Subsonic Civil Transport Aircraft for 2035: An Industry-NASA-University Collaborative Enterprise

MIT / Aurora / Pratt & Whitney

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AIAA SciTech 2015
January 5, 2015

Summary

- MIT, Aurora Flight Sciences, Pratt & Whitney, NASA working together to develop concepts for a 2035 subsonic transport aircraft
- Experiments, computations, and analysis to climb the TRL ladder
  - Large scale powered experiments in NASA Langley 14×22 foot Subsonic Wind Tunnel
  - New engine concepts to power this aircraft
- Achieved project objectives
  - BLI benefit assessment
  - Engine concepts
  - Technology development
- BLI benefit quantified to give $\sim$ 8% power saving for a realistic configuration, the D8
- Proof-of-concept of BLI for civil transports

Outline

University-Industry-NASA Collaboration

University

- Independent examination of concepts
- Education of next generation of engineers

Industry

- Aircraft and engine design, development
- Product knowledge

NASA

- Bridging TRL gap between university and industry
- National facilities for experimental assessment of ideas, computational examination of flow fields

Collboration within **and** between organizations

- Phase 1: $\sim$30 people including 5 faculty, 6 students
- Phase 2: $\sim>$30 people including 2 faculty, 3 staff, 9 students

Program driven by ideas and technical discussions $\Rightarrow$ changes in “legacy” beliefs

NASA Sets Aggressive Technology Goals

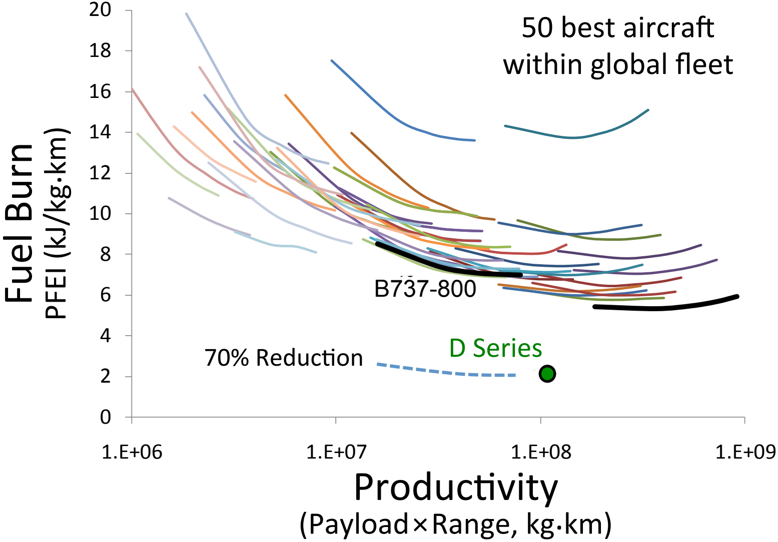
In 2008, NASA put forward an N+3 request for proposals:

> *What would it take to develop an aircraft for the 2025-2035 timeframe which could meet the future civil transport challenges?*

CORNERS OF THE TRADE SPACE	N+1 (2015)*** Generation Conventional Tube and Wing (relative to B737/CFM56)	N+2 (2020)*** Generation Unconventional Hybrid Wing Body (relative to B777/GE90)	N+3 (2025)*** Generation Advanced Aircraft Concepts (relative to user defined reference)
Noise	- 32 dB (cum below Stage 4)	- 42 dB (cum below Stage 4)	-71 dB (cum below Stage 4)
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-40%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

Source???

Fuel Burn and NASA Goals



E. Greitzer et al. 2010, NASA CR 2010-216794

Industry-University Team Members

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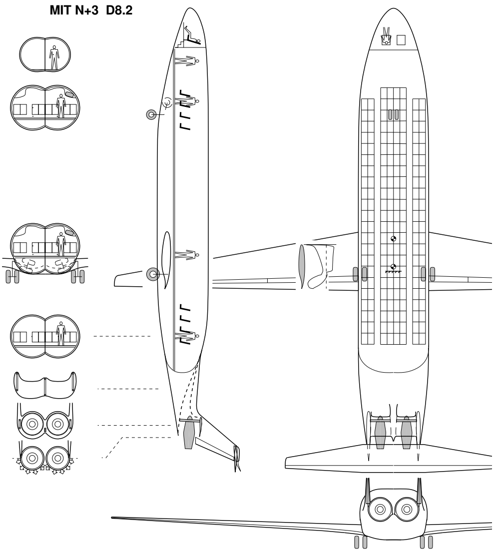
* Graduate Students
+ Non-current

