

Review

The U.S. Air Force Next-Generation Air-Refueling System: A Resurgence of the Blended Wing Body?

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Abstract: The interest in flying wings dates as far as the early years of the aviation age. Early investigations of the feasibility of the concept demonstrated increased aerodynamic efficiency and reduced fuel consumption. However, structural, engine integration, and stability and control issues prevented further development. In the 1990s, a new concept, the blended wing body (BWB), was created to alleviate some of the concerns of flying wings while maintaining increased efficiency and adding further benefits, such as reduced pollutant and noise emissions. Despite the promise, technical hurdles once again proved to be a deal breaker and, as of 2024, the only successful flying wing is the B-2 Spirit, an extremely complex and expensive aircraft. Nowadays, with the world quickly transitioning towards cleaner energy, the interest in the BWB has been renewed. The latest technological advancements in the aerospace industry should make its development more plausible; however, passenger comfort issues remain. Surprisingly, the BWB development may come from an unexpected application, as a tanker aircraft. As the U.S. Air Force is seeking a replacement to hundreds of aging tankers, a startup company was recently funded to develop the concept and build a prototype. In this study, we explore the history of blended designs from its early days, highlighting its opportunities and challenges—and why the design is an intriguing fit for application as a tanker aircraft.

Keywords: USAF; NGAS; tanker; BWB

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1. Introduction

1.1. Brief History of Flying Wing Designs

It is appropriate to state that, in the early days of aviation, configurations resembled neither the dominant tube and wing nor flying wing configurations, with most aircraft featuring a wooden structure and fabric wings. The term flying wing is adequate to describe tailless aircraft that have no distinct fuselage, carrying its crew, payload, and fuel inside the wing structure. The first aircraft with a design feature resembling a flying wing was the Dunne D-8 (1911), a tailless biplane featuring swept wings and washout to prevent tip stall and increase pitch stability [1]. In the 1920s, a series of tailless aircraft, known as Westland–Hill pterodactyl, demonstrated looping and rolling capabilities [2].

The semi flying wing, developed by Jack Northrop in 1928, had no fuselage but still featured vertical stabilizers [3]. Intrigued by the aerodynamic benefits of fewer non-lifting surfaces, Northrop's developments led to a pure flying wing in 1940, the N-1M "Jeep". The design, shown in Figure 1, showed decent handling ability [4], demonstrating the potential of the flying wing configuration. However, it also suffered from engine overheating due to its placement within the airfoil. Still, the promise prompted the USAF to pursue the development of a flying wing bomber, the Northrop N-9M (1942).

Parallel to the developments by Northrop in the 1930s, the Horten brothers worked on a flying wing concept in Germany. The first aircraft to fulfill the definition of flying wing was the Horten I glider (1933). After a requirement for a heavy bomber by the Luftwaffe in 1943, the Horten brothers designed the Ho 229 (Figure 2).



Figure 1. Northrop N-1M “Jeep” flying wing (Courtesy of Smithsonian National Air and Space Museum. Available at <https://airandspace.si.edu/collection-media/NASM-NASM2015-04014> (accessed on 25 May 2024).

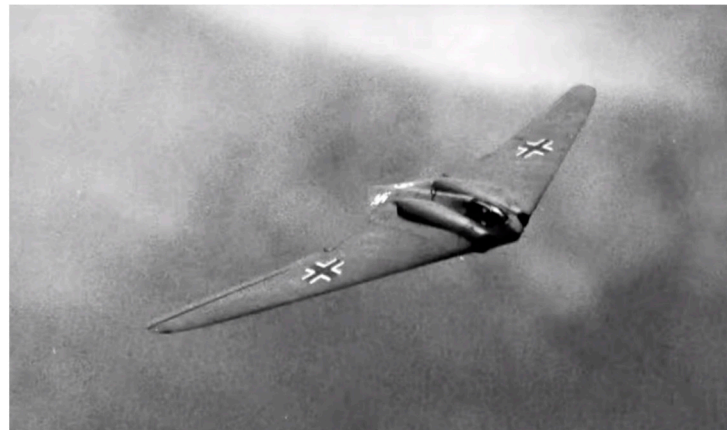


Figure 2. The Ho 229 in flight (public domain).

The flying wing configuration was favored by the Horten brothers due to its high aerodynamic efficiency. The design was also the first flying wing powered by turbojet engines. It featured flaps, elevons, and drag rudders for control and stability. The design, described as “decades ahead of its time” [5], first flew in the final months of the second World War II in 1945. However, after a fatal accident with its test pilot, the aircraft never entered serial production [6].

Following the end of the war, prototypes were sent to the U.S. for evaluation [7], and the German designs were extensively studied by American engineers, which likely contributed to the further developments by Northrop. The YB-35, built as a scaled-up version of the N-1M, first flew in 1945. The YB-35 was powered by four piston engines, each activating a pair of contra-rotating propellers. Some of the airframes were converted to carry early jet engines and designated as YB-49.

At the time, the aircraft suffered from poor handling and engine problems, and the program was ultimately cancelled in favor of the B-36 program [8]. Up to that point, development of this revolutionary design was constrained to military applications—like most cutting-edge inventions in the aerospace industry. The U.S. Air Force also shifted its focus towards supersonic aircraft in the early 1950s. Nevertheless, the lessons learned greatly impacted the development of the first flying wing to enter serial production decades later, the Northrop Grumman B-2 spirit.

