ENVIRONMENTALLY RESPONSIBLE AVIATION – REAL SOLUTIONS FOR ENVIRONMENTAL CHALLENGES FACING AVIATION

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Abstract

The combined reality of persistently strong growth in air traffic and the vital economic role of the air transport system result in continued demand for the progress of technology for the reduction of aircraft noise, emissions of oxides of nitrogen, and fuel burn. NASA's Environmentally Responsible Aviation (ERA) project has set aggressive goals in these three areas including a noise goal of 42 dB cumulative below the Stage 4 certification level. The goal for the reduction of oxides of nitrogen is 75% below the current standard. The fuel burn reduction goal is 50% below that of a current state-of-the-art aircraft. Furthermore, the overall goal of ERA is to mature technologies that will meet these goals simultaneously and with a timeframe of 2020 for technical readiness. This paper outlines the key technologies and the progress achieved to date toward the goals.

2. Reducing community noise – goal setting and identification of key technology areas

2.1. Overview

Over the last decade an increasing amount of research effort has been focused specifically on the aeroacoustic effects related to advanced aircraft configurations and to the associated effects of propulsion airframe integration (distinguished by the term Propulsion Airframe Aeroacoustics (PAA)). This is recognition of the opportunity for both noise reduction [2] and performance gains. The opportunity is attributed both to the growing evidence of the number of PAA effects as well as their magnitude. PAA can include both reducing the noise sources that arise specifically from integration of propulsion and airframe and using the installation itself as a means to reduce noise. From a research point of view, the challenges have been daunting, largely a result of the far more complex experimental and predictive approaches required to address integrated propulsion and airframe aircraft systems. Furthermore, sufficient definition of the aircraft and engine systems is required both in the formulation of experiments, for prediction methods and then again to develop overall aircraft noise assessment. However, those same system models, particularly for unconventional aircraft, have been hampered by the lack of sufficient experimental and predictive capability.

Therefore, to advance through these significant challenges, NASA has emphasized all three key elements, those of PAA experiments, higher fidelity system noise prediction methods, and system assessment. The first two are the focus of this section as they relate more to the acoustics discipline. Furthermore, the PAA element of ERA is pursuing a technology development cycle in three stages, an initial pathfinding study (2003-2005), a critical stage (2008-2010), and currently a high fidelity stage (2008-2012). This three-stage process will aim to produce a relatively high level of understanding, technology readiness, and system noise benefit assessment for the Hybrid Wing Body (HWB) concept in particular, and also serve as a foundation for other advanced concepts. The key components of the development cycle, key results to date, and future plans are outlined in the sections below.

2.2 Pathfinding Acoustic Assessment of HWB Concept

With the growing interest over the last decade in advanced aircraft configurations that could enable a step change in noise reduction, there have been several very successful international workshops including the 8th CEAS Aeroacoustics of New Aircraft and Engine Configurations held in Budapest, Hungary, November, 2004 and the Revolutionary Aircraft for Quiet Communities Workshop held in Hampton, Virginia, USA in July, 2007. These workshops showed a breadth of innovative low noise aircraft concepts and prediction methods under development. However, these workshops also point out the many gaps in methods and data that are required to perform high quality assessments of an advanced aircraft concept. For these reasons NASA began a pathfinding study in 2003 focused on the hybrid wing concept both for the obvious noise reduction potential but also because there was a growing database related to the Boeing BWB, a representative example of a HWB concept. The Hybrid Wing Body aircraft configuration represents an unconventional aircraft concept that introduces the fundamental change of installing the engines on top of the airframe and, in addition, producing lift with the fuselage itself with the implication of eliminating the traditional high lift system with flaps. By themselves, relative to the paradigm of conventional aircraft, these changes represent the potential for a step change in noise reduction.

The primary objective of this NASA pathfinding study was a basic understanding of the PAA effects due to the differences in configuration between a conventional tube-and-wing and the HWB. To accomplish this the two configurations were matched with the same current technology turbofan engines and sized to meet the same mission requirements. The second objective was to understand the implications for noise of the hybrid wing body configuration and assess the potential noise reduction achievable by using fewer and relatively near term technologies. The study was primarily performed by Geoffrey Hill of NASA and concluded in 2005 with only some elements of the study published [2,3] and the final results compiled in presentation form by Thomas [4] in 2007. In contrast to flight dynamics or aerodynamics, this study was limited by the almost complete lack of high quality acoustic data or prediction methods for many of the aircraft components, a situation that is generally the case when attempting a complete noise assessment of an unconventional aircraft. The shielding of engine sources, a key PAA effect representing much of the noise reduction potential of the HWB, could not be done adequately at that time with prediction methods. A detailed shielding experiment [5] albeit with a simplified point noise source [6] and no flow effect was used to supply the noise assessment with the effect of shielding. Within the constraints of this study, the baseline HWB was assessed at a level of 22 dB cumulative below Stage 4 with aft radiated noise from the jet and fan exit as the components clearly representing the potential for additional noise reduction. The potential for noise reduction was assessed by moving the engines two fan nozzle diameters upstream of the trailing edge to provide some shielding surface for aft radiated noise. Next, a significant assumption was made that PAA technology from advanced chevrons and the pylon effect could, in the physical limit, move jet noise sources, across the whole frequency range, all the way to the nozzle exit. Finally, assuming complete success of this strategy, the potential noise reduction of the HWB was assessed at 42 dB cumulative below stage 4. This result then became the basis for the aggressive N+2 noise goal of NASA's ERA project. This study showed that with a few key, relatively near term PAA technologies, if successfully developed and applied, the HWB could produce a step change in aircraft noise reduction without a large array of higher risk and longer term technologies and operational changes.

