Hybrid Wing Body Configuration System Studies

Craig L. Nickol[1]
NASA Langley Research Center, Hampton, VA 23681

Linwood A. McCullers[2]
ATK, Hampton Virginia 23681

The objective of this study was to develop a hybrid wing body (HWB) sizing and analysis capability, apply that capability to estimate the fuel burn potential for an HWB concept, and identify associated technology requirements. An advanced "tube with wings" concept was also developed for comparison purposes. NASA's Flight Optimization System (FLOPS) conceptual aircraft sizing and synthesis software was modified to enable the sizing and analysis of HWB concepts. The noncircular pressurized centerbody of the HWB concept was modeled, and several options were created for defining the outboard wing sections. Weight and drag estimation routines were modified to accommodate the unique aspects of an HWB configuration. The resulting capability was then utilized to model a proprietary Boeing blended wing body (BWB) concept for comparison purposes. FLOPS predicted approximately a 15 percent greater drag, mainly caused by differences in compressibility drag estimation, and approximately a 5 percent greater takeoff gross weight, mainly caused by the additional fuel required, as compared with the Boeing data. Next, a 777-like reference vehicle was modeled in FLOPS and calibrated to published Boeing performance data; the same mission definition was used to size an HWB in FLOPS. Advanced airframe and propulsion technology assumptions were applied to the HWB to develop an estimate for potential fuel burn savings from such a concept. The same technology assumptions, where applicable, were then applied to an advanced tube-with-wings concept. The HWB concept had a 39 percent lower block fuel burn than the reference vehicle and a 12 percent lower block fuel burn than the advanced tube-with-wings configuration. However, this fuel burn advantage is partially derived from assuming the high-risk technology of embedded engines with boundary-layer-ingesting inlets. The HWB concept does have the potential for significantly reduced noise as a result of the shielding advantages that are inherent with an over-body engine installation.

Nomenclature

BLI = Boundary layer ingestion
BWB = Blended wing body
CAEP = Committee on Aviation Environmental Protection
FLOPS = Flight Optimization System
HLFC = Hybrid laminar flow control
HWB = Hybrid wing body
LE = Leading edge
L/D = Lift-to-drag ratio
LDN = Day-night average sound level
LTO = Landing and takeoff
M = Mach number
NOx = Nitrogen oxides
OEW = Operating empty weight
SFC = Specific fuel consumption

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[1] Aerospace Engineer, Aeronautics Systems Analysis Branch, MS 442, AIAA Senior Member.
[2] Aerospace Engineer, ATK

T/W = Thrust-to-weight ratio
TOGW = Takeoff gross weight
TSFC = Thrust specific fuel consumption
TRL = Technology readiness level
ZFW = Zero fuel weight

I. Introduction

Hybrid wing body (HWB), commonly known as blended wing body (BWB), configurations have been postulated, analyzed and optimized over at least the past 20 years. A reference to the BWB is found in an October 1990 Douglas Aircraft Company paper that compared advanced subsonic transport aircraft designs for the 21st century.[1] Since then, a wide variety of applications for the BWB concept have been studied, including passenger transports; commercial freighters; and military tanker, bomber, and cargo aircraft. The evolution of the BWB concept is captured as part of a recent NASA technical memorandum[2] with a chronology of approximately 60 BWB references for system-level studies. The significant amount of effort that is evidenced by this chronology, which spans more than two decades, highlights the unique challenges and potential payoffs that are associated with the HWB configuration. Structural design, stability and control, propulsion/airframe integration, and internal layout are a few areas that differ significantly from the traditional tube-with-wings design. With the assumption that the HWB design and manufacturing challenges can be successfully addressed, the HWB concept has the potential for reductions in fuel burn, emissions, and noise compared with today's aircraft, and more significantly, compared with future peer-technology tube-with-wings aircraft. Current NASA aeronautics research in the subsonic fixed wing area is focused on improving the metrics of noise, emissions, fuel burn, and takeoff field length, with the overall goal of improving the air transportation system's capacity while simultaneously minimizing environmental impacts. Table 1 presents the goals for those metrics for near-, mid- and far-term timeframes.

Table 1. NASA Subsonic Transport System Level Metrics

Corners of the trade space	N+1 (2015) Conventional tube and wing (relative to B737/CFM56)	N+2 (2020) Unconventional hybrid wing/body (relative to B777/GE90)	N+3 (2030-2035) Advanced aircraft concepts (relative to user-defined reference)
Noise	–32 dB (cum below Stage 4)	–42 dB (cum below Stage 4)	55 LDN (dB) (at average airport boundary)
LTO NOx emissions (below CAEP 6)	–60%	–75%	Better than –75%
Performance: aircraft fuel burn	–33%	–40%	Better than –70%
Performance: field length	–33%	–50%	Exploit metroplex concepts

In the table, N represents the aircraft that are currently flying. Therefore N+1 represents next generation technology (i.e., what might appear on a 737 or A320 replacement); N+2 represents the following generation of technology targeted at a twin-aisle 777-sized aircraft; and N+3 represents far-term technology goals. The HWB configuration is of great interest to acousticians because of the potential for large reductions in noise from shielding. Studies that were completed in support of the Silent Aircraft Initiative investigated this potential by optimizing an entire HWB aircraft configuration for low noise.[3] In addition, the HWB configuration has been studied in the context of short takeoff and landing requirements to enable the N+2 field length goal.[4] The focus of this paper is the N+2 fuel burn metric. To set feasible N+2 fuel burn metric targets and identify the required technology levels, a system-level tool was needed to size and analyze HWB configurations.

