Integration of Propulsion-Airframe-Aeroacoustic Technologies and Design Concepts for a Quiet Blended-Wing-Body Transport

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This paper summarizes the results of studies undertaken to investigate revolutionary propulsion-airframe configurations that have the potential to achieve significant noise reductions over present-day commercial transport aircraft. Using a 300 passenger Blended-Wing-Body (BWB) as a baseline, several alternative low-noise propulsion-airframe-aeroacoustic (PAA) technologies and design concepts were investigated both for their potential to reduce the overall BWB noise levels, and for their impact on the weight, performance, and cost of the vehicle. Two evaluation frameworks were implemented for the assessments. The first was a Multi-Attribute Decision Making (MADM) process that used a Pugh Evaluation Matrix coupled with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). This process provided a qualitative evaluation of the PAA technologies and design concepts and ranked them based on how well they satisfied chosen design requirements. From the results of the evaluation, it was observed that almost all of the PAA concepts gave the BWB a noise benefit, but degraded its performance. The second evaluation framework involved both deterministic and probabilistic systems analyses that were performed on a down-selected number of BWB propulsion configurations incorporating the PAA technologies and design concepts. These configurations included embedded engines with Boundary Layer Ingesting Inlets, Distributed Exhaust Nozzles installed on podded engines, a High Aspect Ratio Rectangular Nozzle, Distributed Propulsion, and a fixed and retractable aft airframe extension. The systems analyses focused on the BWB performance impacts of each concept using the mission range as a measure of merit. Noise effects were also investigated when enough information was available for a tractable analysis. Some tentative conclusions were drawn from the results. One was that the Boundary Layer Ingesting Inlets provided improvements to the BWB's mission range, by increasing the propulsive efficiency at cruise, and therefore offered a means to offset performance penalties imposed by some of the advanced PAA configurations. It was also found that the podded Distributed Exhaust Nozzle configuration imposed high penalties on the mission range and the need for substantial synergistic performance enhancements from an advanced integration scheme was identified. The High Aspect Ratio Nozzle showed inconclusive noise results and posed significant integration difficulties. Distributed Propulsion, in general, imposed performance penalties but may offer some promise for noise reduction from jet-to-jet shielding effects. Finally, a retractable aft airframe extension provided excellent noise reduction for a modest decrease in range.

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Nomenclature

CO_2	=	Carbon Dioxide Emissions
DOC+I	=	Direct Operating Cost + Insurance
L/D	=	Lift to Drag Ratio
LdgFL	=	Landing Field Length
LE	=	Leading Edge
NO_x	=	Nitrous Oxide Emissions
OASPL	=	Over All Sound Pressure Level
RDT&E	=	Research, Development, Test, and Evaluation
SPL	=	Sound Pressure Level
SFC	=	Specific Fuel Consumption
TE	=	Trailing Edge
TOFL	=	Takeoff Field Length
TOGW	=	Takeoff Gross Weight

I. Introduction

NASA's long term goal of reducing transport aircraft noise by a factor of 4 relative to 1997 state of the art has given the field of Propulsion-Airframe-Aeroacoustics (PAA) a major role in noise research and has sparked interest in the examination of revolutionary, low noise, aircraft and engine configurations at the conceptual design level. In addition, many individual low noise PAA technology and design concepts have come under study. PAA, more thoroughly defined in Ref. 1, generally refers to noise associated with the installation of the aircraft propulsion system into the airframe. PAA technologies and design concepts are therefore means of reducing noise through modifications to the propulsion-airframe integration, or even to the aircraft configuration itself. This tight coupling of low noise PAA design with the aircraft configuration demands systems analysis, in concert with noise analysis, to examine how the weight, performance, and cost of the aircraft will be affected with the integration of low noise technologies and design concepts. Unfortunately, many of the newer noise technologies and design concepts, since they are in early development, lack sufficient information to properly account for all their integration aspects. In addition, revolutionary aircraft configurations generally lie outside the empirical databases that many aircraft sizing and synthesis tools rely on. Implementation of a systems analysis framework that can adequately study advanced PAA configurations is therefore a significant challenge and can presently only be done to a limited extent.

The work in this paper was motivated by the desire to examine implementation of a systems analysis framework for revolutionary PAA configurations as well as examine and catalog several PAA technologies and design concepts of interest to NASA's Quiet Aircraft Technology Project. A 300 passenger (pax) Blended-Wing-Body (BWB) aircraft powered by two General Electric (GE) 90-like engines, shown in Fig. 1, was used as a "revolutionary" test bed configuration with which certain PAA technologies and design concepts could be integrated. This configuration was selected since it contains a significant design database for an aircraft considered to be in the "revolutionary" category. Also, compared to a conventional transport, it offers greater potential for low noise PAA design due to its expansive planform and over-the-wing mounted engine configuration. A 300 passenger GE-90-like version of the BWB was chosen due to its similarity in size to the 777/GE-90 system, which is considered representative of present day state of the art. In all the studies, it was desired to evaluate how a particular low noise technology, design concept, or configuration would improve the BWB's noise levels and also how it would affect its weight, performance, and cost.

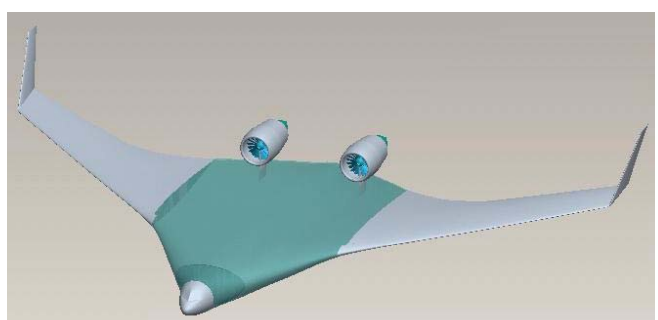

Figure 1. 300 passenger BWB Test Bed Configuration.

II. Multi-Attribute Decision Making Process

It was first desired to provide an initial qualitative evaluation and ranking of a wide range of PAA technologies and design concepts, applied to the BWB, in a short period of time. This task was enabled using a Multi-Attribute Decision Making (MADM) process.[2] The procedure employed was inspired by the Technology Ranking Methodology used at the Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology.[3]

Baseline

Propulsion System type	Single	Hybrid				
Inlet type	Circular	Semi-Circular BLI	Mail Slot BLI S-duct	Freestream S-duct	LE Edge Mail Slot	
Engine Size	Large Main	Medium Distributed (6-10) @ > 30,000 lbs Thrust	Small Distributed (10-50) @ 6,000-30,000 lbs Thrust	Mini/Micro Distributed (50+) @ 2,000-6,000 lbs Thrust		
Engine Type	Gas Turbine	Gas Turbine Powered Ducted Fans	Electric (Fuel Cell) Driven Ducted Fans			
Engine Mount	Podded	Buried in Airframe				
Engine Placement	Aft Mounted	Mid Mounted	Forward Mounted	TE Mounted		
Fuel Type	Hydrocarbons	Liquid Hydrogen				
Trailing Edge Geometry	Current BWB	Fixed Trailing Edge/Tail Ext.	Retractable Trailing Edge/Tail Ext.	Thermal/Fluidic Sheet		
Trailing Edge Noise Control	none	Active Flow Control (Sucking or Blowing)	Serrated TE			
Nozzle	Circular Nozzle	Distributed Exhaust Nozzle	High Aspect Ratio Rectangular Nozzle	S-duct Exhaust	Series of separated rectangular nozzles	Variable geometry HARN nozzle
High Lift	Slats & Elevons	Slats & Elevons with Continuous Moldline Tech.	Thrust Vectoring	Circulation Control		

Figure 2. Morphological Matrix of Propulsion-Airframe-Aeroacoustic Configurations for the BWB.

The details of this process, including the mathematics, are discussed in Ref. 4. Only the basic procedure and results are discussed here.

The list of PAA technologies and design concepts, considered for integration into the BWB baseline, was compiled through literature searches, discussions with researchers and program management, and team brainstorming. The technologies and design concepts were then catalogued using a morphological matrix, shown in Fig. 2. A morphological matrix is a functional decomposition of a particular system of interest; in this case, the BWB's propulsion and high lift system. Each row in the matrix, or functional component, has two or more concepts to choose from for integration. Complete propulsion configurations may therefore be formed by selecting one concept from each row. The baseline configuration, corresponding to the BWB in Fig. 1, is defined by the circled components in Fig. 2. A description of each of the technologies and design concepts in the matrix is provided in Ref. 5.

A. Pugh Evaluation Matrix Technology and Design Concept Assessment

All of the technologies and design concepts catalogued in the morphological matrix were next evaluated qualitatively using Pugh Evaluation Matrices,[6] portions of which are shown in Fig. 3. Pugh matrices are tools that succinctly and compactly list impacts that a certain technology will have on a system requirement. Technologies are arranged in columns and design, or "customer", requirements form the rows. The matrix is populated by assigning a number, representing a qualitative engineering judgment, as to how the technologies impact the requirements. Weights, or "customer importances", are assigned to the requirements that qualitatively express their importance relative to the other requirements.

