NASA/CR-2003-212670

Blended Wing Body Systems Studies: Boundary Layer Ingestion Inlets With Active Flow Control

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The Boeing Commercial Airplane Group, Seattle, Washington

December 2003

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Prepared for Langley Research Center
under Contract NAS3-01140, Task 7

December 2003

Acknowledgments

This document summarizes the efforts of many participants, all of whom were essential to the successful evaluation of Boundary Layer Ingestion with Active Flow Control technology as applied to future technology airplanes. This study was funded by the NASA Langley Research Center under the technical direction of Mr. Karl Geiselhart as a part of the UEET Propulsion Airframe Integration Project managed by Mr. Michael Watts. The authors gratefully acknowledge the contributions of:

Phantom Works Program Management	Jan Syberg
BCAG Project Management	Dave Daggett
Phantom Works Project Management	Ron Kawai
CFD Analyses	Doug Friedman
Airplane Integration	Jennifer Whitlock
Airplane Performance	Alan Okazaki
Engine Performance Modeling	Jim McComb
Engine Performance Effects	Matt Naimi
Weights	Antonio Gonzales

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EXECUTIVE SUMMARY

This study was conducted by the Boeing Company under the Ultra Efficient Engine Technology/Propulsion Airframe Integration Project. The study was to determine the potential propulsion airframe integration improvement using Boundary Layer Ingestion (BLI) inlets with Active Flow Control (AFC). Engine installation design analyses, supported by CFD, were performed on a Blended Wing Body (BWB) aircraft with advanced, turbofan engines mounted atop the aft end of the aircraft. The results are presented showing that the optimal design for best aircraft fuel efficiency would be a configuration with a partially buried engine, short offset diffuser using AFC, and a “D-shaped” inlet duct that ingests the boundary layer air.

The baseline engine installation design was a low-risk, conventional pylon-mounted turbofan on the aft end of the BWB. Other designs were evaluated where the engine would be lowered close to, or partially within, the body of the aircraft. This reduces ram drag, eliminates the weight and drag of the pylon, reduces the overall exposed surface area of the engine, lowers the cross sectional signature for possible future military uses and may improve the thrust reverser performance.

Moving the engine close to the aircraft body results in several performance losses that were included in the overall assessment. An engine mounted close to the fuselage will ingest low energy boundary layer air resulting in lower thrust. The inlet will also ingest a mixture of low velocity boundary layer air and high velocity free stream air resulting in a non-uniform flow pattern at the engine fan face that may upset engine performance and result in higher specific fuel consumption.

Several airflow control technologies were introduced into the study to see if they could help cancel the performance losses associated with ingesting boundary layer air. In addition, differently designed offset inlets were studied to see if their integrated design might improve overall airplane performance.

CFD models showed that if AFC technology can be satisfactorily developed, it would be able to control the inlet flow distortion to the engine fan face and reduce powerplant performance losses to an acceptable level. The weight and surface area drag benefits of a partially submerged engine shows that it might offset the penalties of ingesting the low energy boundary layer air. The performance capability of the active flow control system, and the power required to operate such a device, will be instrumental in the ultimate airplane performance analysis. As this technology is still in the investigation phase, the performance capability and required power are still unknown and were not included in the study.

This study concluded that the fuel efficiency benefit the airplane might be able to achieve, from ram drag reduction alone, would be 6.3% when compared to a conventional pylon-mounted engine. When including engine performance losses, drag and weight effects, this is reduced to 5.5%. This assumes that AFC achieves insignificant inlet distortion levels and requires negligible power to drive the system. Without adequate AFC, a longer, narrower diffuser with less BLI and passive airflow

control devices would be required and the maximum airplane performance benefit would only be 0.4%. These analyses were based on changes to the nacelle and pylon only. The study did not evaluate the integrated overall effect on airplane aerodynamic performance. Such an analysis may show the improvement in overall streamlining will have an even larger benefit.

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BPR	Bypass Ratio
BWB	Blended Wing Body Aircraft
CAEP	ICAO Committee on Aviation Environmental Protection
CO	Carbon Monoxide
CFR	United States Code of Federal Regulations
EI_{NOx}	Emissions index for NOx given as grams of NOx/Kg fuel
GEAE	General Electric Aero Engine
HC	Hydro-Carbons
ICAO	International Civil Aviation Organization
kg	kilogram
kts	nautical miles per hour
lb	pound
LTO	Landing Take-Off cycle
MTOW	Maximum Take-Off Weight
NASA	National Aeronautics and Space Administration (USA)
NOx	Nitrogen Oxides
NMI	Nautical mile
OPR	Overall Pressure Ratio
PAX	passengers
SLST	Sea Level Static Thrust
st-mi	Statute Mile
std	Standard
SFC	Specific Fuel Consumption
TOGW	Take Off Gross Weight
UEET	Ultra Efficient Engine Technology

1.0 INTRODUCTION

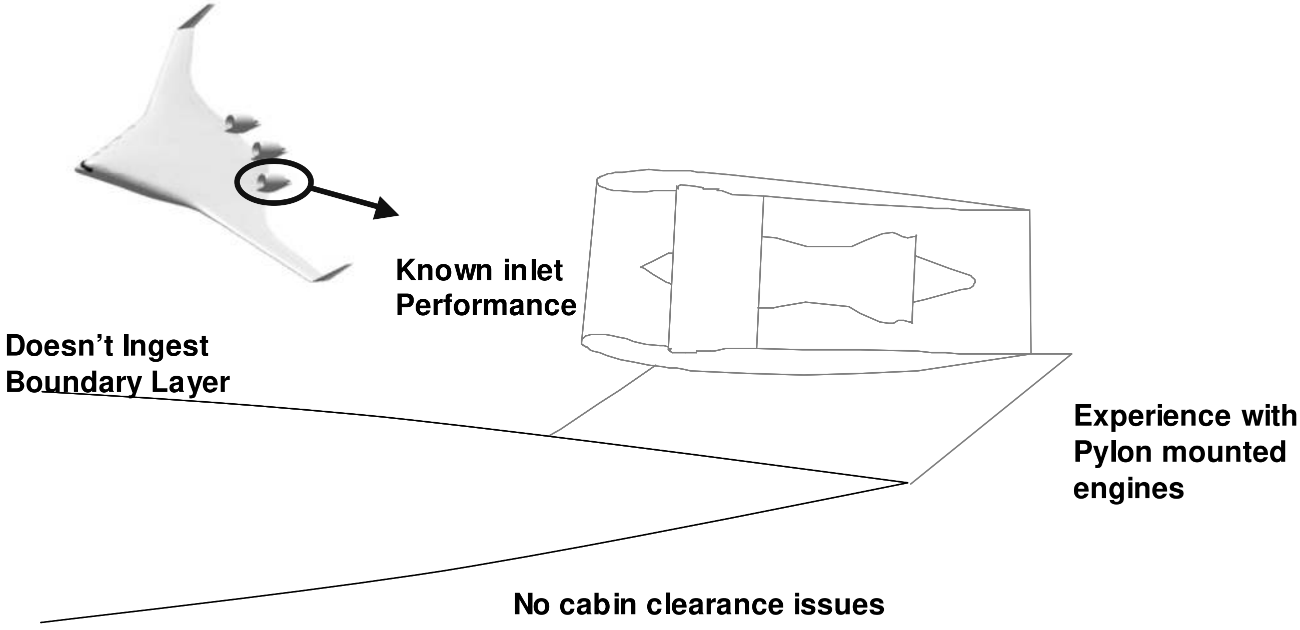
In the quest to continually improve airplane fuel efficiency, new technologies, designs and propulsion/airframe installation schemes must be investigated for their potential to offer improvements.

Previous studies have shown the potential for reduced airplane fuel consumption by using Ultra Efficient Engine Technology (UEET) powerplants(1). These powerplants, exhibiting fuel efficiency improvements in the range of 10% SFC reduction, allowed airplanes to be designed such that the combined airframe/powerplant package enabled a 16-18% airplane fuel use reduction. Proper engine fan diameter sizing, and associated installation effects, are also important to address in achieving optimum fuel efficiency. Engines with the best fuel efficiency sometimes do not provide the best airplane fuel efficiency. This is due to installation weight and drag penalties that are often associated with these improved fuel-efficient engines. In one propulsion/airframe integration study, airplane fuel efficiency actually decreased 4.2% when engines with a 2.6% fuel efficiency improvement were installed(2). Thus, without proper design of Propulsion Airframe Integration (PAI), overall airplane performance can be adversely affected. However, new PAI design schemes may also offer the potential to improve airplane fuel efficiency beyond already well-designed systems by further reducing drag and weight

1.1 Problem

Can boundary layer ingestion (BLI) engine inlets, using active flow control to prevent separation and control distortion, result in improved PAI designs that reduce fuel use?

For Blended Wing Body (BWB) aircraft, mounting the engines within the aft part of the fuselage may result in reductions in ram drag from BLI and offer weight and drag benefits by eliminating the engine pylon, reducing the nacelle exposed surface area and eliminating any potential engine/wing interference drag issues. However, present designs currently have the engines mounted on the upper surface of the fuselage as shown in Figure 1.1. The reasoning of such an installation is that this type of installation is well known, airplane/engine performance is proven and understood, and the design can be implemented with today’s technology.



Boeing has used proven designs to reduce uncertainty until further studies could be done on buried engine designs

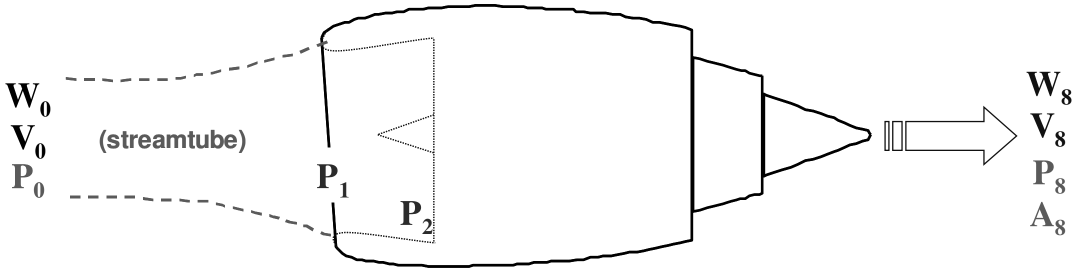
Figure 1.1. BWB with pylon mounted engines

There are several engine performance issues with burying the powerplants within the fuselage. These problems will be discussed next and need to be solved before such installations can be considered viable.

Presently, engines on an aircraft are typically placed in the freestream air. As shown in Figure 1.2, an undisturbed flow of free stream high velocity air flows towards the engine with a certain mass flow (Wo), velocity (Vo) and pressure (Po). This air enters the engine inlet (station 1 indicated as P_1) and continues to the inlet of the engine fan (P_2). Mass (fuel), velocity and pressure are added to the airstream within the engine and exhausted out the aft end of the engine (W_8, V_8, and P_8). An efficient engine installation will convert the energy in the free stream air into thrust. This will mostly be in the form of momentum thrust, which is a function of the amount of mass flow and the velocity at which it is expelled. A smaller portion will be in the form of pressure thrust, or the differential in pressure that is created behind as compared to in front of the engine.

If one determines the amount of air that the engine requires, and follows that airflow level upstream of the engine into the freestream, the area defined by that airflow level is defined as the "streamtube".

The difference in pressure between the engine inlet (P1) and the freestream (Po) is called "inlet capture pressure recovery". The difference in pressure between the engine inlet (P1) and the fan face (P2) is called "diffuser pressure recovery" and will be discussed next.



Momentum (Ram) Drag = $\frac{W_0 V_0}{g}$ ⇨

⇦ **Momentum Thrust** = $\frac{W_8 V_8}{g}$

⇦ **Pressure Thrust** = $(P_8 - P_0) A_8$

Other important factors:

Inlet Capture Pressure Recovery = $P_1/P_0=1.0$

Diffuser Pressure Recovery = P_2/P_1

Legend:
W = Mass Flow
V = Velocity
P = Pressure
A = Area

Figure 1.2. Engine performance definitions

Current turbofan engines operate best when the velocity at the fan face (P2) is about 0.6 Mach. As many current jet aircraft cruise at 0.85 Mach flight velocity, the freestream air first needs to be slowed down before it enters the fan. Most of this slowing occurs outside of the engine, upstream of the inlet. Figure 1.3 illustrates the phenomenon wherein the freestream air approaches the engine inlet and is slowed to about 0.5 Mach. From here it accelerates around the inlet lips into the throat and is then again slowed by the inlet diffuser to reach 0.6 Mach entering the fan. As the velocity is decreased, the efficient engine inlet converts the kinetic energy in the air back into a rise in pressure. The total pressure recovery is typically in the range of 0.998 or 99.8% efficient.