NASA's primary tool for aircraft conceptual design, analysis, and optimization is FLOPS (Flight Optimization System). Given mission requirements and related inputs, FLOPS is capable of sizing an aircraft and optimizing its performance subject to a variety of constraints. The sizing algorithms were created for traditional tube-with-wings configurations. Much of the weight estimation routine utilizes statistical weight-estimating relationships that are derived from an optimization-based curve-fitting approach based on data from traditional configurations. An analytically based wing weight estimation capability is available for use with more detailed wing planform definitions. However, FLOPS is not capable of analyzing a nontraditional configuration such as the HWB without significant deviations from the standard process. Modifications have been made to FLOPS to include an option to lay out and size an HWB cabin. In addition, the FLOPS weight routines have been updated with an option to estimate the weight of an HWB. These modifications, combined with propulsion and aerodynamic inputs, enable an HWB mission analysis. The FLOPS users manual has been updated to reflect these changes, primarily in the documentation for the weights module.[5] Provided below is a description of these changes, a comparison of an HWB FLOPS analysis to a Boeing BWB analysis, and an application study that addresses the N+2 fuel burn metric from Table 1.

II. FLOPS Modifications for HWB Sizing and Analysis

A. Geometric Definition

The HWB has a distinctly shaped cabin compared with that of the traditional tube-with-wings configuration. For the purposes of this development, we assume that the cabin is shaped like a “home plate” in baseball, with the point at the nose of the aircraft. This home-plate-shaped cabin is sized by assigning an area to each passenger (by using standard packing rules for the number abreast, seat pitch, and passenger class) and allowing for the required number of utility areas (i.e., lavatories, galleys, and closets) based on the number of passengers in each class. The area that is required for passengers and utilities is combined with the areas for aisles and wasted space which results from the specific geometry, to define the required total cabin area. Specific packing and area assumptions per passenger class can be found in reference 5.

With the cabin area computed from the passenger data (or input directly) and a leading-edge (LE) sweep defined, two more data points are required to define the cabin. The first is the location of the rear spar, which is assumed to be located along the rear wall of the passenger cabin (see Figure 1). Two new variables were created to represent the

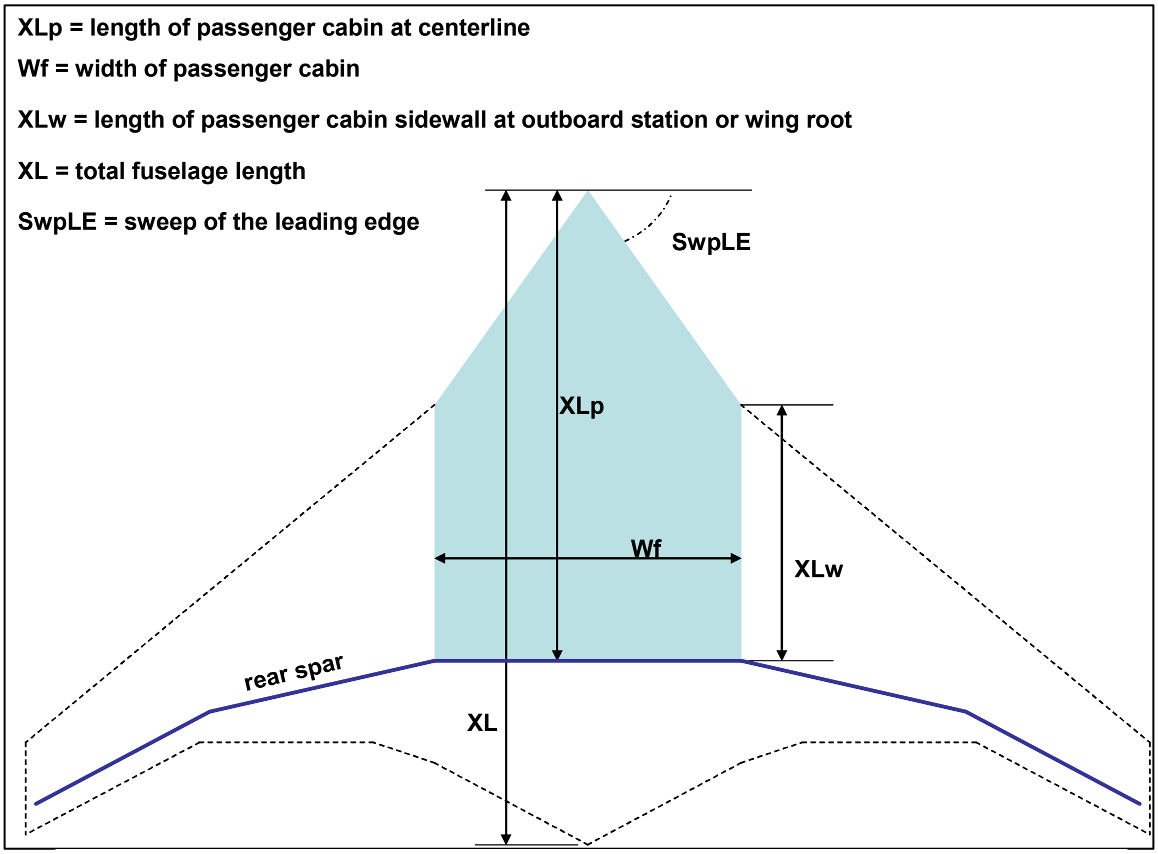

Figure 1 . HWB FLOPS implementation geometric layout.