For the present case, two matrices were constructed, one consisting of noise requirements for the BWB and the other of weight, performance, and cost requirements. Two matrices were desired for the evaluation since the relative weighting between the groups of noise requirements and weight/performance/cost requirements was to be varied parametrically. The matrices were populated by judging, qualitatively, how a particular PAA technology or design concept would impact a particular requirement if it was integrated into the BWB's baseline propulsion system. The impact was assigned relative to the baseline component that the PAA technology would be replacing. The impact

Weights, Performance and Cost Requirements (Evaluation Criteria)	Customer Importance	Inlet Types				
		Semi-circular BLI	Freestream S-duct	Mail Slot BLI S-duct	Leading Edge Mail Slot Inlet	Datum
Empty Weight	**10**	9	9	9	9	**10**
Fuel Weight	**10**	11	7	11	10	**10**
Low Speed Lift	**0**	9	7	7	9	**10**
Low Speed Drag	**0**	11	7	11	13	**10**
Cruise Drag	**0**	13	7	13	13	**10**
Low Speed Thrust	**0**	11	9	11	9	**10**
Range	**0**	11	7	11	10	**10**
Initial Cruise Altitude Capability	**4**	11	9	11	10	**10**
TOFL	**5**	11	9	11	10	**10**
LdgFL	**4**	10	9	9	10	**10**
CO2	**4**	11	7	11	10	**10**
NOx	**4**	11	7	11	10	**10**
Stability/Balance	**5**	10	10	10	10	**10**
Reliability / maintainability	**5**	10	10	10	10	**10**
Safety	**8**	10	10	10	10	**10**
Passenger Compartment	**4**	9	9	9	9	**10**
Fuel Capacity	**2**	9	9	9	7	**10**
Cabin Noise	**2**	10	10	10	10	**10**
RDT&E Cost	**7**	9	10	9	9	**10**
Production Cost	**7**	10	10	10	9	**10**
DOC + I	**0**	11	9	11	10	**10**

Noise Requirements		Customer Importance	Inlet Types				
			Semi-circular BLI	Freestream S-duct	Mail Slot BLI S-duct	Leading Edge Mail Slot Inlet	Datum
Takeoff Noise	High-Lift Noise	**8**	10	10	10	10	**10**
	Trailing Edge Noise	**6**	10	10	10	10	**10**
	Aft Fan Noise	**10**	10	10	10	10	**10**
	Forward Fan Noise	**5**	9	11	10	13	**10**
	Turbine Noise	**7**	10	10	10	10	**10**
	Nozzle/Jet Noise	**9**	10	10	10	10	**10**
Landing Noise	High-Lift Noise	**10**	10	10	10	10	**10**
	Trailing Edge Noise	**6**	10	10	10	10	**10**
	Aft Fan Noise	**10**	10	10	10	10	**10**
	Forward Fan Noise	**4**	9	13	10	13	**10**
	Turbine Noise	**7**	10	10	10	10	**10**
	Nozzle/Jet Noise	**5**	10	10	10	10	**10**
	Landing Gear	**9**	10	10	10	10	**10**

Figure 3. Portion of Pugh Matrices for Both Noise and Weight/Performance/Cost Requirements.

judgments were mapped to the numeric values 1, 4, 7, 9, 10, 11, 13, 16, and 19. 10 represented the baseline and therefore no impact. Numbers below 10 represented negative, or “undesired”, impacts and numbers above 10 represented positive, or “desired”, impacts. Lowering TOGW or reducing jet noise would be obvious examples of “desired” impacts. Weightings of the requirements were numbered 0 through 10 with 10 representing the most important requirements. Requirements with a zero weighting are directly correlated to other requirements (eg. cruise drag is correlated to fuel weight) and this zero weighting prevented double book keeping in the TOPSIS analysis.

The noise and weight/performance/cost Pugh matrices were initially populated by the authors in a team setting. In order to improve the accuracy of the judgments, select experts from NASA, industry, and academia were solicited to review the numbers pertaining to their area of expertise and suggest any corrections. Many responded and helpful corrections were received. This process ensured that the inherently subjective matrix values were backed by a broad range of expert knowledge and opinion.

The full Pugh matrices are published in Ref. 5. The matrices provided a succinct mapping of PAA technology impacts to the BWB design requirements and allowed the subsequent technology rankings to be conveniently tracked.

B. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The qualitative impacts in the Pugh matrix were then inputted into a TOPSIS analysis. The mathematical details are described in Ref. 4 but are omitted here for brevity. The purpose of the TOPSIS analysis was to process the Pugh matrix cell values and assign aggregate rankings of the technologies and design concepts. The rankings describe how well, relative to the baseline and each other, the technologies or design concepts satisfy, overall, the requirements specified in the Pugh matrices. The ranking values are expressed as non-dimensional degrees of “closeness” to a theoretical “ideal solution”.

Normally a TOPSIS analysis produces a single series of closeness coefficients for each technology. Since it was desired to parametrically vary the relative importance of the noise requirements group to the weight/performance/cost group however, a "Noise Scale Factor" was created. The Noise Scale Factor (NSF) was defined as a number between zero and one that acts as a multiplier for the noise Pugh matrix requirement weighting factors. 1-NSF is then multiplied to the weightings of the weight/performance/cost requirements. When the two Pugh matrices are then combined into the TOPSIS analysis, technology rankings will therefore be influenced by the importance of noise to the aircraft design relative to the other group of requirements. An NSF of zero causes technologies to be ranked as though noise considerations have no importance in the BWB design. Conversely an NSF of 1 causes technologies to be ranked as though noise is the most important design driver. An NSF of 0.5 means that the requirements in the noise Pugh, as a group, have equal importance with the requirements in the weight/performance/cost Pugh, as a group. For a given noise scale factor then, the highest rankings will indicate PAA technologies or design concepts that provide the BWB with the best balance of noise and weight/performance/cost impacts.

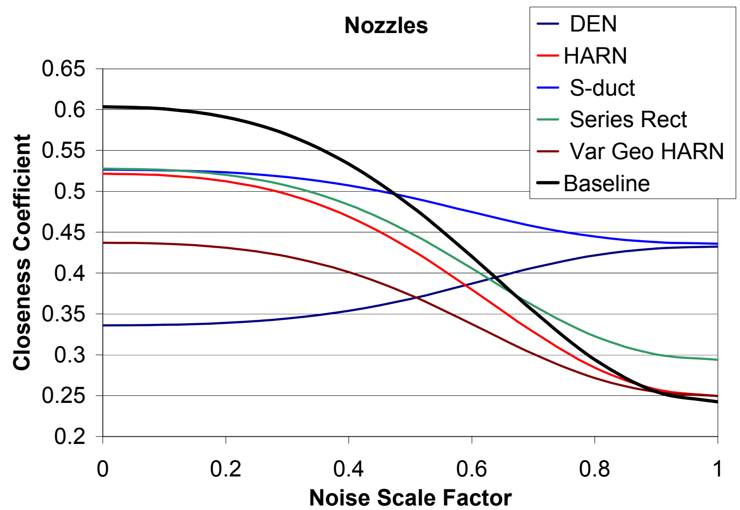

Figure 4. Distribution of Nozzle Technology and Design Concept Rankings for all Noise Scale Factors.

Figure 4 shows the distribution of rankings for all of the technologies and design concepts in the nozzle category of the morphological matrix for the full range of noise scale factors. This category was chosen since it exhibits typical behavior of the technology rankings. At NSF=0, the nozzle technologies are ranked only according to their performance impacts since noise has no importance. It is observed that, since the baseline is ranked highest at NSF=0, all of the technologies impose some sort of performance penalty and the baseline, which is an open circular nozzle, is therefore the best option. At NSF=1, the situation is reversed and the rankings are arranged according to which technology provides the highest reduction in noise. A distributed exhaust nozzle and an S-Duct are the highest ranked in this area. At some point in the distribution, all of the advanced technologies cross over the baseline curve and become more highly ranked. This "cross-over point" is an indication of how important noise considerations must be in the design before a particular technology impacts the overall system just as favorably as the baseline.

Figure 5 shows the rankings for Noise Scale Factors of 0, 0.5, and 1. The baseline, denoted by the red bar, is one of the highest ranked technologies at NSF=0 meaning that most of the technologies do impose weight, performance, or cost penalties. The baseline is however one of the lowest ranked for NSF=1 meaning that most technologies do fulfill their intended purpose and provide a noise benefit. The degree to which the technologies impose penalties or provide benefits can be ascertained by the relative magnitudes of the rankings. For NSF=0, the two Boundary Layer Ingesting (BLI) Inlet configurations are ranked slightly higher than the baseline circular inlet since they are expected to provide better cruise fuel economy. Fuel Cell Ducted Fans are however ranked much lower due to the expected penalties in weight that a fuel cell/electric motor system would impose. For NSF=1, circulation control is ranked the highest meaning it provides the best noise benefit of all the technologies and design concepts. This is largely the result of the improved operations that result from powered lift. Rather than one noise source being mitigated by the technology, the whole aircraft is moved farther away from the community. Forward mounted engines are the next highest ranked since many of the aft radiated noise sources are shielded by the BWB's planform. The semi-circular BLI inlet is ranked lower than the baseline at NSF=1. This is due to the fact that the increase in inlet flow distortion from ingesting the boundary layer is likely to increase the fan noise. The technology is therefore not one that will provide a noise benefit by itself, but will likely facilitate other PAA configurations, such as embedded engines, that will provide a noise benefit. As will be shown later, BLI inlets are useful for offsetting performance penalties that other technologies impose.

Figure 6 shows the Noise Scale Factors at which the technologies cross over the baseline curve. Three technologies (medium sized engines, liquid hydrogen fuel, and a serrated trailing edge) are consistently ranked

Table 1. Technology and Design Concept Reference List.

#	Technology/Design Concept	#	Technology/Design Concept	#	Technology/Design Concept
1	Semi-Circular BLI Inlet	11	Mid Mounted	20	Distributed Exhaust Nozzle
2	Mail Slot BLI Inlet	12	Forward Mounted	21	High Aspect Ratio Rec. Nozzle
3	Freestream S-Duct Inlet	13	TE Mounted	22	S-Duct Exhaust Nozzle
4	LE Mail Slot Inlet	14	Liquid Hydrogen Fuel Type	23	Series of Separated Rec. Nozzles
5	Medium Distributed	15	Fixed Trailing Edge Ext.	24	Variable Geometry HARN
6	Small Distributed	16	Retractable TE Ext.	25	Cont. Moldline Slats & Elevons
7	Mini/Micro Distributed	17	Thermal/Fluidic Sheet	26	Thrust Vectoring
8	Gas Turb. Ducted Fans	18	Active Flow Control	27	Circulation Control
9	Fuel Cell Ducted Fans	19	Serrated TE	28	Baseline (Red)
10	Buried in Airframe				

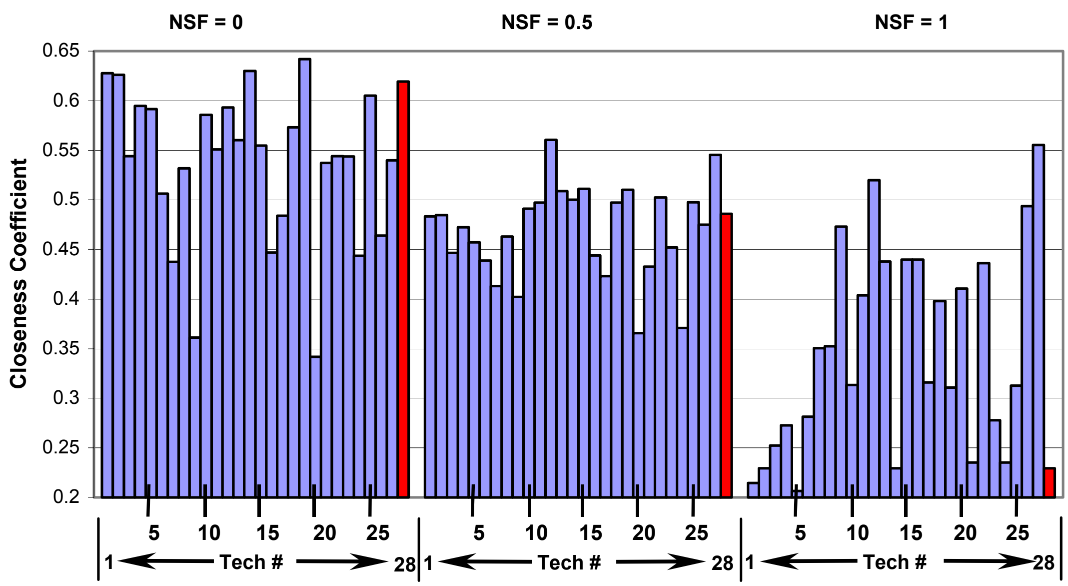

Figure 5. PAA Technology and Design Concept Rankings for Different Noise Scale Factors.

