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Aircraft System Study of Boundary Layer Ingesting Propulsion

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A trade-factor-based system study has been carried out to identify fuel burn benefits associated with boundary layer ingestion (BLI) for generation-after-next (N+2) aircraft and propulsion system concepts. The analysis includes detailed propulsion system engine cycle modeling for a next-generation, Ultra-High-Bypass (UHB) propulsion system with BLI using the Numerical Propulsion System Simulation (NPSS) computational model. Cycle modeling was supplemented with one-dimensional theory to identify limiting theoretical BLI benefits associated with the blended wing body reference vehicle used in the study. The system study employed low-order models of engine extractions associated with inlet flow control; nacelle weight and drag; fan performance; and inlet pressure losses. Aircraft trade factors were used to estimate block fuel burn reduction for a long-range commercial transport mission. Results of the study showed that a 3-5% BLI fuel burn benefit can be achieved for N+2 aircraft relative to a baseline high-performance, pylon-mounted, UHB propulsion system. High-performance, distortion-tolerant turbomachinery, and low-loss, low-drag inlet systems, were identified as key enabling technologies. Larger benefits were estimated for N+3 configurations for which larger fractions of aircraft boundary layer can be ingested.

Nomenclature

A	=	area (in.^{2})
AR	=	inlet aspect ratio (w / h)
c, C	=	aircraft chord (ft or in.)
D	=	amount of aircraft viscous drag ingested by propulsion systems (lbf)
F_n, F_N	=	engine net thrust (lbf)
FB	=	fuel burn (lbs)
h	=	inlet height (ft or in.)
H	=	boundary layer shape factor (δ^* / θ)
k	=	boundary layer pseudo-energy thickness (in.)
K	=	boundary layer pseudo-energy factor (k / θ)
M	=	Mach number
n	=	unit surface vector

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P	=	pressure (psi)
P_T, P_t	=	total pressure (psi)
R	=	wake recovery factor ($1-\Delta_j/\Delta_0$)
T	=	thrust (lbf); temperature (°R)
U	=	velocity (ft / s)
V	=	free stream velocity (ft / s)
V_x	=	axial component of free stream velocity (ft / s)
w, W	=	inlet width (ft or in.)
x, X	=	axial coordinate or dimension (in.)
y	=	transverse or vertical coordinate or dimension (in.)

Greek:

δ^*	=	boundary layer displacement thickness (in.)
Δ	=	wake velocity defect relative to freestream or jet velocity condition
ρ	=	density (slug / ft^3)
τ	=	wall shear stress (psf)
θ	=	boundary layer momentum thickness (in.)

Subscripts / Superscripts:

∞, 0	=	freestream condition
j	=	propulsion system jet velocity condition
MA	=	mass averaged quantity
s	=	static condition
T	=	stagnation condition
x	=	axial component

I. Introduction

A key goal of next-generation propulsion systems is to provide continued reductions in fuel burn relative to the best gas turbine engines in development today. One path to achieve this is to enable boundary layer ingesting (BLI) propulsion systems, which can provide significant improvements in propulsive efficiency by producing thrust from the reduced velocity boundary layer air. The next generation of ultra-high bypass (UHB) turbofan propulsion systems will feature bypass ratios between 15 and 18 and fan pressure ratios in the 1.25 – 1.35 range. Such engine cycles will result in significantly reduced thrust specific fuel consumption (TSFC). The implementation of this class of propulsion system in a boundary layer ingesting environment would provide substantial vehicle-level fuel burn benefits for N+2 and N+3 aircraft. A key challenge associated with boundary layer ingesting propulsion systems is the ability of the turbomachinery to operate efficiently in highly distorted flow. In particular, a high-performance, distortion-tolerant fan will be required. This paper describes a system study of a BLI propulsion system conducted under NASA sponsorship. The overall goal of the contract was to design a boundary layer ingesting fan with less than a 2% reduction in fan efficiency at cruise and less than a 2% reduction in stall margin relative to a clean-inflow baseline. As a precursor to the detailed inlet and fan design, a high-level, trade-factor-based aircraft system study was carried out to identify the most attractive regions of propulsion system design space. The study showed that compact-inlet, aft-mounted propulsion systems (Figure 1) can provide on the order of a 3 – 5% fuel burn reduction relative to a clean-inflow, pylon-mounted, advanced UHB baseline.

[1]Blended Wing Body geometry from the Boeing Company, Kawai, R. T., Friedman, D. L., and Serrano, L., *Blended Wing Body (BWB) Boundary Layer Ingestion (BLI) Inlet Configuration and System Studies,* NASA CR-2006-213534, December 2006.

Figure 1. Blended Wing Body Aircraft with Aft-Mounted Boundary Layer Ingesting Propulsion System

When considering system-level performance for advanced aircraft with BLI propulsion, the usual separation of the performance of the aircraft and the propulsion system is more difficult than for traditional aircraft. Pylon-mounted (podded) engines in conventional installations ingest clean, free stream flow at the cruise design point. The approach of separating the engine from the airframe is implemented by defining stream tubes upstream and downstream of the engine (Figure 2). The flow and components inside these stream tubes belong to the engine manufacturer and components outside the stream tubes belong to the airframe with the possible exception that the external surface of the nacelle may be included in the engine accounting.