The pathfinding study resulted in setting the 42 dB cumulative goal as well as a foundation for a critical stage of development that would require high fidelity, large scale experimental data and PAA technology for the key jet noise related source (section 3). It would also require that the next step in the aircraft system definition and system noise assessment be made in this critical stage (section 4).

2.3. Critical Stage 2009 HWB PAA LSAF Experiment

To meet a critical level of experimental investigation of HWB aeroacoustics required an experiment that focused on what was expected to be the most difficult noise source to predict and reduce, jet noise and it's PAA effects. This PAA experiment had to be large enough in scale for both frequency scaling and high fidelity geometry, include forward flow effect, and include the PAA effects through the relevant propulsion airframe integrated model geometry. Boeing in the Low Speed Aeroacoustics Facility (LSAF) accomplished this experiment [7] in 2009. The LSAF was configured for a 9 ft by 12 ft free jet in the very large anechoic chamber with far field polar angle microphones at three azimuthal angles and a high resolution phased array traversing system. There were three parts to the experiment. The first part used a high fidelity airframe model with flow through nacelles to document airframe noise sources including the slat, trailing edge, and elevon. The second part used a broadband point source to produce a basic database of shielding for point sources that could be an approximation for the shielding of engine sources internal to the nacelle. The largest part of the experiment focused on the key PAA effects of jet noise. The objective was to provide an understanding of the shielding effectiveness as a function of engine gas condition and location as well nozzle configuration. A 4.7% scale separate flow nozzle of a bypass ratio seven engine was run at characteristic cycle points under static and forward flight conditions. The effect of the pylon and its orientation on jet noise was also studied as a function of bypass ratio and cycle condition.

This critical stage study also selected the PAA technology for the nozzle system and developed the PAA technology through configuration of the nozzle and pylon system. PAA technology options were selected based on prior PAA research of interest for conventional configurations, specifically the acoustic effect of the engine pylon [8-13] and unique PAA chevron nozzles designed to reduce source noise [14] including favorable interaction with the effect of the pylon [14-16].

In order to assess jet noise shielding, a planform representation of the airframe model, also at 4.7% scale was traversed relative to the jet nozzle from downstream to several diameters upstream of the wing trailing edge. Installations at two fan diameters upstream of the wing trailing edge provided only limited shielding in the forward arc at high frequencies for both the axisymmetric and a conventional round nozzle with pylon. This was consistent with phased array measurements suggesting that the high frequency sources are predominantly located near the nozzle exit and, consequently, are amenable to shielding. The mid to low frequencies sources were observed further downstream and shielding at these frequencies was insignificant. Chevron designs generally aim to reduce low frequency noise while at the same time minimizing an increase in the high frequency region. The design intent for the chevrons in this study considered the potential impact of shielding through altering the location of jet noise sources. A more aggressive chevron was designed with enhanced immersion to impact the source locations more significantly with the anticipation that the increase in the high frequency part of the spectra could be shielded.

In general, shielding effectiveness varied as a function of cycle condition with the cutback condition producing higher shielding compared to sideline power. The configuration with the aggressive chevron and a pylon oriented opposite to the microphones produced the largest reduction in jet noise, a combination of reducing the source and relocating jet sources upstream for more effective shielding. More detailed discussion of this database can be found in Czech, Thomas, and Elkoby [7] including the effects of point source shielding, additional shielding from vertical and elevon surfaces, and the source and shielding effects from nozzle and pylon technologies. This database provided the new high quality data for critical elements of an updated HWB system noise assessment in 2010.

2.4. Critical Stage 2010 HWB System Noise Assessment

Thomas, Burley, and Olson [17] performed a critical stage system noise assessment of a hybrid wing body configuration in 2010. They used updated NASA HWB aircraft [18] and turbofan engine models and the best available NASA system noise assessment method based on ANOPP. The experimental results from Czech, Thomas, and Elkoby [7] were used for the key noise sources and their interaction effects with the airframe to provide data directly into the noise assessment where prediction methods are still inadequate. NASA engine and aircraft system models were created to define the hybrid wing body aircraft concept as a twin-engine aircraft for a 7500 nautical mile mission. The engines were modeled as existing technology high bypass ratio (approximately 7) turbofans.

The potential for additional noise reduction with relatively near term technologies was assessed, however, with high quality data and improved assessment methods compared to the pathfinding study. Several configurations were studied and the results are summarized in Figure 1 in Effective Perceived Noise Level (EPNL), dB. The baseline HWB assessed at 22 dB below Stage 4, a level that results primarily from lower airframe noise on approach (absence of flaps and a lower approach speed), shielding of fan inlet noise, and the faster climb on takeoff. Configuration 2 reduces the aircraft noise to 31.6 dB below Stage 4 due to simple shielding effect from the two diameters of shielding surface that primarily impacts fan exit and core noise but has little impact on jet noise.

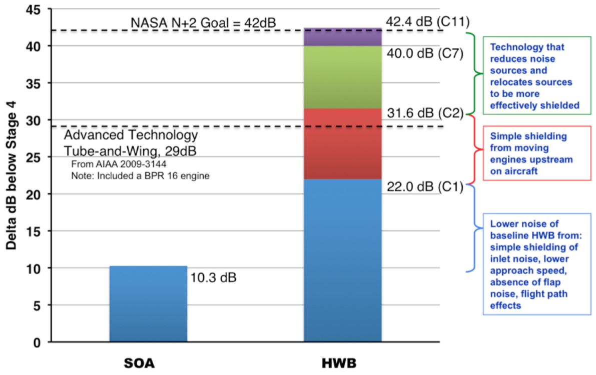

Fig. 1. Critical system noise assessment results summary from 2010 study [17].