Plus 13 undergratuate students
Plus others at P&W and Aurora

The D8 Aircraft Concept



E. Greitzer et al. 2010, NASA CR 2010-216794
A. Uranga et al. 2014, AIAA 2014-0906

- B737-800/A320 class
- 180 PAX, 3,000 nm range
- Double-bubble lifting fuselage with pi-tail
- Two aft, flush-mounted engines ingest ∼40% of fuselage BL
- Cruise Mach 0.72

−37% fuel with current tech (configuration)

−66% fuel with advanced tech (2025-2035)

No "magic bullet"

System Impact of BLI

BLI benefits

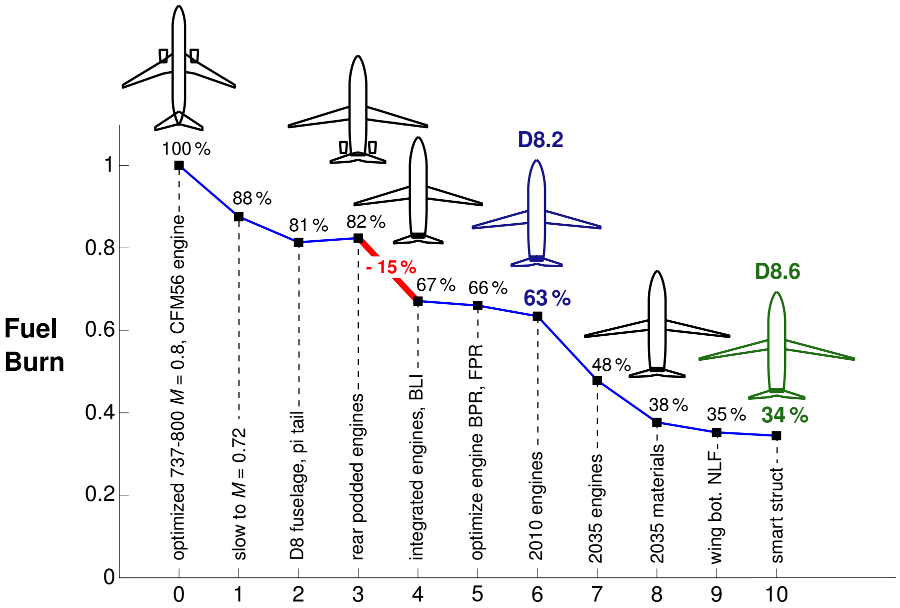
- *Aerodynamic* (direct) benefits
  - Reduced jet and wake dissipation
  - Reduced nacelle wetted area
- *System-level* (secondary) benefits
  - Reduced engine weight
  - Reduced nacelle weight
  - Reduced vertical tail size
  - Compounding from reduced overall weight

"Morphing" sequence: B737-800 $\mapsto$ D8

- Features of D8 introduced one at a time
- Sequence of conceptual aircraft designs, optimized at each step (TASOPT)

E. Greitzer et al. 2010, NASA CR 2010-216794
M. Drela 2011, AIAA 2011-3970
A. Uranga et al. 2014, AIAA 2014-0906

Morphing Sequence: B737-800 ↦ D8.2 ↦ D8.6



Phase 2 Research Thrusts

Task 1: airframe-propulsion system integration

- Define/design aft section of D8: integration of engines into fuselage
- Quantify aerodynamic benefit of boundary layer ingestion (BLI)
- Propulsor performance with distortion from BLI
- Phenomena, expected (and unexpected) behavior
- Combined experimental and computational approach

