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Blended Wing Body (BWB) Boundary Layer Ingestion (BLI) Inlet Configuration and System Studies

Ronald T. Kawai, Douglas M. Friedman, and Leonel Serrano
Boeing Phantom Works, Huntington Beach, California

December 2006

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Nomenclature

A, a	Area
AFC	Active Flow Control
AR 2	Aspect Ratio 2
AR 0.86	Aspect Ratio 0.86
BLI	Boundary Layer Ingestion
BPR	By Pass Ratio
BWB	Blended Wing Body Aircraft
CFD	Computational Fluid Dynamics
Cp	Pressure coefficient
CL	Lift coefficient
ESFC	Equivalent Specific Fuel Consumption
ETOPS	Extended Twin Operations
FC	Flow Control (active or passive)
g	Gravitational constant
K	1,000
kts	Nautical miles per hour
lb	Pound
M	Mach number
MTOW	Maximum Take-Off Weight
NASA	National Aeronautics and Space Administration (USA)
nmi	Nautical mile
PAI	Propulsion Airframe Integration
PFC	Passive Flow Control
P, p	Pressure
Pt	Total pressure
R	Universal gas constant
SLST	Sea Level Static Thrust
SFC	Specific Fuel Consumption
T, t	Temperature
Tt	Total temperature
TOGW	Take Off Gross Weight
UEET	Ultra Efficient Engine Technology
V	Velocity
W	Mass flow rate
3-D	Three dimensional
γ	Ratio of specific heats

Subscripts

0	Freestream
1	Inlet Capture
2	Downstream

Foreword

This study was funded by the NASA Langley Research Center as a part of the Ultra Efficient Engine Technology Program, Propulsion Airframe Integration Project managed by Mr. Michael Watt. This study was conducted as a Task Order under the technical direction of Mr. Karl Geiselhart. This task was administered as a part of the Revolutionary Aero Space Engine Research program managed by Mr. Richard Shaw in the Boeing Phantom Works. The study was conducted by the Boeing Phantom Works in Huntington Beach California. Mr. Ronald Kawai was the technical manager. The majority of the technical work was the CFD analyses of BWB configurations with BLI inlets conducted by Mr. Douglas Friedman and Mr. Leonel Serrano. These analyses used the NASA developed OVERFLOW program. Airframe integration and mission performance analyses were done by Mr. Alan Okazaki, Mr. David Bruns, and Mrs. Jennnifer Whitlock.

Executive Summary

This study was conducted by the Boeing Phantom Works under the Ultra Efficient Engine Technology Program 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). Propulsion 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 some boundary layer air.

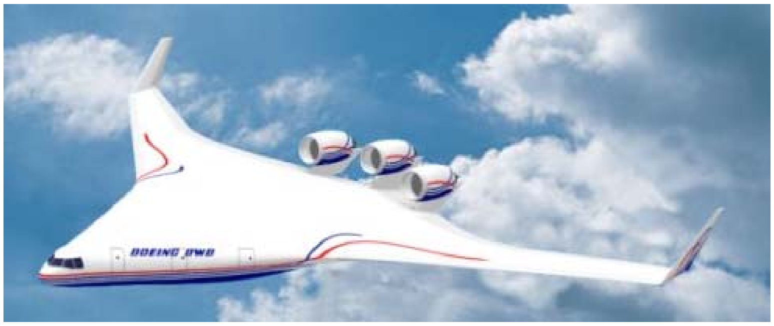
The comparison baseline engine installation design was a low-risk, conventional pylon-mounted turbofan on the aft end of the BWB with the inlet elevated above the boundary layer. More aggressive designs were evaluated to improve the integrated airplane performance. The nacelle was surface mounted with the inlet ingesting the boundary layer to reduce ram drag, and to minimize the total wetted surface area that reduces viscous drag and nacelle weight. Ingesting the boundary layer however, results in a lower inlet total pressure recovery. The lower inlet total pressure recovery results in a lower pressure in the fan nozzle for compression work done. This then results in an offsetting increase in specific fuel consumption. The lower energy boundary layer flow also creates lower total pressure areas resulting in a non-uniform flow pattern at the engine fan face. If this inlet flow distortion is excessive, a fan compression efficiency degradation will result from increasing the fan match area in order to increase the fan stall margin for engine operability. If the distortion exceeds the ability to rematch, maintaining operability would require a major fan redesign resulting in a lower overall efficiency. This operability constraint could be alleviated by controlling the boundary layer flow to limit distortion.

Recent developments in AFC, such as reported in Reference 1, show promise as a means to reduce inlet distortion both by preventing flow separation in a diffuser, and creating more uniform total pressure patterns that can be within engine operability limits. This study was therefore conducted to determine the potential benefits and requirements for AFC to enable boundary layer ingestion inlet configurations that reduce ram and viscous drag and propulsion integration weight to reduce fuel burned and emissions.

The greatest potential benefit of up to a 10% reduction in fuel burned was identified as potentially achievable if AFC can be used for boundary layer control to enable a short offset BLI inlet. The 10% level could be achieved from improved integration that reduced viscous drag and weight but the specific configurations studied suffered from pressure drag that appears to be from external flow separation. It is recommended that continuing work be performed to eliminate the separated flow and evaluate PFC to limit the inlet total pressure distortion to levels within the operability limits of the engine in the event of a failure of the AFC system.

Introduction

This report presents the results from a NASA Langley Research Center sponsored study to determine the potential benefits and requirements for reducing fuel consumption and emissions by employing Boundary Layer Ingesting (BLI) inlets enabled by Active Flow Control (AFC). Boundary layer ingestion has been long recognized as a means to reduce propulsion system ram drag. This drag reduction benefit has been deterred in transport aircraft because the resulting excessive inlet flow distortion exceeded operability limits for highly efficient engines with low noise characteristics. Studies were conducted such as in Reference 1, identifying the emerging AFC technology as a potential method for controlling this distortion. More recently, the experimental work presented in Reference 2, confirms the ability to control this distortion within acceptable levels using AFC. The present study demonstrates the benefits and requirements with recommendations for continuing effort to lead to a practical improved propulsion airframe integrated system. The use of BLI should result in the greatest ram drag reduction where the maximum boundary layer thickness is present. A revolutionary configuration, described in Reference 3, was selected having the greatest opportunity with the engines located on the upper aft surface of the airplane. This study was based on the Blended Wing Body airplane configuration depicted in Figure 1. The configuration was developed for this evaluation and reported in Reference 4. A recent chronology describing the features of a BWB type airplane is presented in Reference 5.



BWB Model 450-1U

Thrust:	**63K (SLS)**
Payload :	**98,280 lb.**
Design Range:	**7750 nmi**
Engine Type:	**BPR 11 Direct Drive Fan**

Figure 1. Baseline Blended Wing-Body trijet configuration used for this study.