Configuration 7 includes a package of technologies that can reduce source levels and impact the source distribution so as to enhance the effectiveness of the same shielding surface length. This configuration includes the advanced PAA type of chevrons that reduce source noise and also relocate sources upstream across a wide frequency range. The standard pylon with a known strong acoustic effect is rotated to the crown position above the nozzle and airframe resulting in a favorable azimuthal directivity of jet noise. Of course, an implementation of this configuration would require a second pylon in the keel position of a design that creates a weak acoustic effect but would also meet other vehicle requirements. This could be accomplished in the simplest approach if the pylon could be closed out before the exit plane of the core nozzle, or better before the exit plane of the fan nozzle. Configuration 7 also takes advantage of the crown pylon by adding an acoustic liner to the wall surfaces of the crown pylon, internal to the fan nozzle. The fan exit noise component is the second highest component on both approach and cutback and it could be further attenuated with the application of acoustic liner to the crown pylon. This increases the area of acoustic liner in the bypass duct that can reduce fan exit noise and, furthermore, projections of more advanced liner technology can be factored in based, in part, on prior computational results [19, 20]. Therefore, the crown pylon can be a rare dual noise reduction device reducing jet noise as well as fan exit noise simultaneously. The resulting system noise of Configuration 7 showed a cumulative 40 dB below Stage 4.

Configuration 11 adds three additional technologies to address the noise components that are still highest after the effect of the technologies on Configuration 7. Adding projected benefits from more advanced chevrons, pylon technology and, quiet landing gear, Configuration 11 adds 2.4 dB more noise reduction for a total of 42.4 dB below Stage 4. Figure 1 compares levels to the noise of the reference SOA configuration and to the noise level for an advanced technology tube-and-wing aircraft. This advanced technology aircraft with ultra high bypass ratio (BPR 16) engines mounted under the wing was assessed by Berton, Envia, and Burley [21] at 29 dB cumulative below Stage 4. Configuration 11, even with the existing technology high bypass ratio (BPR 7) turbofan engine, meets the NASA N+2 noise goal of 42 dB and exceeds the advanced technology tube-and-wing by more than 13 dB.

By meshing the approach and takeoff flight path information for a simulated single event landing and takeoff, ground contours of sound exposure level (SEL) can be assembled. Figure 2 plots the ground contours for the SOA aircraft and the HWB with Configuration 11. The HWB configuration shows a dramatic reduction in the area within a given ground contour level. If the area of the SOA aircraft is normalized to 1.0, then for the parameters of this calculation the area for the HWB C11 is 0.34 for an overall reduction of 66% in ground area. This calculation clearly demonstrates the significant potential benefit to airport communities of the HWB aircraft designed for low noise.

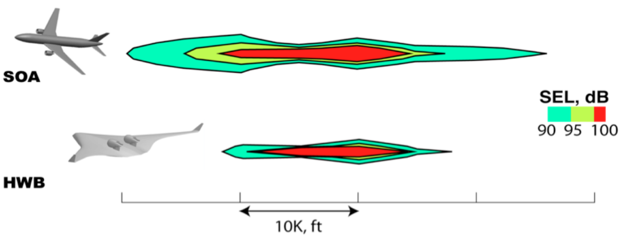

Fig. 2. Calculated ground contours of Sound Exposure Level (SEL), dB, for the state-of-the-art reference aircraft and the HWB with technologies applied (C11) [17]

Several conclusions were achieved at this critical stage. Jet noise is the dominant component at both cutback and takeoff conditions and is a particular challenge because of the distributed sources. The total installation of the jet through the combination of the pylon orientation at the crown with the aggressive chevron design was very effective at reducing the jet source level and increasing shielding effectiveness. Chevron technology has advanced rapidly in recent years for jet source noise reduction. The fact that chevrons can be effective at the combined objective of source reduction and relocating sources upstream, making the shielding more effective, opens a new design space for integrated pylon and chevron technology. The benefit of the crown pylon is especially valuable for its simultaneous impact on jet source relocation and fan exit noise attenuation. This benefit of the crown pylon should be studied with higher fidelity experiments and assessment because fan noise radiating from the crown area of the fan duct, away from the airframe, has a higher angle relative to the airframe and is less likely to be shielded. The additional attenuation of fan noise from the crown acoustic liner can mitigate this. This study has also identified the importance of reducing landing gear noise at the source.

Starting from Configuration 11, additional reductions could be obtained from a few logical approaches. First, the verticals could be moved from the inboard position to winglets for a small noise benefit and for the better aerodynamics of the original HWB concept. This change in the verticals together with deflection of the elevons up would likely assess the concept at more than 43 dB. Because jet (at sideline and cutback points) and landing gear noise (at approach point) would still be the dominant noise components, the technologies relevant to reducing these sources and enhancing jet shielding should be advanced further. And finally, considering a configuration that would include higher bypass ratio engines (approaching BPR 10) that are currently being introduced into service (or even higher bypass ratio engines being considered for application in a few years) this next configuration should be able to exceed the 42 dB goal by a considerable margin.

A new configuration like the HWB does introduce a new paradigm for noise reduction. Even with its inherent potential, a low noise HWB must be designed from inception with noise as a goal in order to maximize the noise reduction especially including the propulsion airframe aeroacoustic technology developed simultaneously for source reduction and increased shielding effectiveness. The capability is growing to conduct additional trade studies for low noise, efficient HWB configurations given the prior knowledge base from other disciplines, the high quality experimental data and system noise assessment methodology assembled for this study, and the identified advanced airframe, acoustic liner, and PAA technologies.