above or below the baseline over the whole range of NSFs and therefore have no cross-over point. All of the technologies except for the two BLI inlets are ranked below the baseline for NSFs below their cross-over and are ranked higher after. The BLI inlet technologies however are reversed since they provide a fuel weight improvement for a small penalty in fan noise. For the technologies that provide noise benefits and impose performance penalties, the cross-over points give a sense of how much of a tradeoff is being made since they indicate how important noise considerations must be, amongst the set of BWB design requirements, in order for the technology to be worth considering over its baseline component. The lower the NSF at the cross-over, the less of a tradeoff is being made between noise and performance. As is observed in Fig. 6, nearly half of the technologies have cross-over points below NSF=0.5 meaning noise does not have to have equal importance with the other group of requirements for these technologies to be ranked higher than the baseline. Forward mounted engines have the lowest cross over point due to all of the noise benefits mentioned earlier and since they are only expected to impose minor cruise drag penalties from the over-the-wing installation. Both of the high aspect ratio nozzles require noise to be the over-arching design requirement due to expected duct weight and thrust loss penalties. Most cross-over points lie between NSFs of 0.4 and 0.7 indicating that much of the technology and design concept set is oriented toward aircraft where noise is amongst the most important of requirements.

Some conclusions were drawn from the MADM process. First, nearly all of the technologies and design concepts provided a noise benefit but required a tradeoff in the BWB's weight, performance, or cost. The magnitude of the tradeoff was indicated by the technology's cross-over point and most technologies required noise considerations to have near equal importance compared to the other design requirements. Since transports of today, and those of the near future, generally do not place such an emphasis on noise, there still remains a need to find PAA related

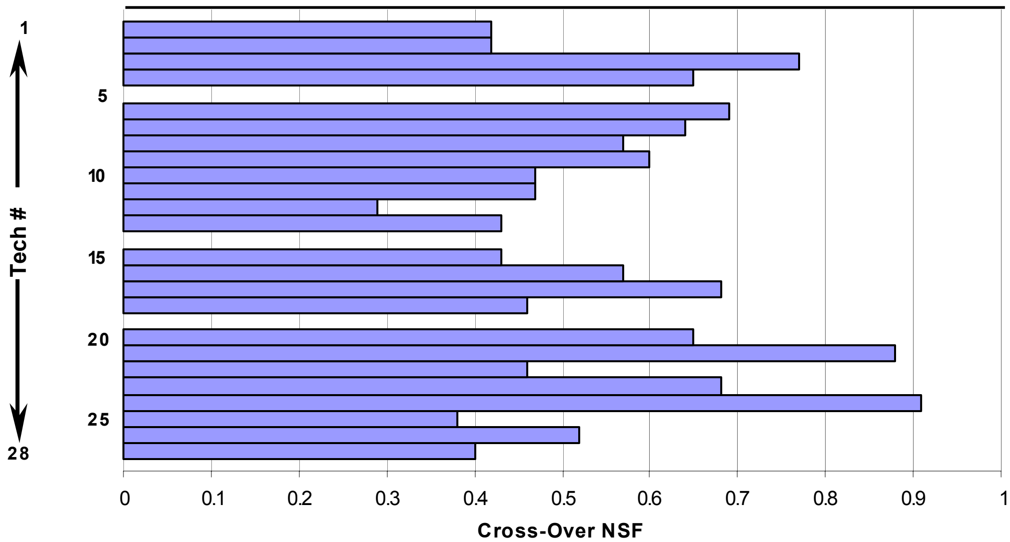

Figure 6. Technology/Design Concept Cross-Over Points.

technologies and design concepts that require less of a tradeoff, or provide a synergistic performance benefit. This analysis also underscores the difficulty in elevating noise to a primary design driver since it often runs counter to other design requirements.

Although the MADM process did provide useful insights into the list of PAA technologies, it should be stressed that the results are fundamentally based on qualitative, conceptual judgments of engineers and not on detailed systems analysis. The accuracy of the assessments was improved by obtaining a broad consensus of opinion among many different researchers and robustness of the rankings with Pugh matrix number perturbations was verified in Ref. 4. Difficulty was also encountered in evaluating the individual isolated effects of the technologies and design concepts when integrated into the BWB baseline as many only made sense in the context of a more advanced propulsion system. Despite these limitations, the MADM process fulfilled its intended purpose. It allowed a large number of PAA technologies and design concepts to be examined and catalogued in a relatively short period of time. The Pugh matrices, by themselves, allowed the individual effects of the technology integration on specific design requirements to be clearly and concisely tracked. The TOPSIS analysis provided a sense of how the technology set compared overall to the baseline BWB propulsion system and showed how the rankings changed as the noise emphasis on the design was parametrically varied. Finally, a sense of the tradeoffs involved for many of the technologies was also gained.

III. Systems Analyses on Down-Selected Advanced BWB Propulsion Configurations

Following the MADM process, systems analyses were performed on a down-selected set of advanced propulsion configurations for the 300 passenger BWB baseline. The objective was primarily to assess impacts on the BWB's performance but noise was also assessed when feasible. The advanced propulsion configurations were chosen from the morphological matrix and, due to programmatic needs, were oriented toward jet noise reduction technologies. Configurations were generally kept simple as well for ease of analysis.

A. Baseline Aircraft

Results of the systems analyses were referenced to a baseline 300 passenger BWB aircraft powered by two GE-90-like turbofans as shown in Fig. 7. The BWB aircraft was used to assess how advanced propulsion configurations compared to the conventional, podded configuration defined as the baseline in the Morphological Matrix. This particular BWB aircraft was designed to fly a standard transport mission carrying 300 passengers 7,500

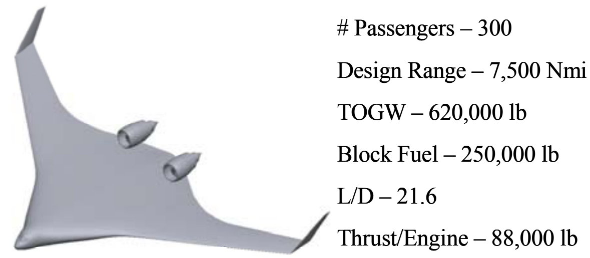

Figure 7. BWB Podded Engine Baseline.

Nmi. The aircraft model was sized and optimized for minimum TOGW using the FLight OPtimization System (FLOPS) sizing and synthesis program. Weight and performance output from FLOPS is shown in Fig. 7. The GE-90-like engine model was created using the Numerical Propulsion Simulation System (NPSS) and the Weight Analysis of Turbine Engines (WATE) programs. For distributed propulsion studies, an NPSS/WATE model of a Rolls-Royce AE3007-like engine, a regional jet sized turbofan, was also used. Both engines were "rubberized" meaning they could be sized up or down depending on the thrust requirements calculated in FLOPS. Noise was analyzed using NASA's Aircraft NOise Prediction Program (ANOPP) with a calibrated GE-90-like model and an uncalibrated AE3007-like model.

In all of the studies done of advanced technologies, the impact on the BWB's performance was measured using the mission range as a measure of merit. Traditional mission analysis either calculates TOGW based on a fixed mission range or vice-versa. For these studies, the baseline fuel weight, rather than the TOGW, was held fixed and the engines were resized based on the required sea-level static thrust calculated in FLOPS. Based on this allowed engine resizing, the gross weight would usually vary slightly.

B. Embedded Engines With Boundary Layer Ingesting Inlets

Figure 8a). BWB Design with BLI Inlets.

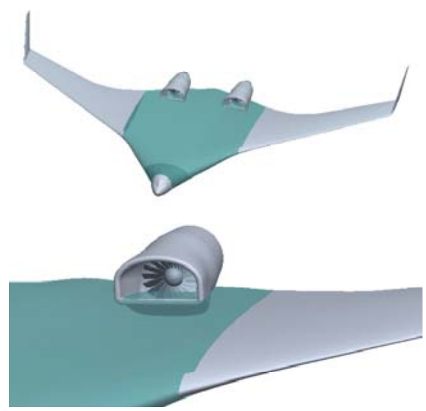

Figure 8b). 300 pax BWB with BLI Inlets.

The propulsion systems of previous BWB designs incorporated Embedded Engines and Boundary Layer Ingesting Inlets as shown in Fig. 8a). Although Boeing's 450 design employs podded engines, as does the 300 pax baseline in this study, work has continued in the development of BLI inlets[7] and flow control devices for the inlet ducts.[8] A study was performed to assess the improvements in the BWB's mission range that occur when podded engines are replaced with the embedded BLI system. As shown in Fig. 8b), the propulsion system for this study involved the two GE-90-like engines embedded into the airframe.

Boundary layer ingestion provides a propulsive benefit due to a reduction in ram drag. This benefit is however offset by diminished pressure recovery in the inlet duct and increased flow distortion at the fan face. For this study, it was assumed that active flow control devices could minimize distortion to the point where it would not impose a significant performance penalty. The ram drag and inlet pressure recovery were assessed by computing the boundary layer thickness using flat plate theory and considering the chord-wise distance between the inlet and the leading edge. The computed boundary layer thickness was corrected by comparing to 3-D computational results from Ref 8. The weight of the inlet, including S-Duct, was computed through empirical weight equations.