The BWB 450 is powered by 3 UEET direct drive turbofan engines. The engines are installed in podded nacelles supported by struts with the inlets located above the boundary layer. A previous study to determine the potential benefit from BLI inlets with AFC on this configuration was conducted in

Reference 6. This previous study assessed the benefit potential at a 5 ½% reduction in fuel burned and emissions. The study was based on a nacelle substitution bases wherein the podded nacelles were replaced by BLI inlet nacelles and the benefit in airframe drag estimated by factoring the total airplane viscous drag from the change in total airplane wetted surface area. This simplified method considered only the first-order airframe integration effects. This current study was therefore conducted by using a full viscous Navier-Stokes analysis of the airplane with the inlet operating at typical mass flow ratios. The drag and lift were calculated using the NASA developed OVERFLOW Computational Fluid Dynamics (CFD) code. The first BWB BLI inlet configuration analyzed was the “30% [delta/height]” configuration designed in Task Order #7. It had a highlight width to height aspect ratio (AR) of 2. This BWB configuration in shown in Figure 2.

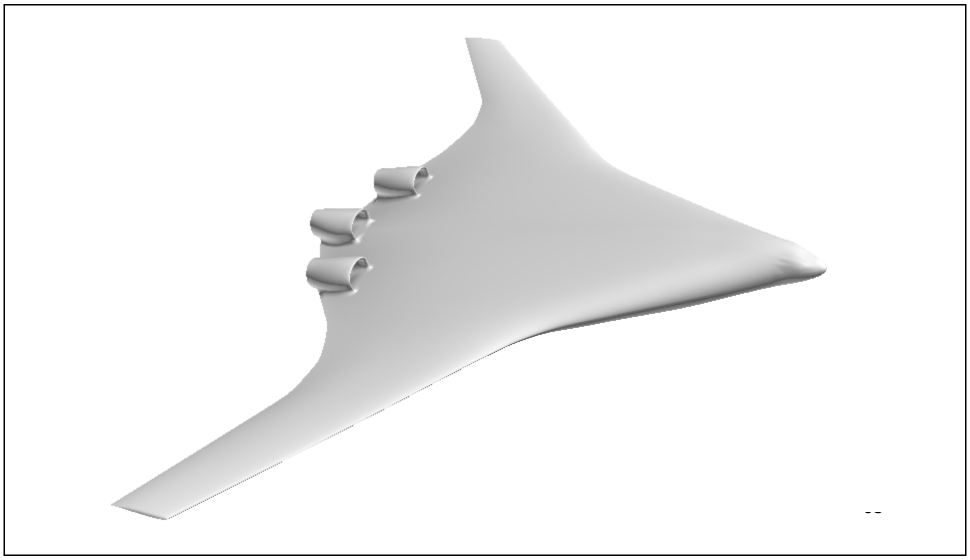


Figure 2. BWB-450 with AR (Aspect Ratio = width/height) 2.0 BLI Inlets.

The installed inlet configuration developed for CFD analyses is show in Figure 3. The nacelle was designed for a short fan duct and the core cowl and primary exhaust nozzle were not included because most of the CFD analyses were done with flow through nacelles.

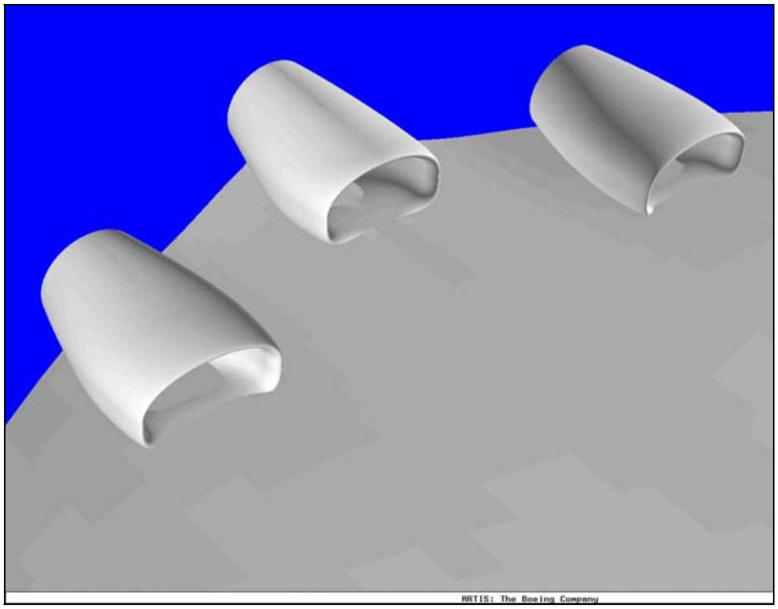


Figure 3. Close-up of AR=2 inlets without fillets.

A second configuration with a lower width to height ratio (AR 0.86) was also studied. This configuration was designed to do two things: (1) reduce the boundary layer ingestion in order to reduce the total pressure distortion, and (2) decrease the divergence in the external channel flow between the nacelles. The second configuration is shown in Figure 4.

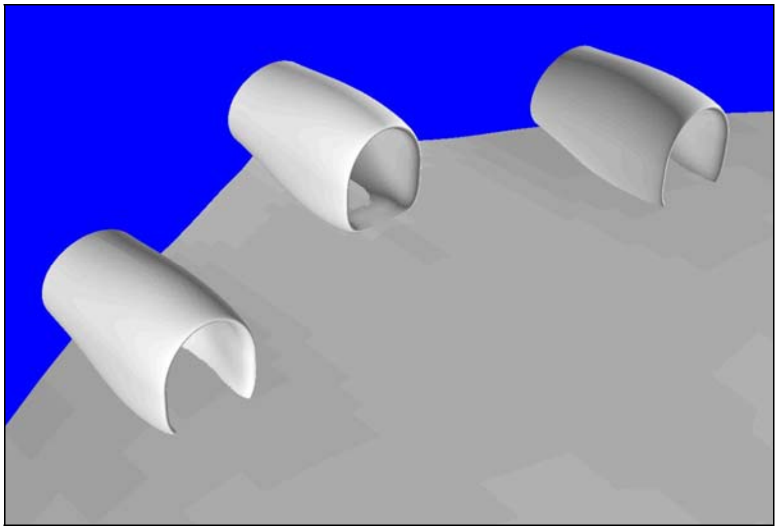


Figure 4. Close-up of AR=0.86 inlets without fillets.

A variation of this second configuration included canting of the outboard nacelle in order to align the inlet with the local onset flow angle. This was done in an effort to further reduce inlet distortion and drag. This third configuration is shown in Figure 5.