Figure 2. Stream Tubes Divide the Engine Internal Flow from the Airframe Flow

Normal propulsion bookkeeping accounting for ram drag, inlet pressure recovery, cycle efficiency, and thrust production can adequately describe the propulsion system performance. Off-design performance requires incorporating the concepts of additive drag, spillage drag, etc., to account for situations where the stream tubes are

not cylinders and the inlet and/or exit conditions do not match free-stream conditions. Aircraft performance is well-described with the typical parameters of weight, airframe drag, nacelle drag, and interference drag associated with the propulsion system installation.

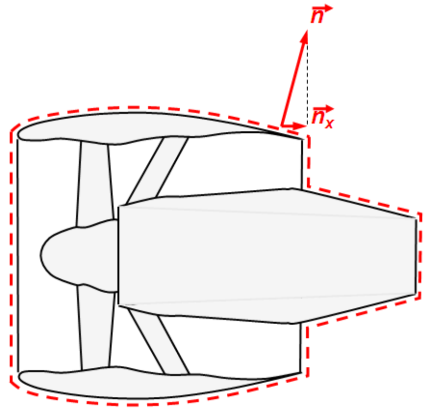
When boundary layer ingestion is introduced, the airframe and propulsion system are more highly coupled. Drag produced on the airframe is manifested in the form of lower momentum fluid in the boundary layer, which is ingested by the turbofan engines. The propulsion system no longer takes clean, free stream flow onboard even at the design point, and as such the conventional propulsion performance bookkeeping must be modified to account for this situation. In addition, the inlet flow distortion is at least an order of magnitude higher than is typically the case at cruise operation for conventional propulsion system installations. Furthermore, with the configuration under investigation the engine exhaust mixes directly with the aircraft wake, whereas in a conventional configuration the engine exhaust and the aircraft wake mix separately. All of these effects increase the degree of coupling between the airframe and the engines, requiring new approaches for analyzing and designing BLI propulsion systems.

II. System Analysis Approach

In order to identify BLI propulsion concepts with the most promise for providing system-level benefits, a high-level, trade-factor-based study was defined. This study utilized boundary layer profiles and the external flow field associated with the Boeing N2A-exte blended wing body (BWB) aircraft. This aircraft is derived from previous Boeing BWB design work based upon the original SAX-40 aircraft, and forms the basis for several recent studies carried out by Boeing and MIT[1-3]. This reference aircraft is an advanced, BWB design for podded or BLI propulsion, with an extended trailing edge aimed at providing additional aft acoustic shielding of jet noise. The vehicle is designed for a 7,500 nautical mile mission and is within the large commercial transport class. The design cruise Mach number is 0.8 at an altitude of 35,000 feet. The reference vehicle differs from the aircraft illustrated in Figure 1 in that the engines are housed in pylon-mounted nacelles raised above the airframe so that they do not ingest any boundary layer air. The reference propulsion system for the current study was a UHB turbofan, with a cycle chosen to have a bypass ratio of 16 and a fan pressure ratio of 1.35. This type of engine is consistent with the N+2 time frame, and would employ a suite of advanced technologies in the engine core, bypass stream, and nacelle. The system study attempted to capture the vehicle impacts associated with changes in propulsion system drag, and to a lesser extent weight, where these changes could be estimated using low-order, empirical-based models. Propulsion system performance changes due to BLI operation were accounted for in the engine cycle model. Use of the same airframe and engine cycle for both podded and BLI configurations is intended to give a more precise evaluation of BLI benefits exclusive of any other airframe or engine features.

The aircraft flow field results define engine inflow conditions for various podded and BLI propulsion system configurations. As will be described later, a new BLI module has been added to the Numerical Propulsion System Simulation (NPSS) engine thermodynamic model in order for the bulk-property effects of boundary layer ingestion to be properly modeled at the engine cycle level. The amount of boundary layer ingested into the engine, and the local external flow conditions, vary as a function of inlet axial position on the aircraft and as a function of inlet aspect ratio (inlet width divided by inlet height). Moving the propulsion system forward on the aircraft upper surface pushes the inlet into a higher-velocity external flow region where the boundary layer is also thinner. Wider inlets can capture a larger fraction of the available boundary layer, and as such can increase the propulsion system benefit associated with BLI but will necessarily be longer and heavier, pushing the inlet forward and negating some of the expected benefits. The location of the inlet was tied to the inlet aspect ratio by assuming a straight taper from the inlet to the engine face and prescribing a maximum allowable wall angle. This is a crude approach, but will capture some of the more basic effects of inlet shape prior to actually designing the inlet.