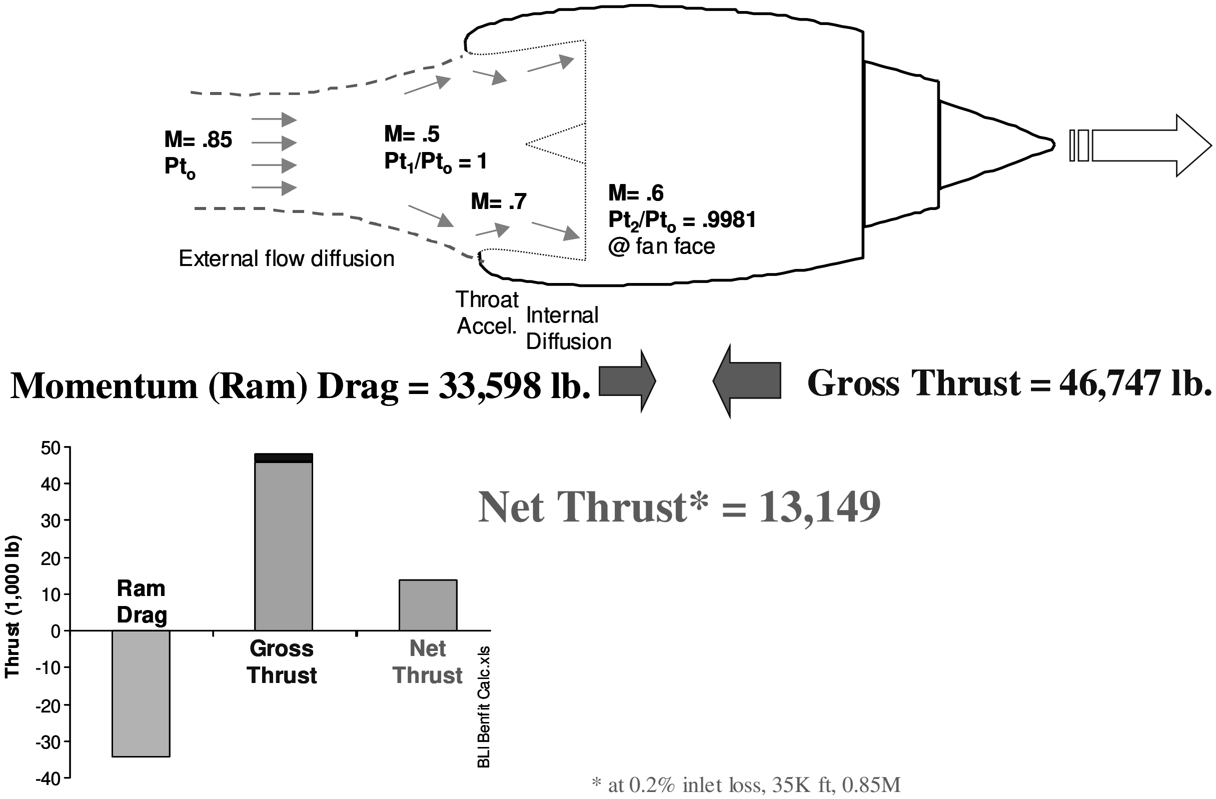


Figure 1.3. Conventional inlet velocity profile, pressure recovery and ram drag

When an engine is buried into the airplane fuselage with BLI inlets, it will ingest a portion of the lower energy boundary layer air. Figure 1.4 shows the velocity profile differences between a conventional freestream mounted engine and an engine inlet positioned close to the fuselage. The Boundary Layer Ingestion (BLI) inlet consumes a portion of the lower energy air near the fuselage and a portion of the freestream air.

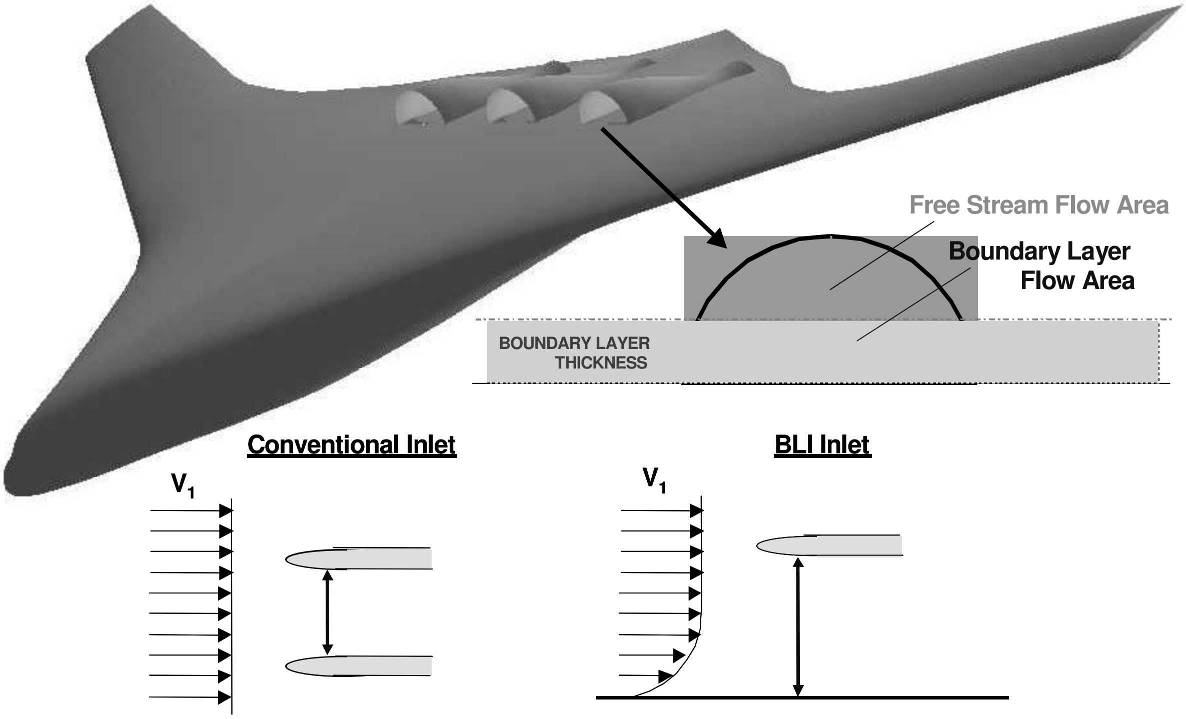


Figure 1.4. Buried engines ingest low energy boundary layer air

From the ram drag equation presented in figure 1.2, it is apparent that a large ram drag reduction will be experienced by ingesting the lower velocity boundary air. However, this ram drag reduction is partially offset by the pressure recovery loss. As Figure 1.5 shows, the pressure recovery for a BLI inlet (97.7%) is poorer than a conventional inlet (99.8%). Thus, the aircraft performance assessment must include the engine performance degradation that offsets the ram drag reduction from BLI.

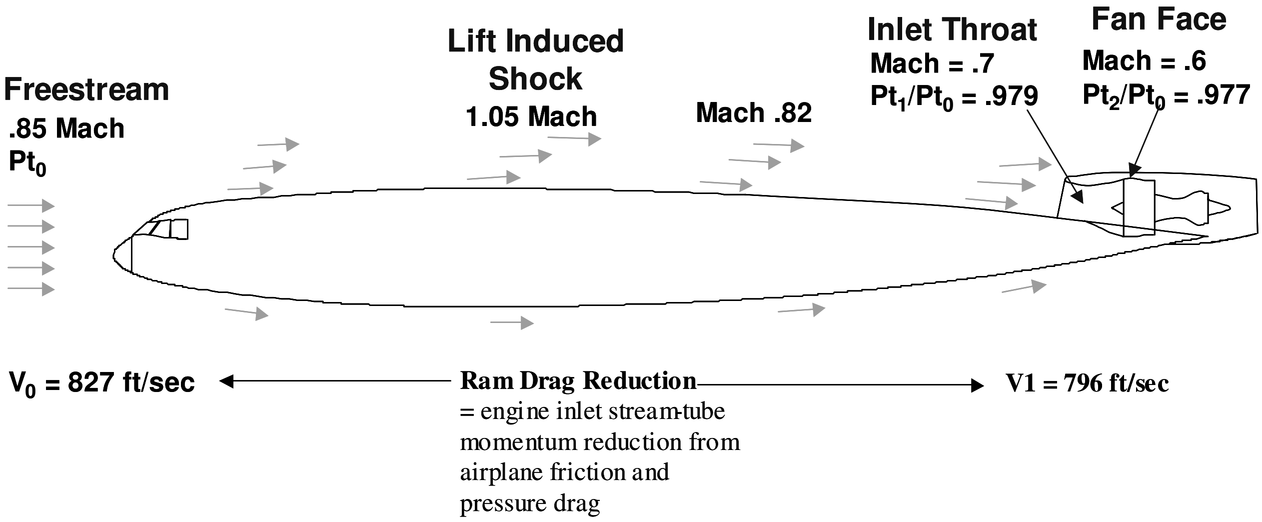


Figure 1.5. Boundary layer air ingestion results in reduced pressure recovery

1.2 Purpose of the Study

The purpose of this study was to determine potential fuel savings benefits from BLI inlets with AFC. The NASA Ultra Efficient Engine Technology (UEET) program is developing the technology base for major reductions in emissions and fuel consumption in future commercial transport aircraft. The Propulsion Airframe Integration (PAI) project is an element of the UEET program directed towards contributing to the reductions in CO_2 emissions and reducing fuel burned by advancing airframe integration technologies. This study was conducted as RASER Task Order No.7 in the PAI Project.

While past studies have identified the improvement potential from the ram drag reduction from boundary layer ingestion inlets, other airframe integration benefits are also possible as shown in Figure 1.6. This study was to determine the benefit potential considering installation requirements in the BWB 450-1U aircraft.

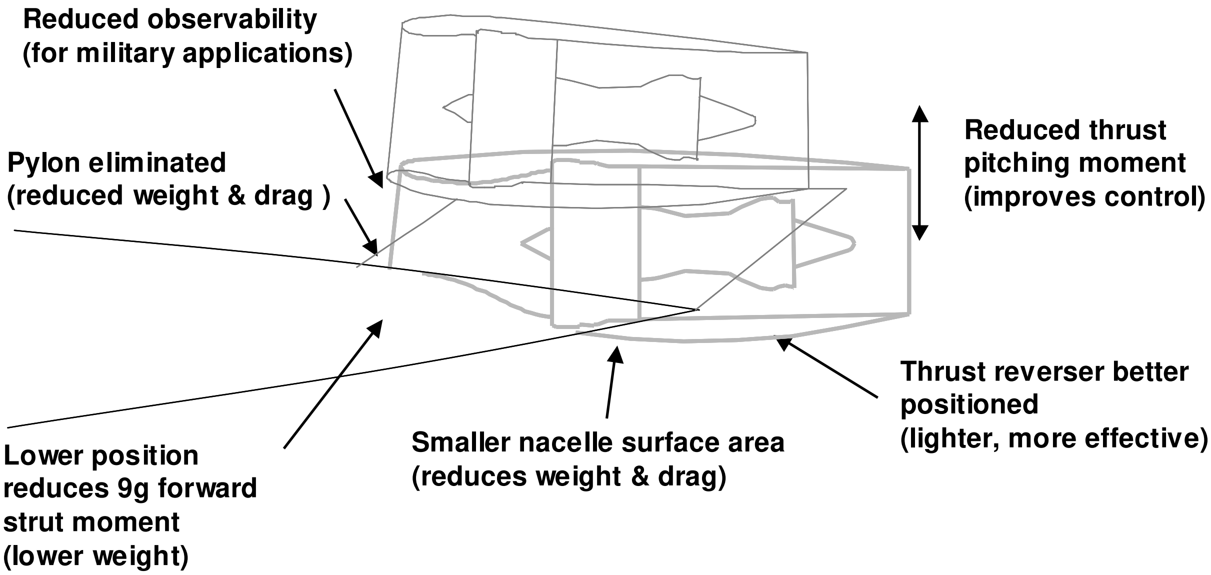


Figure 1.6. Advantages of buried engines on the BWB

1.3 Work Task Description

This study was conducted as a part of the PAI Project to determine the benefit potential from using Boundary Layer Ingestion (BLI) inlets with Active Flow Control (AFC). Active flow control as envisioned herein is use of pulsating air jets for boundary layer control. This type of AFC is an emerging technology that promises to enable boundary layer control with much lower secondary flow rates than required with continuous flow. Further, there have been experimental validations of control capability with zero net flow devices. AFC may thus require much lower energy levels and, with zero net flow devices, enable boundary layer control from electric powered vibrating diaphragms or pumps. AFC may thus result in highly efficient boundary layer control to enable BLI inlets.