2.5. High Fidelity ANOPP2 System Noise Methodology

NASA introduced the Aircraft NOise Prediction Program [22] (ANOPP) about 30 years ago to provide a capability for predicting the noise from aircraft in flight. Since that time the ANOPP system has continuously been used by government agencies, academia and the aircraft industry to assess aircraft noise and evaluate the noise reduction potential of new technologies. ANOPP relies primarily on semi-empirical methods for predicting the various aircraft noise sources and hence is most accurate and applicable for those configurations in which the empirical models are based. Those configurations are dominated by the basic tube-and-wing designs with under-the-wing mounted engines. Application of ANOPP for configurations that deviate much from those designs is considered outside the range of validity for which the models were intended. To remedy this limitation, NASA is developing a next generation aircraft noise prediction capability called ANOPP2.

The objective of ANOPP2 is to provide a system noise prediction capability that is applicable to current and future aircraft designs. ANOPP2 is being designed to be of varied-fidelity, ranging from the current empirical based models to higher fidelity prediction capabilities that can be used to provide accurate assessment of future designs and new technologies. The current ANOPP assumes that the sources are at a single point, typically the center of gravity of the vehicle. The effects due to shielding or reflection of noise from the airframe are estimated using the ANOPP method based on Maekawa [23] or may be provided to ANOPP as experimentally determined noise suppression. In contrast, the next generation ANOPP2 will locate the noise sources at their true locations thereby allowing for the effects of installation to be examined. The propulsion airframe aeroacoustic installation effects such as noise scattering and those effects associated with flow interactions between components will be an integral part of the noise source computation. Methods for noise propagation through the atmosphere will account for changes in environment, such as wind and temperature gradients as well as variable ground impedance and elevation. The engine and airframe noise prediction methods will range from the current empirical methods to higher order methods and be selectable by the user based on the fidelity required. In order to accommodate and implement these ANOPP2 features and requirements an adaptable framework is being developed that accommodates current/future prediction methods, propagation algorithms, and flow solutions components. At this time the framework is in its initial stages of development. Several capabilities including the current ANOPP and advanced jet noise prediction codes have been implemented within the ANOPP2 framework and are being tested.

Of particular emphasis, critical to analysis of HWB configurations is the inclusion of capabilities to predict acoustic shielding and scattering effects. The ANOPP2 options being developed and validated for noise scattering prediction vary in fidelity and include a method based on Kirchhoff diffraction theory [24], a jet noise scattering method based on a wave packet noise model coupled with a boundary element scattering method [25] and the Fast Scattering

Code, which is based on the equivalent source method [26].

2.6. High Fidelity 14 by 22 Wind Tunnel HWB Validation Experiment

While much progress has been made through the pathfinding and critical stages of development, the next stage aims to achieve a higher level of readiness by filling in significant gaps through a coordinated, interconnected set of efforts. These efforts include, first, a multidisciplinary design of a low noise HWB drawing on the experience of past efforts. Second, development of prediction methods relevant to unconventional aircraft that are then integrated into ANOPP2. Third, a large-scale high fidelity experiment that includes the full HWB aircraft model with integrated airframe and propulsion simulation. And finally, the ANOPP2 system noise prediction method will be validated with the high fidelity experimental results including EPNL system noise assessment to be compared with the 42 dB N+2 noise goal.

A team funded by NASA and led by Boeing Research and Technology [27] is developing two HWB aircraft concept designs referred as N2A and N2B with the basic airframe of both concepts evolved from the original SAX40 aircraft of the Cambridge-MIT's Silent Aircraft Initiative [28]. The N2A configuration has twin high bypass ratio turbofan engines mounted on pylons above the HWB airframe. The N2B is an embedded engine version of the HWB concept and will include boundary layer ingestion and advanced engine architecture with a single core driving multiple fans. Both concepts are designed to be HWB freighters with a payload of 103,000 pounds and a range of 6,000 nautical miles. NASA is collaborating with the Boeing team by providing engine system definition and aircraft noise prediction expertise. The Boeing team includes the Massachusetts Institute of Technology (MIT); the University of California at Irvine (UCI); and the United Technologies Research Center. The university teams are focusing much of their effort on developing new methods to model and predict jet and turbomachinery noise shielding. Once validated, these new prediction methods will be integrated into NASA's Aircraft Noise Prediction Program, or ANOPP2, which is itself being expanded to incorporate prediction capabilities for advanced vehicle designs such as the HWB.

The N2A configuration is the initial focus of the NASA HWB test program, with testing of the N2B configuration to follow in later years. The N2A HWB configuration is being designed to achieve the targeted noise reduction level of 42 dB and a fuel burn reduction of at least 25% relative to a conventional aircraft for the equivalent mission. At present, laminar flow control is not included in the N2A design. Laminar flow will be required to achieve the fuel burn reduction goal of 40%, and will be investigated in future system studies and experiments as a design iteration on N2A.

NASA and the Boeing team are collaborating on the plans for large-scale wind tunnel aerodynamic and acoustic testing of the N2A HWB configuration. Initial testing in 2011 will examine the basic aerodynamic characteristics. In 2012, detailed aeroacoustic testing will validate the low noise characteristics of the N2A design. Subsequent tests will focus on much more detailed aerodynamic and low speed flight stability and control characteristics. The objectives of the aeroacoustic test will be to determine the noise spectral levels and directivity of the N2A HWB and its components, and examine noise shielding parameters such as engine location, vertical tails and nozzle configurations to determine their effect on noise. Finally, results from this test will be used to validate new acoustic shielding prediction methods being developed by MIT, UCI, and NASA as well as NASA's upgraded system noise predictive capabilities for multiple aircraft noise sources.