The close coupling of the airframe and engine requires a new way of handling inlet and exit conditions. Figure 3 illustrates a control surface that can be used to analyze closely-coupled airframes and propulsion systems, either podded and exposed only to the potential field of the airframe, or true BLI systems. Recognizing that neither the inlet nor exhaust is ever exposed to free stream conditions, the stream tubes upstream and downstream of the engine are eliminated. Instead, the properties associated with the flow field of the airframe (typically pressure, temperature, and Mach number) are applied directly at the inlet and exit planes. This approach essentially removes one half of the isolation assumption in that the impact of the airframe flow field on the engine is admitted, but the potential impact of the engine and nacelle on the airframe is still being ignored. In cruise, with a well-designed inlet and nacelle, that assumption should be reasonable.



$$Fn = \oint V_x \, \rho \vec{V} \cdot \vec{n} \, dA + \oint (P - P_\infty) \vec{n}_x \, dA - \oint \vec{\tau}_x \, dA$$

Fan Nozzle
Primary Nozzle
Inlet

Fan Nozzle
Primary Nozzle
Inlet
Core Cowl
Nacelle External

Core Cowl
Nacelle External

Figure 3. Control Surface for Computing Net Thrust of Closely-Coupled Propulsion Systems

The cycle analyses for the baseline podded installation and the various boundary layer-ingesting configurations were done using an existing NPSS model of a typical UHB turbofan. This model was modified to accommodate the ingestion of the boundary layer. In the standard model, the free stream flight conditions, named "Amb," are applied to the inlet, primary nozzle exit, and secondary nozzle exit. In order to model the BLI configurations, a pre-solver function was inserted outside the solver loop that uses tabular data to compute the flow field conditions at the inlet plane and at the planes of the primary and secondary nozzle exits. These conditions were loaded into three additional flight condition modules as shown in Figure 4. All components between the inlet and the nozzles, representing the largest part of the cycle model, remained unchanged. These components are represented by the "Core Stream" and "Fan Stream" notations in the figure.

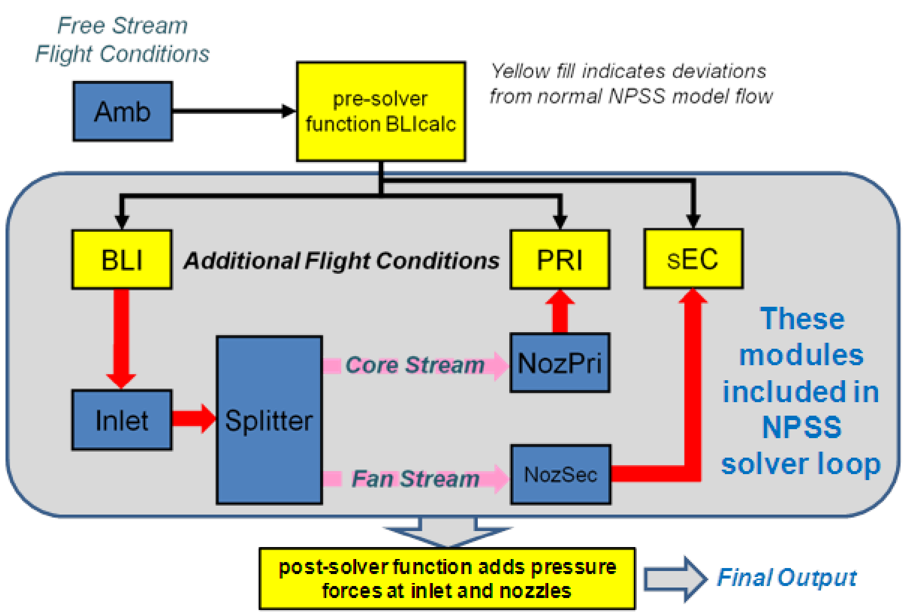
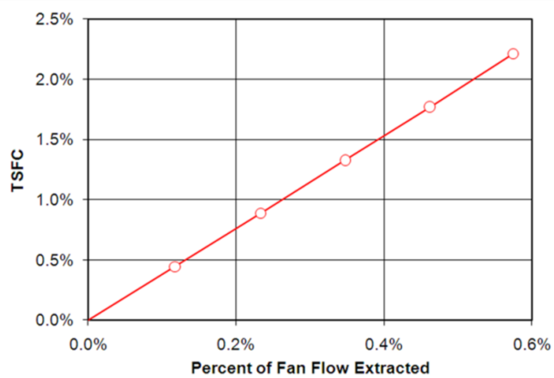


Figure 4. Modifications to NPSS Cycle Model to Incorporate Effects of BLI

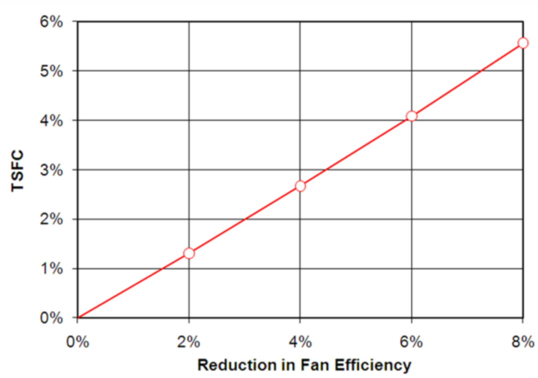
With these inlet and exit conditions defined, the NPSS model was solved. For a specified inlet location, the solution is complete at that point; however, the pressure forces at the inlet and at the nozzle exits must be adjusted to account for the fact that the local pressure is not the free stream pressure, as assumed in typical NPSS models. That function is accomplished in a post-solver module which also adjusted the ram drag, spillage drag, etc. In cases where it was desired to run to a specified thrust, the inlet position could not be completely determined prior to running the solver. The thrust is varied by modifying the weight flow through the engine which changes the fan diameter and hence the inlet size. The wall angle constraint results in the inlet plane being translated fore and aft to accommodate the new fan diameter; therefore, the fan diameter and inlet position are iterated in a loop surrounding what is shown in Figure 4.