Uncertainty in key input variables was taken into account through probabilistic analysis. Triangular input distributions, shown in Fig. 9, represent input ranges defined by a "minimum", "maximum", and "most likely" value. The inputs of interest to the analysis were the empirical "k" factor of the inlet pressure recovery,[9] the

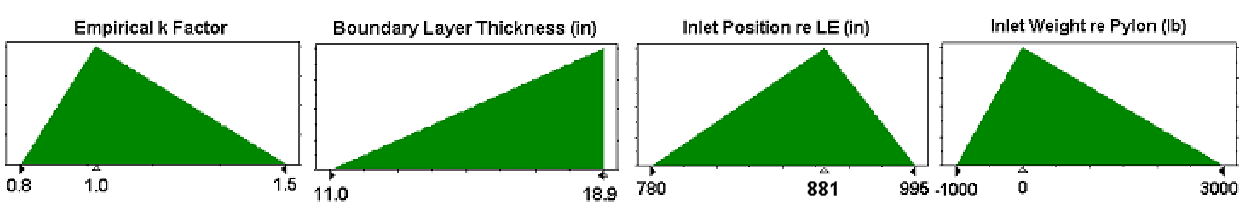

Figure 9. Input Distributions for BWB-BLI Mission Range Analysis.

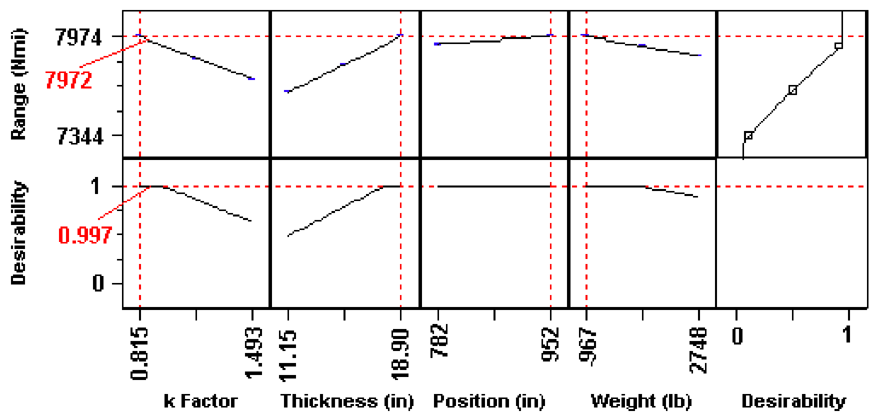

Figure 10. Sensitivities and Desirability Function for the BWB-BLI Monte Carlo Simulation.

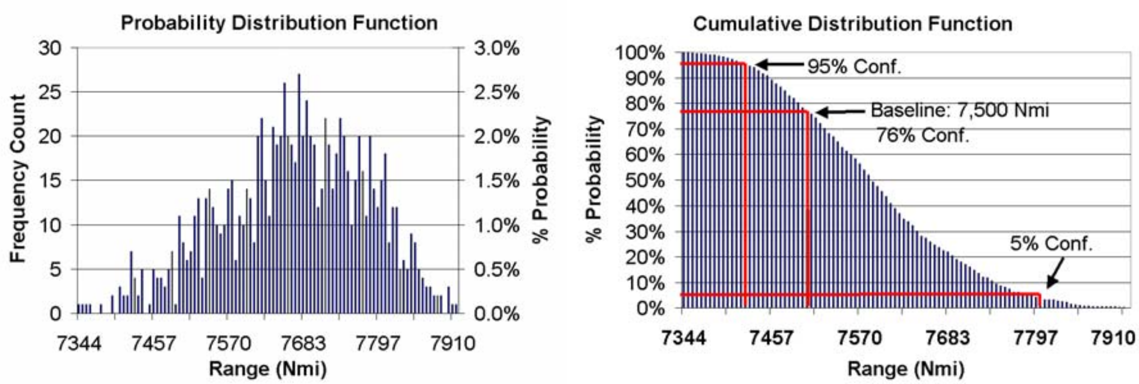

Figure 11. Probability Density Function and Cumulative Distribution Function for the BWB-BLI Monte Carlo Simulation.

thickness of the ingested boundary layer, the distance of the inlet from the wing leading edge, and the inlet weight. For the k factor, 1.0 was considered most likely, 0.8 optimistic and 1.5 corresponded to the same pressure recovery from uniform inlet flow. The boundary layer thickness distribution was set to 18.9 in, corresponding to CFD results, for a maximum and most likely value, and 11.0 in, from flat plate theory, as a minimum. The inlet weight was expressed relative to the weight of the pylon being replaced and its minimum value is –1,000 lb which corresponds to an engine weight reduction from the pylon elimination. 3,000 lb was set as the maximum and takes into account extra weight from added structure. For a most likely case, the changes in weight associated with the removal of the pylon and the addition of support structure were assumed to cancel each other. Following the input definitions, a Monte Carlo simulation of 1,000 cases was run. For each case, input values were selected based on the defined distributions. Each case was then run through the propulsion and mission analysis tools and the mission ranges were computed. The data was then regressed using the statistical software package JMP® and results are shown in Figs. 10 and 11. Figure 10 shows the sensitivities of the mission range response to the four inputs. When range is maximized, the boundary layer thickness is the most influential input followed by the empirical k factor. Working with the desirability function allowed optimization of the response. As is expected, the mission range was maximized when the k factor was at its lowest, the boundary layer thickness was at its highest, the inlet position was at its highest (since the boundary layer has more length to develop), and the inlet weight was at its lowest. Figure 11 shows the Probability Density Function (PDF) and the Cumulative Density Function (CDF) produced by the simulation results. Responses for each case in the Monte Carlo were placed into bins of specified width which are shown in the plots.

The PDF shows the bounds of the variability in the BWB's mission range and also gives a sense of where the mission range value is most likely to lie. For the present study, the BWB-BLI configuration's mission range lies between about 7,344 and 7,910 Nmi and the most likely range, given the defined BLI design space, is about 7,667 Nmi. The CDF, which is the integral of the PDF, shows the cumulative percent confidence that the BWB-BLI configuration will meet or exceed a certain mission range. There is 95% confidence that the mission range will be equal to or greater than about 7,420 Nmi and only 5% confidence that it will be equal to or greater than about 7,781

Nmi. There is about 76% confidence that the range will be equal to that of the baseline configuration which also means that 76% of the design space will improve upon the baseline range.

A deterministic mission range prediction for the BWB-BLI configuration was obtained by entering in the most likely values for the four inputs. This produced a mission range of 7,850 Nmi which is a 4.7% improvement over the baseline. According to the CDF though, there is a very low confidence of this value being met or exceeded but this can be attributed to the fact that the most likely value for the boundary layer thickness, which is the most influential variable, lies at the edge of the design space. This fact can also explain why the PDF is skewed slightly toward higher mission ranges. Figure 12 shows the BWB-BLI configuration deterministic performance results from FLOPS. The block fuel is the same as the baseline since it was a fixed parameter but small improvements in the TOGW, and L/D, were obtained. A large reduction in required thrust per engine, of about 8,000 lb, was gained due to the savings in ram drag during takeoff, approach, and climb.

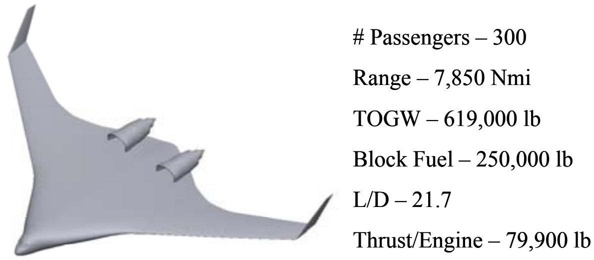

Figure 12. BWB-BLI Configuration Sizing Results for a Deterministic Prediction.

Noise was not assessed in the BLI study since a proper analysis would require acoustic test data of the propulsion configuration which does not currently exist. Future joint NASA and Air Force tests are however being planned to gain a better understanding of BLI noise. Although some inlet fan noise benefit should be gained from the S-Duct geometry, it is likely that the increased distortion at the fan face would make the fan noise, and therefore the noise of BLI configuration, slightly louder than a podded configuration. This qualitative assessment is reflected in the TOPSIS analysis, in Fig. 5, where the BLI inlet is ranked slightly higher than the baseline circular inlet for low NSF (where weight/performance/cost Pugh matrix requirements are dominant) but lower for high NSF (where noise requirements are dominant).

C. Distributed Exhaust Nozzle[10] Performance Assessment

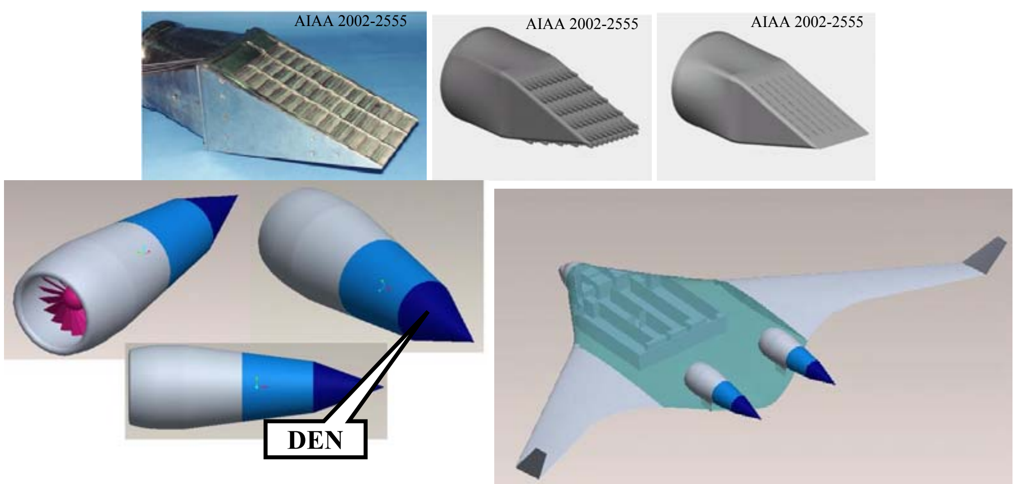

Figure 13. Distributed Exhaust Nozzles Integrated into the BWB.

A distributed exhaust nozzle (DEN) is a technology that lowers jet noise by forcing the jet flow through a series of specially designed holes or slots. The noise reduction is achieved by improving the mixing characteristics of the jet with the ambient air, and by shifting the frequency of the peak noise to a level where it is more easily attenuated in the atmosphere and more favorably weighted on perceived noise scales. Traditional designs, shown in the top of Fig. 13, have been wedge shaped since they are more amenable to integration into an airframe. For this study however, it was desired to examine only the effect of the nozzle's weight and thrust penalties on the BWB's mission range with minimal redesign of the airframe so an axisymmetric conical shape, integrated into a standard turbofan, was examined.