Phase 2 Research Thrusts

How

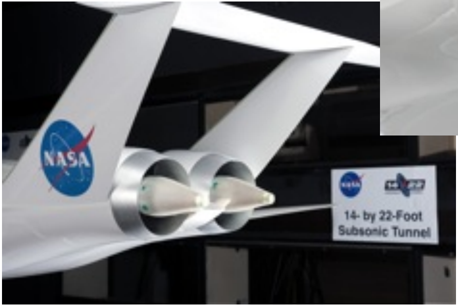
- Direct, back-to-back comparison of non-BLI and BLI configurations
  (podded) (integrated)
- Turbomachinery characterization

Tools

- Analytical analysis (1D power balance)
- Experiments at NASA Langley 14×22 wind tunnel and MIT tunnels
- Computational studies
- Close collaboration with NASA

Goals of Phase 2, Task 1

1. Define/design aft-section of D8



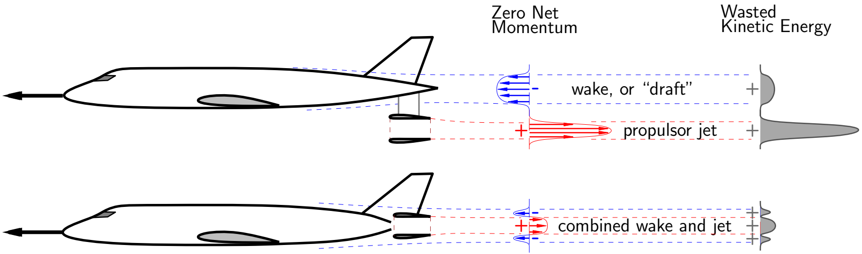
Photos NASA/George Homich

Goals of Phase 2, Task 1

2. Quantify aerodynamic benefit of BLI for D8-type configuration
   - 8.4% with equal nozzle area
   - 10.5% with equal mass flow
3. Develop methodology for studying aircraft configurations with BLI
4. Define technology road map for the D8: next steps to increase TRL

BLI Analysis

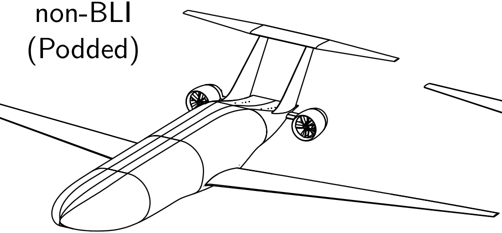
- Ambiguous decomposition into drag (airframe) and thrust (propulsion system)
- Use power balance method instead of force accounting
- BLI reduces wasted KE in combined jet+wake



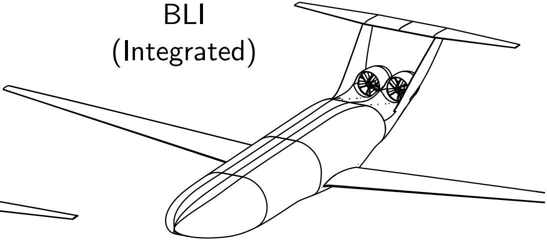
M. Drela 2009, AIAA Journal 47(7)

BLI Benefit

non-BLI
(Podded)



BLI
(Integrated)

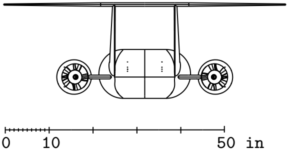


Metric: Mechanical flow power, P_K, transmitted to the flow by propulsors

$$\text{BLI benefit} = \frac{P_{K_{\text{non-BLI}}} - P_{K_{\text{non-BLI}}}}{P_{K_{\text{non-BLI}}}}$$

$$\approx \text{ 8\% to 10\%}$$

Non-BLI (Podded) Configuration



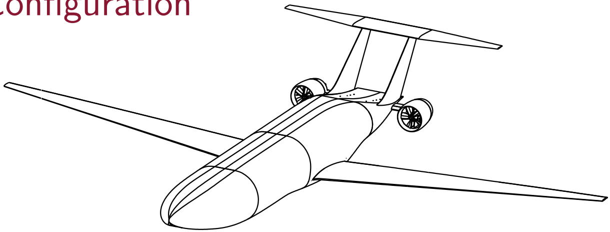
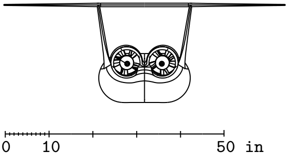