The HWB aeroacoustics test will be conducted in the 14- by 22-Foot Subsonic Tunnel, commonly referred to as the 14x22, at NASA's Langley Research Center in Hampton, Va. The wind tunnel test section will be configured for acoustic testing, with its side walls removed and the ceiling raised and positioned well above the flow's shear layer. The test section floor will be designed specially to provide a streamlined surface for the wind tunnel flow while maintaining good aeroacoustic absorption. The floor will be formed by lowering the model cart and mounting embedded acoustic wedges under an acoustically transparent surface. Surfaces away from the tunnel flow will be covered with standard acoustic treatment. A full-span wind tunnel model of the N2A HWB with engine noise simulators will be positioned inverted in the test section. A traversing overhead phased microphone array as well as stationary microphones will be used to perform the acoustic measurements.

The wind tunnel model will be built by Boeing. It will be a 5.8% scale, 12-foot span model. The model scale was determined by the wind tunnel size and microphone frequency limitations. It will allow acoustic measurements to be performed over the full scale equivalent range of 230 Hz to 4.1 kHz (4 to 70 kHz, model scale) that is critical to aircraft noise assessment. The test model will have a modular design to maximize testing capabilities. It will consist of a fixed wing to which various components such as control surfaces, flow-through nacelles and landing gear will be attached. The control surface components will include a drooped and a stowed leading edge to model high lift and “clean” wing configurations, twelve elevons that will be deflected along the wing trailing edge to match specific flight conditions, and vertical fins of several sizes and dihedral angles with movable rudders and multiple fuselage positions for the engine noise shielding study. The modularity will also allow for the model support strut to attach to either the top or bottom surface of the model for upright or inverted testing, and the aft body section will be removable to enable testing of other types of exhaust nozzles such as embedded engines. The high fidelity of the geometric details that are important to acoustics, particularly on the landing gear assembly, the trailing edges and control surfaces also will be emphasized.

The jet noise will be generated by two, dual-stream, hot-jet engine simulators. The mid and rear portion of the simulators will match the 5.8% scale nacelles of the N2A HWB. The front-burner region of the simulators, along with the air and propane supply lines and mounts, will be faired to minimize effect on the HWB fuselage flow field. The simulators will be configured to match the engine bypass ratio and operating cycles of the N2A HWB design.

Enclosed high-intensity broadband noise generators will be used to determine insertion loss due to shielding by the HBW airframe of the fan and turbomachinery inlet and exhaust noise. The broadband noise will be generated by a series of opposing jet-impingement devices in the open interior of specially designed engine nacelles. The nacelles inlet and exhaust will be capped alternately to isolate noise radiation from either the inlet or outlet of the nacelles. The inlets and exhausts also will be instrumented with unsteady surface pressure sensors to monitor the noise source strength. Acoustic characteristics of jet-impingement devices of different sizes and air pressures are being evaluated to determine the most suitable design.

The phased microphone array will consist of 97 quarter-inch microphones flush mounted to a lightweight, 8-foot diameter, rigid circular panel. Integrated inclinometers and accelerometers will be used to monitor tilt and vibration of the panel. A two-dimensional traverse system will be used to position the array at different locations above the test model. The array and the traverse structure will remain positioned outside of the test section flow and shear layer. The array traverse, as well as the model stand and the engine simulators’ support hardware, will be streamlined, faired and acoustically treated where possible to minimize noise and acoustic reflection. The acoustic phased array data will be processed using NASA’s advanced array processing method DAMAS, which stands for deconvolution approach for the mapping of acoustic sources. This method is used to accurately quantify position and strength of the noise sources. The resulting deconvolved array output is explicit and used to generate high spatial resolution noise source localization maps. The phased microphone array will be able to measure noise sources that are well below the wind tunnel background noise level.

The new jet engine noise simulators and the advanced phased microphone array acquisition, traversing and processing system, together with the installation of new acoustic wall treatment, will result in a major capability upgrade to the 14x22 wind tunnel. This upgrade is necessary to meet the unique acoustic challenges of measuring such a low-noise aircraft model. When completed, this aeroacoustic test will have produced the first detailed noise mapping of a high fidelity geometry, HWB aircraft design using new advanced acoustic measurement capability, as well as a benchmark acoustic data base for HWB that is applicable to full scale vehicles.

2.7. Open Rotor Propulsion Airframe Aeroacoustics

Ultra high bypass turbofan engines and open rotor engines both offer the prospect of further fuel burn reduction potential. Both engine options also have system installation challenges that are the subject of current study. The assessment of the integration effects for both engine options is essential to determining the total system performance and how the two engine options will compare. When open rotor research and development reached a peak in the 1980’s, the aircraft noise of open rotor engines was seen as a significant issue. In the present time, against the backdrop of lower aircraft noise levels, currently and in the future; the noise challenges for open rotors are more significant. Again, the assessment of propulsion airframe aeroacoustic integration effects is important for an accurate assessment of the aircraft system noise. As discussed above, PAA effects also promise the potential for noise reduction with a favorable configuration and installation. Given the HWB study of Thomas, Burley, and Olson [17] showing the potential of meeting the N+2 noise goal with a turbofan engine, the logical progression is to study the PAA effects for an open rotor to determine the potential of meeting the N+2 noise goal with an open rotor HWB.

For this reason, ERA has funded Boeing to perform an open rotor PAA experiment in the Boeing LSAF patterned after the successful PAA experiment of Czech, Thomas, and Elkoby [7]. This open rotor PAA experiment is scheduled for late 2010. A 12-inch diameter counter rotating open rotor rig will be the propulsion noise source. The PAA effects of the open rotor with two aircraft types will be studied to provide a more comprehensive PAA effect database. A state-of-the-art tube and wing aircraft and a HWB will be the two aircraft types. The open rotor rig will be positioned in various locations on both aircraft and the axial, height, and spanwise spacing with respect to the airframe will be key parameters. The rig pylon will be configured with trailing edge blowing as a noise reduction device. Additional parameters include angle of attack, wind tunnel Mach number, and variations in the vertical surfaces on the HWB. The speed of the front and aft rotors will be varied in order to impact the source directivity pattern. The effect of shielding of the airframes can be documented for the different source directivity patterns thereby expanding the understanding of the PAA effects for open rotors.