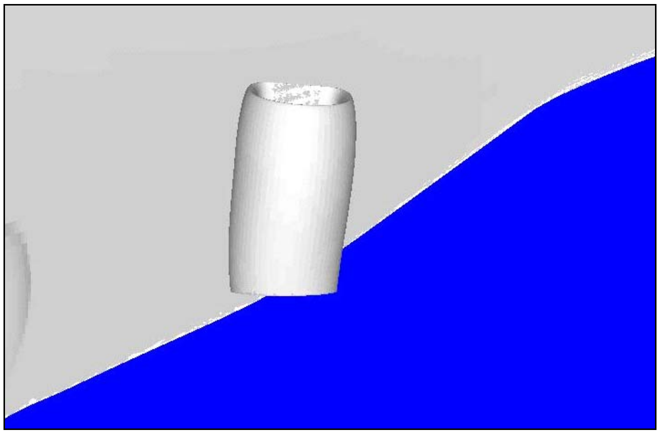


Figure 5. AR=0.86 outboard nacelle with inlet canted outboard 4.5 degrees.

A fourth configuration was developed by the addition of a boundary layer diverter “bump” just forward of the inlets, as shown in Figure 6.

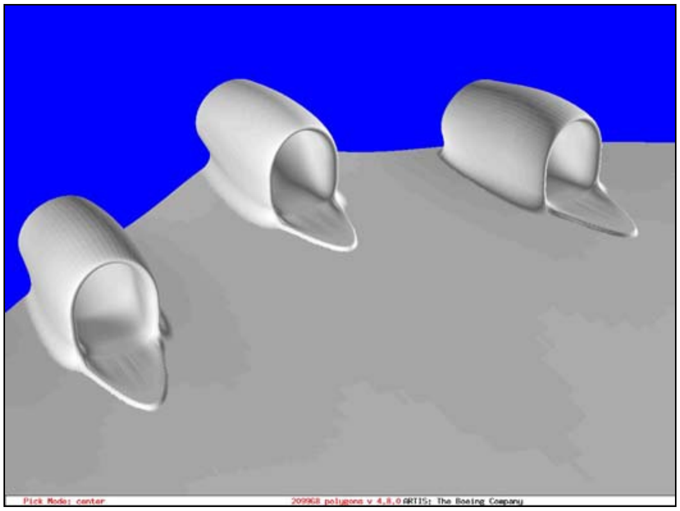


Figure 6. AR=0.86 nacelles with outboard canting and diverter "bumps."

As noted below, calculating the ram drag reduction from boundary layer ingestion directly on a BWB is difficult. Analysis on a flat plate with the inlet mass flow ratio of unity is straightforward. On a BWB this difficulty is because the separation between the stream tube entering the inlet and the flow by-passing the inlet can not be readily defined.

THRUST-DRAG ACCOUNTING ISSUES:

- Classical division between engine and airframe is easy to define for strut-mounted nacelles.

- Highly integrated geometries, such as BLI nacelles, cloud differentiation of engine and airframe: where does the airframe stop and the engine begin?

Figure 7 depicts the changes in the flow path of the boundary layer flow on a BWB before entering a BLI inlet. The flow accelerates around the forebody, passes through an adverse pressure gradient through the shock structure and then diffuses from the wing/body upper flow field and further from external inlet flow diffusion.

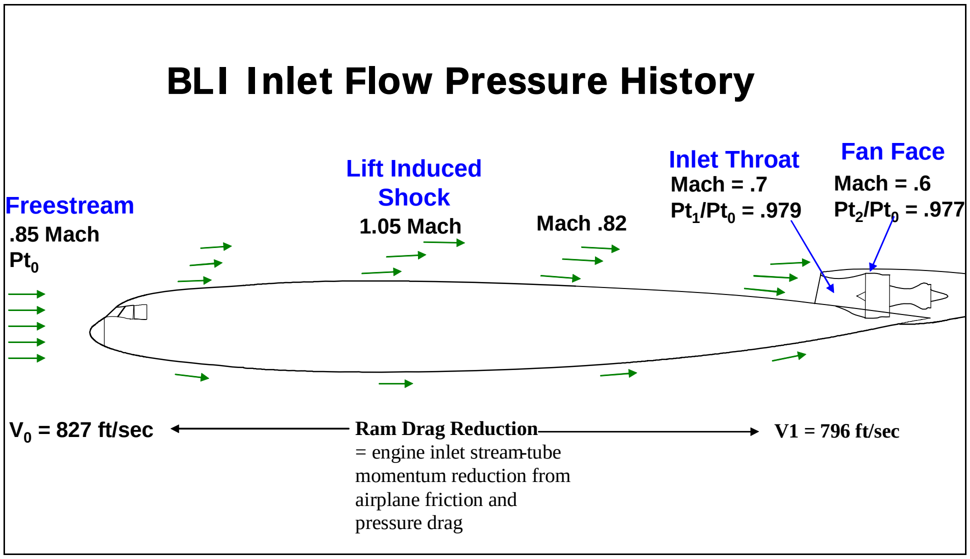
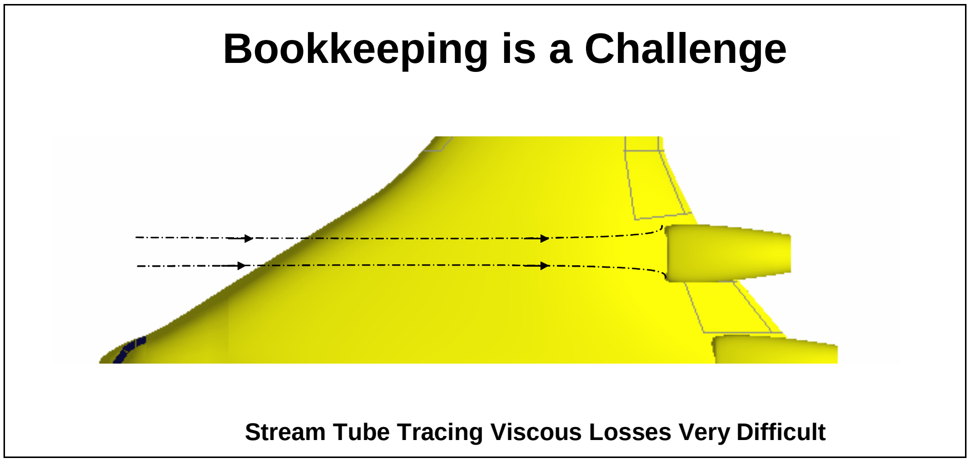


Figure 7. Typical BLI inlet flow pressure history.