Photo NASA/George Homich

BLI (Integrated) Configuration



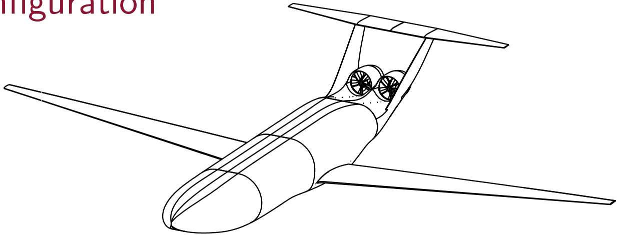
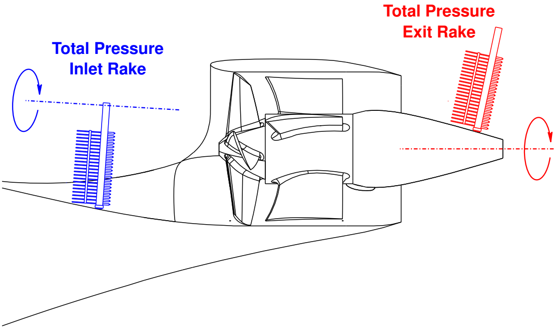
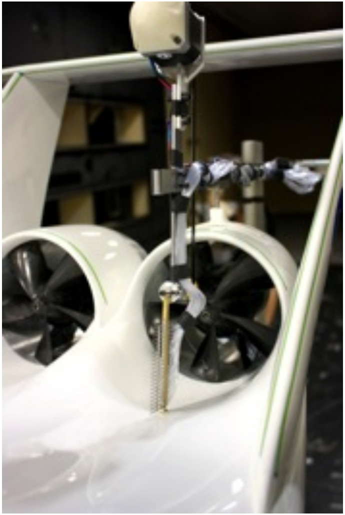


Photo NASA/George Homich

Survey Propulsor Inlet and Outlet

Rotating rake system
in wind tunnel experiments





Integrated Propulsor Ingested Flow

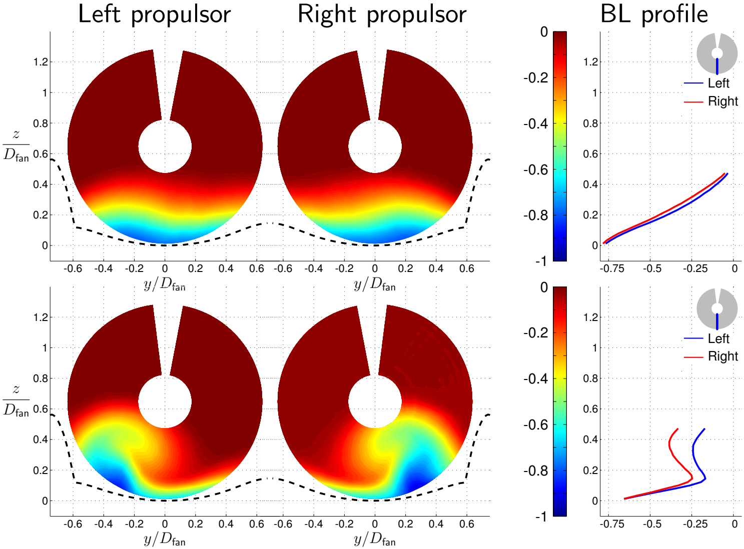
"Benign" stratified flow

Total pressure coefficient $C_{p_t} = \dfrac{p_t - p_{t_\infty}}{q_\infty}$

Experiments

$\alpha = 2^\circ$
11 kRPM
(cruise)

$\alpha = 6^\circ$
13 kRPM
(climb)



Importance of Experimental Results

- Wind tunnel experiments $\rightarrow$ proof-of-concept
- Assessment of D8 configuration
  - Aerodynamic performance
  - Computations crucial in data reduction and interpretation
- First back-to-back assessment of BLI vs non-BLI
- BLI benefit results applicable to full-size aircraft when using mechanical flow power as performance metric computations