This new database, together with updated open rotor source prediction methods and aircraft system models, will be used by NASA to assess the system noise of HWB aircraft with open rotors and other potential unconventional aircraft configurations.

3. Reducing fuel burned – goal setting and identification of key technology areas

Fuel burn reduction is a second key focus area for ERA. In order to identify a feasible, yet aggressive goal for this critical metric, a systems analysis study was performed. A baseline vehicle was identified and modeled, then three advanced concepts were designed and their performance was compared to the baseline vehicle. The potential for a 50% reduction in fuel burn was estimated as a result of this study.

This section describes the technical basis for this estimate.

The 777-200LR with GE90-110B engines was selected as the baseline vehicle. This is a large, twin-aisle long range transport in the passenger class of interest to ERA. The 777-200LR was introduced into service in 2006, however the first 777 entered service in the mid-1990's, and is representative of technology levels of that timeframe. State-of-the-art technology is represented by the 787; however, calibration data for the 787 is not yet available. Therefore, the 777 was selected as the baseline due to the availability of calibration data. When 787 data is available, this baseline will be updated. A "777-200LR-like" baseline model was created utilizing geometry, weight, and performance data found in reference [29]. The operating empty weight was obtained from reference [30]. A baseline mission of 7,500 nm with maximum payload was selected as the calibration point. The maximum payload of 118,100 lb is comprised of 301 passengers in a three-class seating arrangement, their baggage, and additional bulk cargo. A "GE90-110B-like" engine model was developed at the NASA Glenn Research Center utilizing their Numerical Propulsion System Simulation (NPSS) code. The engine deck, geometry and mission parameters served as inputs to the Flight Optimization System (FLOPS) code, and the resulting performance estimates were compared with the published data. Next, weight and drag estimates were adjusted to achieve a close match to the published data. These calibration adjustments are necessary to correct the model to account for "unknown unknowns". In this case, the empty weight was increased by 7.0%, and the overall drag was decreased by 3%. In addition, 11,600 lb of cargo container weight was included, in order to match operating empty weight. These calibration adjustments are then applied to the advanced tube and wing configuration as well, in order to maintain consistency. The resulting calibrated model for the "777-200LR-like" baseline predicts TOGW, empty weight, and total fuel to within 0.25% of the published values. See reference [31] for a more detailed description of the baseline calibration modeling process utilizing FLOPS.

Technology increments were then applied to the baseline model in order to create an advanced tube-and-wing design. The focus of ERA is on technologies with the potential to mature to TRL=6 in 2020, to support a 2025 entry into service (EIS). These "N+2" technologies include advanced structural materials and construction concepts, advanced engines, aerodynamic drag reduction techniques, and advanced subsystems. In the materials arena, stitched composites have the potential to provide significant weight savings compared to conventional sandwich composite construction or aluminum. Reference [32] highlights a specific application of stitched composite technology, named Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS), for the design of a hybrid wing body. PRSEUS, or other instantiations of stitched composites, are also applicable to other aircraft concepts, including traditional tube-and-wing shapes. Sandwich composites are assumed to enable a 5% weight reduction to the fuselage compared to an all-metal design, and a 15% weight reduction for the wings and tails. Stitched composite construction (PRSEUS) is estimated to save an additional 10%, for a total weight savings of 14.5% for the fuselage, and 23.5% for the wing and tails. Additional structural weight savings are assumed for the wing by utilizing an active gust load alleviation system, described in references [33] and [34]. This system is predicted to reduce the wing bending material weight by 1.7% by actively utilizing the aircraft's flight control system to counter the effects of gusts.

Advances in engine technology are expected to yield significant fuel burn reductions in the 2025 timeframe. An in-depth design study was recently completed with a major commercial aircraft engine developer to model estimated 2025 engine performance assuming a host of advanced materials, cooling, sizing and installation technologies applied to ultra-high bypass ratio direct drive and geared turbofan engine architectures. This proprietary study indicated that a specific fuel consumption (SFC) of 0.46 is feasible for this engine size, with an installed engine thrust-to-weight ratio of 4. These estimates yield an engine capable of significantly lower fuel burn (and emissions) compared to the baseline engine.

Aerodynamic technologies include laminar flow control, riblets, and variable trailing edge camber. In addition, the wing aspect ratio is allowed to grow from 9.8 (baseline) to 11 (slightly higher than the 787) in order to decrease induced drag. Laminar flow is a well characterized phenomenon that can provide significant reductions in skin friction drag. However, achieving laminar flow on swept wings operating at high Reynolds numbers is challenging. Active flow control (e.g., suction systems) can be utilized to achieve laminar flow in cases when fully natural laminar flow is not feasible, however active systems require power, weight and volume. Hybrid laminar flow control (HLFC) combines elements of active flow control with natural laminar flow (NLF) in an attempt to achieve the benefit of laminar flow with minimum power, weight and volume increments. Reference [35] provides an excellent overview of this technology area. For the HLFC system, 50% chord laminar flow was assumed for the wing upper surface, and both surfaces on the horizontal and vertical tails. Also, 50% chord natural laminar flow was assumed for the engine nacelles. The HLFC system weight was predicted to be 3,155 lb, and a 0.2% fuel flow penalty was applied to account for the energy required to operate the system. In addition, a 1% cruise drag penalty was assumed for the NLF airfoil relative to an optimized turbulent airfoil design. No laminar flow was assumed for the wing lower surface, due to the use of a Krueger flap. The Krueger flap enables the required high lift performance for takeoff and landing, and also helps to shield the leading edge from contamination. Riblets are very small, flow-aligned grooves that can be applied to the aircraft surface to reduce turbulent skin friction drag. Reference [36] describes flight test results that demonstrated a 6% drag reduction. This technology was applied to the turbulent fuselage to capture these projected drag reductions. Variable trailing edge camber utilizes a “smart” trailing edge consisting of segmented flaps that are optimally deflected for minimum drag throughout the flight profile. Reference [37] presents a design optimization study for a three-segment active trailing edge flap system. An overall drag reduction of 1% was assumed for this technology.