In order to determine the incremental performance improvements, the baseline BWB 450-1U was modified to incorporate buried engines with BLI intakes. The engine nacelle and inlet were configured to reduce distortion by utilizing vortex generators. The buried engine nacelles and inlets were then reconfigured to incorporate AFC. This study progression is seen in Figure 1.7.

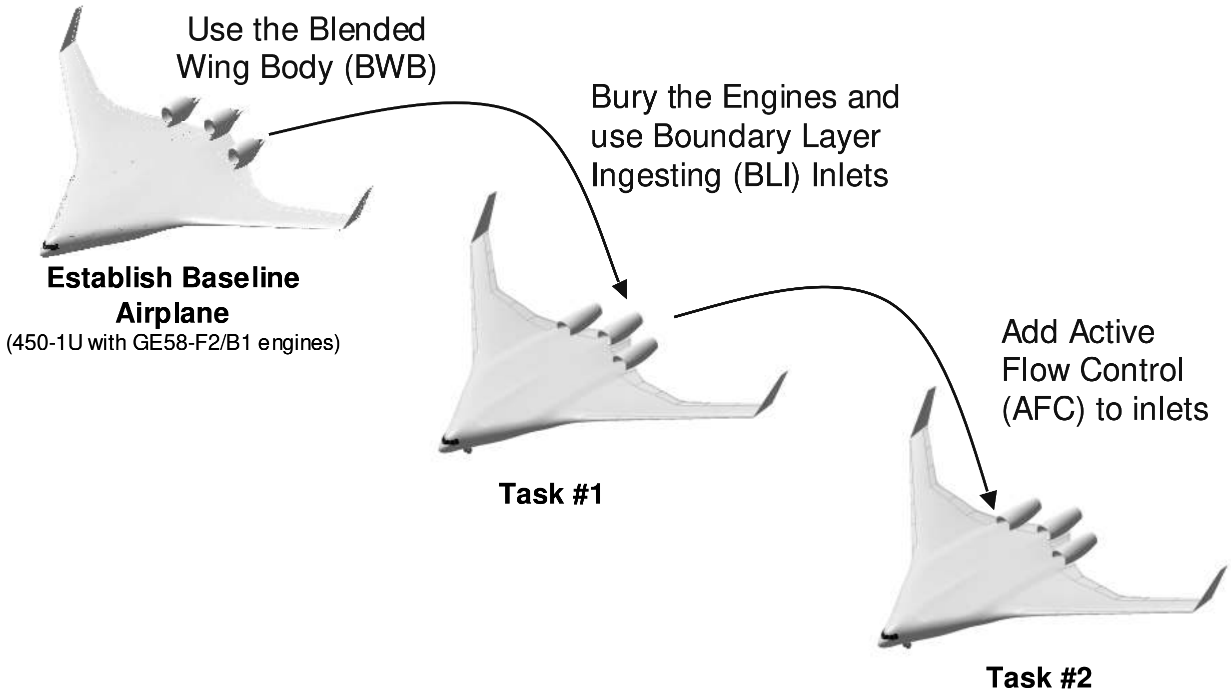


Figure 1.7. Work task flow

The sequence for designing and analyzing the buried engines along with their respective inlets is shown in Figure 1.8.

- Submerge engine with short offset diffuser
- Evaluate reduced ram drag
- Account for loss in pressure recovery
- Define AFC requirements to control distortion

Figure 1.8. Buried engine design assumptions

1.4 Baseline Airplane Description

In a previous study(3) an advanced passenger BWB airplane (model BWB 450-1U) with airframe technology improvements and UEET engines was redesigned from an earlier design (model BWB 450-1L). This updated aircraft was used in the study and is shown below.

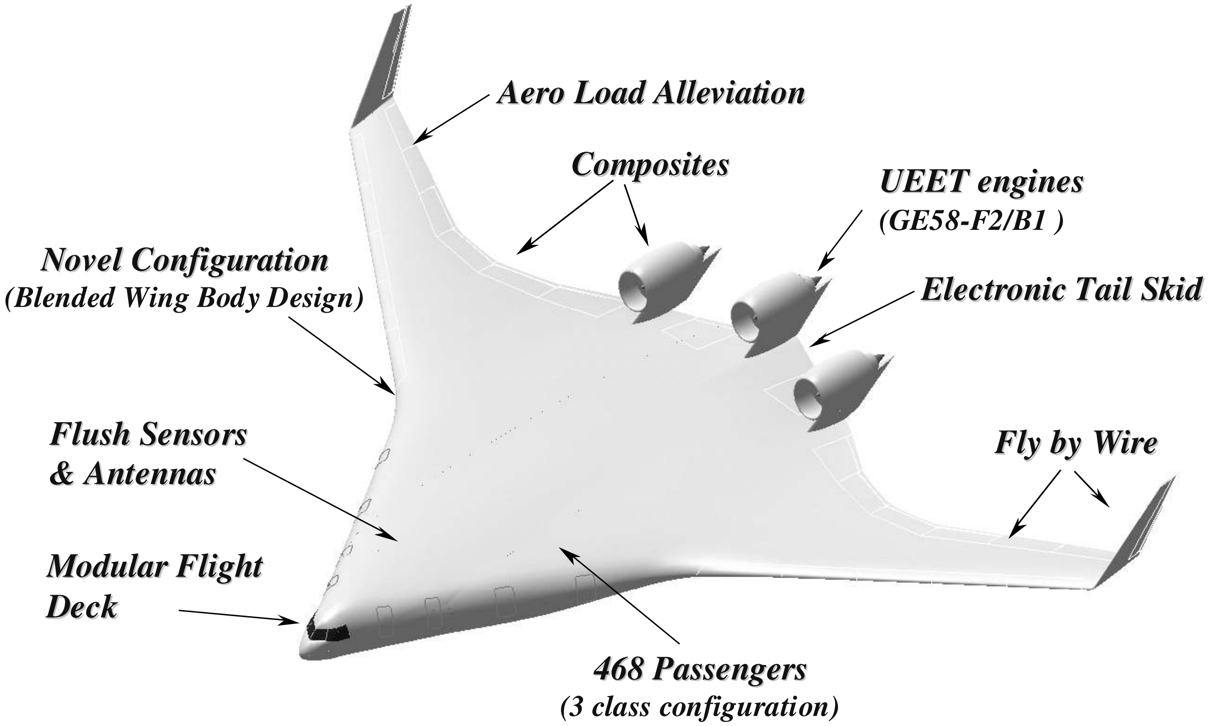


Figure 1.9. Baseline BWB 450-1U study airplane features

As shown in Figure 1.10, the redesigned baseline BWB 450-1U airplane, with UEET engines and aerodynamic refinements, is almost 24% more fuel efficient than the previous BWB design. BLI inlets with AFC can provide even greater improvements beyond those seen with the BWB 450-1U.

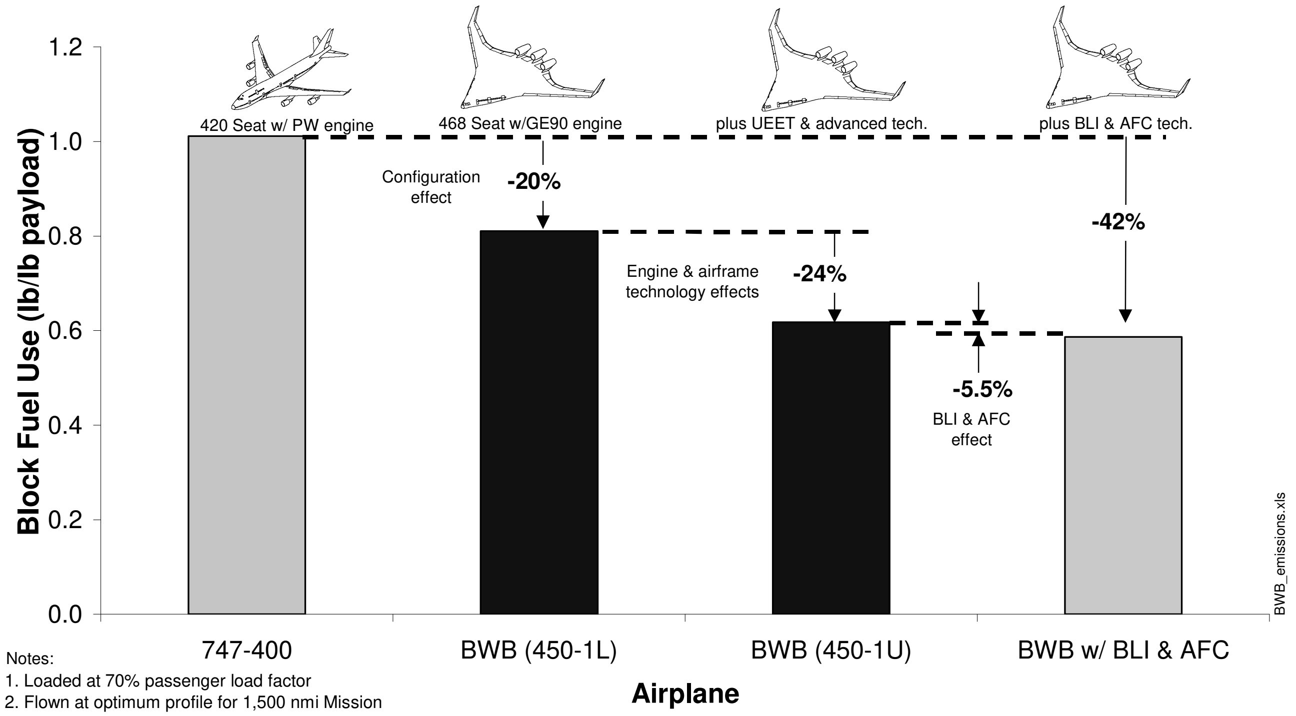


Figure 1.10. Baseline BWB fuel efficiency

2.0 ANALYTICAL PROCEDURE

2.1 Airplane Analysis

Figure 2.1 shows the analysis procedure used in evaluating different BLI inlet configurations. BLI inlet geometries are defined and the viscous flow field into the inlet and through the diffuser is calculated. The nacelle is configured in a Unigraphics model from which changes in weight and drag are determined. The calculated pressure recovery is then used in the engine performance model. All the changes are then input into the Boeing CASES airplane sizing and mission analysis program.

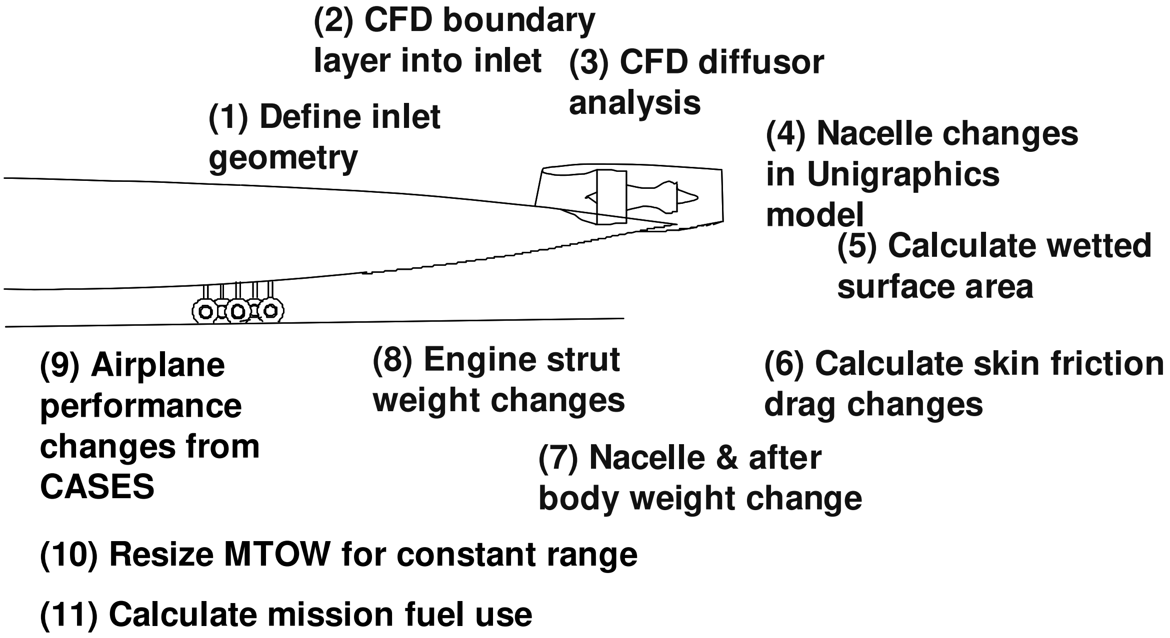
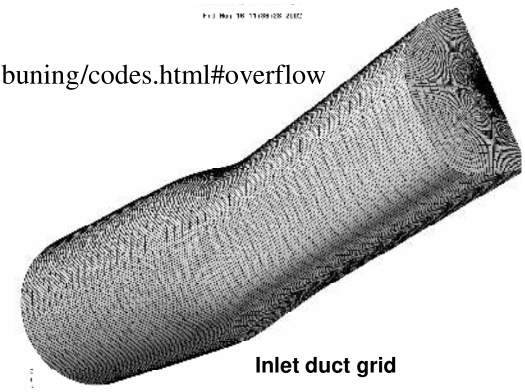


Figure 2.1. Airplane analysis procedure

2.2 Flow Field Modeling

CFD models were used to model the air flow field through the inlet diffuser and used in calculating system performance. The program used is called OVERFLOW and was developed by NASA as shown in Figure 2.2.