Outline

N+3 D8 Engine Requirements

- D8.6 N+3 conceptual aircraft, engine bypass ratio (BPR) ~ 20
- Low drag (low thrust), high pressure ratio imply decrease in compressor exit corrected flow, flow area, to 1.5 lbm/s (CFM 56 has 7 lbm/s)

$$\frac{\dot{m}\sqrt{T_t}}{Ap_t} = f(M_{\text{exit}}) \quad \text{or} \quad \text{corrected flow} = A_{\text{exit}} f(M_{\text{exit}})$$

- Implies blade heights < 0.4" – with **conventional** architecture

High Efficiency, High OPR Small Core Compressors

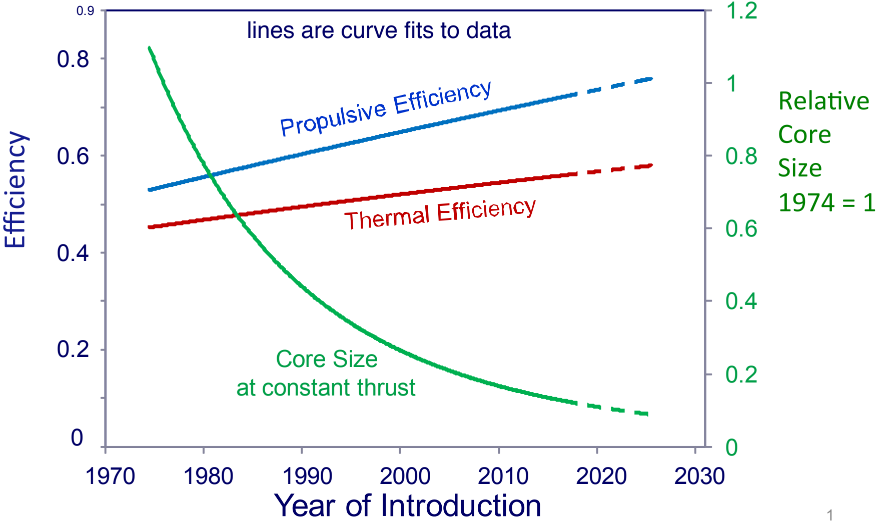
- What mechanisms limit small core compressor efficiency?
  - Low Reynolds number
  - Tip gaps relative to chord
  - Manufacturing accuracy
- How can we mitigate effects of size on efficiency?
- What are mechanical constraints for engine layout and rotor dynamics?
  - Big fan – small core

Phase 2 Research Thrusts

Task 2: high efficiency, high pressure ratio small core engines

- Limits to performance
- Technology opportunities for performance enhancement
- Innovative propulsion system architectures

Cores Shrink As Efficiency Improves [Epstein 2013]



High Efficiency, High OPR, Small Core Challenges

- Disk burst “1-in-20 rule”
- Close-coupled exhausts
- Propulsive efficiency with BLI
- Performance of small core turbomachinery
- Engine architecture and structural integration

Accomplishments 1/2

- Determined BLI benefit in first back-to-back BLI vs non-BLI comparison

  $10.5 \pm 0.7\%$ at equal mass flow

  $8.4 \pm 0.7\%$ at equal nozzle area

  - Scaling for experimental BLI quantification
  - BLI benefit quantification and uncertainty assessment
  - No show-stoppers for D8 concept

- Determined propulsor inlet distortion for BLI aircraft

- Observed fan efficiency loss to be much less than total BLI benefit (1–2% versus 15%)

Accomplishments 2/2

- Defined approaches to mitigate effects of distortion on turbomachinery performance
  - Tradeoffs different than for “conventional” fan operation
- Identified mechanisms and drivers for small core, high efficiency, high OPR compressor technology
- Carried out conceptual design of small core engine
  - Architecture enables flow path with decreased non-dimensional tip clearance
  - Architecture enables meeting of 1-in-20 rule

Acknowledgments

Funding

NASA Fundamental Aeronautics Program, Fixed Wing Project under Cooperative Agreement NNX11AB35A

Thanks to

Staff at NASA Langley 14×22 Foot Subsonic Wind Tunnel

NASA Fixed Wing Project management

N. Cumpsty, Y. Dong, A. Epstein, E. Gallagher, A. Murphy, J. Sabnis, G. Tillman, H. Youngren