location of the rear spar as a percent of the chord on the centerline and at the side-of-body. Several options are available for defining the final point. The computational hierarchy is as follows:

1. The length of the passenger cabin at the centerline (XLp) can be input. Or, if the total fuselage length (XL) is input, then XLp is determined based on the location of the rear spar.
2. The width of the passenger cabin Wf can be an input. If both XLp and Wf are input, then all of the dimensions are defined, which overrides the computation or input of cabin area.
3. The ratio of the passenger cabin centerline length to the cabin width (XLp/Wf) can be input by using the variable CRATIO.
4. If none of the above are input, then the length of the cabin sidewall at the outboard station or wing root, XLw, can be input. If XLw is not input, then the default is 38.5 ft based on a required cabin height at the outboard station of 8.25 ft and by assuming a 15-percent-thick airfoil and a rear spar at 70 percent chord.
5. To ensure sufficient cabin height at the outboard fuselage station, a minimum allowable XLw may be input and will override any computed or input value of XLw.

Once the cabin dimensions are determined, an outboard wing panel can be defined and added to the side of the cabin. One of three options can be used to define the outboard wing:

1. Specify the total wing span, and FLOPS will add a trapezoidal panel out to the total semispan with the root chord equal to the length of the passenger cabin sidewall at the outboard station or wing root (XLw), and the tip chord equal to a user-defined input or a default value.
2. Utilize the detailed wing definition in FLOPS, starting at the cabin side-of-body and proceeding to the wing tip.
3. Utilize the detailed wing definition in FLOPS, starting at the centerline of the cabin.

B. Weights Estimation

FLOPS utilizes its standard wing weight estimation methodology for the outboard wing section. This methodology includes three weight terms that are combined to produce a total wing weight:

1. W1 relates to wing bending loads
2. W2 represents control surfaces and shear material
3. W3 depends entirely on wing area and covers a variety of miscellaneous items

For the HWB analysis, a fourth term W4 is added to account for the wing weight that is associated with the area directly aft of the cabin (see Figure 2).

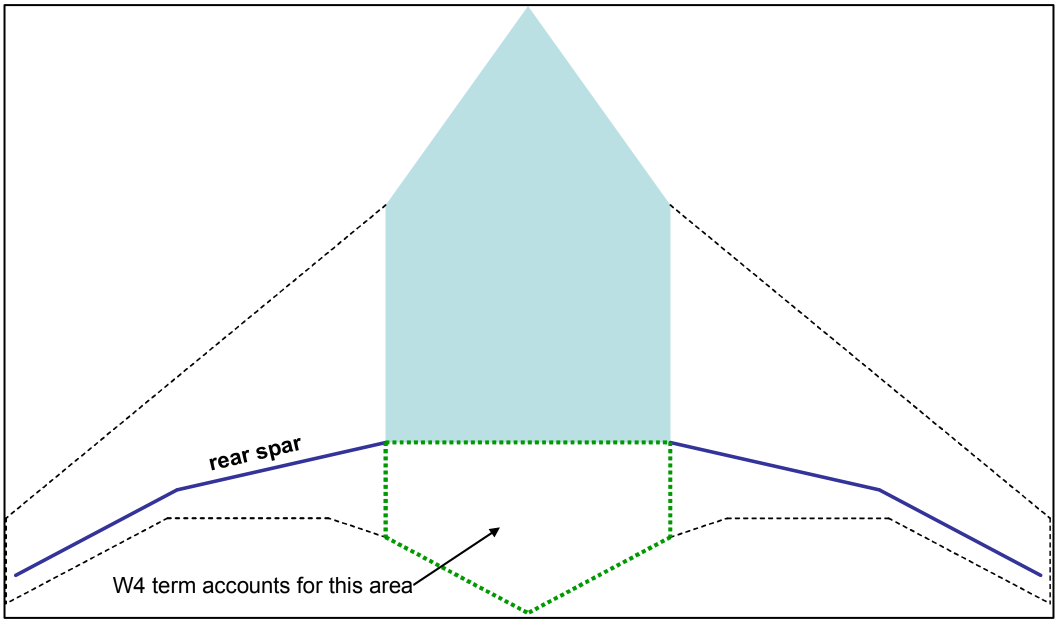

Figure 2. Aft centerbody weight that is accounted for by wing weight W4 term.

The weight of the HWB pressurized fuselage is estimated with the following relationship:

$$Wfuse_{(HWB)} = 1.8 * DG^{0.167} * ACABIN^{1.06}$$

where DG is the design gross weight and ACABIN is the HWB cabin area. This empirical relationship was developed by Bradley[6] and is based on a regressed finite-element analysis that is scaled to the Boeing data. The structural concept assumes the use of a single outer shell with thick skin, deep stringers, and Y-braced internal ribs.

C. Comparison to Boeing BWB Configuration

A proprietary Boeing BWB concept design was modeled and analyzed in FLOPS with the code enhancements that were made for HWB analysis. The results were compared with Boeing estimates to determine areas and magnitude of agreement and disagreement; however, validation of the FLOPS HWB analysis capabilities will remain problematic until consistent (i.e., apples to apples) and higher quality (i.e., large-scale test) data are available.