- **Single block grids** or Chimera overset* (structured) grid systems.
- Turbulence model choices include: Baldwin-Barth, **Spalart-Allmaras,** 2-eq. k-ω, 2-eq. SST
- NASA web site
  http://ad-www.larc.nasa.gov/~buning/codes.html#overflow

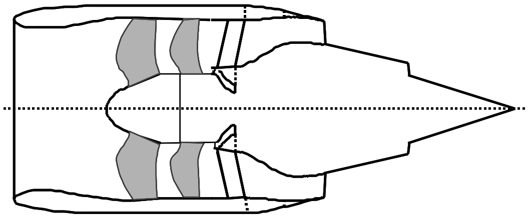


* to be used in follow-on task

Figure 2.2. Overflow CFD analysis tool

EDASA is Boeing's engine performance modeling program that calculates design point and off-design performance for the airplane operating envelope. As shown in Figure 2.3, the engine performance characteristics were determined using the Boeing EDASA engine model that was programmed to match the GE58 F2/B1 UEET engines.

- EDASA cycle model created to match GE supplied cruise performance at Mach 0.85, 35K ft
- Calculates design and off-design thermodynamic performance, mechanical design, dimensions and weights for turbofan and turbojets
- Exchange factors and performance sensitivities created by modeling engine cycle.



GE58-F2/B1 UEET powerplant

*Boeing Engine Design and System Analyzer

Figure 2.3. EDASA engine modeling tool

The changes in engine performance, drag and weight were determined and the airplane sized for constant payload range and mission analyses conducted using the Boeing CASES program. CASES (Computer-Aided Sizing and Evaluation System) is a Boeing-developed sizing and performance computer program that includes aero, propulsion, and weight modules and enables interdisciplinary optimization (figure 2.4).

Boeing developed CASES is an inter-disciplinary analysis system for optimization and evaluation of aircraft

Uses modules for:

- Configuration layout
- Aerodynamic design
- Stability and control
- Propulsion
- Weights
- Aerodynamic performance

Figure 2.4. CASES airplane performance & design tool

BLI inlet performance for boundary layer ingestion into the inlet was determined by calculating the change in ram drag between freestream and inlet capture airflow streams (Figure 2.5).

$$W_0V_0/g - ((W_1V_1/g + (P_1 - P_0)\ A_1))$$

Ram drag reduction calculated from change in flow momentum from freestream to capture

- Engine performance changes calculated for reduction in ram drag and inlet pressure recovery
- Assumed that losses are from boundary layer flow that enters fan only
- Engine performance losses based on all losses in fan by-pass flow

Figure 2.5. Ram drag calculation

3.0 RESULTS OF ANALYSIS

3.1 Initial configuration

The starting point configuration was an inlet in which the boundary layer width to height ratio was 1.9, with length 3 times the fan diameter and a centerline offset of 1 fan diameter. This configuration was based on having a boundary layer thickness of 30% of the capture height from the Reference UEET Task 27 design. The inlet and engine were installed on the BWB450-1U meeting requirements for the passenger accommodations and provisions, and structural arrangements. Figure 3.1 shows the baseline BLI inlet and S-duct.

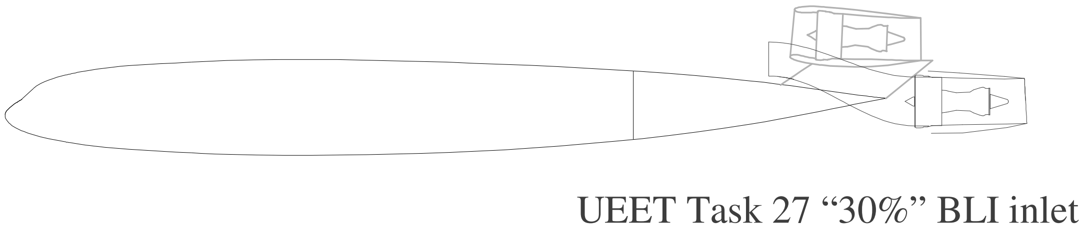


Figure 3.1. 30% inlet S-duct

The performance results of the study are shown are shown in Figure 3.2. The large overhang with increased exposed wetted surface areas resulted in weight and drag increases. While there is a 6.85% benefit from ram drag reduction (expressed as equivalent sfc which is the change in net thrust), the net effect is a 3.1% increase in fuel burned for the design mission.

	BASELINE PODDED	**TASK 27 "30%"**
	<u>Center Engine Comparison</u>	
Capture PT1/PT0	**1**	**0.974**
Ram Drag ESFC (%)	**0**	**-6.85**
Inlet Recov PT2/PT0	**0.998**	**0.971**
Engine SFC (%)	**base**	**5.69**
Drag (%)	**base**	**1.29**
Weight (lbs)	**base**	**16300**
	<u>Airplane Comparison</u>	
Design TOGW (lbs)	**768200**	**796000**
TO Thrust (lb/eng)	**63300**	**66100**
Block Fuel (lbs)	**249760**	**257500**
delta fuel (%)	**base**	**3.1**
3,000 nmi Range: 70% Load Factor (68,795 lbs)		
TOGW (lbs)	**56600**	**588400**
Fuel Burned (lbs)	**85800**	**88300**
delta fuel (%)	**0**	**2.9**

Figure 3.2. Pylon mounted engine versus baseline BLI inlet

3.2 Optimized Design without Active Flow Control

In order to improve the configuration, the inlet needed to be shortened and the diffuser offset reduced. Without AFC, the best approach was judged to use vortex generators to eliminate separation and control distortion. The configuration developed by Bernie Anderson ("A Study on the Blended Wing Body Outboard Inlet S-Duct with BLI Control," 1997), of NASA Glenn Research Center, was selected as the starting point for evaluation. It had been optimized for maximum pressure recovery and minimum distortion by altering the geometry and adding vortex generators. As a result, the corners were rounded and the boundary layer capture width reduced. The configuration is shown in Figure 3.3.

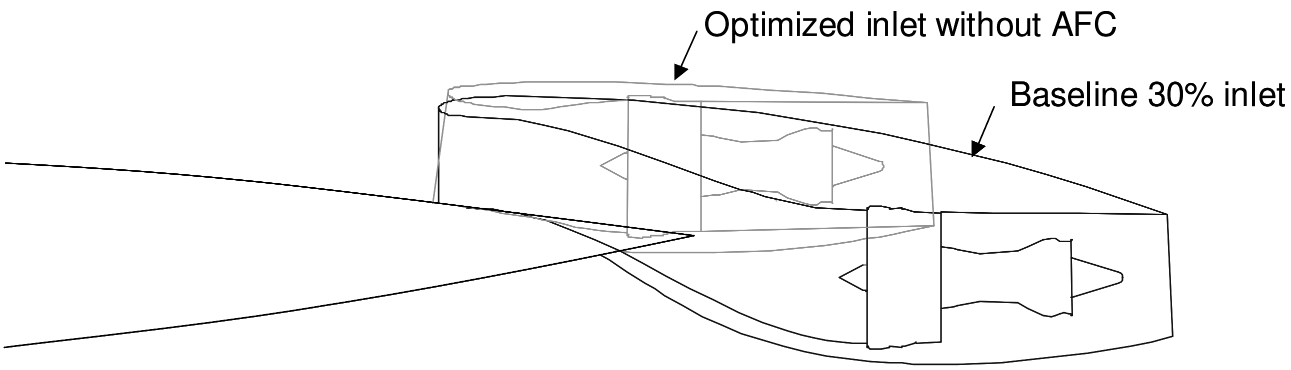
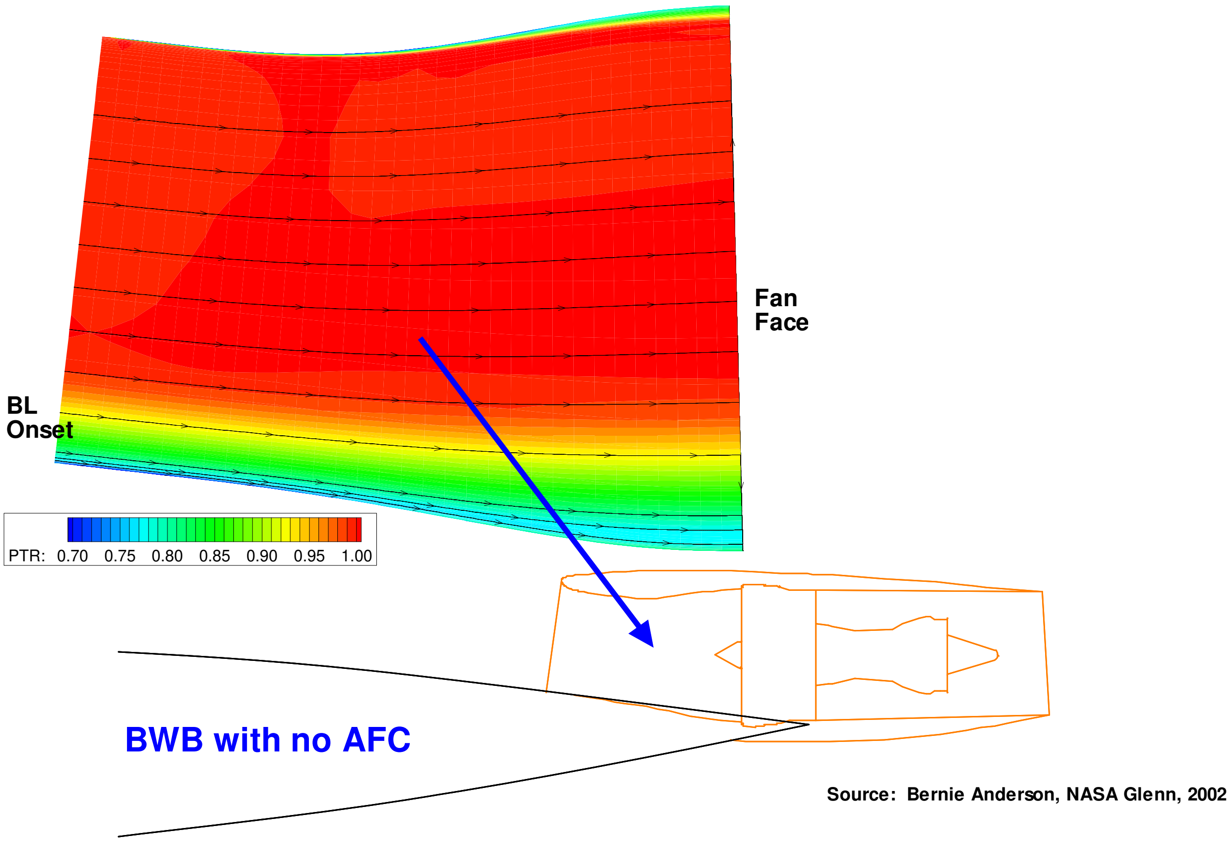