On an airplane during cruise, the inlet mass flow ratio is less than unity and as depicted in Figure 8, the flow entering the inlet includes the viscous losses of the propulsion flow stream-tube but the actual boundary between the inlet stream-tube scrubbed surface and the by-passed flow is not readily defined. This inlet stream tube may also have a varying cross section as it passes over the BWB upper surface. Further, some form drag from the flow accelerating around the fore-body and deceleration on the after-body is in the inlet stream-tube. In addition, at high speed flight, there are compressibility losses since the flow around the BWB upper surface becomes supersonic and then shocks back down to subsonic just upstream of the inlets.

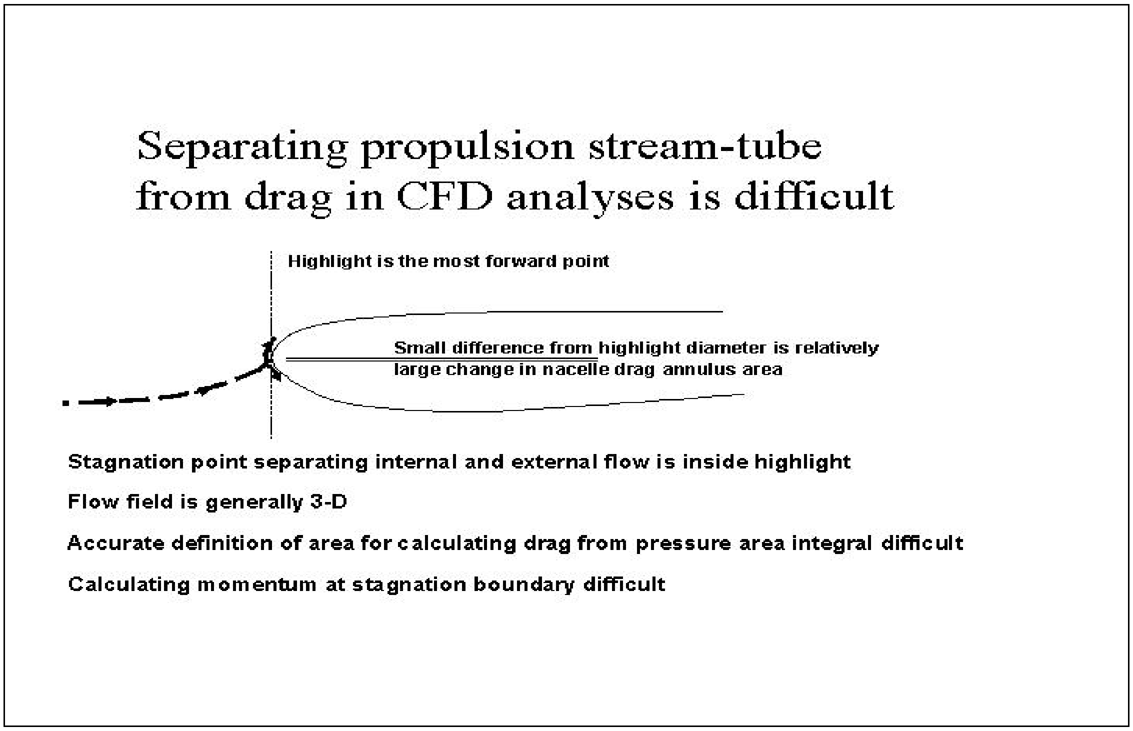


Bookkeeping is a Challenge

Stream Tube Tracing Viscous Losses Very Difficult

Figure 8. BLI inlets ingest flow that has scrubbed varying portions of the wing.

Another difficulty in determining a surface pressure area integral is locating the separation boundary between internal and external flow. A relatively small change in the location of the dividing streamline can have a large change in the calculated nacelle drag. As shown in Figure 9, this dividing line is inside of the highlight when the inlet mass flow ratio is less than unity and moves upward or downward with changes in mass flow ratio.



Separating propulsion stream-tube from drag in CFD analyses is difficult

Highlight is the most forward point

Small difference from highlight diameter is relatively large change in nacelle drag annulus area

Stagnation point separating internal and external flow is inside highlight

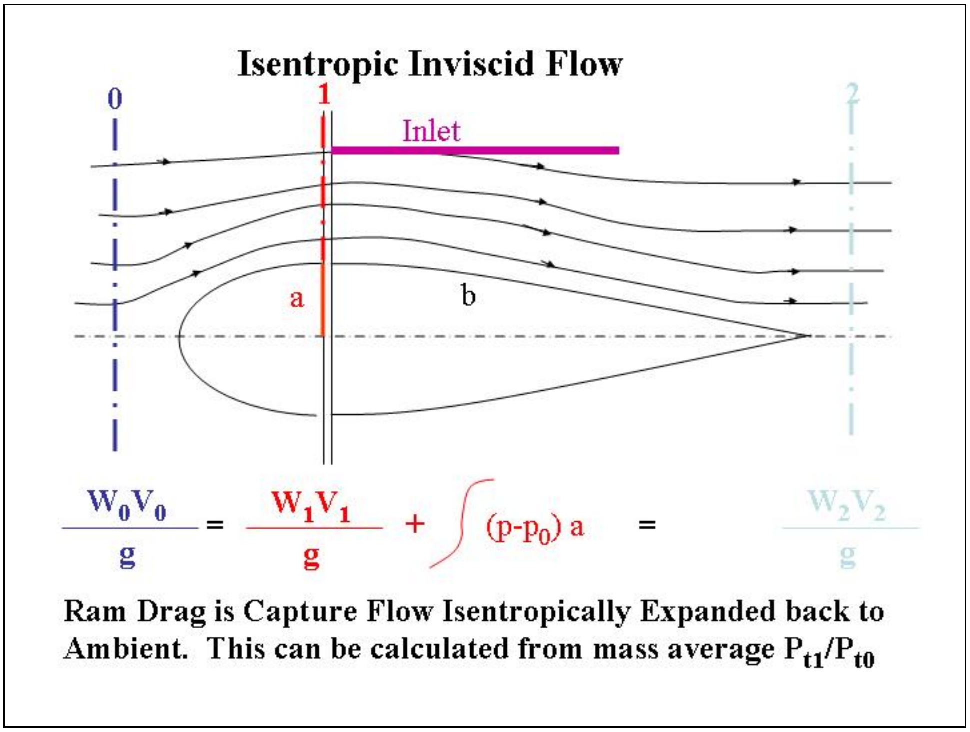
Flow field is generally 3-D

Accurate definition of area for calculating drag from pressure area integral difficult

Calculating momentum at stagnation boundary difficult

Figure 9. Difficulty of separating engine from airframe in CFD analyses.