The BWB-450 baseline design is described by Liebeck.[7] This baseline design was utilized at one time by Boeing to perform technology insertion and planform optimization studies. Figure 3 shows a three-view of the BWB-450 baseline configuration.

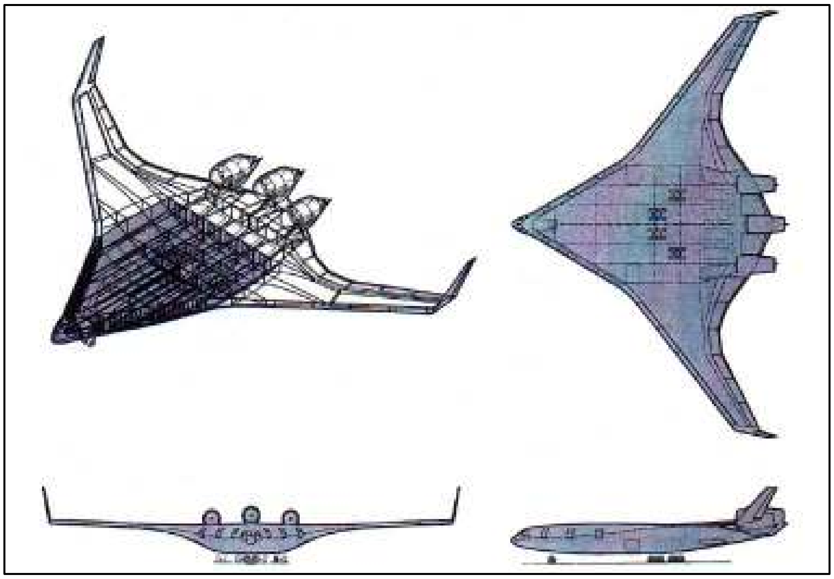

Figure 3. Boeing BWB-450 baseline configuration.

The pressurized cabin area was first modeled with inputs for passenger number and allocation, LE sweep, and cabin width. The FLOPS defaults for seat pitch and number of passengers abreast were modified to match the Boeing cabin area with an assumption of the same number of passengers (i.e., 26 in first class, 91 in business class, and 351 in economy class for a total of 468). Business class seat pitch was changed from the default value of 39.0 inches to 41.0 inches; economy class pitch was changed from 32.0 inches to 34.0 inches; and the number of business-class passengers seated abreast in a bay was changed from the default value of five to four (the BWB-450 passenger layout diagram shows passengers in business class seated four abreast). These modifications, which were required to match the Boeing cabin area, indicate that the default sizing rules in FLOPS may be less conservative than those used by Boeing.

Next, by utilizing the detailed planform/wing data that were available from Boeing, the concept was modeled in FLOPS with the detailed wing option starting at the centerline. Because the actual chord values on the centerline and side-of-body are inputs, this option produces a more accurate representation of the geometry. Three GE-90-like engines were installed and their thrust was varied to minimize TOGW subject to a 300 ft/min rate of climb requirement at $M = 0.85$ and 35,000 ft.

Figure 4 presents a comparison of the cruise drag polars from FLOPS with three data points taken from the Boeing BWB-450 data. After adjustments were made to the FLOPS data to match the BWB-450 wing reference area and altitude, for both altitudes FLOPS predicts a higher drag coefficient (+10 to +18 percent at 39,000 ft and +15 percent at 35,000 ft). The primary source of this difference is compressibility drag.