Figure 3.3. Optimized inlet without AFC compared to 30% inlet S-duct

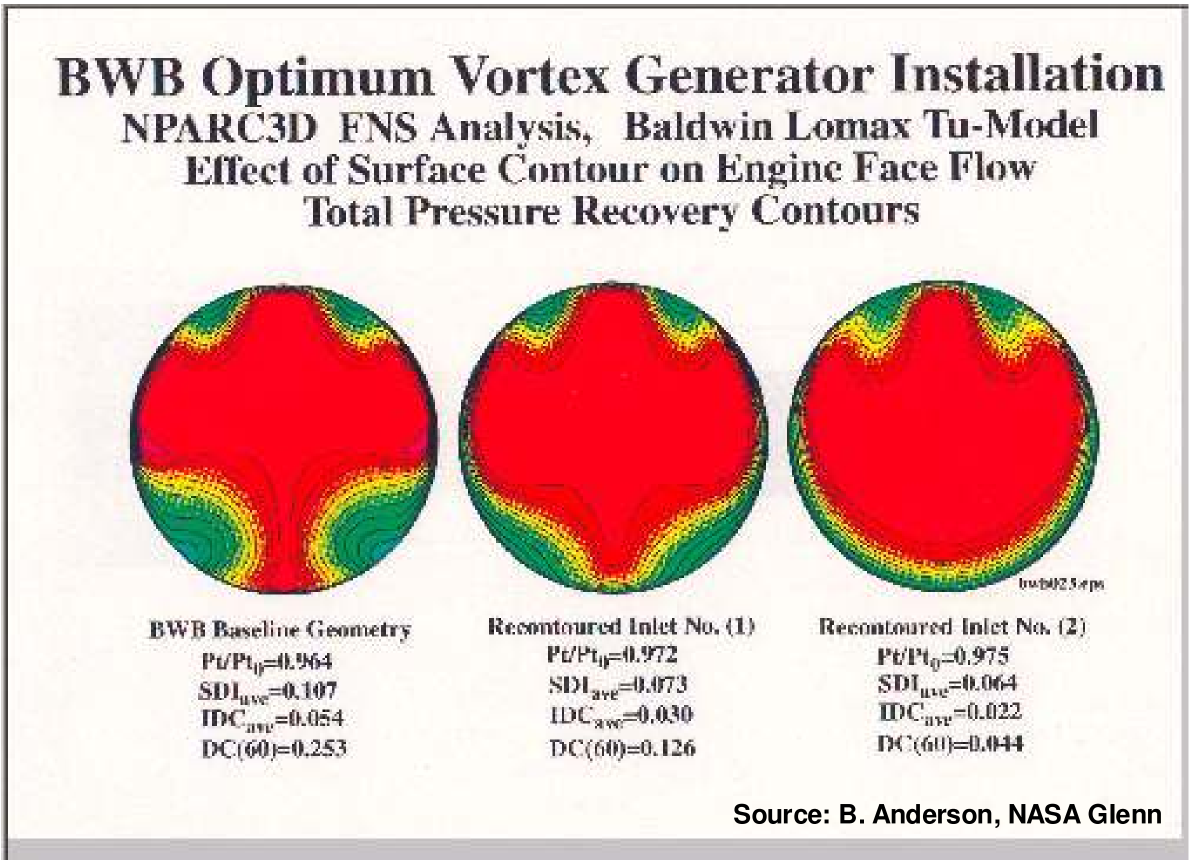
A CFD model was used to construct an offset diffuser for the BWB that had less nacelle surface area than baseline inlet and also avoided airflow separation within the diffuser. An OVERFLOW CFD analysis of this inlet is shown in Figure 3.4 (without the vortex generators).



Source: Bernie Anderson, NASA Glenn, 2002

Figure 3.4. Pressure profile of offset diffuser with no AFC

This inlet still experienced airflow flow distortion but by adding vortex generators to the inside of the inlet, the distortion level could be significantly reduced as shown in figure 3.5. This reference study assumed that these vortex generators would redistribute the low energy air around the periphery of the inlet and achieve this level of distortion.



BWB Optimum Vortex Generator Installation

NPARC3D FNS Analysis, Baldwin Lomax Tu-Model

Effect of Surface Contour on Engine Face Flow

Total Pressure Recovery Contours

BWB Baseline Geometry
$Pt/Pt_0=0.964$
$SDI_{ave}=0.107$
$IDC_{ave}=0.054$
$DC(60)=0.253$

Recontoured Inlet No. (1)
$Pt/Pt_0=0.972$
$SDI_{ave}=0.073$
$IDC_{ave}=0.030$
$DC(60)=0.126$

Recontoured Inlet No. (2)
$Pt/Pt_0=0.975$
$SDI_{ave}=0.064$
$IDC_{ave}=0.022$
$DC(60)=0.044$

Source: B. Anderson, NASA Glenn

Figure 3.5. Acceptable distortion levels were achieved by vortex generators

The performance with this configuration is shown in Figure 3.6. The benefit from ram drag reduction is 5.14% but the engine performance losses with weight and drag effects results in a net improvement of -0.4%for the design mission.

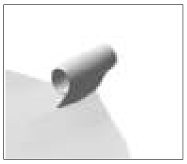
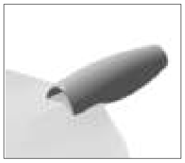
	BASELINE PODDED	TASK 27 "30%" w/AFC	Max Benefit No AFC
			
		Center Engine Comparison	
Capture PT1/PT0	**1**	**0.974**	**0.984**
Ram Drag ESFC (%)	**0**	**-6.85**	**-5.14**
Inlet Recov PT2/PT0	**0.998**	**0.971**	**0.974**
Engine SFC (%)	**base**	**5.69**	**4.92**
Drag (%)	**base**	**1.29**	**-0.22**
Weight (lbs)	**base**	**16300**	**600**
		Airplane Comparison	
Design TOGW (lbs)	**768200**	**796000**	**767500**
TO Thrust (lb/eng)	**63300**	**66100**	**63100**
Block Fuel (lbs)	**249760**	**257500**	**248700**
delta fuel (%)	**base**	**3.1**	**-0.43**
3,000 nmi Range: 70% Load Factor (68,795 lbs)			
TOGW (lbs)	**56600**	**588400**	**566100**
Fuel Burned (lbs)	**85800**	**88300**	**85500**
delta fuel (%)	**0**	**2.9**	**-0.4**

Figure 3.6. Performance of redesigned BLI inlet with no AFC

3.3 Optimized Design with Active Flow Control

Since the purpose of this study was to determine the potential improvements possible with AFC and define the associated technology needs, a diffuser optimization method was used and a 20 degree maximum wall turning angle selected as the bases for determining the potential. This diffuser selection was judgmental such that AFC would need to improve beyond what might be possible with fixed vane vortex generators. In this configuration, the inlet highlight width was increased from the no AFC configuration in order to increase the boundary layer capture to increase the ram drag reduction. This configuration is shown in Figure 3.7.

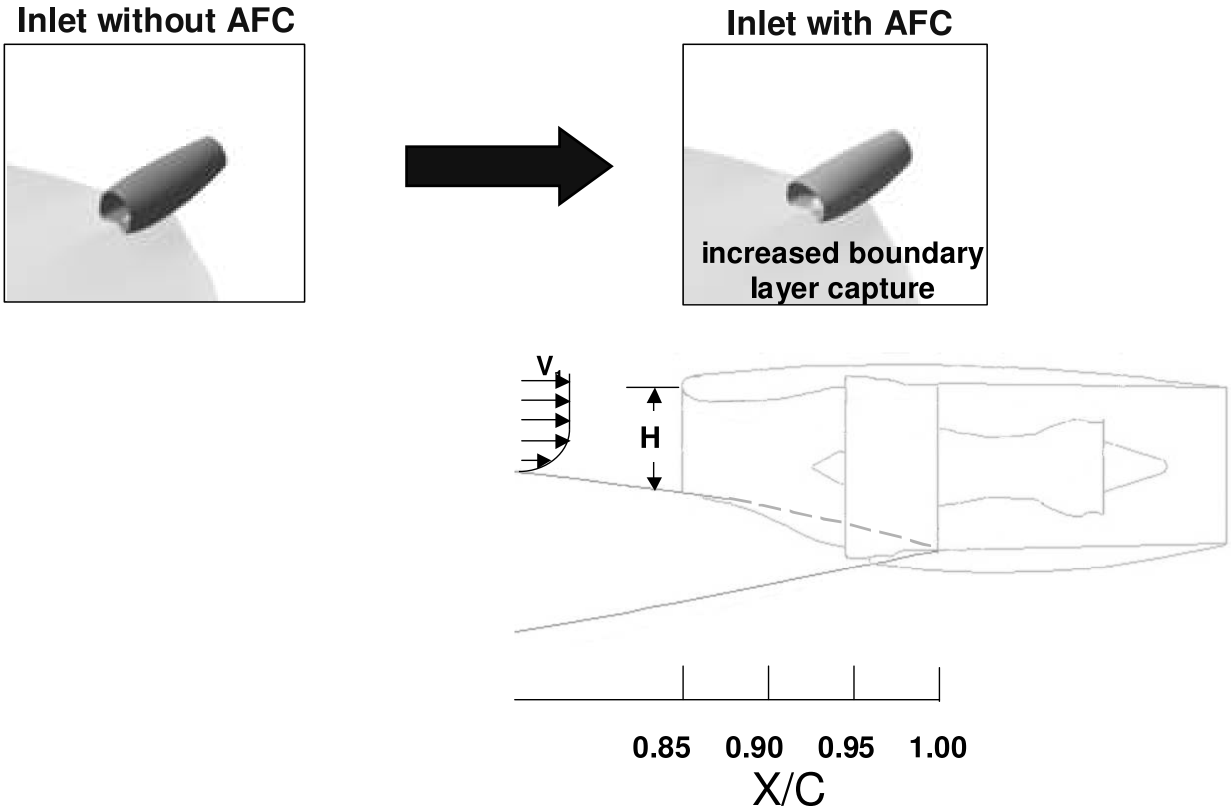


Figure 3.7. Shortened offset diffuser design changes

Using the shortened diffuser enabled by the use of AFC, a 17% reduction in nacelle surface area was achieved as is shown in Figure 3.8.

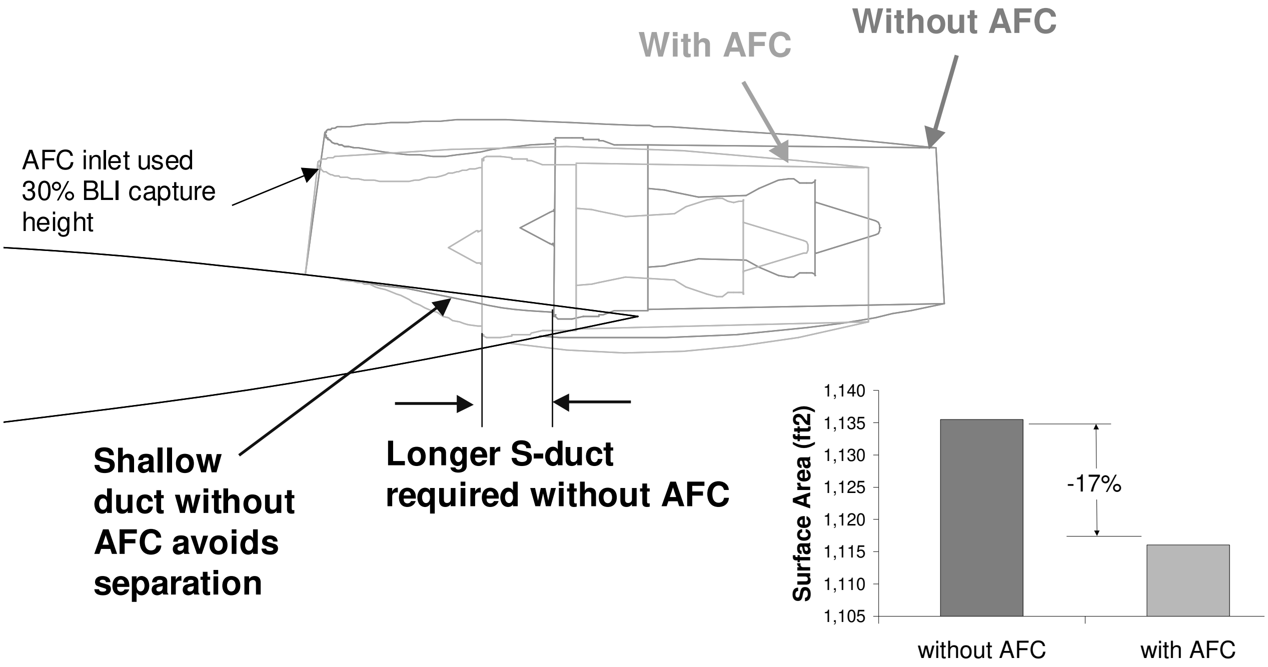


Figure 3.8. Shortened offset diffuser with AFC

The ram drag reduction benefit is 6.27%. The engine performance loss with the SFC change due to the change in inlet pressure recovery is 5.1%. These changes were input into the BWB 450-1U CASES model along with the change in drag and operating empty weight. The airplane was resized for the design payload range and mission performance analysis conducted. The comparative result is a net 5.5% reduction in fuel burned for the case with AFC for the design mission. The results are shown in Figure 3.9. The last case for BLI with AFC includes the PAI benefit from thrust reverser integration relative to the comparison baseline pylon mounted (podded) engine. The other two BLI configurations could also benefit which would improve the fuel burned 1.9%.