The BLI cycle studies were run with a nominal fan efficiency, inlet pressure recovery, and other cycle inputs. To account for performance penalties associated with reduced fan efficiency, increased inlet pressure losses, bleed or power extractions, etc., the baseline (podded) NPSS model was executed over a range of each parameter to determine the sensitivity of the engine TSFC, the basic measure of cycle performance, to those parameters. Typical results are summarized in Figure 5. The reason for this approach is to eliminate the need to rerun the NPSS model as better estimates of the inlet and fan performance are obtained throughout the course of on-going, more detailed aerodynamic design.



Aircraft Trade Factors

Parameter	% Fuel Burn Change
TSFC (1% change)	1.28
Drag (1% change)	1.25
Weight (1000 lb. change)	1.90



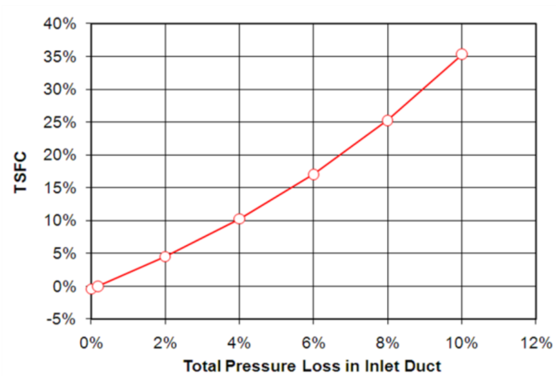


Figure 5. Engine Sensitivities and Aircraft Trade Factors

Aircraft-level trade factors for the Boeing N2A-exte vehicle were derived from the corresponding trade factors for a synthesized large commercial transport vehicle defined by United Technologies Research Center (UTRC) in recent Integrated Total Aircraft Power Systems (ITAPS) studies[4] from several vehicles of similar size and range. The trade factors correspond to a vehicle that was scaled based upon required fuel load. Fuel burn is the primary metric that was used in the aircraft-level system study trades, and so associated vehicle-level trade factors for propulsion system TSFC, drag, and weight were defined. To estimate the mission fuel burn for a specified engine/airframe architecture, a starting estimate of TSFC is obtained from the tabulated results of the BLI variations run in NPSS. Then, estimates of additional inlet losses, fan efficiency losses, etc., are combined with the corresponding sensitivities to provide TSFC impacts associated with these effects. The TSFC-to-fuel-burn trade factor is then used to calculate the fuel burn impact of each element. Incremental weight and drag estimates and the

associated aircraft trade factors are then used to compute these fuel burn impacts, and the net fuel burn for the architecture in question is determined by summing all of the individual contributions.

III. Results

A key parameter governing the potential benefit of ingesting the boundary layer is how much of the viscous drag on the vehicle is available to the inlets as a fraction of the total net thrust produced by the propulsion systems. This dependence is derived using one-dimensional theory as reported by Smith[5]. For the airframe in question, the design point computational fluid dynamics (CFD) solution was processed to determine how much of the viscous drag was available as a function of the inlet axial location (Kawai[6]). As shown in Figure 6, only 12.4% of the total drag (equal to total engine net thrust for steady, level flight) is available if the engines are constrained to be on the upper surface of the vehicle in the middle portion of the airframe highlighted by the ellipse in Figure 6. This is true even if the engines are mounted such that the inlet plane is at the aft end of the airframe. For a more reasonable location (x/c = 0.80), 11% of the total drag can be ingested by the propulsion systems.

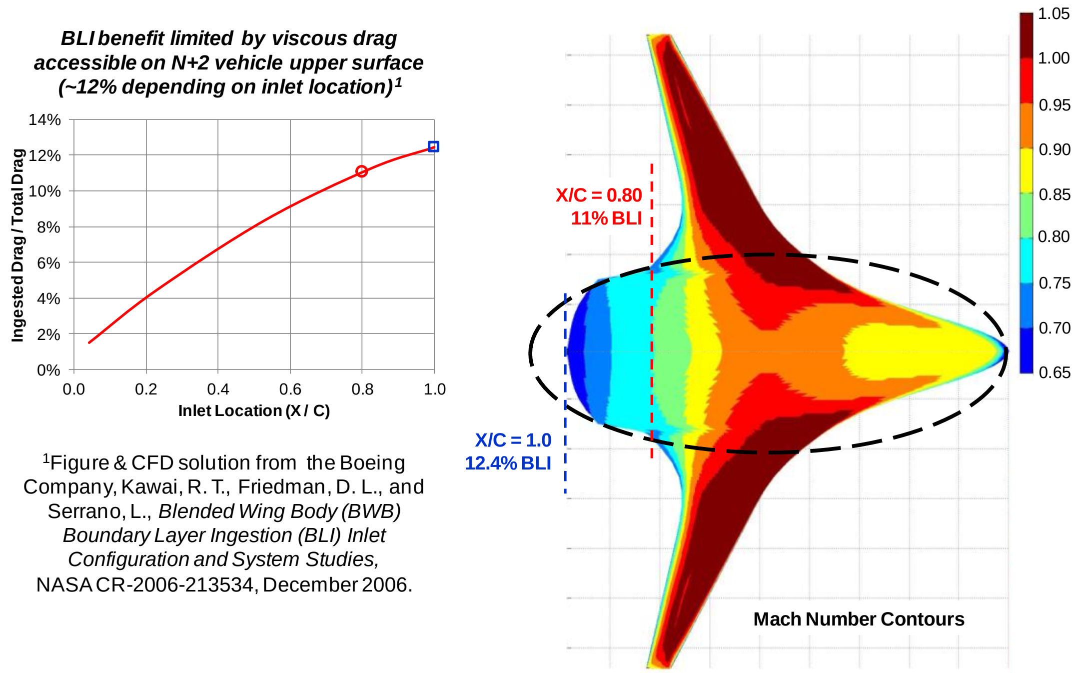


Figure 6. Fraction of Viscous Drag Available for Boundary Layer Ingestion on BWB Aircraft