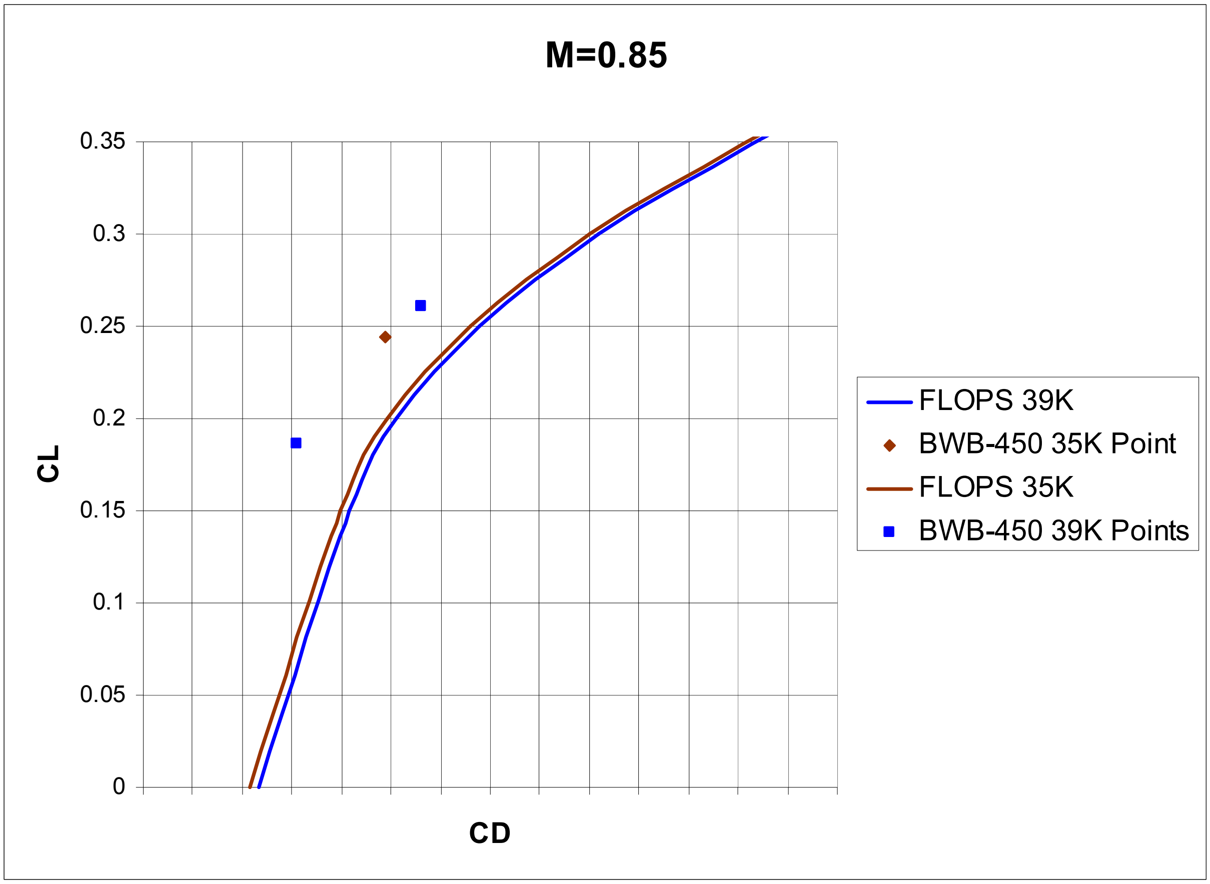

Figure 4. BWB-450 and FLOPS cruise drag comparisons at *M* = 0.85.

Table 2 shows the weight comparison between the BWB-450 data and the FLOPS output. Consistent comparisons are not possible because of the lack of information on the definition of the BWB-450 weight categories. FLOPS predicts an 11 percent higher total structural weight as a result of wing and centerbody estimates. The large percent difference for the winglets is a relatively insignificant overall weight difference. The propulsion system weight is significantly higher as a result of the higher drag estimate. These higher weights are offset by lower FLOPS estimates in the systems and furnishings and equipment categories; thus, similar estimates result for operating empty weight (OEW) and zero fuel weight (ZFW). Because of the lack of additional breakout for the BWB-450, pinpointing the source of these differences is not possible. The higher drag estimate from FLOPS results in an 11 percent increase in fuel required.

Table 2. Weight Estimation Comparison.

	Difference between FLOPS results and BWB-450 data, percent
Structure	11
Centerbody	10
Wing	12
Winglet	60
Propulsion	19
Systems	-18
Furnishings and operational items	-12
OEW	1
Design payload	0
Design ZFW	1
Design total fuel	11
Design block fuel	11
Takeoff gross weight	5

III. Application Study for “N+2” Fuel Burn Metric

The BWB-450 comparison highlights the large amount of uncertainty that is associated with HWB sizing and analysis. Without a “gold standard” for validation, absolute predictions must be treated skeptically; however, relative predictions between concepts of the same configuration can be useful. FLOPS was utilized to create a baseline tube-with-wings reference vehicle which was calibrated to published payload-range data. Then, an HWB equivalent concept was sized with identical mission assumptions and estimation methodology, with the exception of the estimate of centerbody weight as presented earlier. The uncertainty associated with the HWB analysis should be considered when comparing the tube-with-wings configuration to the HWB. Next, a series of advanced technologies were applied to the HWB model individually to determine the relative benefits of each technology. Less uncertainty is associated with this analysis since the relative benefits are being assessed utilizing the same configuration. Finally, the same technology increments, when applicable, were applied to the baseline tube-with-wings reference vehicle for a more consistent, albeit more uncertain, comparison with the HWB concept.

A. Modeling the Baseline Tube-with-wings Reference Vehicle

The 777-200 was selected as the baseline reference vehicle because it is the newest twin-aisle aircraft with published payload-range data. A baseline model of a 777-200ER (initially termed the “increased gross weight” or “high gross weight” option, then called “extended range”) with a 305-passenger, three-class configuration was developed using a combination of publicly available data for geometry, weight, and performance characteristics[8] and a GE90-like engine model that was developed at the NASA Glenn Research Center. A FLOPS model was created by applying the 777-200 geometric and design mission parameters, and the FLOPS-predicted mission performance was calibrated to a specific point on the 777-200 payload-range diagram that is provided in reference 8. A maximum gross weight, 7500-nm-range mission was selected, which corresponds to a 656,000 lb takeoff gross weight (TOGW) and an approximately 380,000 lb OEW plus payload weight. Although a detailed mission profile is not provided in reference 8, some parameters are specified on the payload-range diagram, such as a cruise Mach number of 0.84 and typical mission rules, that imply a standard international reserve mission of 5 percent reserve fuel, 200-nm divert, 30-minute hold time, plus a second hold segment equal to 10 percent of the flight time. After the model was created, the internally computed FLOPS aerodynamic performance and weight predictions were adjusted to achieve a range of 7500 nm with a gross weight of 656,000 lb. The impacts of engine specific fuel consumption and aircraft *L*/*D* cannot be separated when matching range performance. The accuracy of the GE90-like engine model thus impacts the accuracy of the calibrated FLOPS aerodynamic performance. For example, if the actual engine thrust specific fuel consumption (TSFC) is higher than that in the model, then the range-calibrated aerodynamic efficiency will be lower than the actual efficiency.