	BASELINE PODDED	TASK 27 "30%" w/AFC	Max Benefit No AFC	Max Benefit With AFC
		Center Engine Comparison		w/Short Duct
Capture PT1/PT0	1	0.974	0.984	0.979
Ram Drag ESFC (%)	0	-6.85	-5.14	-6.27
Inlet Recov PT2/PT0	0.998	0.971	0.974	0.973
Engine SFC (%)	base	5.69	4.92	5.13
Drag (%)	base	1.29	-0.22	-1.93
Weight (lbs)	base	16300	600	-6400
		Airplane Comparison		
Design TOGW (lbs)	768200	796000	767500	746300
TO Thrust (lb/eng)	63300	66100	63100	61100
Block Fuel (lbs)	249760	257500	248700	236000
delta fuel (%)	base	3.1	-0.43	-5.5
3,000 nmi Range: 70% Load Factor (68,795 lbs)				
TOGW (lbs)	56600	588400	566100	553800
Fuel Burned (lbs)	85800	88300	85500	81400
delta fuel (%)	0	2.9	-0.4	-5.1

Figure 3.9. Performance data of inlet with AFC

The OVERFLOW CFD analysis of the diffuser with BLI is shown in Figure 3.10. The resultant circumferential distortion level is in excess of that allowable for engine operability. AFC would need to prevent the flow separation from occurring on the lower surface, and redistribute the low energy flow for acceptable circumferential and radial distortion indices.

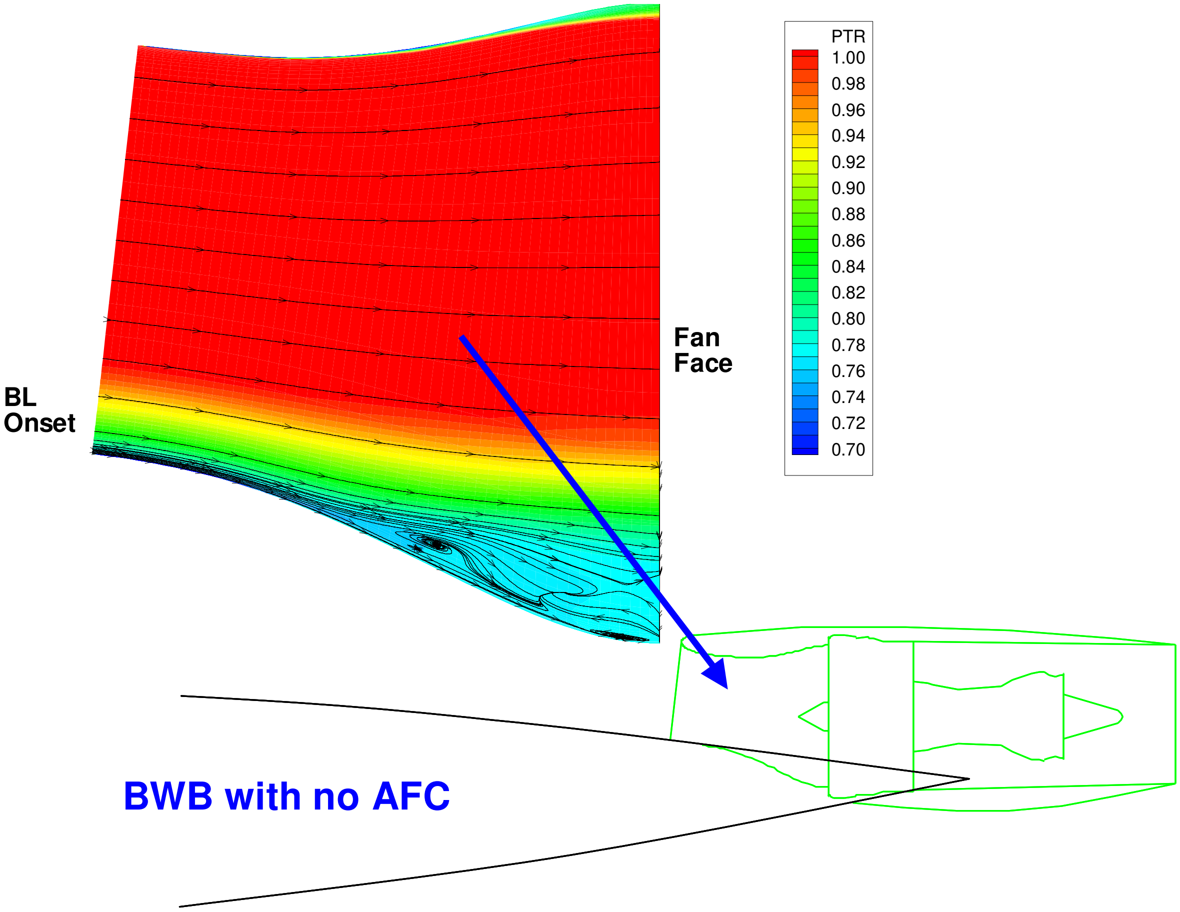


Figure 3.10. Pressure profile of shortened diffuser without AFC

Pulsing or periodic flow actuators located in the throat region may provide the necessary boundary layer control and are shown in Figure 3.11.

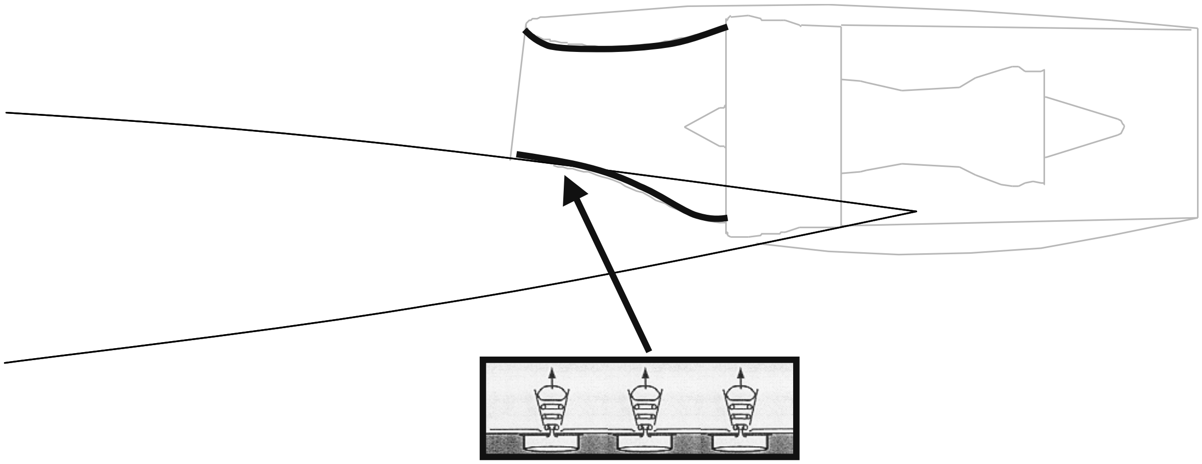


Figure 3.11. Shortened offset diffuser with addition of AFC

4.0 DISCUSSION OF RESULTS

For BLI inlets with passive and flow control devices that are able to achieve sufficiently low levels of distortion, the likely fuel efficiency gains that could be achieved, as well as the levels of performance tradeoffs, are shown in Figure 4.1. The BLI inlet with AFC achieved a 5.5% reduction in mission fuel use over the baseline BWB airplane with UEET engines. This assumes that AFC eliminates inlet distortion for no performance penalty. This fuel savings potential also does not take into account the power required to drive the AFC system (since this is presently unknown). The BLI inlet without AFC achieved 0.4% reduction in fuel use.

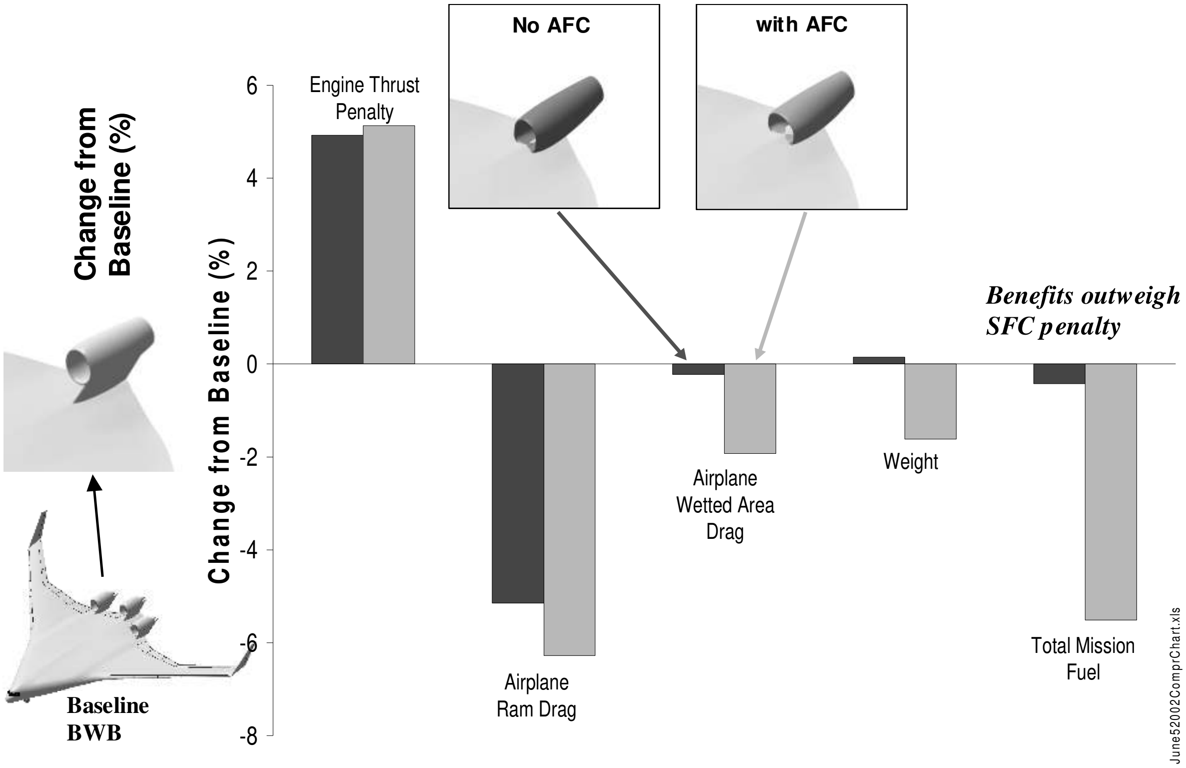


Figure 4.1. Diffuser effects on airplane with and without AFC

The importance of maximizing the benefit from improved propulsion airframe integration can be seen by comparing with the theoretical benefit. Figure 4.2 shows the theoretical relation between ram drag reduction and engine performance loss as the degree of boundary layer ingestion is varied. Increasing boundary layer ingestion results in a decreasing total pressure recovery into the engine and increases the distortion. The decreasing pressure recovery results in an increasing loss in net thrust. The difference between the decrease in ram drag and net thrust loss is the net benefit from boundary layer ingestion into the inlet provided that the AFC is able to achieve acceptably low levels of distortion. With the inlet recovery of 0.973, the net benefit from boundary layer ingestion into the engine is about 1%. Most of the PAI benefit results from use of AFC to enable a short offset diffuser.