The more promising architectures were those that placed the inlet aft of x/c = 0.80 and spanned the width of the aft body. Two factors led to this result. First, ahead of x/c = 0.80, the velocity at the edge of the boundary layer is higher than the free stream velocity and ingesting air at velocities above free stream is detrimental. Second, ingesting all of the available boundary layer leads to the maximum benefit if there are no offsetting penalties.

The maximum theoretical BLI benefit can be estimated using the well-known theory developed by Smith[5]. The theory is based largely upon one-dimensional flow physics, energy-based propulsion analysis, and the treatment of wake properties through integral parameters. In this article, Smith derives an expression for propulsive efficiency in the presence of wake ingestion[5]. Propulsive efficiency is shown to be a function of the jet velocity ratio, as is the case for non-BLI propulsion, and in addition is shown also to be a function of the ingested airframe drag fraction, a boundary layer pseudo-energy factor, and a wake recovery parameter. The ingested airframe drag fraction is defined as D / T, where D is the portion of the airframe viscous drag ingested into the propulsion systems, and T is the total aircraft propulsion system net thrust (equal to the total vehicle drag for steady, level flight) and is in fact the parameter plotted in Figure 6. The pseudo-energy factor of the incoming boundary layer is shown to be directly related to the shape factor H[5,7]. The wake recovery parameter, R, is defined as the ratio of the difference of the wake depth at the exit of the propulsor to the incoming wake depth ($1-\Delta_j/\Delta_0$), with R= 0 representing no

modification of the wake and R=1 representing a complete elimination of the wake. Smith points out that propulsors tend to naturally flatten incoming wakes, so while values for R equal to either zero or 1 are limiting cases, R likely takes on a value somewhere in between for most applications[5].

A comparison of several of the architectures investigated to the theoretical maximum possible benefit as computed by Smith's method[5] is shown in Figure 7. In applying the theory, the jet velocity ratios from the NPSS cycle model were used for the baseline and BLI cases operating at equal thrust conditions. The pseudo-energy factor K was calculated from the boundary layer shape factor in the aft region of the BWB aircraft[6]. Lord[8] performed an independent alternative calculation of the maximum achievable BLI benefit using two-dimensional momentum theory applied to the boundary layer profile developing on the aircraft centerline. This calculation yielded a maximum achievable BLI propulsive efficiency benefit of 5%, in good agreement with the Smith theory results which as seen in Figure 7 are on the order of 5-6%. Drela[9] used a dissipation-based power balance approach to evaluate the magnitude of the BLI benefit for two-dimensional flows where the ingested drag fraction is much larger, approaching 100%. These more idealized cases yield significantly larger BLI benefits, on the order of 15-20% reductions in propulsive power.

Two of the architectures shown in Figure 7 are capable of ingesting 11% of the total aircraft drag and yet show different TSFC benefits. The reason for this has to do with the axial position of the inlet. The TSFC estimates used to generate Figure 7 came directly from the NPSS model which includes the ram drag and part of the pressure integral around the control volume shown in Figure 3. In particular, it includes the pressure forces on the inlet face and on the exit faces of the core and fan nozzles. The analysis held the exit of the fan nozzle constant at the trailing edge of the vehicle and allowed the inlet plane to move to accommodate the length of the inlet. The 3-engine case required larger diameter engines and thus a longer inlet to keep the slopes of the sides of the inlet within the prescribed limits. A simple rectangular-to-circular duct (Figure 8) was used to estimate the axial position of the inlet face for various aspect ratios (AR in the figure) and vertical offset.