The two main impacts of this DEN integration scheme are weight and thrust penalties. The weight penalty is small, only consisting of the nozzle and mixing shroud weights and weight from extra pylon structure required to support the engine's aft center of gravity shift. The thrust penalties, resulting from the obstruction of the jet flow, however are rather large. Different DEN designs have been studied and their gross thrust penalties generally range from 5 to 10%.[10] This affects the BWB's performance since the engines must be resized to produce enough thrust to meet engine-out 2nd segment climb requirements and must operate at a higher SFC in order to produce their required thrust at cruise.

Figure 14 is a summary of the DEN integration study. Probabilistic analysis was used due to the uncertainty in both the weight and thrust penalty estimates. Triangular input distributions of the nozzle weight and gross thrust penalties were inputted which were designed around "minimum", "maximum", and "most likely" values. The nozzle weight penalty was estimated to be 1,821 lb and a ±10% uncertainty band was placed around it. 8% was chosen as a gross thrust penalty for a representative DEN that was designed for aggressive noise reduction and ±1% was chosen as an uncertainty band. A Monte-Carlo simulation was then performed that selected input values, based on the defined distributions, and obtained BWB mission ranges for 1,000 cases. The results were then regressed. The sensitivities of the two input variables are shown in Fig. 14 and it is observed that the gross thrust penalty affects the mission range far more than the nozzle weight. This is expected since the gross thrust fraction is highly influential to the engine SFC whereas the nozzle weight is only a small fraction of the total vehicle weight. The PDF and CDF of the 1,000 cases are also shown. Discrete patterns are clearly evident in the two distributions and this is due to the fact that the mission range is dominated by one variable, the gross thrust fraction, and that the Monte Carlo simulation sampled these values in 0.1% increments. Referring to the PDF in Fig. 14, the distribution of likely mission ranges spans values between roughly 5,115 and 5,642 Nmi with the highest frequency bin concentrated near 5,410 Nmi, indicating that this is the most likely mission range. The CDF shows a 95% confidence that the BWB-DEN configuration will meet or exceed 5,178 Nmi, 50% confidence that it will meet or exceed 5,379 Nmi, and 5% confidence that it will meet or exceed 5,577 Nmi.

All of the above results indicate that the thrust penalty, imposed by the conical DEN integrated into the BWB's podded engines, highly affects the mission range. Referring to the "most likely" value in the PDF, range is reduced about 28%. It must be stressed however that this particular DEN design was not optimized for integration into standard, podded, turbofan engines as was attempted here. Ref. 10 reports that a more likely integration will involve many distributed engines, embedded in the airframe, with the DEN integrated into the trailing edge as is evident by its closeout geometry. This integration could potentially provide performance enhancements by "filling in" the wake of separated trailing edge flow with the jet exhaust[11] and might therefore partially offset the penalties from the thrust

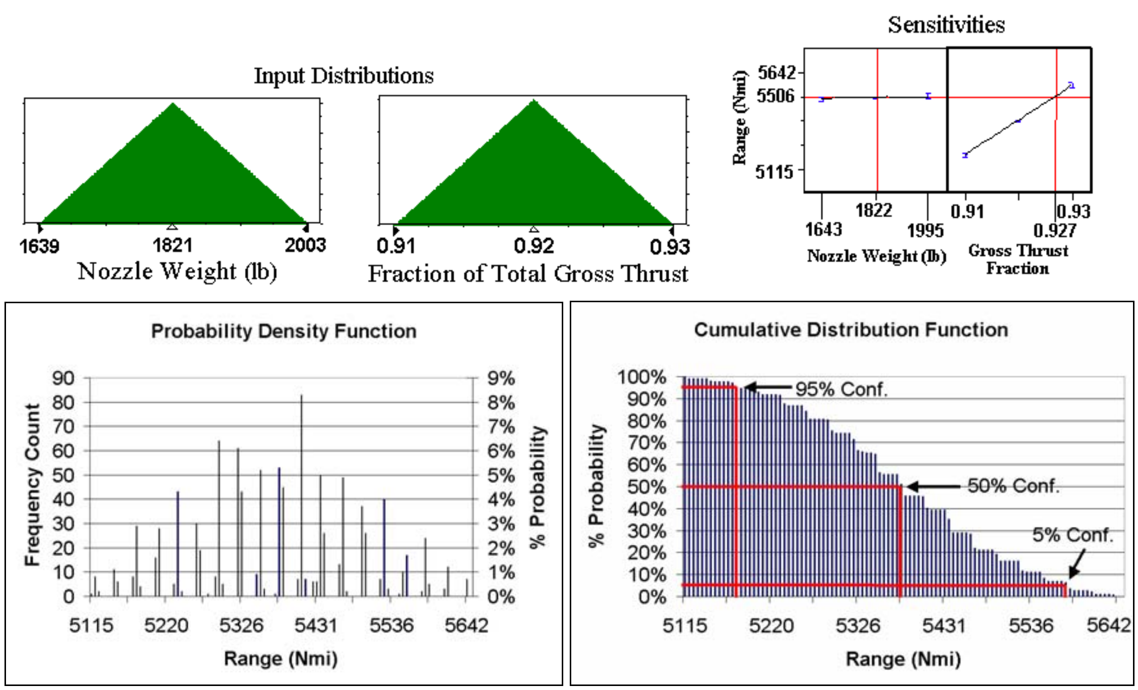

Figure 14. Summary of Probabilistic Analysis of Podded DEN Propulsion System.

loss. This type of integration scheme would however require a much more involved analysis and significant redesign of the BWB's aft airframe which was not within the scope of this study.

The purpose of this study was to examine the individual effect of the thrust and nozzle weight penalties on the BWB's mission range and assess what performance improvements would need to be provided from an advanced integration scheme. As is evident, the thrust penalty results in a rather large decrease in the mission range and significant performance improvements must be obtained. Mission range improvements from BLI inlets were not assessed since they were not expected to significantly offset the penalties.

D. High Aspect Ratio Nozzle Jet Noise Assessment

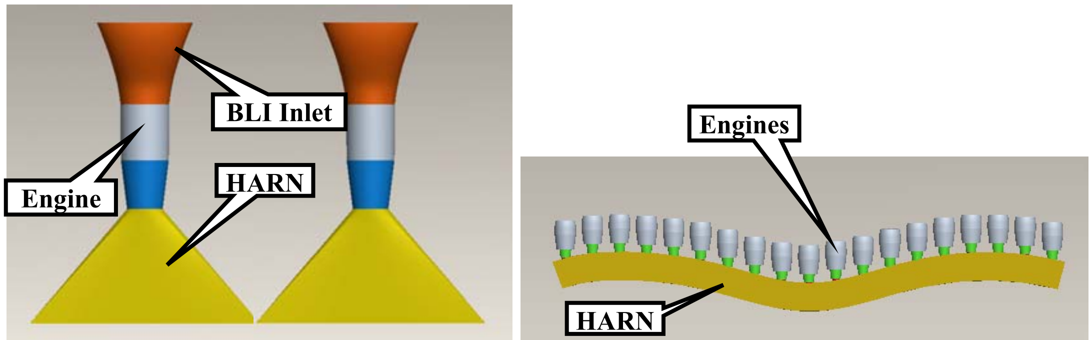

Figure 15. Integration Schemes for a High Aspect Ratio Nozzle.

A High Aspect Ratio Nozzle (HARN) was defined in this study as a rectangular jet nozzle having exit dimensions that form an aspect ratio, defined as the ratio of width to height, that generally falls within the range of 20 to 1,000 or larger. It was desired to examine such a nozzle as a possible low noise alternative to a traditional round nozzle. Although it remains to be conclusively determined, a HARN is thought to emit less noise than an equivalent round nozzle for a few reasons. First, the exit turbulence length scale will be lower since it is generally dependent on the smallest length dimension of the nozzle. Therefore, the fine scale mixing will likely be enhanced. Secondly, the frequency range, also dependent on the smallest dimension, will be shifted upward, as in a distributed exhaust nozzle, and lead to noise reduction from increased atmospheric absorption. Finally, a HARN is thought to be generally quieter at azimuth angles near the plane of the nozzle's major axis. Figure 15 shows two possible HARN integration schemes for the BWB. The first passes the jet flow of the two GE-90-like engines (embedded with BLI inlets) through round to HARN transition ducts indicated in yellow. The second applies to a distributed propulsion setup and is simply a nozzle through which the collective jet flow of all the engines is passed. The curved shape of the nozzle is characteristic of the BWB's trailing edge.

A jet noise analysis was performed on a HARN nozzle, sized (on the basis of aspect ratio) to be integrated into the BWB, and compared to an equivalent round nozzle to examine whether or not the HARN would be quieter. The round nozzle jet noise was predicted in ANOPP, using the SGL prediction method defined in SAE ARP 876,[12] and the HARN noise was scaled from test data from Munro and Ahuja[13,14] using the scaling laws developed in the papers. Table 2 shows the parameters used in the analysis. The aspect ratio of the HARN was determined by constraining the nozzle to have the same exit area as the two GE-90-like engines combined (108.7 sqft) and to have a width 85% of the BWB's wing span. This fixed the maximum possible aspect ratio at 312.5. With this aspect ratio, the exit area had to be limited to 1 sqft for the noise analysis since a higher area would cause the jet Strouhal Numbers to lie outside of the range of available test data. A jet velocity of 930 ft/s and an observer distance of 50 ft was chosen. The round nozzle was defined to have the same exit area and jet velocity as the HARN. The ratio of eddy convection Mach No. to the Mach No. of the jet was set to 0.36 for the HARN and to 0.65 for the round nozzle as suggested by Munro and Ahuja.[14]

Table 2. HARN and Round Nozzle Parameters.