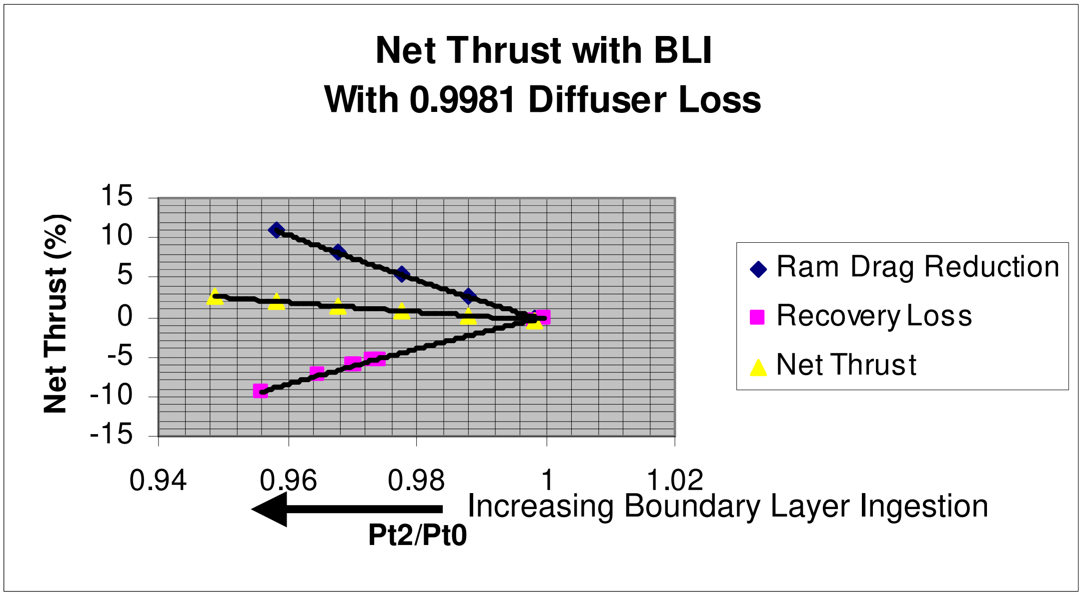


Figure 4.2. BLI and pressure recovery effects on net thrust

These results are dependent on the engine cycle selected. The GE58 engine used has a by-pass ratio of 11. As seen in Figure 4.3, the net thrust loss is dependent on the by pass ratio. An engine with a lower by-pass ratio would have a higher fan pressure ratio resulting in a lower loss with inlet pressure recovery. The SFC without BLI would, however be higher and the total integrated system needs to be optimized.

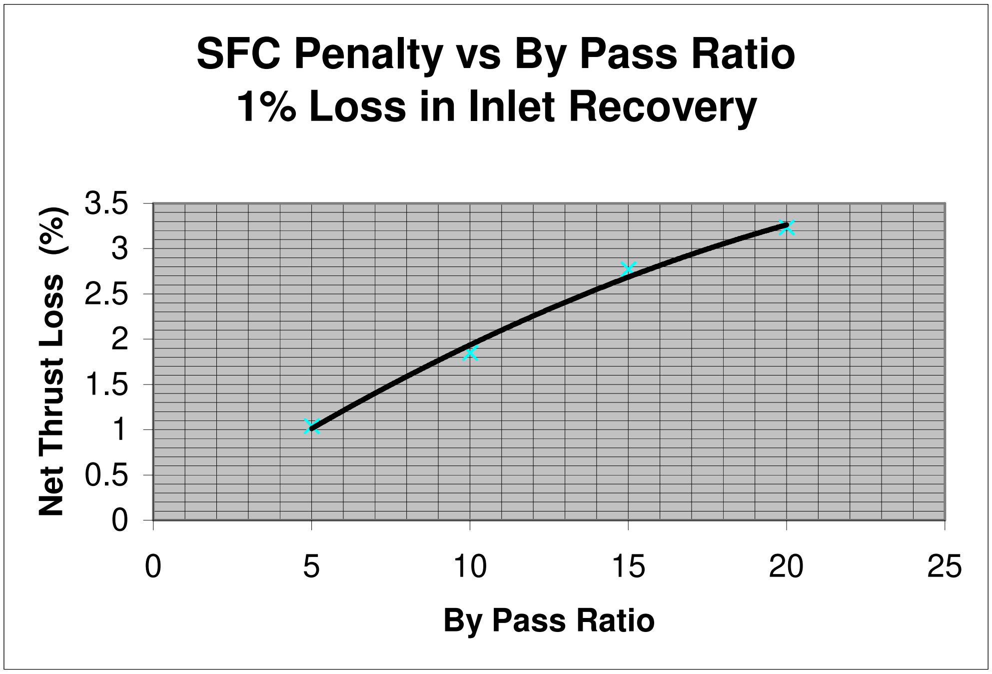


Figure 4.3. Bypass ratio effects on net thrust

5.0 CONCLUSIONS AND RECOMMENDATIONS

AFC, to eliminate separation, would enable short diffusers that result in less airplane wetted area, less drag and less weight. AFC to reduce inlet distortion could enable BLI installations that would result in ram drag reductions as well as less weight and drag by eliminating the engine pylon. However, this reduction must be balanced against the engine inlet pressure recovery penalty. Even larger airframe integration benefits of BLI may result from inlet/airframe configuration optimization.

Figure 4.2 shows that, if AFC can be effectively implemented, with negligible power requirements, buried engine installations with BLI inlets could further improve the BWB's fuel efficiency an additional maximum of 5.5% for the BWB 450-1U with the GE58 F2/B1 engines. This, along with configuration effects and engine efficiency improvements, would enable the BWB to possibly achieve a 42% reduction in fuel use over a current 747-400 aircraft.

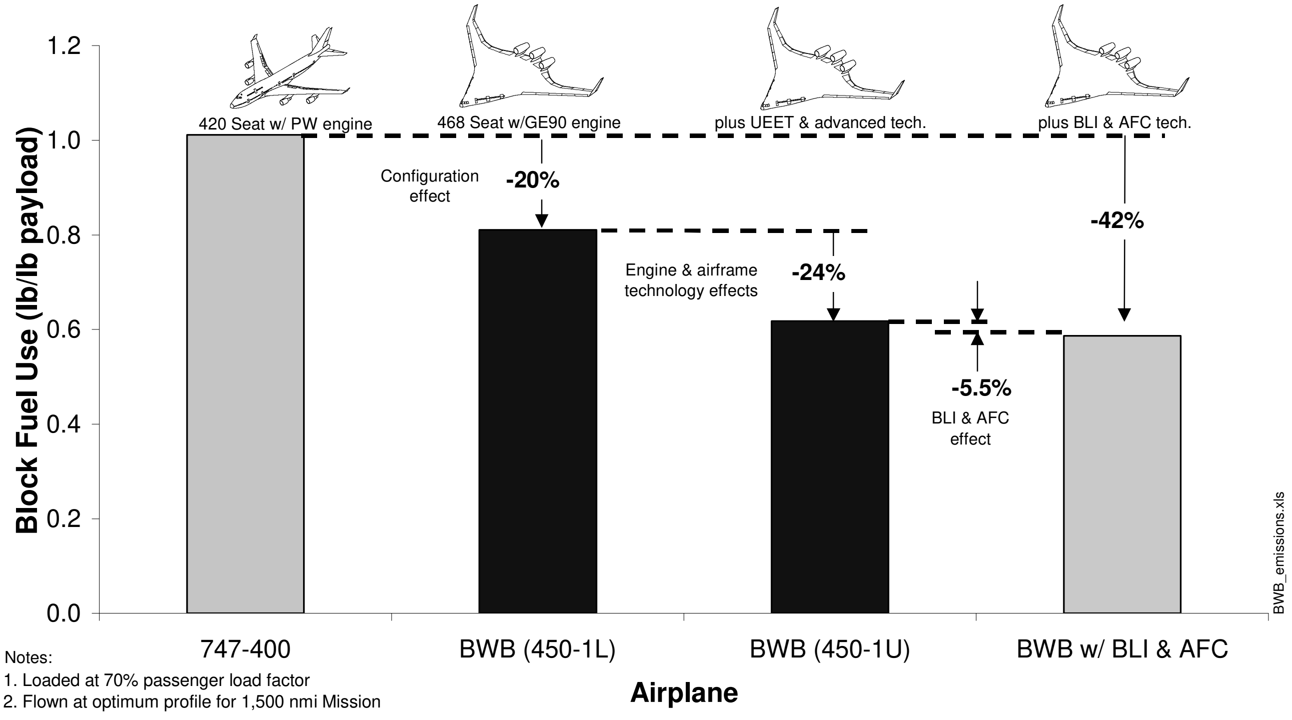


Figure 5.1. Potential fuel savings of BLI with AFC

Buried engine installations with BLI intakes would greatly reduce the airplane frontal and cross sectional areas. This reduction would be beneficial for military applications as it would reduce the radar signature of the airplane. Figure 4.3 shows the comparison between the pylon mounted engine and the buried engine installation.

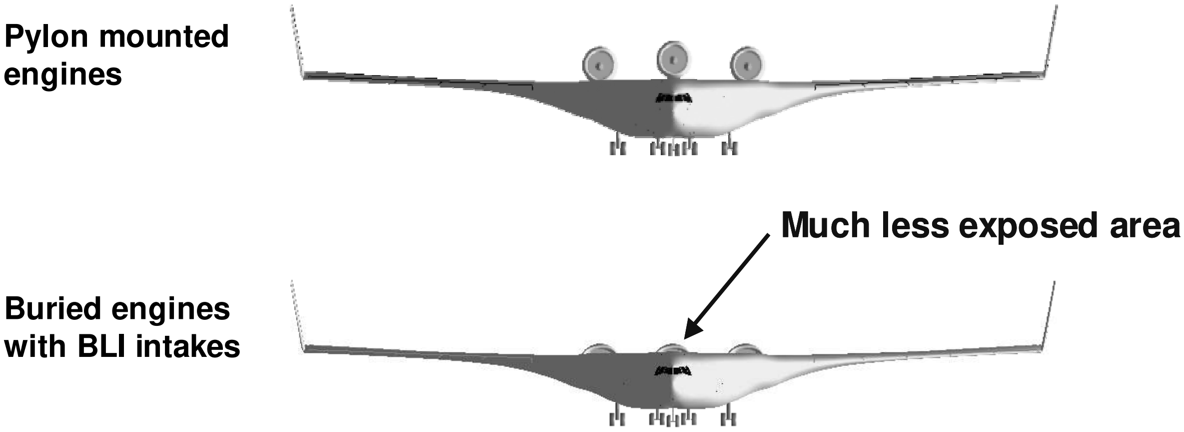
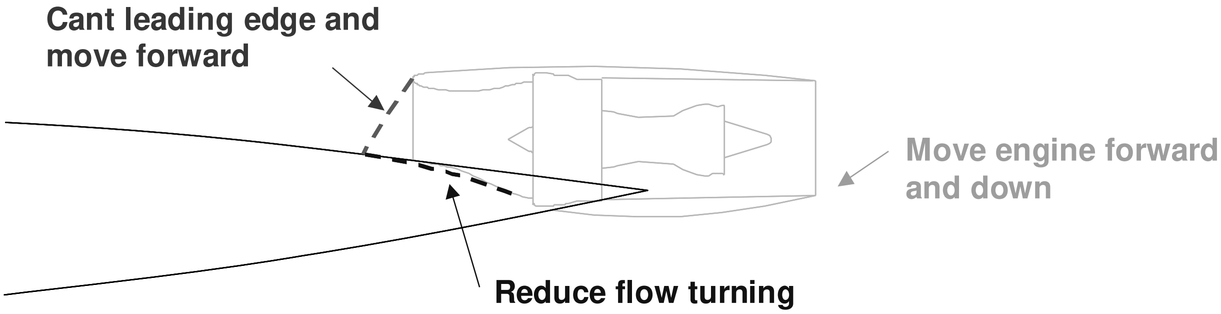


Figure 5.2. Buried engines potential for military applications

Continuing technology development of AFC is needed and recommended in order to achieve the boundary layer control needed for short offset diffusers. Continuing configuration improvements studies are also recommended. Figure 5.3 depicts improvements that may increase the fuel burned benefit beyond the 5 ½%

As noted above, the level of improvement could improved with a lower by-pass ratio engine since it would have a lower penalty for loss in pressure recovery. The overall integrated effect would need to be evaluated since lower by-pass ratio engine would have a higher sfc without BLI.