The analyses conducted herein therefore determine the reduction in ram drag from BLI based on calculating the mass averaged total pressure of the flow entering the inlet using a freestream reference. The forebody force is removed by determining the inlet momentum for the flow with isentropic diffusion back to ambient pressure. As depicted in Figure 10, this method corrects for the flow acceleration around a forebody that creates a forward force which, in inviscid flow would be countered by diffusion back to freestream or ambient conditions.



Isentropic Inviscid Flow

$$\frac{W_0 V_0}{g} = \frac{W_1 V_1}{g} + \int (p-p_0)\, a = \frac{W_2 V_2}{g}$$

Ram Drag is Capture Flow Isentropically Expanded back to Ambient. This can be calculated from mass average P_{t1}/P_{t0}

Figure 10. Method for computing ram drag.

One dimensional isentropic flow functions noted in Figure 11 were used.

One Dimensional Flow Mometum Ratio

Pt/P = $\left[1 + \frac{(\gamma-1)}{2} M^2\right]^{\frac{\gamma}{\gamma-1}}$ **Tt/T =** $\left[1 + \frac{(\gamma-1)}{2} M^2\right]$

$\gamma = 1.4$ $(\gamma-1) = .4$ $\frac{(\gamma-1)}{2} =$ **0.2** $\frac{\gamma}{\gamma-1}$ **= 3.5** **V1 = M1** $\sqrt{\gamma \text{ gRT1}}$

g = 32.174 R = 53.35

= **49.02 x M1** $\sqrt{\text{T1}}$

M0 = 0.85 **Alt = 39,000 ft** **T0 = 390.0 R** **P0 = 2.854 psia = 410.98 psf**

Tt = 446.355 **Pt = 659.1374 psf**

Pt1/Pt0 =(Pt1/P1)/Pt0/P0) for flow expansion to P1 = P0

Figure 11. Inlet capture V! for ram drag determination.

From the mass averaged total pressure, the ram drag velocity for the capture total pressure is calculated . From this, the ram drag to freestream velocity ratio, which is the momentum ratio, is then determined. The results versus inlet capture pressure recovery is shown in Figure 12.

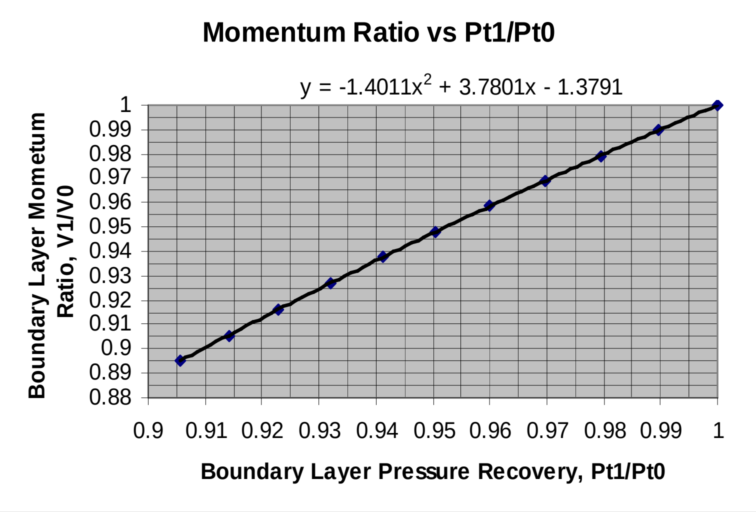
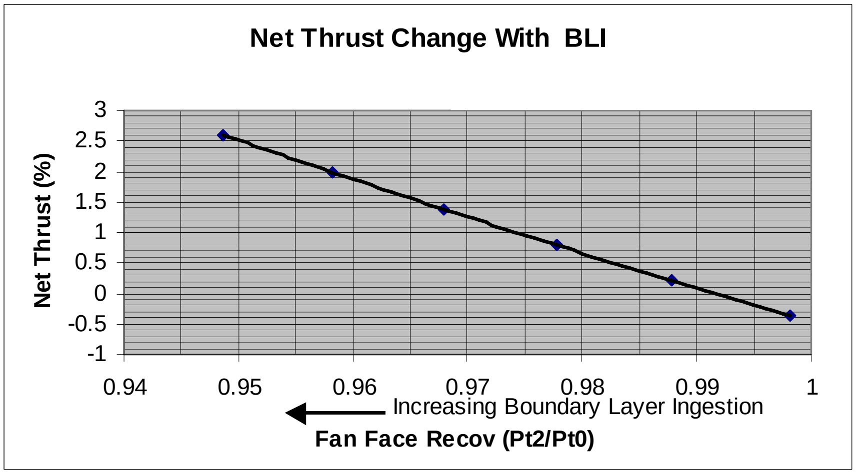


Figure 12. Variation of BL momentum ratio (V1/V0) with total pressure recovery ratio (PT1/PT0).

A cycle model of the UEET study engine was used to determine the ram drag to net thrust ratio. This factor is used to determine the change in net thrust from the reduction in ram drag. The same cycle model was used to determine the net thrust loss from the loss in inlet pressure recovery. The loss in net thrust was calculated for all of the total pressure losses in the fan by-pass flow. Combining the ram drag reduction with the net thrust can then be shown versus inlet pressure recovery. This net change in propulsive force is shown in Figure 13. The results shows that while there is a relatively large reduction in ram drag with boundary layer ingestion, it is largely offset by the engine performance loss from the lower total pressure recovery.



Note: Does not include engine losses that may result from distortion

Figure 13. Variation of net thrust with fan face recovery ratio (PT2/PT0).

These results are based on the engine maintaining operability with no change in match required by the fan due to distortion. If the distortion is excessive, as depicted in Figure 14, the fan operating line would need to be shifted by opening the fan nozzle area. This would result in a further loss in fan efficiency.

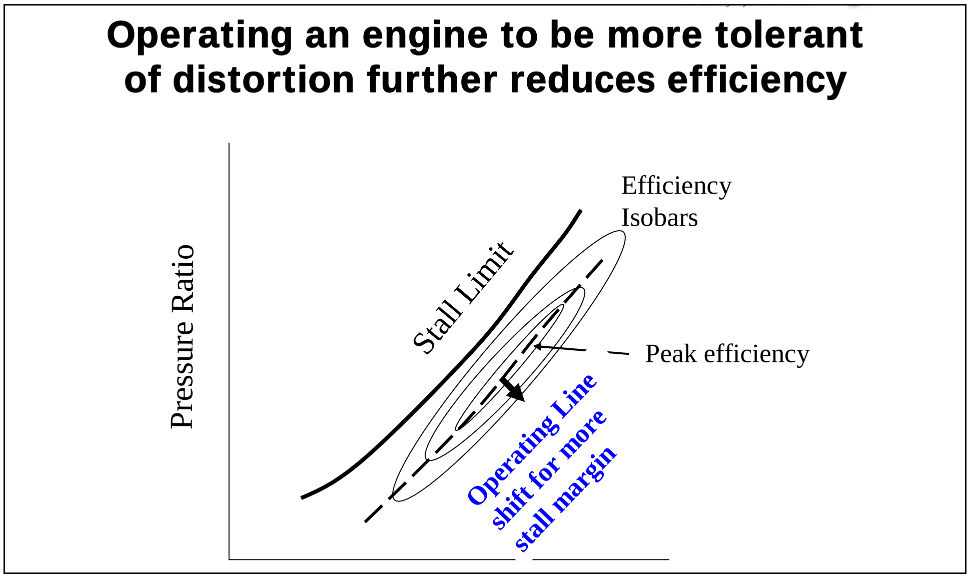


Figure 14. Explanation of how distortion effects engine efficiency.