HARN	Round Nozzle
Area = 1.0 sqft	Area = 1.0 sqft
h = 0.679 in	Diameter = 1.128 ft
w = 17.7 ft	Vj = 930 ft/s
AR = 312.5	R = 50 ft
Vj = 930 ft/s	Mc/Mj = 0.65
R = 50 ft	
Mc/Mj = 0.36	

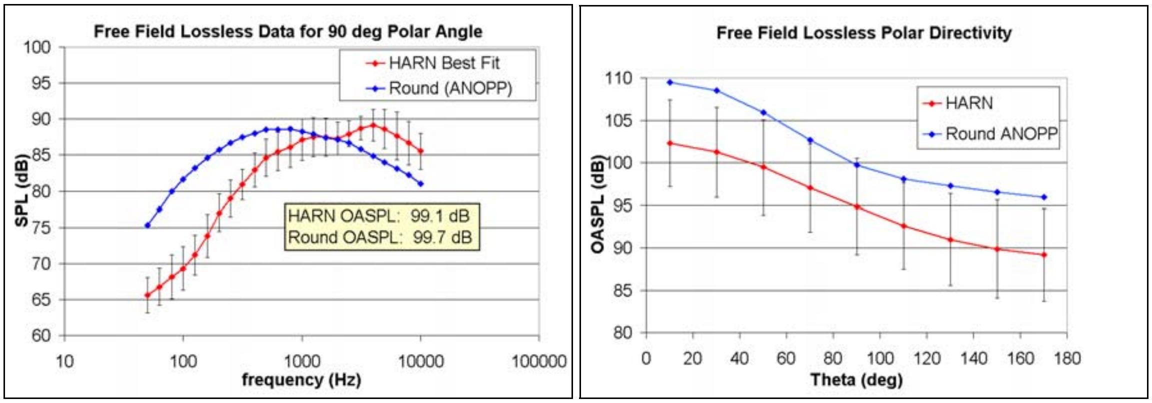

Figure 16. Results of the High Aspect Ratio Nozzle Jet Noise Study.

Figure 16 shows free field, lossless noise results of the two nozzles. An SPL vs. frequency spectrum was obtained for a polar angle of 90 deg which is in the plane of the nozzle exit. Approximate error bars, based on the general outer limits of the data scatter, are placed around the HARN values. Despite somewhat successful efforts in Ref. 14 to develop appropriate relations to collapse the data, an approximately ± 3 dB variation is still seen.

An upward shift in the peak frequency is evident in the SPL curve. However, equivalent Strouhal No. scaling to the full scale BWB HARN places the peak frequency at approximately 384 Hz, a location at which neither a significant atmospheric absorption benefit nor any perceived noise benefit could be realized. The OASPLs at 90 deg are shown in the chart and are virtually identical. The OASPL vs. polar angle results are also shown in Fig. 16. Here the HARN data scatter is much greater due to the introduction of Doppler scaling of the Strouhal No. An estimate of the best fit of the data generally lies 6 dB below the round nozzle OASPLs but the error spread is about ± 7 dB. This shows an inconsistency with the 90 deg OASPL comparison which is nearly equal. Unfortunately, test data was only available for one azimuth angle which is in the plane of the minor axis. Therefore, the noise at angles close to the plane of the major axis, presumed to be lower, could not be examined. Given these results, it was therefore inconclusive in general as to whether or not integration of the HARN into the BWB's propulsion system would result in a jet noise reduction. A recent study by Manneville et al.[15] however surveyed a large body of test data on High Aspect Ratio Nozzles and the overall trends observed suggest noise reductions are possible. Reduction of noise from aft radiated engine sources such as the fan, core, and turbine is also possible by acoustically lining the transition duct.

Despite any possible noise benefits that a HARN might have, many difficulties are associated with the integration. Transition ducts from large engines, as pictured in Fig. 15, would not be desirable due to large weight penalties and space considerations. Also, thrust losses would likely occur from flow separation on the side walls. Therefore, a passage for the collective jet flow of small, distributed, embedded engines seems to be the only worthwhile application of a HARN to a BWB transport.

E. Distributed Propulsion

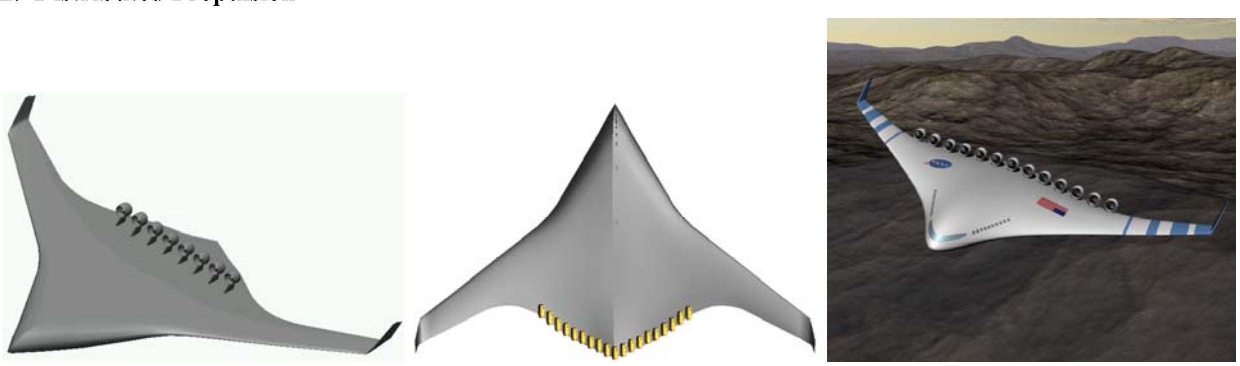

Figure 17. Notional Distributed Propulsion Configurations for a BWB.

Recent work by researchers[11,15,16,17] has been done examining propulsion systems that break the traditional twin turbofan engine configuration into arrays of many smaller engines. Three primary motivations exist for this research.

The first is potential enhancements to performance and noise that come from more flexible airframe integration constraints. Smaller engines may be arranged in more locations around the airframe with less impacts to the vehicle aerodynamics. This creates the opportunity for arrangements that create synergistic performance and noise improvements. Potential arrangements for the BWB, consisting of small engines mounted along the trailing edge, are shown in Fig. 17. This arrangement creates an opportunity for drag reduction by "filling in" the wake of separated trailing edge flow.[11] The second motivation is elimination of the engine-out over sizing requirement. Turbofan engines in a twin configuration must be sized to produce twice as much thrust as required for takeoff and climb to allow for an engine-out scenario. A large number of engines would render the thrust loss from one engine failure negligible and therefore eliminate the need for this requirement. In addition, certain engines may be deactivated at cruise to increase fuel efficiency. The third motivation is cost related. Orders for large numbers of small engines could potentially shift engine manufacturing to a more standardized, mass production setup. This could potentially allow effects from economies of scale and workforce learning curves to lower the unit price. Maintenance costs could potentially decrease as well since off-the-shelf replacements of engines could supplant costly repairs and overhauls.

A study was done to examine the distributed propulsion concept from the standpoint of engine weight and propulsive efficiency by calculating the BWB's mission range for different numbers of engines. The GE-90-like engine deck was used to examine numbers of engines ranging from 2 to 20 and the AE3007-like deck was used for numbers ranging from 20 to 96. Two different decks were used due to the realistic limits at which the engines could be scaled. Given a specified number of engines, the appropriate engine deck was scaled in FLOPS and the engine size and thrust per engine were calculated based on engine-out takeoff and climb requirements and range optimization. The results are shown in Fig. 18. It is observed that increasing the number of engines with GE-90-like cycles from 2 to 18 produces a 5.9% drop in mission range. The same trend is seen in the AE3007-like results but to a lesser degree. Increasing the number of engines from 20 to 96 produces a mission range drop of only 2.1%, which is only half that of the GE-90-like cycle. Observing the results for both engine cycles, it is clear that distributed propulsion setups will decrease range. This result can be attributed to the increase in propulsion sub-system related weight (engine mounts, fuel systems, accessories, etc.). The large difference in range observed between the two engine cycles reflects the fact that smaller turbofans are generally less efficient than large ones due to the practical limits of the core size and turbine inlet temperature. Distributed propulsion configurations will therefore require creative sub-system layouts and new and more efficient engine development to minimize these penalties.

The effect of multiple engines on jet noise was also examined using Stone's model for co-annular jets in ANOPP.[12] A GE-90-like jet noise model, calibrated to publicly available levels reported by Gliebe,[18] was used. For each case, the engine size was scaled so that the prescribed number of engines produced as much thrust as the two baseline engines. As the number of engines was increased, it was desired to examine if the jet noise decrease from reduced engine size and therefore expanded jet area, would outweigh the noise increase from adding more engines. It was also desired to examine if multiple engines would produce jet noise at a sufficiently higher frequency which would result in a noise reduction through increased atmospheric absorption. Results are shown in Figs. 19 through 22.

Figure 19 shows free field lossless SPL vs. frequency results for the GE-90-like jet noise at a polar angle (defined in the figure) of 130° and a distance of 50 ft. As the number of engines increases, the SPL spectra is shifted to higher frequencies as is expected, but the SPL peaks remain nearly constant demonstrating that the effects on the

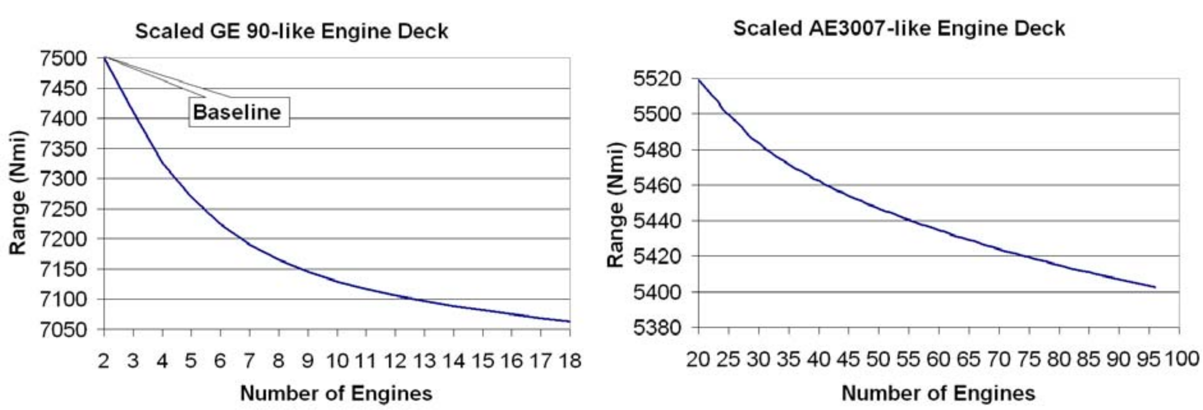

Figure 18. BWB Mission Range Results for Different Numbers of Engines.

