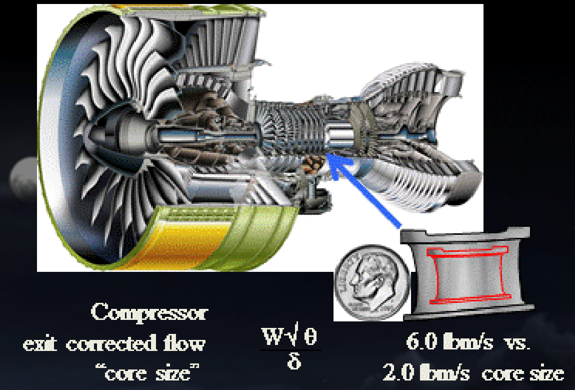
- Significant fuel savings can yet be realized through advances in propulsion system technologies

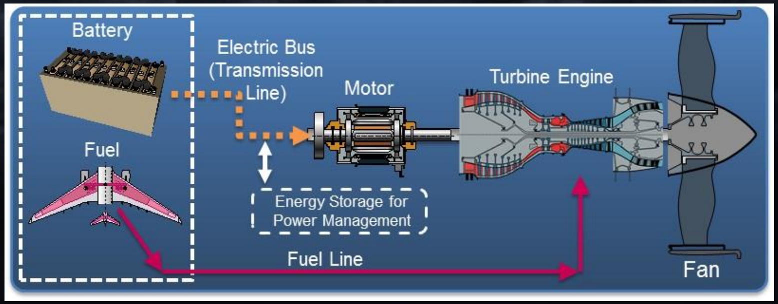
- Continued increases in thermal efficiency (via higher OPR) will present design challenges

- Introduction of electric-based architectures could produce additional total energy usage reduction

- Exciting opportunities for an industry that was deemed as being “mature”







Questions?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