Subsystem improvements were assumed in the areas of hydraulics, controls and auxiliary power. Traditional hydraulic lines and actuators are replaced with wires and electromechanical actuators resulting in a 10% weight savings compared to the baseline system. Reference [38] provides an overview of this technology. In addition, the baseline auxiliary power unit (APU) is replaced by a solid oxide fuel cell/gas turbine hybrid system that runs during cruise as well as on the ground. This advanced APU is assumed to provide a 1% reduction in fuel burn. References [39] and [40] provide additional details for this advanced system.

Utilizing the calibrated baseline model as a point-of-departure, each of the preceding technologies was applied one at a time, and the resulting fuel burn reductions were estimated. A fully optimized design, meeting all constraints and mission requirements, was produced for each of the technology increments. Finally, all of the technologies were applied simultaneously to represent the advanced tube-and-wing configuration. The total fuel burn reduction in the “all-on” case is less than the summation of the incremental fuel burn reductions, as a result of the interactions between the technologies. The results are presented in a “waterfall” chart format, see Figure 3. Reference [31] provides additional details regarding this type of analysis and presentation format.

The hybrid wing body (HWB) configuration offers engine noise shielding, as well as the potential to further reduce fuel burn compared to an advanced tube-and-wing configuration. References [41] and [42] provide additional details on the HWB concept. Therefore, an advanced HWB was modeled, following the procedure described in Reference [31]. The centerbody was sized for 301 passengers, and pylon mounted, podded engines were installed above the aft centerbody. A 12.8% weight increment was applied to account for the pylon weight, and a 10% skin friction increase was applied to account for the pylon drag. The advanced technologies described above for the tube-and-wing design were then applied to the HWB design. The only difference is the assumption of HLFC for the outer wing lower surface, due to the elimination of the leading edge high lift system. The HWB has a much greater wing area than a tube-and-wing design sized for the same mission, and it was assumed adequate low speed performance could be obtained without a leading edge high lift device, enabling laminar flow on both the upper and lower wing surfaces. Figure 4 presents the HWB waterfall chart (HWB300A design), which shows an overall fuel burn reduction of 49.8% compared to the 777 baseline.

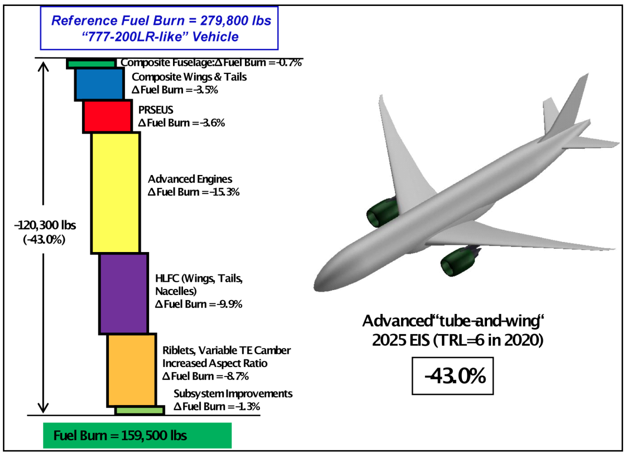

Fig. 3 – Advanced tube and wing waterfall chart.

Finally, two additional technologies were applied to the HWB design; embedded, boundary layer ingesting (BLI) engines, and laminar flow control on the centerbody upper surface. Embedded BLI engines have been studied for application to the HWB configuration in detail, and, if successfully integrated, they may provide an increase in propulsive efficiency relative to the podded engine installation. See references [43] and [44] for additional information. The HWB has a relatively large centerbody surface area; therefore, centerbody laminar flow has the potential to make a significant contribution towards fuel burn reduction. Laminar flow was assumed on the centerbody upper surface from the leading edge to the BLI inlets. Increments for weight (1.5 times the air conditioning system weight) and fuel flow (0.2% fuel flow increase) were assumed as well. Of course, applying laminar flow to the centerbody negates the need for riblets, and reduces the embedded BLI benefit. However, Figure 5 (HWB300B design) shows that the overall benefit of centerbody laminar flow outweighs these disadvantages, and a 5.5% reduction in fuel burn is estimated. This contributes to an overall

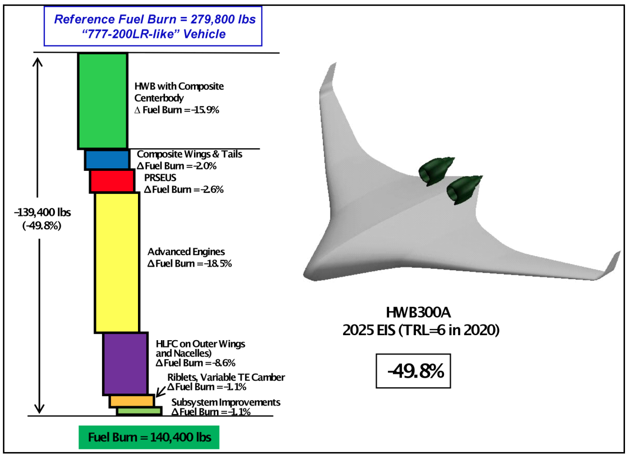

Fig. 4 – Advanced Hybrid Wing Body HWB300A waterfall chart.