The effect on engine efficiency was determined with the results shown in Figure 15. These results assume that the distortion level could be accommodated by a rematch. Based on experience, it appears that the actual distortion levels calculated exceeded the ability for a rematch. In any event, the effect on engine SFC is shown in Figure 15. The additional 10% to 15% loss in SFC would be prohibitive. Flow control is therefore needed for distortion control and AFC is a promising means to accomplish this.

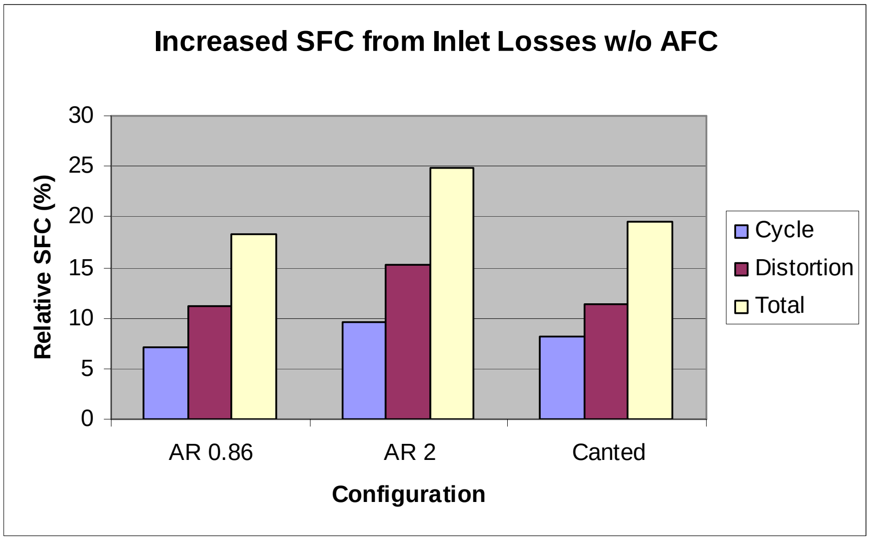


Figure 15. Effect of cycle and distortion on engine SFC.

Integration of the BLI inlet configurations that places the nacelle on the surface, versus elevated on struts, results in a large reduction in wetted surface area which results in a large reduction in viscous drag as shown in Figure 16. The viscous drag reduction is much greater than the reduction in wetted area would suggest because the lower local Reynolds Number on the podded nacelle results in a higher nacelle surface skin friction coefficient than the airplane average. Reducing the strut-mounted nacelle wetted area thus results in a disproportionately larger reduction in viscous drag. This result also shows that the effect of nacelle changes on a BWB type must be evaluated based on an analysis of the whole airplane.

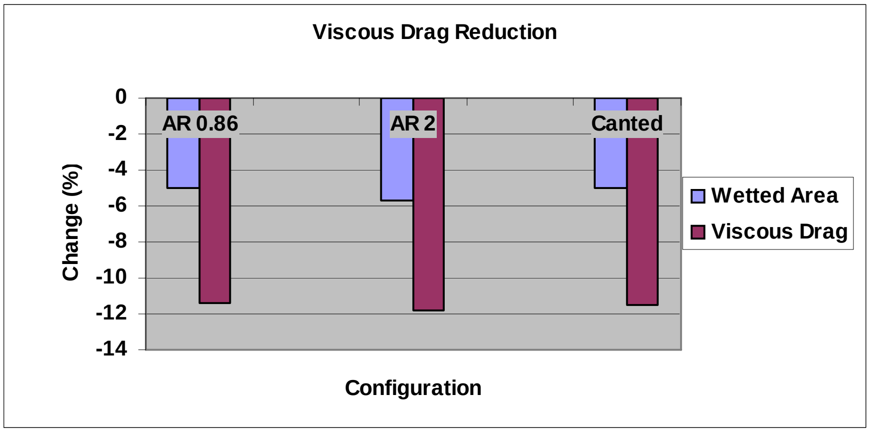


Figure 16. Effect of wetted area on drag.

The configurations as analyzed resulted in a large reduction in viscous drag but an even larger increase in pressure drag still resulted in a net increase in total drag. These results are shown in Figure 17.

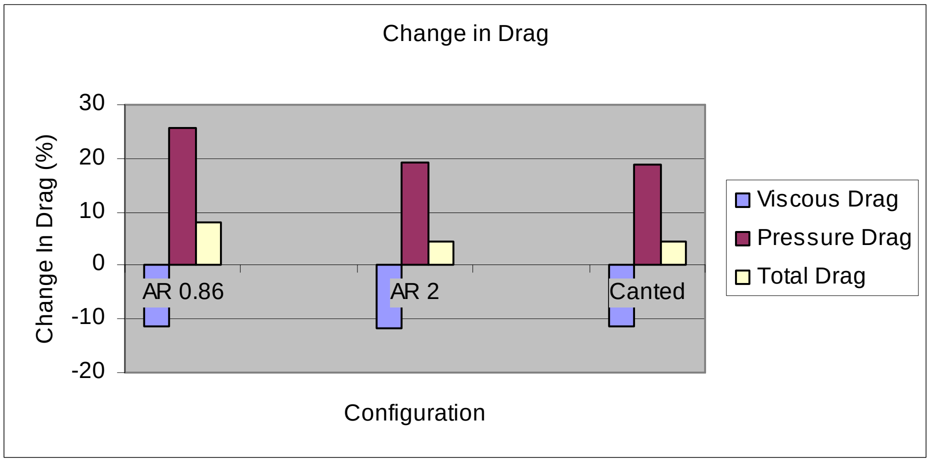


Figure 17. Relative contributions of pressure and viscous drag to total drag.