The final step in the development of a baseline model that was representative of the Boeing 777-200ER aircraft was to ensure that the FLOPS sizing was consistent with that of the actual aircraft. For typical FLOPS sizing, the varied parameters are engine thrust and wing area, with an objective to minimize the gross weight that is required to meet the mission. The wing area and the thrust of the actual aircraft can be sized by additional considerations that are outside the scope of FLOPS. For example, the wing or engine may be oversized for a future growth version of the aircraft. Without any adjustments to the weight and the aerodynamic calibrations that are described above, the FLOPS-sized vehicle for the selected mission resulted in a gross weight of 656,000 lb, an OEW plus payload of 375,900 lb (approximately 380,000 lb actual), and a mission fuel weight of 280,400 lb (276,000 lb estimated actual). The FLOPS estimate of block fuel burn (i.e., mission fuel burned not including reserve fuel) is 237,000 lb.

B. Modeling the HWB300

An HWB concept was then sized to an equivalent mission definition, including payload, range, and reserve mission assumptions. The basic planform shape of the BWB-450 was utilized to give a centerbody LE sweep of 60 deg and a CRATIO (cabin-centerline-length–to–cabin-width ratio) of 1.68. These two parameters, combined with the passenger mix (i.e., 305 passengers with 24 in first class, 54 in business class and 227 in economy class) defined the pressurized cabin area of 2960 ft^2. Aft (unpressurized) centerbody area was added to accommodate the engine installation. Outboard wing panels were defined, again following the BWB-450 planform, but with a reduced outboard semispan of 80 ft. Combined with a sized cabin width of 48.7 ft, the total wingspan was 208.7 ft. Two GE90-like engines were installed, and the engine thrust was varied to find a minimum TOGW by imposing a rate of climb requirement of 300 ft/min at 35,000 ft and $M = 0.84$. The engine installation utilized vertical pylons that were sized to ensure that the bottom of the inlet was above the boundary layer to avoid negative impact on the engine performance. A 12.8 percent engine installation factor and a 10 percent increase in nacelle wetted area were applied to account for the weight and drag of the vertical pylons. Figure 5 shows a top view of the HWB300 concept.

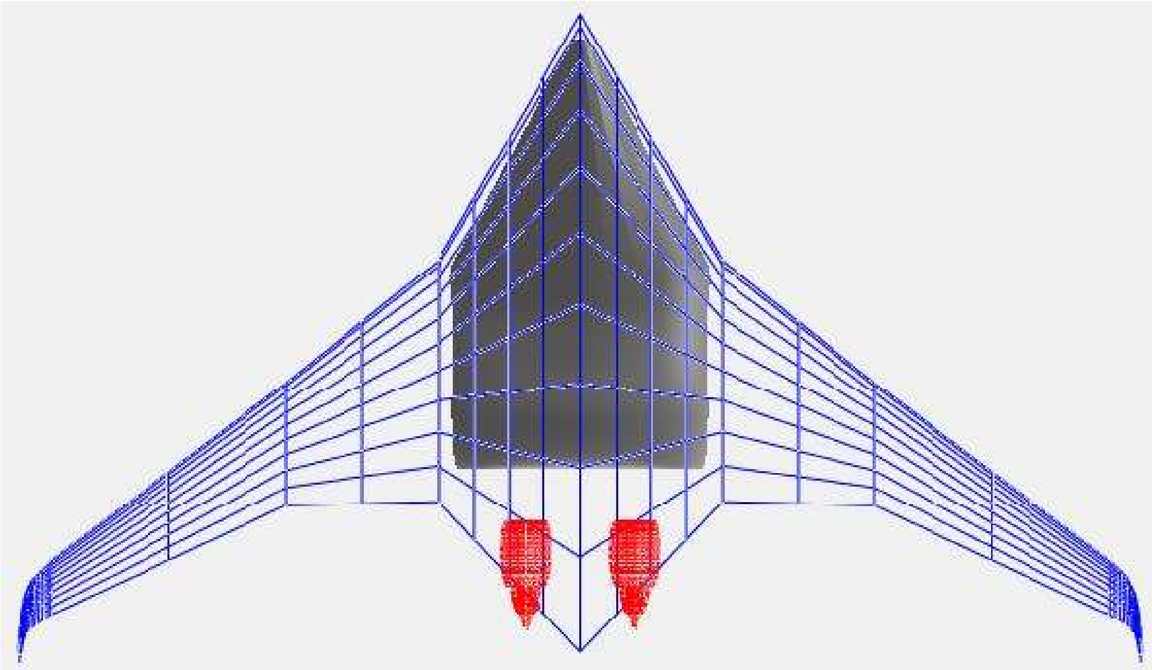

Figure 5. HWB300 concept with 2960 ft^2 pressurized cabin.

For the basic HWB300 concept, an all-composite centerbody section was assumed; however, the outboard wings and propulsion system technology levels were equivalent to the 777 reference vehicle. The TOGW of this basic HWB was 594,400 lb, and the block fuel burn was 206,570 lb, which represents roughly a 13 percent decrease compared with the 777 reference vehicle. Next, a series of advanced technology assumptions were developed and applied individually to the basic HWB300 concept.