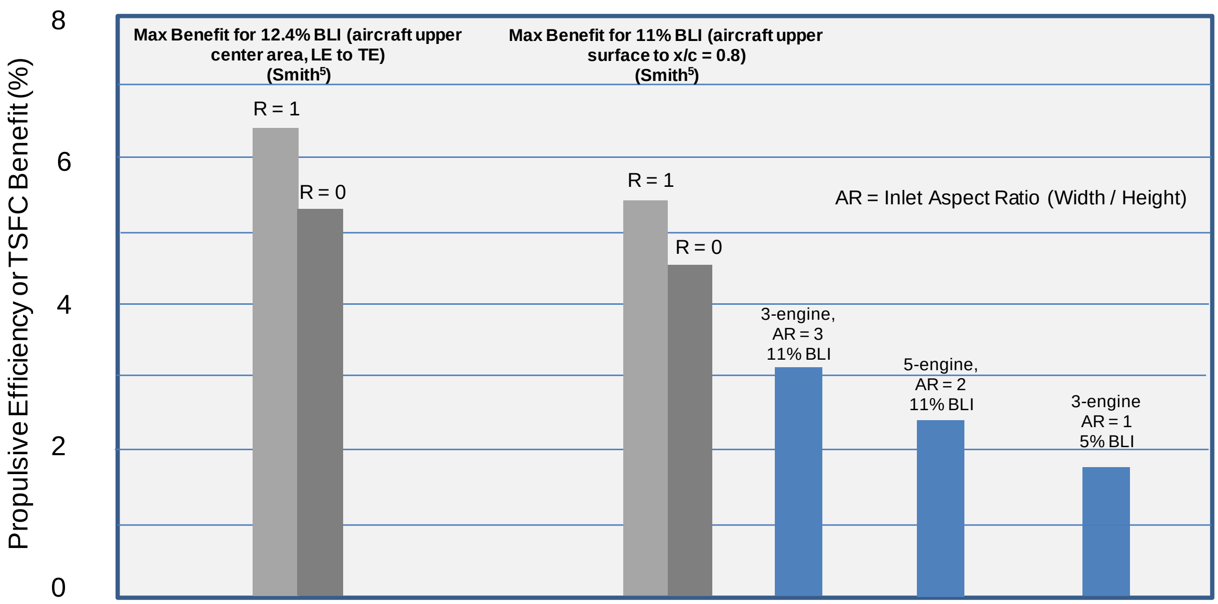


Figure 7. TSFC Benefit for Several Architectures Compared to Theoretical Limits

The forward position of the 3-engine configuration incurred less drag from the combination of the pressure force on the inlet and the ram drag. From this standpoint, it is a more desirable configuration than the 5-engine configuration; however, when the additional weight and drag of the longer inlets are factored in, the 5-engine architecture provides lower net fuel burn. Note than neither of these architectures matches the theoretical maximum which is for a zero-length propulsor at the aft end of the vehicle. The 3-engine architecture with an inlet of aspect ratio equal to 1.0 yields an even lower benefit because it cannot capture as much of the viscous drag.

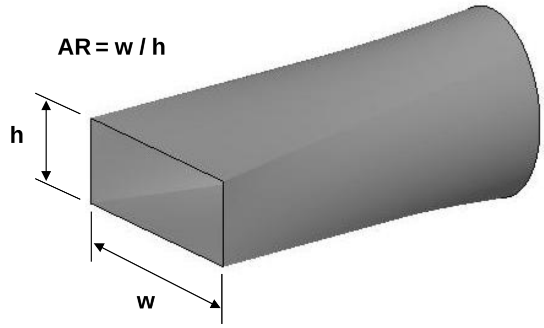
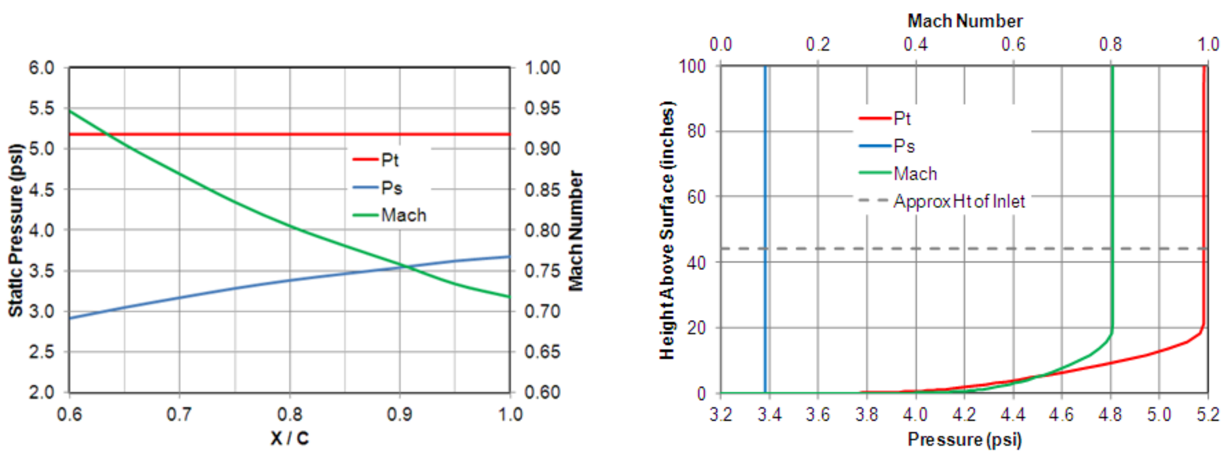


Figure 8. Typical Rectangular-to-Circular Inlet Duct

The variation of the Mach number and static pressure outside the boundary layer are shown as a function of axial position in the upper left portion of Figure 9. The upper right plot in that figure shows the boundary layer profiles at x/c=0.80 with the nominal inlet height shown at 44 inches above the surface. It can be seen that when the inlets are confined to the middle portion of the upper surface, a significant fraction of the ingested air comes from outside the boundary layer. The height for any given set of cycle parameters was computed by the NPSS model. To facilitate the NPSS calculation, the curves shown were integrated from the surface to various values of inlet lip height and tabulated for use by the model. The integrated (mass-averaged) total pressure as a function of averaging height off of the aircraft surface is plotted in the lower right portion of Figure 9. The exhibits in this figure illustrate the complexity of the computations required to accurately assess BLI concepts.