Relative to the strut-mounted configuration, the lift coefficient, CL, of the BLI configurations at constant angle of attack increased. This showed that the loss in lift from the increase in surface static pressure due to external flow diffusion ahead of the inlet was more than recovered from re-acceleration of the flow around the nacelle. Investigation of the surface pressure distributions and flow patterns as shown in Figure 18, shows there are supersonic zones and localized flow separation even for the improved channel flow design of the lower AR nacelles. It is therefore believed that additional work can reduce the pressure drag while maintaining CL.

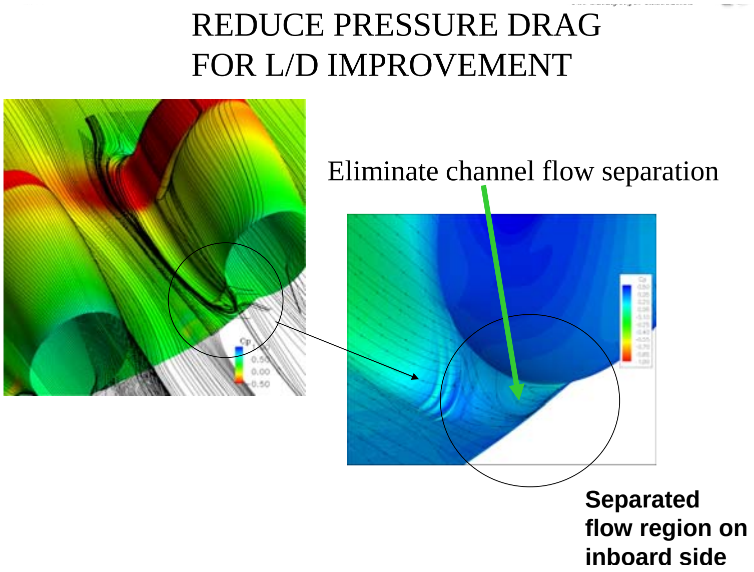
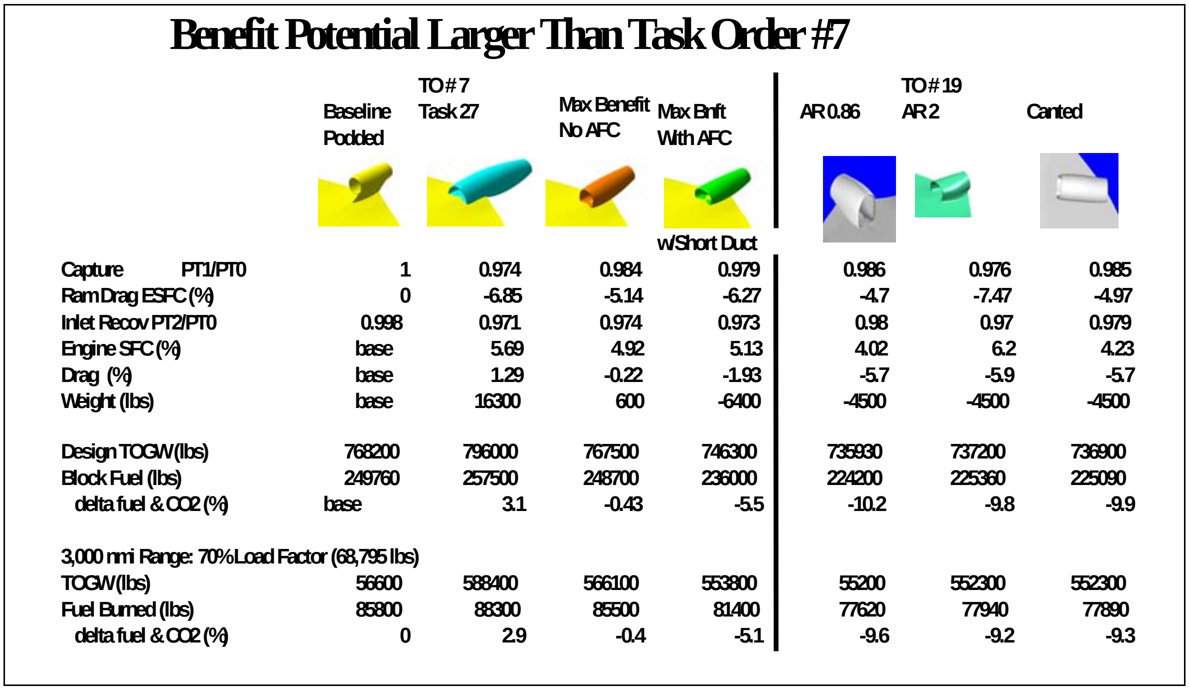


Figure 18. Areas for possible reduction of pressure drag.

The potential for configurations enabled by AFC is therefore maintaining the pressure drag level of the strut-mounted nacelles with the reduced drag and weight of the BLI nacelles. This improvement requires reducing inlet distortion to acceptable levels for engine operability. The results from Reference 2 show this is achievable and should require only a fraction of the actuator flow used there because of the shorter diffuser with less offset in this study. A system optimization, as shown below, resulted in a lower fuel burned for the AR 0.86 configuration than the AR 2. This would further decrease the demands on the FC system by reducing the level of BLI reducing distortion levels.

Using the viscous drag and weight reduction from the BLI inlet configurations with the pressure drag levels from the strut-mounted installations is then the benefit potential enabled by AFC. The results from these drag level are shown in Figure 19. The results are compared to the results from Reference 6 which was done under RASER Task Order #7. The greater improvement potential is primarily due to the proper analyses of viscous changes where reductions in nacelle drag account for local Reynolds Number effects.



Benefit Potential Larger Than Task Order #7

	Baseline Podded	TO # 7 Task 27	Max Benefit No AFC	Max Bnft With AFC w/Short Duct	AR 0.86	TO # 19 AR 2	Canted
Capture PT1/PT0	1	0.974	0.984	0.979	0.986	0.976	0.985
Ram Drag ESFC (%)	0	-6.85	-5.14	-6.27	-4.7	-7.47	-4.97
Inlet Recov PT2/PT0	0.998	0.971	0.974	0.973	0.98	0.97	0.979
Engine SFC (%)	base	5.69	4.92	5.13	4.02	6.2	4.23
Drag (%)	base	1.29	-0.22	-1.93	-5.7	-5.9	-5.7
Weight (lbs)	base	16300	600	-6400	-4500	-4500	-4500
Design TOGW (lbs)	768200	796000	767500	746300	735930	737200	736900
Block Fuel (lbs)	249760	257500	248700	236000	224200	225360	225090
delta fuel & CO2 (%)	base	3.1	-0.43	-5.5	-10.2	-9.8	-9.9
3,000 nmi Range: 70% Load Factor (68,795 lbs)							
TOGW (lbs)	56600	588400	566100	553800	55200	552300	552300
Fuel Burned (lbs)	85800	88300	85500	81400	77620	77940	77890
delta fuel & CO2 (%)	0	2.9	-0.4	-5.1	-9.6	-9.2	-9.3

Figure 19. Comparison of podded and BLI nacelle installations.