- Sweep leading edge to reduce back pressure on wing shock
- Enables moving forward to reduce wetted surface area
- Reduces engine support moments
- Reduce lower diffuser surface adverse pressure gradient

Figure 5.3. Suggestions for future follow-on work

REFERENCES

1. Daggett, D.L., et. al. *Ultra-Efficient Engine Technology Systems Integration and Environmental Assessment*, NASA CR 2002-211754, July 2002
2. Daggett, D.L., et. al. *Ultra-Efficient Engine Diameter Study*, NASA CR 2003-C03-003, January 2003.
3. Daggett, D., Kawai, R. and Schuster, E. *UEET Task 33 BWB Systems Studies*, December 2001.
4. Spaid, F. and Wakayama, S., *Living Aircraft, Application of Advanced Technologies to Commercial Transports,* The Boeing Company Final Report under NAS1-20342, October 1999
5. Austin, T., *UEET Task 17: Blended Wing Body Boundary Layer Ingestion Inlet Flow Control Study,* Boeing Final Technical Report, Oct. 2000
6. Austin, T., et. al. *UEET Task 27: System Study of Active Flow Control Enhanced BLI Inlet for BWB Type Aircraft,* The Boeing Company, August 2001
7. Anderson, B. H., *A Study of the Blended Wing Body Outboard Inlet S-Duct with BLI Control,* NASA Glenn Research Center, unpublished report.

APPENDIX A. EMISSIONS

The GE engine used on the BWB concept airplane utilized a low NOx emissions combustor called the “Twin Annular Pre Swirl” (TAPS) combustor as shown in Figure A.1. This combustor is part of the UEET technology suit whose objective was to achieve a 70% reduction in Landing Take Off (LTO) regulatory NOx levels from CAEP 2 levels. Figure A.2 shows that the combustor achieved a 69% NOx level. This is a 50% reduction from current engine technology, such as that of the GE90-94B engine.

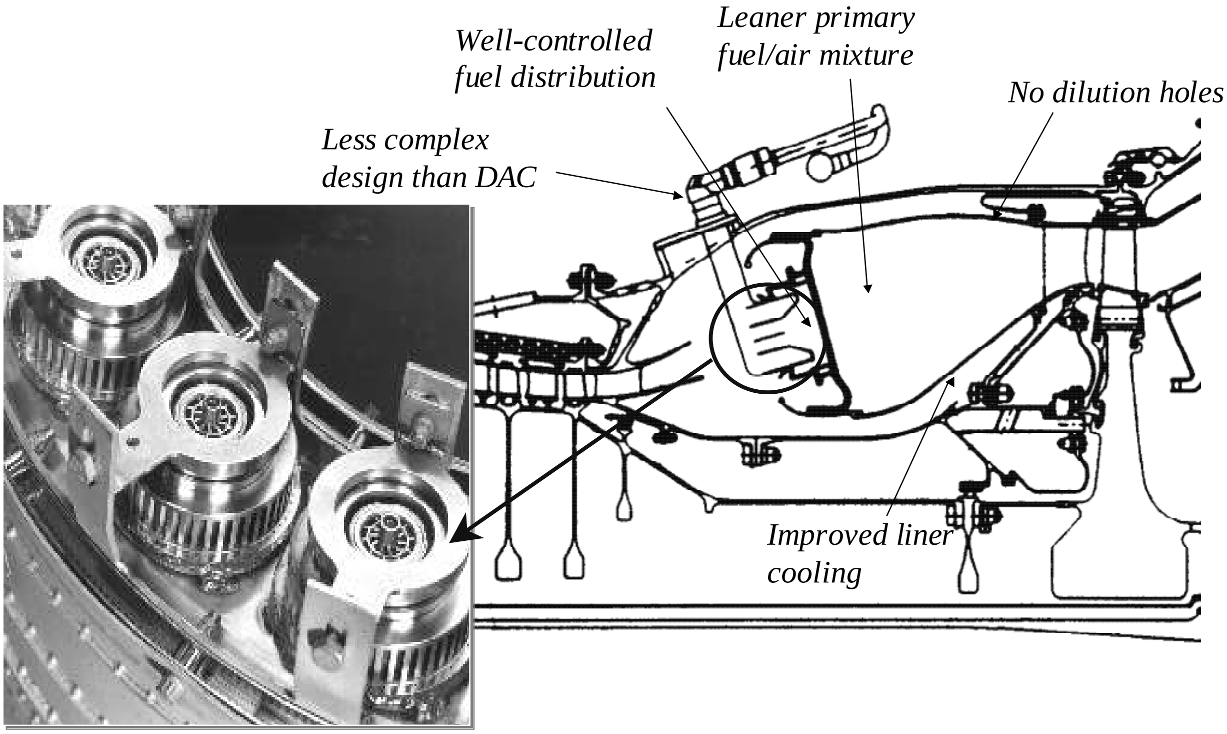


Figure A.1. GE’s low NOx combustor design

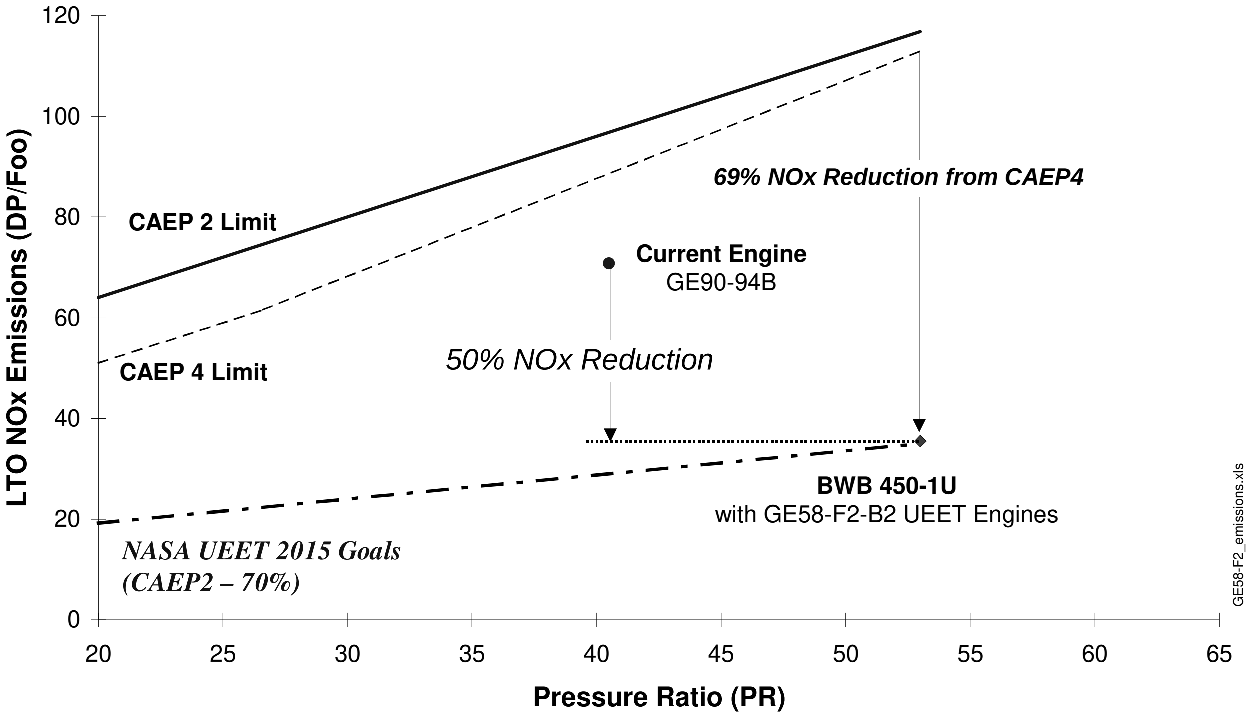


Figure A.2. GE Low NOx combustor emissions level.

Figure A.3 illustrates the GE UEET engine emissions as compared to both current technology GE90 and PW4000 series engines. Regulatory NOx levels are substantially reduced, however, due to combustor tradeoffs, hydrocarbon (HC) and carbon monoxide (CO) emissions increased from the baseline engines. All emissions levels are far below CAEP2 regulatory levels.

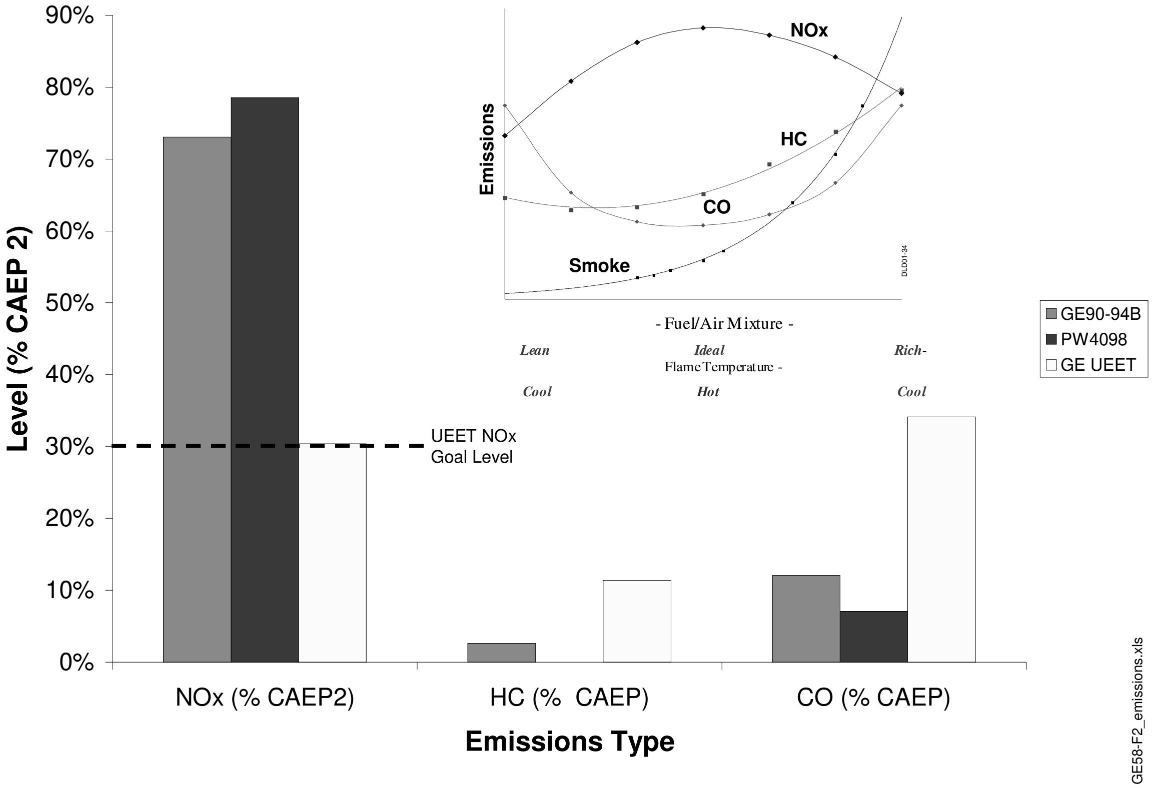


Figure A.3. UEET powerplant emissions levels

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 01- 12 - 2003	**2. REPORT TYPE** Contractor Report	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE
Blended Wing Body Systems Studies: Boundary Layer Ingestion Inlets With Active Flow Control

5a. CONTRACT NUMBER
NAS3-01140

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Daggett, David L.; Kawai, Ron; and Friedman, Doug

5d. PROJECT NUMBER

5e. TASK NUMBER
7

5f. WORK UNIT NUMBER
23-714-05-30

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/CR-2003-212670

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 05
Availability: NASA CASI (301) 621-0390 Distribution: Nonstandard

13. SUPPLEMENTARY NOTES
Langley Technical Monitor: Karl A. Geiselhart
An electronic version can be found at http://techreports.larc.nasa.gov/ltrs/ or http://ntrs.nasa.gov

14. ABSTRACT

A CFD analysis was performed on a Blended Wing Body (BWB) aircraft with advanced, turbofan engines analyzing various inlet configurations atop the aft end of the aircraft. The results are presented showing that the optimal design for best aircraft fuel efficiency would be a configuration with a partially buried engine, short offset diffuser using active flow control, and a "D-shaped" inlet duct that partially ingests the boundary layer air in flight. The CFD models showed that if active flow control technology can be satisfactorily developed, it might be able to control the inlet flow distortion to the engine fan face and reduce the powerplant performance losses to an acceptable level. The weight and surface area drag benefits of a partially submerged engine shows that it might offset the penalties of ingesting the low energy boundary layer air. The combined airplane performance of such a design might deliver approximately 5.5% better aircraft fuel efficiency over a conventionally designed, pod-mounted engine.

15. SUBJECT TERMS
BWB; Boundary layer ingestion; Active flow control; Engine installation

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	39	(301) 621-0390