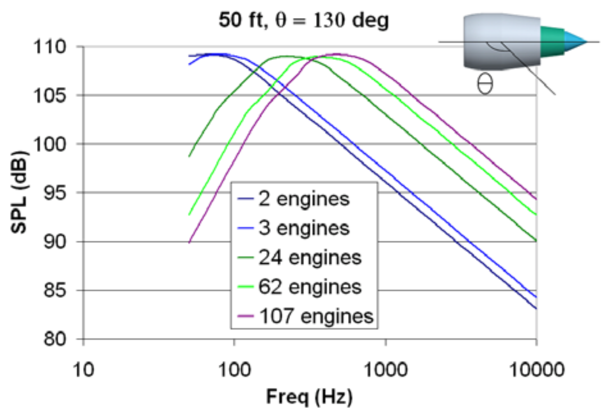

Figure 19. Free Field Lossless Jet Noise SPL for Different Numbers of Engines.

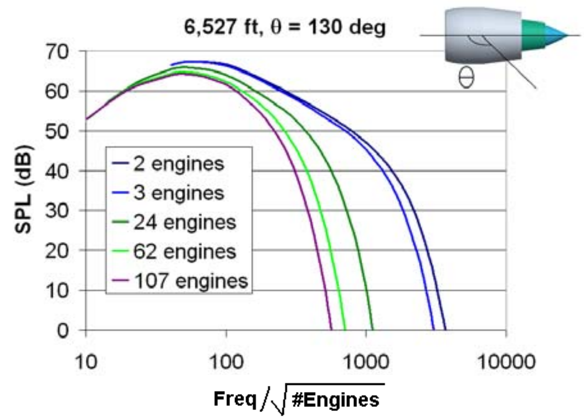

Figure 20. Propagated Jet Noise SPL for Different Numbers of Engines for a Steady Flyover.

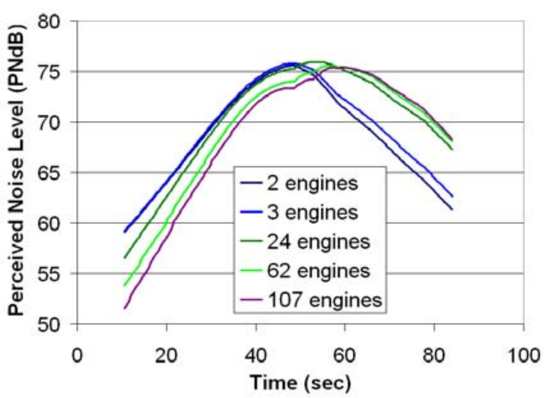

Figure 21. Jet Noise PNL vs. Time Trace for Different Numbers of Engines for a Steady Flyover.

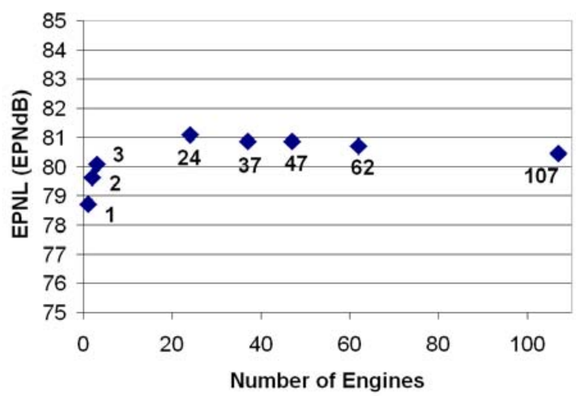

Figure 22. Jet Noise EPNLs for Different Numbers of Engines for a Steady Flyover.

jet noise of reduced engine size and increased engine number tend to balance each other. Unfortunately, the peak SPL for higher numbers of engines lies around 800 Hz which is a more heavily weighted frequency in perceived noise metrics. To examine atmospheric propagation effects, the noise levels were calculated for a steady flyover, at 160 knots and 5,000 ft altitude, of the jet noise source over a single ground observer. Figure 20 shows the SPL vs. a Strouhal No. scaling parameter for the point in the flyover path at which the line from the source to the ground observer falls on the polar arc at 130°. The Strouhal No. scaling parameter collapses the curves for the free field lossless case and thus allows the atmospheric absorption benefit to be seen. The steeper slopes observed for larger numbers of engines indicate that a significant benefit from atmospheric absorption is obtained.

Figure 21 shows the Perceived Noise Level (PNL) vs. time traces for the flyover at the ground observer. A significant reduction from atmospheric absorption is observed in the front half of the traces as the aircraft approaches the observer. As the aircraft moves away however, a significant increase in noise is observed. This may be attributed to the higher frequencies of the smaller engines, observed in Fig. 19, being more heavily weighted on the PNL scale. Figure 22 shows the variation in Effective Perceived Noise Levels (EPNLs) for different numbers of engines. The EPNL is an integration of the PNL (with discrete tone correction) over the time period of the flyover so the absorption benefit and PNL weighting penalty are therefore rolled into one number. Since the EPNL for different numbers of engines hardly varies, it may be concluded that the absorption benefit and weighting penalty largely balance each other. No net jet noise benefit may therefore be associated with distributed propulsion.

Despite no net benefit being provided by the higher frequencies of jet noise from small engines, there is still potential for a benefit from the effects of jet-to-jet shielding. For a BWB distributed propulsion setup, such as those shown in Fig. 17, sideline levels are likely to be reduced since noise produced by jets closer to the center will be shielded by jets on the outside. Potential also exists for noise benefits from embedded configurations as the size of each engine offers more opportunities for tighter airframe integration.

F. Fixed and Retractable Aft Airframe Extension

Due to its planform shape and engine mounting scheme, the BWB offers significant opportunities for airframe shielding of engine noise from ground observers. The baseline 300 pax configuration, in Fig. 7, particularly indicates prospects for reduction of forward radiated noise sources such as the fan inlet. Aft radiating sources, such as the fan exit, core, and jet however are subject to very little airframe shielding and are largely free to radiate to the ground. Due to the logarithmic nature of noise source addition, lowering one particular source far below the others will have an insignificant effect on the overall noise levels. It therefore stands to reason that aggressive shielding of forward radiated noise but neglect of aft radiated noise will not have as significant of an effect as might be envisioned. A full assessment of the community noise reduction from airframe shielding with the present 300 pax baseline is currently in progress.

Figure 23. 300 pax BWB Baseline With Notional Aft Airframe Extensions.

For this study, it was desired to investigate potential ways to better shield aft radiated engine noise with the BWB airframe. Unfortunately, the axial placement of the engine nacelles on the BWB is constrained by the location of the transonic shock line and cabin noise considerations so moving the nacelles forward is a generally sub-optimal solution. Another solution involves extending the aft portion of the airframe as shown in Fig. 22. Obvious system impacts of this modification are weight penalties from added structure and drag penalties from added wetted area. Fortunately, the drag penalties may be eliminated at cruise by the use of a retractable extension, akin to a flap system, that would only be deployed on takeoff and landing when noise reduction is needed. This modification would however come at the cost of increased sub-system weight.

The noise benefit that could be obtained with an aft airframe extension and the performance impacts associated with the added weight and drag were assessed for the 300 pax BWB. The assessments were also made with the BWB-BLI configuration to see if the propulsive benefits found earlier might offset the added penalties.

The geometry of the aft airframe extension, as shown in Fig. 23, generally maintains the BWB's trailing edge shape and was modeled as a simple trapezoidal wing. Extension lengths studied were ½, 1, 2, and 3 engine fan diameters. The length was constrained below 3 engine fan diameters to allow for adequate tip back on takeoff and landing. The extension geometry was entered into the 300 pax baseline FLOPS input file for mission analysis. FLOPS then computed the additional weight using horizontal tail weight equations and the additional skin friction drag. The extra weight from the retractable system was accounted for by increasing the aft airframe and extension weights by 15%, a number derived from previous experience in swing wing studies. For the BLI configuration, a model producing the "most likely" range of 7,667 Nmi (not the deterministic range of 7,850 Nmi) was used. For this model, the empirical "k" factor was set to 0.873, the boundary layer thickness to 13.7 in, the distance from the leading edge to the inlet to 884.5 in, and the inlet weight relative to the pylon was set to –97.4 lb.

Figure 24 shows the results of the mission analysis for three configurations consisting of the fixed and retractable airframe extensions for the podded baseline and the retractable extension for the BLI configuration. The decreases in range are shown for the baseline, ½, 1, 2, and 3 engine diameter extensions. For the fixed extension, fairly modest range decreases of about 10% for the 2 engine diameter (2-D) and 14% for the 3 engine diameter (3-D) extensions are observed but are not quite as severe as originally expected. These decreases are however dramatically reduced for the case of the retractable extension and are only about 4.4% and 7% for the 2-D and 3-D extensions respectively. Since these decreases are nearly half that of the fixed extension, and extra weight is added for the retractable system, it is apparent that the drag penalty of the extension contributed to most of the loss in mission range. The BLI configuration's propulsive benefit clearly offsets the weight and performance penalties and only about 2% and 5% range losses are observed for the 2-D and 3-D extensions respectively. For the 1-D extension and below, the BLI aircraft has greater range than the baseline.

Although this study shows positive results for the retractable extension, the extra weight was estimated very roughly. In addition, such a modification would pose additional complexity to the aircraft and require some redesign. The structure of the aft airframe, particularly the engine mounts, would have to be modified. Also, the inboard elevons would have to be either combined with the retractable system, or an alternate means of vehicle control, particularly for takeoff rotation and landing flare, would have to be found. A fixed extension however would likely improve longitudinal control since the elevons could potentially be farther from the aircraft's center of gravity. Despite these extra considerations that weren't taken into account, it is still likely that a retractable extension would be worth installing over the fixed extension given the cruise drag savings.

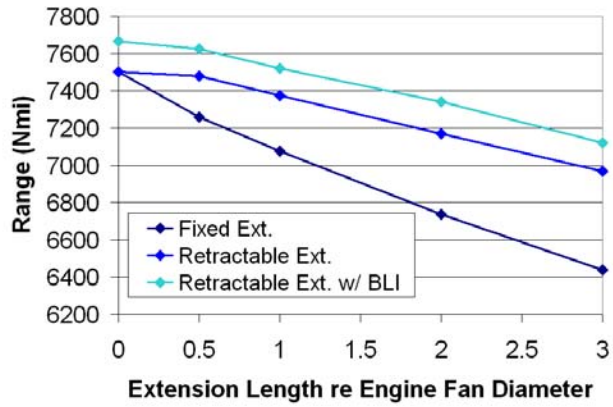

Figure 24. Mission Analysis for Aft Airframe Extension Configurations.