Another consideration is the unknown reliability of AFC actuators. Engines in modern transport aircraft are extremely reliable, as testified by use of twins in ETOPS operations. In order to avoid redundancy that in itself increases the probability of a malfunction due to a larger number of components, it is recommended that AFC system be fail operational. A twin airplane is fail safe in that continued safe flight is maintained with a single engine failure. Maintaining flight reliability would, however, require that an AFC system failure not significantly increase engine failure rates. Thus it is recommended that the degree of BLI be limited to that for which engine operability can be maintained with an AFC system failure. This could conceivably be use of a combination of PFC (e.g. fixed vortex generators) along with AFC actuators.

Conclusions

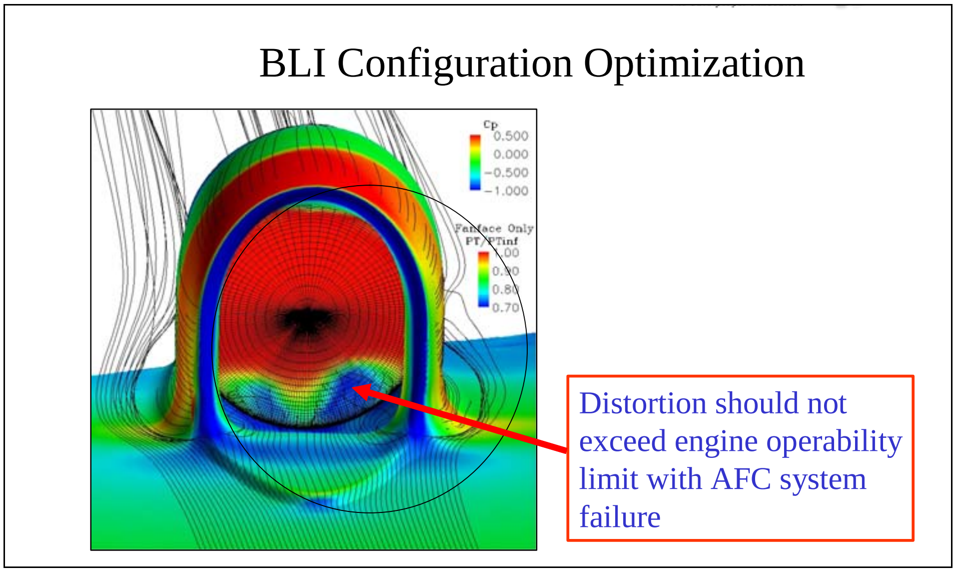
The conclusions from this study are listed in Figure 20. AFC shows the potential for a 10% reduction in fuel burned, and hence emissions on a BWB. The benefits are largely due to the ability to flush mount the engine with a short offset diffuser. Further investigations are warranted to optimize the configurations to reduce pressure drag.

CONCLUSIONS

- **AFC should enable a short offset BLI inlet resulting in large reductions in wetted surface area to potentially reduce fuel burned 10%**
- **Full airplane analyses are required to assess changes on a BWB**
- **BLI results in a large reduction in ram drag but this is largely offset by the reduced total pressure**
- **recovery**
  BLI inlet is still needed for flush engine mounting to achieve the benefits
- **Further investigations should be conducted including a risk assessment**

Figure 20. Summary of conclusions.

These optimizations should take reliability into consideration as a part of the investigation for fail-operational systems, particularly since maximizing the degree of BLI is not as beneficial as reducing wetted area. This is depicted in Figure 21.



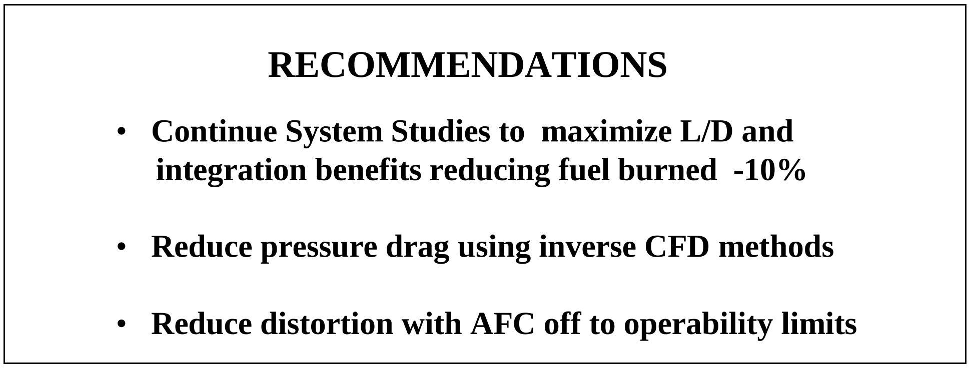
BLI Configuration Optimization

Distortion should not exceed engine operability limit with AFC system failure

Figure 21. CFD solution of BLI installation with "bump" type diverter.

Recommendations

Since there is a large potential improvement in reducing fuel burned and emission from BLI inlets with AFC, continuing study is recommended. The recommendations are listed in Figure 22. The continuing effort can use inverse methods to reduce pressure drag. The reliability issues should be included using AFC where the significant benefits can be the ability to vary control. A combination of fixed vane vortex generators with AFC to provide the variability function should be explored.



RECOMMENDATIONS

- **Continue System Studies to maximize L/D and integration benefits reducing fuel burned -10%**
- **Reduce pressure drag using inverse CFD methods**
- **Reduce distortion with AFC off to operability limits**

Figure 21. Recommendations for future work.

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14. ABSTRACT

A study was conducted to determine the potential reduction in fuel burned for BLI (boundary layer ingestion) inlets on a BWB (blended wing body) airplane employing AFC (active flow control). The BWB is a revolutionary type airplane configuration with engines on the aft upper surface where thick boundary layer offers the greatest opportunity for ram drag reduction. AFC is an emerging technology for boundary layer control. Several BLI inlet configurations were analyzed in the NASA-developed RANS Overflow CFD code. The study determined that, while large reductions in ram drag result from BLI, lower inlet pressure recovery produces engine performance penalties that largely offset this ram drag reduction. AFC could, however, enable a short BLI inlet that allows surface mounting of the engine which, when coupled with a short diffuser, would significantly reduce drag and weight for a potential 10% reduction in fuel burned. Continuing studies are therefore recommended to achieve this reduction in fuel burned considering the use of more modest amounts of BLI coupled with both AFC and PFC (Passive Flow Control) to produce a fail-operational system.

15. SUBJECT TERMS
BWB, Boundary Layer Ingestion, Active Flow Control, Engine Installation, CFD, Overflow

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