$$P_{T(MA)}(y)=\frac{\int_0^y \rho U P_T\, dy}{\int_0^y \rho U\, dy}$$

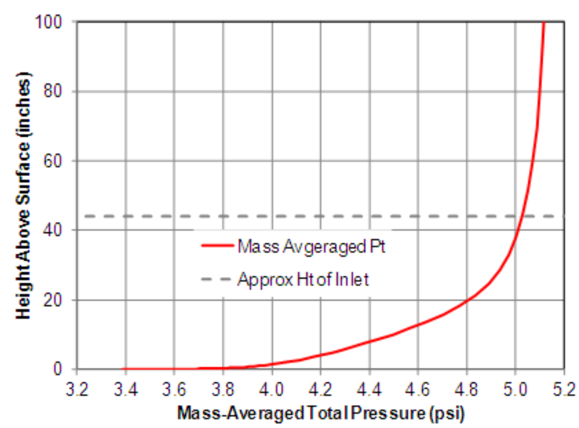


Figure 9. Typical Flow Parameters and Boundary Layer Profiles

Once the cycle benefit in terms of TSFC has been calculated for an architecture, it is converted to a benefit relative to the baseline (either 3 or 5 similar engines in a podded configuration at approximately the same axial location) and then the mission fuel burn benefit is computed by applying the aircraft trade factors to all contributing elements. This process is illustrated in Figure 10 for the 5-engine architecture. The NPSS model was run with nominal values for such parameters as inlet pressure loss and horsepower extraction. Where the actual parameter values for the architecture in question differ, the charts shown in Figure 5 were used to adjust the engine TSFC. Other factors which do not affect TSFC but which do affect fuel burn (e.g. incremental weight and drag) are also factored in at this point to yield a total fuel burn benefit.

The best architecture is G, which is a 5-engine configuration that has individual inlets integrated flush onto the airframe upper surface. Each engine having its own inlet allows better flow conditioning at the engine face. The shape of the inlet is not rectangular; however, the aspect ratio concept can be retained if we define it to be the width-squared divided by the inlet area much as the aspect ratio of a non-rectangular wing is defined.

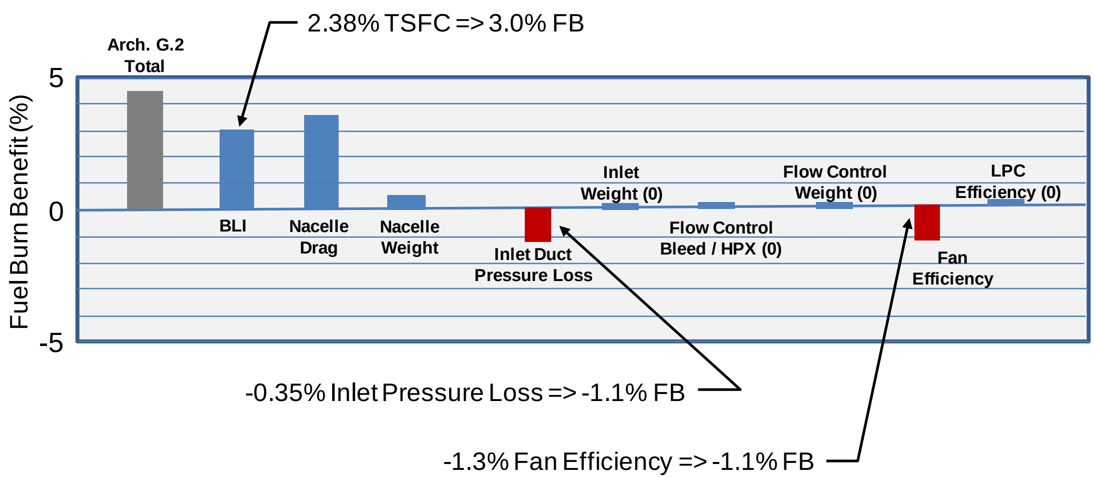


Figure 10. Fuel Burn Benefit of the 5-Engine Architecture

The result in Figure 10 shows that the overall fuel burn benefit for architecture G is just over 4.5%. The overall benefit consists of positive contributions from the BLI cycle-related propulsive efficiency improvement, nacelle drag reduction, and a small reduction in nacelle weight. Inlet pressure losses, and the reduction in fan efficiency associated with operating the fan in distorted flow, are the penalties that must be included to properly estimate the net benefit. It should be noted that the data in Figure 10 have incorporated inputs related to inlet pressure loss and fan efficiency that come from the higher-fidelity, CFD-based design of the coupled inlet / fan system. Some of these results are reported in a companion paper by Florea, et al.[10] Not shown in Figure 10 are the 3-engine architecture results, which also provided an overall benefit in excess of 3%. An uncertainty analysis on the system study model inputs resulted in an estimated overall fuel burn benefit uncertainty of approximately ±0.5%.

The system study tool was also used to provide an estimate of the benefits associated with much larger ingested drag fractions, which might be possible with more advanced N+3 distributed propulsion installations or other advanced configurations. According to Smith's theory, for D / T values in the 30-40% range the current engine cycle could achieve on the order of an 8-10% propulsive efficiency benefit[5]. This would yield an estimated fuel burn reduction in the 8-11% range, even accounting for the addition of weight and power extraction associated with a flow control subsystem (a system requiring in excess of 50 pounds, and a fan bleed extraction of 0.6%, was included for each engine). Clearly, larger D / T fractions afford substantially increased vehicle-level BLI benefits.