A noise analysis was also performed to assess the benefits of the extensions. For this study, a model of the baseline GE-90-like engine was constructed using ANOPP. Engine noise sources considered were fan inlet noise with duct treatment, fan exhaust noise with duct treatment, combustor or "core" noise, and jet noise. Turbine noise was neglected since its levels are usually well below the other sources. Airframe noise sources of the BWB were not modeled. Engine state tables for the noise model were taken from the NPSS cycle analysis and takeoff and approach profiles of the 300 pax baseline were computed in FLOPS. A cutback maneuver was added to the takeoff profile which is typical practice for noise certification flights. The engine noise sources were then analytically "flown" along the takeoff and approach trajectories and the noise was propagated through the atmosphere. The Effective Perceived Noise Levels (EPNLs) were then calculated at the three FAR-36 Stage 3 certification observer locations. All four engine noise sources were then calibrated to publicly available GE-90 EPNLs as reported by Gliebe.[18] This was performed using artificial suppression factors in the ANOPP code which "forced" the predictions to their reported values. The calibrations were made for a FLOPS predicted Boeing 777-like certification flight path and engine size which is the normal operating environment of the GE-90. Levels then changed slightly for the BWB flight path and engine size.

Acoustic tests have been performed by Clark and Gerhold[19] to assess the shielding capability of the BWB airframe. As shown in Fig. 25, a broadband noise source, consisting of four impinging jets, was placed in a nacelle above a 3% scale model of the BWB 450-1L. Microphone arrays in the acoustic chamber were used to measure the source noise with and without the presence of the model and obtain insertion loss maps for different source frequencies. A follow-on experiment in 2003 produced insertion loss maps for different axial and lateral source placements, an example of which is shown in Fig. 25. This data was used to create approximations of the shielding from the extension. Fig. 26 shows the axial and lateral locations at which the engine noise sources were assumed to lie for the baseline, 1-D, and 2-D configurations. These were the source locations and configurations for which insertion loss data was available. The maps were then applied as sets of suppression factors to the ANOPP source predictions. In all three configurations, the fan inlet source was suppressed using the baseline map since it was not, in reality, moving forward.

The EPNL results for each source and for the whole propulsion system at the cutback certification point is shown in Fig. 27. Fan Inlet noise is not included since only one suppression map was used in the analysis. In reality, the

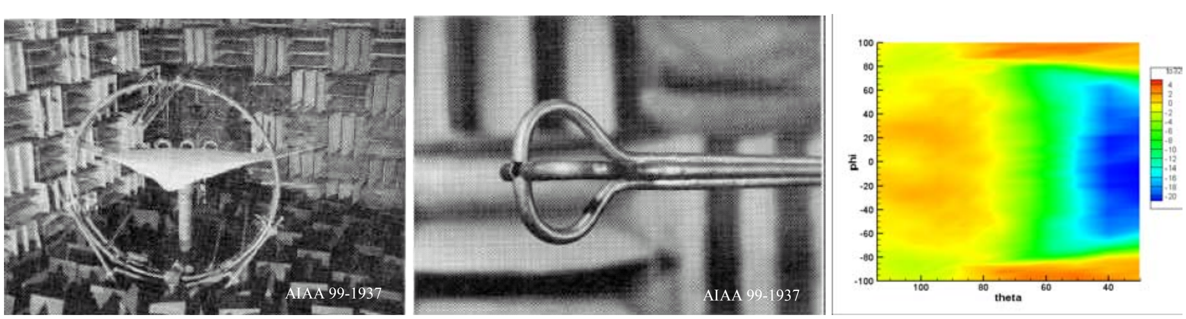

Figure 25. BWB Acoustic Shielding Experiments.

extension should not affect the fan inlet noise significantly since this source is a predominately forward radiating source. Substantial noise reductions are observed in the displayed sources and in the total propulsion system. For the 1-D configuration, the three individual sources experience nearly the same reduction which is about 3 EPNdB. For the 2-D configuration, the fan exhaust noise clearly benefits the most as it is reduced by nearly 15 EPNdB. Reductions for the 1-D and 2-D configurations are called out in the figure for the overall noise and are 2.7 and 8.4 EPNdB respectively. The results therefore indicate that extending the airframe to shield the aft sources will provide a very substantial noise reduction.

The noise results at the sideline point are not included since unusually large reductions, close to those calculated at the cutback point, were observed. Since the shielding of the extension was approximated by using an insertion loss map for a source location forward of the trailing edge, it is likely that much of the shielding benefit seen at the sideline was due to the presence of the BWB's wing. The analysis was therefore not considered valid since, in reality, the engine sources will remain at the trailing edge and not have the path to the sideline obstructed by the wing. The results at the approach point are not included either since an adequate jet noise prediction at low throttle settings could not be obtained.

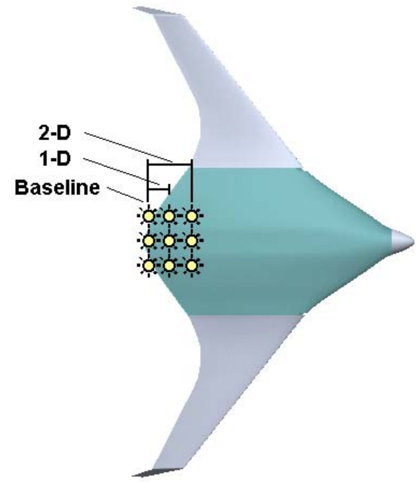

Figure 26. Axial Locations at Which Insertion Loss Maps Were Developed.

The noise analysis, although promising, contains four major assumptions. First the noise source, for which the insertion loss maps were based, was an arbitrary broadband source rather than an actual engine. Second, the effect of the extension was simulated by moving the engine sources forward rather than extending the airframe aft. As mentioned before, this led to what are believed to be exaggerated reductions at the sideline. Third, the insertion loss maps reflect a noise source configuration for three engines (which represents the 450-1L model) rather than the two engines of the 300 pax. Finally, in reality, the jet noise source radiates much of its noise downstream of the nozzle in the jet plume. Any aft airframe shielding would therefore probably not affect the jet source as much as the analysis indicates. Work is continuing on better assessing the shielding potential of the BWB's airframe through experiment and, more recently, computational analysis.[20]

As has been found, an aft airframe extension appears to be a very promising means of reducing the BWB's noise signature. Another option, that could potentially result in less of a weight penalty, involves reshaping the BWB airframe so that the aft portion protrudes past the engines, but the overall airframe wetted area remains conserved. This solution could however have negative implications on the BWB's aerodynamic efficiency. Fortunately, the BWB's planform shape offers flexibility for optimal aerodynamic and aeroacoustic design and, with careful study, it appears possible to find a well balanced solution.

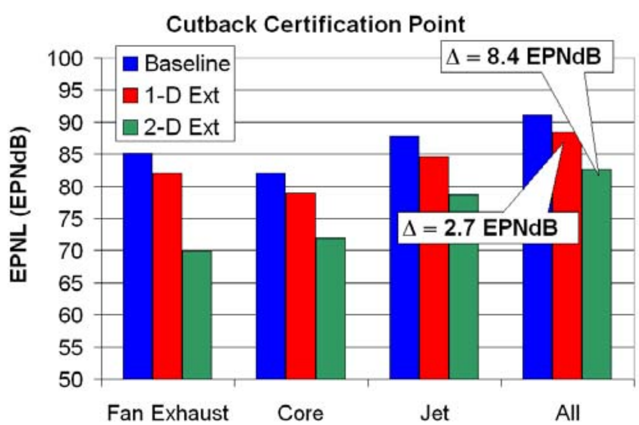

Figure 27. Source and Overall Noise Levels at the Cutback Certification Point.

IV. Conclusions

A series of studies were undertaken to examine the noise reduction potential and system impacts of several propulsion-airframe-aeroacoustic technologies and design concepts. A 300 passenger Blended-Wing-Body aircraft with two GE-90-like engines in a podded configuration was used as the study baseline. The BWB propulsion system was functionally decomposed into a morphological matrix and alternative component technologies and design concepts were brainstormed. This technology and design concept list was then evaluated using a Pugh Evaluation Matrix and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). This analysis produced subjective rankings of the technologies and design concepts as to how well they satisfied, overall, a list of noise, weight, performance, and cost requirements. The analysis also showed how the rankings varied as the noise requirements became more and more important in the design. Nearly all of the PAA technologies and design concepts produced a noise benefit but degraded the BWB's performance. Circulation control was seen as a promising noise technology since the expected operational improvements would move the aircraft farther away from the community. Forward mounted engines had the lowest baseline crossover noise scale factor and were therefore seen as providing a good noise benefit and imposing a minor performance penalty. The analysis in general allowed a wide range of PAA technologies and design concepts to be catalogued and evaluated in a short period of time and some tentative conclusions to be drawn regarding their desirability for further study.

Following the TOPSIS analysis, several systems analyses were undertaken on advanced propulsion airframe configurations. An embedded engine with Boundary Layer Ingesting Inlets was studied, using probabilistic analysis, and it was found that a benefit in the mission range could likely be obtained through increased propulsion efficiency. Although not likely providing any noise reduction itself, it was concluded that BLI inlets may enable embedded configurations and offset penalties from other technologies. A podded Distributed Exhaust Nozzle configuration was examined to see how the DEN's thrust penalty would impact the mission range of the BWB. The impact was rather high and it was concluded that a more advanced configuration with synergistic aero-propulsive improvements, such as distributed exhaust over the trailing edge, would have to be implemented in order to offset the thrust penalty. A High Aspect Ratio Nozzle was examined and it was concluded that its application to the BWB should be limited to an embedded engine, distributed propulsion configuration. Its noise reduction potential however could not be fully assessed. A distributed propulsion concept was examined by sizing down GE-90-like and AE3007-like engine decks and assessing the range impact of multiple engines. It was found that penalties exist and they are likely attributed to the extra weight of propulsion sub-systems and the lower efficiency of smaller engines. Jet noise was also studied and it was found that, although the higher frequencies of multiple engines provided an atmospheric absorption benefit, a Perceived Noise Level weighting penalty offset this and the Effective Perceived Noise Levels hardly varied. Further study of jet-to-jet shielding is needed to investigate any potential noise reduction benefits. Finally, an aft airframe extension was examined. It was found that the extra weight and drag of a fixed extension produced a modest range penalty. A retractable extension however eliminated the drag penalty and this was found to be a more desirable option despite the extra weight of the system. Substantial noise benefits at the cutback certification point were observed due to the shielding capability of the extensions. This suggests that an extension, or a general reshaping of the airframe, is a very promising means of reducing the BWB's noise signature.

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