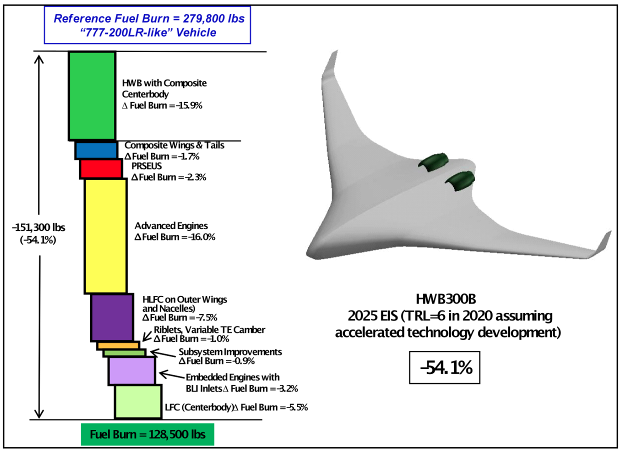

Fig. 5 – Advanced Hybrid Wing Body HWB300B waterfall chart.

Table 1. Key Design Parameters

	777-200LR-like		Advanced T+W		HWB300A		HWB300B	
Payload	118,100	lb	118,100	lb	118,100	lb	118,100	lb
Range	7500	nm	7500	nm	7500	nm	7500	nm
OEW	341,000	lb	268,000	lb	262,000	lb	258,400	lb
Design Fuel	309,800	lb	177,400	lb	155,700	lb	142,600	lb
TOGW	768,900	lb	563,500	lb	535,800	lb	519,100	lb
Cruise Mach	0.84		0.84		0.84		0.84	
Block Fuel	279,800	lb	159,500	lb	140,400	lb	128,500	lb
Wing Area	4,690	ft^2	3,670	ft^2	7,800	ft^2	7,800	ft^2
Span	214	ft	200	ft	208	ft	208	ft
Length	209	ft	209	ft	114	ft	114	ft
Start of Cruise L/D	19.0		22.0		23.1		25.5	

reduction of 54.1% compared to the 777 baseline.

Based on the results of the HWB modeling, a fuel burn reduction goal of 50% compared to the 777 baseline was recommended. This represents an aggressive, yet feasible goal for the 2025 timeframe. Table 1 summarizes key design parameters for the baseline model and the three advanced designs.

4. Reducing oxides of nitrogen – goal setting and identification of key technology areas

The fuel-flexible, low-NOx combustor task of the ERA Project is developing concepts to reduce NOx 75% below the current standard of the Committee on Aviation Environment Protection (CAEP) while reducing aircraft fuel burn by 50% and achieving perceived noise levels 42 dB below Stage 4 limits. In order to satisfy future efficiency and fuel burn goals, an advanced cycle running to a high overall pressure ratio is envisioned. The high pressure ratio engines will increase the challenge of simultaneously achieving the N+2 NOx goal.

Various promising combustor concepts are being investigated. Those concepts are: Lean Direct Injection (LDI); Partial Premixed Injection (PPPI); and Rich Burn/Quick Mix/Lean Burn (RQL).

In addition to meeting N+2 goal for NOx, several key combustion technologies must be overcome before those combustor concepts can be developed. Those technologies are: ignition, lean blow out, turn down, efficiency, low power emissions, smoke, durability, exist temperature profile, and pattern factor target.

In addition, several enabling technologies will also be investigated. For example, lean combustion is susceptible to combustion instability, so improved understanding of the factors that influence and could mitigate dynamics will be needed. Reduced cooling airflow and higher inlet temperatures will drive the need for Ceramic Matrix Composite (CMC) liners. CMC material property and durability are the key focus. Other enabling technologies that will also be investigated are advanced ignition and active combustion dynamics control. Active dynamics control would allow optimization of fuel splits for combustor performance and still maintain protection to avoid combustion dynamics.

The other key goal to be addressed is fuel flexibility. ERA Project will investigate jet fuel, Fischer-Tropsch, or hydrotreated renewable jet fuel. Testing of others suggests that synthetic fuels help to mitigate particulate and smoke emissions.

Ceramic Matrix Composite Development- Ceramic-matrix composites (CMC) offer opportunities for revolutionary changes in propulsion system design and operation. The lower density and higher temperature capability of CMC components, relative to that of metallic components, offer multiple engine advantages, such as weight saving, efficiency and thrust improvements, and reduced specific fuel consumption. NASA has been developing durable, high-temperature CMCs with silicon carbide (SiC) matrices and SiC or carbon fibers for high-temperature structural applications. These SiC/SiC composites are designed to be lightweight (~30% of metal density). A key challenge to the realization of SiC/SiC CMC hot-section components is the environmental degradation of the CMCs in combustion environments. With the advances in the development of thermal/environmental barrier coatings (TEBCs) for CMC applications, also under the ERA program, the performance of CMC components has improved significantly. Recently, SiC/SiC CMC combustor liner and turbine vanes have demonstrated cyclic durability at temperatures up to 1650°C (3002°F), a temperature significantly higher than the thermal capability of metal alloys (~1093°C or ~2000°F).

Concluding Remarks

Technology development paths have been established to pursue the noise, fuel burn, and emission reduction goals of NASA's Environmentally Responsible Aviation project. Enabling technologies are under development with critical progress having been accomplished recently by demonstrating that achieving the noise goal of 42dB cumulative below Stage 4 is indeed feasible with relatively near term technology options integrated on a hybrid wing body aircraft concept. Simultaneous achievement of all three goals is envisioned through the integration of advanced technologies with the hybrid wing body aircraft concept.

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