The first assumption was advanced podded engine technology. Based on work performed at the NASA Glenn Research Center, a 2020-technology-level (i.e., with a technology readiness level (TRL) equal to six in 2012–2013) direct-drive engine with a fan pressure ratio of 1.6 was modeled. The installed thrust-to-weight ratio was 4.0 (if we assume the same 12.8 percent installation factor), and the cruise SFC was 0.516. The resulting TOGW was 565,220 lb, and the block fuel burn was 188,130 lb, which represents nearly a 9 percent decrease compared with the basic HWB300 vehicle.

The second assumption was advanced airframe technologies. These technologies were applied to the basic HWB300 (without the advanced engine assumptions) and included advanced composites for the outboard wings, an advanced hydraulic system (5000 psi versus 3000 psi), and a 1 percent reduction in drag as a result of the use of TE variable camber. The savings that were realized with the use of composites in the wing (over that of an all-metal wing) for the outboard wing sections were applied to the various wing weight terms that were estimated by FLOPS; the savings averaged approximately 25 percent across the entire outboard wing. The resulting TOGW was 561,800 lb, and the block fuel burn was 195,210 lb, which represents approximately a 5.5 percent decrease compared with the basic HWB300 vehicle.

The third assumption was the use of embedded engines with boundary-layer-ingesting (BLI) inlets. This technology has been utilized recently by Plas et al.[9] as part of the Silent Aircraft Initiative study and has been investigated by Rodriguez,[10] Campbell et al.,[11] and Kawai et al.[12] Kawai et al. concluded that active flow control should enable a short offset BLI inlet, which results in a large reduction in the wetted surface area and potentially reduces fuel burn by 10 percent. The GE90-like podded engines of the basic HWB were lowered into the aft fuselage by embedding the nacelle to approximately 40 percent of its diameter. A 6 percent engine installation penalty was applied, and the nacelle wetted area was reduced by 40 percent. No boundary-layer diverters were assumed; therefore, the entire boundary layer would be ingested into the engine. An active inlet flow control system was assumed to minimize the distortion on the fan face caused by the boundary-layer ingestion. A fuel flow penalty of 0.2 percent was assessed to account for the power that was required to run this system. An inlet pressure recovery loss of 1.5 percent was also assessed, which translated to a 3 percent decrease in SFC. The surface-stream tube wetted area forward of the two inlets was estimated to be 7.5 percent of the total wing area; therefore, the skin friction drag that is associated with this area was eliminated. In summary, the advantages of this technology include reduced installation drag and weight and reduced overall vehicle drag. Penalties include the inlet pressure recovery loss and the weight and power that are associated with an active inlet flow-control system. The resulting TOGW was 571,340 lb, and the block fuel burn was 192,640 lb, which represents approximately a 7 percent decrease compared with the basic HWB300 vehicle.

The final assumption was hybrid laminar flow control (HLFC). Young et al.[13] provide an overview of HLFC and discuss the design requirements, including the application of suction over the first 10 to 20 percent of the wing chord and candidate materials and drilling methods for the production of the suction surface. Saric and Reed[14] provide a relatively recent (2004) overview of different laminar flow control strategies and discuss some of the remaining technical challenges. For the purpose of this analysis, the size and complexity of the HLFC mechanical system was assumed to be roughly equivalent to that of the vehicle air conditioning system so its weight was set equal to the estimated weight of the air conditioning system. A 0.3 percent fuel flow penalty was assessed to account for the power that would be required to run the system. The benefits were assumed to apply only to the outboard wing sections and included 66 percent laminar flow on the upper wing surface, 50 percent laminar flow on the lower wing surface, and 50 percent laminar flow on the nacelles. The resulting TOGW was 559,480 lb, and the block fuel burn was 179,300 lb, which represents approximately a 13 percent decrease compared with the basic HWB300 vehicle.

Next, all of the technology assumptions were applied simultaneously to the basic HWB300 vehicle. That is, the advanced podded engine technology levels were utilized in an embedded BLI installation. The advanced airframe and HLFC technologies were also assumed. The resulting TOGW was 489,300 lb., and the block fuel burn was 144,230 lb, which represents approximately a 30 percent decrease compared with the basic HWB300 vehicle and a 39 percent decrease compared with the 777 reference vehicle.

C. Modeling the Advanced Tube-with-Wings

To enable a more consistent comparison between the HWB300 and a tube-with-wings alternative, all of the applicable technology assumptions that were applied to the HWB300 were also applied to a tube-with-wings design. Applicable technologies included the advanced podded engines, the advanced airframe technologies, and the HLFC system (applied to the wings and nacelles only). Similar benefits and penalties were assumed, and the advanced tube-with-wings was sized to the same mission requirements. The resulting TOGW was 503,350 lb, and the block fuel burn was 172,000 lb, which represents approximately a 27 percent decrease compared with the 777 reference vehicle. The advanced tube-with-wings had a ZFW of 299,530 lb, which is 5.5 percent less than the 317,500 lb ZFW of the HWB300. Table 3 shows a comparison of the two concepts. Note that the HWB300 has wetted area that is 25 percent smaller than that of the advanced tube-with-wings.