It should be noted that some of the concepts considered proved to be physically impossible. While exploring inlets with an aspect ratio of 7 can be used to determine whether the pursuit of maximum boundary layer ingestion is beneficial, the resulting inlets simply will not fit onto the upper surface of the airframe. Even if one could fit the engines by changing the airframe design, the high aspect ratio is not attractive because the added weight and drag of the long nacelles and the increased pressure losses due to the longer internal flow path negate the BLI benefits.

Architecture E explored the use of a lower bypass ratio engine cycle (BPR = 7) with the associated higher fan pressure ratio (1.56). Such fans are generally considered to be more distortion-tolerant but are less efficient than the higher bypass ratio (lower pressure rise) fan in the baseline engine. An understanding of the trade between these factors was deemed desirable. Within the constraints of this study, the lower bypass ratio does not appear to be attractive, as it was unable to achieve the performance level of the pylon-mounted, UHB baseline propulsion system even with BLI.

One interesting aspect of the subject study was that none of the N+2 flow control architectures were found to provide a net benefit relative to the baseline. The penalties associated with the bleed or shaft power extractions required to implement the flow control always offset the gains that could be realized due to increased BLI and decreased distortion at the fan face. As discussed earlier, this result was to a significant degree influenced by the relatively small ingested drag fraction available to the engines on the upper center fuselage of the BWB aircraft. For vehicles or propulsion / airframe integration configurations that afford larger ingested drag fractions, flow control was found to trade more favorably and net benefits were able to be achieved as described above.

One of the important factors that affects TSFC is the loss in fan efficiency. In addition to the loss in peak efficiency due to running the fan in distorted flow, there can also be a further loss in efficiency due to operating below peak efficiency in order to achieve a required stall margin. A preliminary assessment of the impact of distortion on the peak efficiency and stall margin was carried out by running DYNTECC, a modified parallel-compressor code. Although stall margin impacts are still being evaluated, the shift off of peak efficiency appears to be small, and is contained within the overall fan efficiency reduction target and performance estimates used in the present study. Using the DYNTECC results and the sensitivity of the engine to inlet pressure loss, a composite figure of merit was derived which was later used to help optimize the inlet. The need for a composite figure of merit was dramatically illustrated by one of the early attempts at inlet optimization wherein only the first harmonic of the pressure distortion was to be minimized. The optimizer created an inlet flow path shape that produced a total pressure deficit equal to that resulting from boundary layer ingestion and located exactly 180 degrees away. The first harmonic was reduced, but flow quality at the fan face and inlet pressure losses were totally unacceptable. The inlet optimization is the subject of a separate companion paper[10].

Completion of the fan aerodynamic design is really only the end of the first major design iteration. With more realistic assessments of the variation of inlet pressure losses and distortion as a function of the global geometric parameters such as inlet length and aspect ratio, and with the map of a fan specifically designed to operate in distorted flow, a second pass can be made through the system study to optimize the engine positioning. Beyond that, one must also account for the impact of the inlet and engine on the airframe design, and consider whether the airframe can be modified to make the overall vehicle / propulsion system even more efficient.

IV. Conclusions

A key goal of next-generation propulsion systems is to provide continued reductions in fuel burn relative to the best gas turbine engines in development today. One path to achieve this is to enable boundary layer ingesting propulsion systems, which can provide significant improvements in propulsive efficiency by producing thrust from the reduced velocity boundary layer air. The next generation of UHB turbofan propulsion systems will feature bypass ratios between 15 and 18, and fan pressure ratios in the 1.25 – 1.35 range. Such engine cycles will result in significantly reduced thrust specific fuel consumption. The implementation of this class of propulsion system in a boundary layer ingesting environment would provide additional significant vehicle-level fuel burn benefits for N+2 and N+3 aircraft. A key challenge associated with boundary layer ingesting propulsion systems is the ability of the turbomachinery to operate efficiently in highly distorted flow.

Under the subject program a study has been carried out to determine the system-level benefits associated with BLI propulsion. Based upon the study results, it is concluded that compact-inlet, aft-mounted propulsion systems can provide on the order of a 3 – 5% fuel burn reduction relative to a clean-inflow, pylon-mounted, advanced UHB baseline turbofan. Significantly larger benefits, on the order of 10%, are possible for N+3 configurations with larger ingested drag fractions. These benefits are within the range of those reported by previous investigators, with the limiting theoretical maximum benefit well-described by the one-dimensional theory of Smith[5]. For N+2 configurations, where access to large fractions of the airframe boundary layer is limited, flow control technology was found not to trade well. Under these conditions the weight and power extraction penalty for flow control was found to be on the order of the BLI benefit provided. For larger BLI fractions associated with N+3 vehicles, these penalties were comparatively smaller, and flow control showed promise for enabling net system-level benefits.

Finally, the subject study identified high-performance, distortion-tolerant turbomachinery and low-loss inlet systems as key technologies that will be required to enable BLI system benefits. These components are highly coupled with each other and with the airframe in BLI installations, and thus will need to be designed using tools that properly account for the coupling effects.

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