Table 3. Summary of Concept Design Data.

	HWB300	Advanced tube-with-wings
Payload	63,745 lb	63,745 lb
(24 First class, 54 business class, 227 economy class @ 209 lb each)		
Range	7500 nm	7500 nm
OEW	253,760 lb	235,780 lb
ZFW	317,500 lb	299,530 lb
Design fuel	171,800 lb	203,820 lb
TOGW	489,300 lb	503,350 lb
Block fuel	144,230 lb	172,000 lb
Total wetted area	15,500 ft^2	20,600 ft^2
Span	209 ft	189 ft
Length	117 ft	207 ft
Start of cruise L/D (@35,000 ft, M = 0.84)	24.6	20

IV. Conclusions

A "waterfall chart" is a format to illustrate the relative incremental contributions of various technologies to an overall metric. Figure 6 shows the results of this study in waterfall chart format. Note that the HWB shape and the composite fuselage assumption alone contributes 12.8 percent out of the 39 percent total reduction in potential fuel burn compared with the 777 reference vehicle. The other four technology areas contribute the remaining 26.3 percent of fuel burn savings.

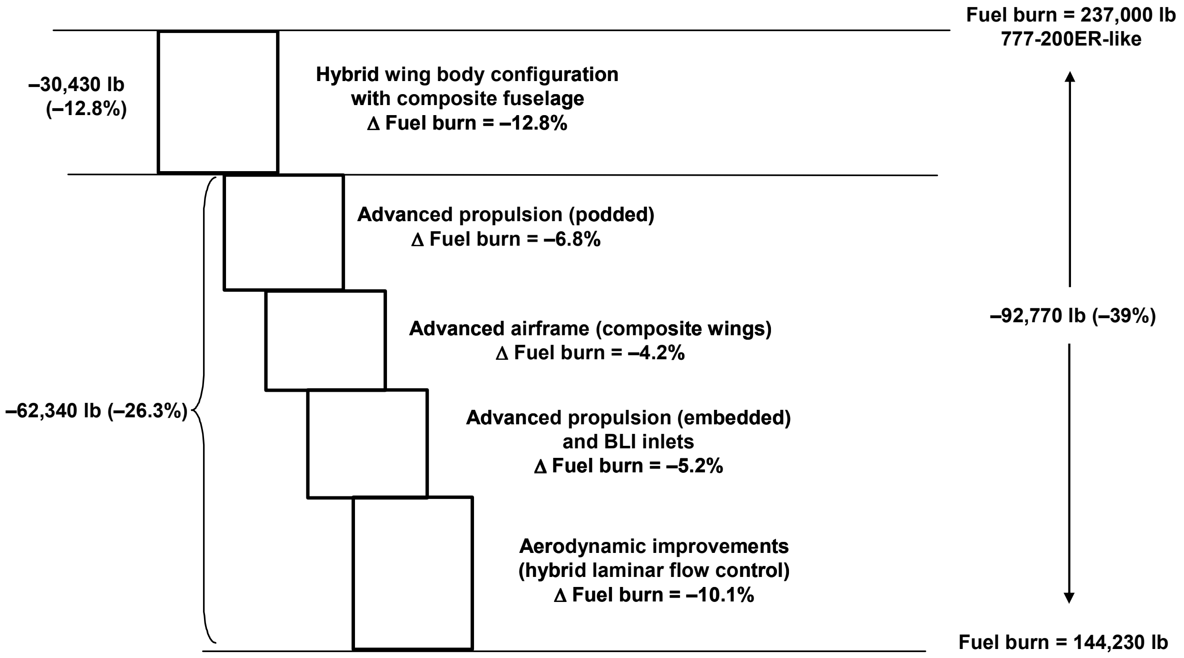

Figure 6. N+2 HWB300 fuel burn reduction waterfall chart.

Note that the fuel burn savings from the individual technologies total 101,430 lb, which is greater than the 92,770 lb savings shown on the waterfall chart for the combined technologies. This difference occurs because when all of the technologies are combined and the HWB300 is sized, the relative contribution of each technology is reduced as a result of interactions between the technologies. For example, if the advanced material assumptions for the wing save a certain percentage of weight with no other technologies present, then the magnitude of the savings will be less for a wing that is smaller as a result of the presence of advanced engines and HLFC. In the waterfall chart, the fuel burn reduction percentages for each technology have been weighted to reflect this interaction.

After the HWB shape is taken into account, the next key technology areas are the HLFC system and the advanced propulsion system. The HLFC system alone has the potential to reduce fuel burn by 10 percent compared with the 777 reference vehicle, and the advanced engines contribute an additional 6.8 percent. Interestingly, both of these key technology areas apply equally well to an advanced tube-with-wings design. Indeed, the advanced tube-with-wings concept showed an overall fuel burn savings of 27 percent compared with the 777 reference vehicle. The embedded engines with BLI inlets are unique to the HWB configuration and have the potential to contribute more than a 5 percent fuel burn savings. The advanced airframe assumptions contribute the final 4 percent of savings toward the overall 39 percent in fuel burn savings potential. In summary, the HWB300 has the potential to provide an additional 12 percent in fuel burn savings over an equivalent technology tube-with-wings concept relative to the baseline reference vehicle, but includes the additional technical challenges of building a noncircular pressure vessel for the HWB centerbody and achieving the performance targets for the embedded BLI propulsion system.

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