Between 1950 and the early 1980s, development of flying wings was dormant, save for one development. After WW2, Reimar Horten immigrated to Argentina and was the program director of the FMA I.Ae 38, a four-engine experimental tailless transport aircraft based on Horten's previous designs. The IA 38 suffered from issues shared by previous flying wing aircraft; it proved to be difficult to control and was underpowered, resulting in poor performance, while the engines also suffered from overheating. The program was ultimately cancelled in 1962 [9,10].

The advanced technology bomber (ATB) program started in 1979 and culminated in the development of the stealth bomber, which first flew in 1989. The development of stealth capabilities, along with the technical challenges of the flying wing configuration, resulted in development costs of USD 23 billion in 2021 money [11]. For comparison, development costs for stealth fighter aircraft were around USD 44 billion the F-22 [12] and the USD 74 billion F-35 [13], both in 2021 money. Unlike in the F-22 and F-35 programs, development costs per aircraft were exacerbated due to the limited number of orders (21).

Despite the high cost, the three-decade operational success and strategic nature of the B-2 prompted the U.S. Air Force to procure the development of its flying wing successor, the B-21 Raider. As of February 2024, the B-21 (Figure 3) is being flight tested and its scheduled entry into service is in 2027 [14,15].



Figure 3. B-21 Raider stealth bomber. Courtesy of the U.S. Air Force.

Other notable recent flying wing designs include several unmanned aerial vehicles such as the Northrop Grumman X-47B, the Lockheed Martin RQ-170 sentinel, the Russian Sukhoi S-70 Okhtonik, and the Indian DRDO Ghatak. China is allegedly also developing a stealth flying wing bomber, known as Xi'an H-20. No public details are available, but a PLAAF recruiting video shows the silhouette of a flying wing bomber similar to the B-2 [16].

Shortly before the first flight of the B-2, when NASA prompted the “renaissance of long haul transport” in 1988 [17], industry and academia scrambled to develop a new concept. The resulting blended wing body (BWB) configuration, which features a distinct, lift generating centerbody and conventional wings, resulted in huge improvements regarding fuel burn, takeoff weight, pollutant emissions, and installed thrust when compared to conventional tube and wing aircraft [18]. The compact design provides structural, aerodynamic, and payload synergy [19]. A flight test model for one of the earliest designs, the X-48C, is shown in Figure 4.



Figure 4. X-48C flight test model (Courtesy of NASA).

Projects featuring BWB configurations were developed mostly in the U.S, especially regarding the main project by McDonnell Douglas/Boeing, the “Silent Aircraft Initiative” and the NASA “Quiet green transport” project. Development also happened in other countries to a lesser extent, most notably through the MOB, VELA, SAX-40, NACRE, and AFCA projects (European Union/United Kingdom) and the TsAGI institute (Russia).

The BWB design also faced a number of technical challenges, namely structural design and manufacturing, as well as stability and control issues, both of which also existed for the early flying wing designs. Additionally, for a long haul transport aircraft, passenger comfort was also an issue [20]. Overall, despite the promise, the complexity of the design and lack of further interest by the aviation industry prevented the concept from becoming a commercial product.

In recent years, as the world has transitioned towards cleaner energy, regulatory agents have been pushing for more energy efficient alternatives such as electrified aircraft. These trends renewed the interest in alternative designs such as the BWB. American startup company JetZero has been working on this design for a commercial aircraft for a few years, but a new opportunity prompted a shift in the design priorities.

1.2. The USAF NGAS Program

The U.S. Air Force (USAF) is currently seeking replacements for its aging tanker fleet, consisting of more than 460 aircraft as of February 2024. In 2023, the USAF launched the Next-Generation Air-Refueling system program through a request for further information to industry [21,22]. The program, formerly known as KC-Z, emphasizes aircraft survivability in contested environments, as well as the capacity to operate from unprepared airfields. However, other mission requirements are not specified.

Shortly after, American company JetZero revealed its BWB tanker concept, allegedly capable of carrying twice as much fuel while requiring half the power of the KC-46 Pegasus [23], the most modern tanker currently employed by the USAF. JetZero was ultimately awarded a USD 235 million contract to build the first prototype of the tanker and partnered with Northrop Grumman, the company with the most experience on flying wings, to build the concept [24]. An artist impression of the tanker BWB is shown in Figure 5.



Figure 5. Artist impression of a blended wing body tanker aircraft (Courtesy of JetZero).

The mission requirements for the NGAS have not been specified or published, but it is reasonable to assume the aircraft will be sized to match the performance of tanker aircraft currently in service with U.S. Air Force. For instance, the KC-46 Pegasus is designed to cruise at Mach 0.80 and 35,000 ft for 7350 nautical miles with a speculated fuel payload of 120,000 lbs [25], though the range and payload are heavily mission-dependent. The new aircraft configuration allows further design flexibility a priori, but the mission requirements are ultimately set by the U.S. Air Force.

1.3. Structure of the Present Work

In this review paper, a number of aspects of the BWB design are explored in the following manner. Research developments are presented in chronological order, separated by major design areas, highlighting the early associated advantages or challenges. Each section is complemented by latest research developments and aerospace technologies that help address these, as well as how these potentials/issues uniquely apply to the BWB tanker design. The design of the BWB with regards to its numerous features is a highly coupled process, and an effort was made to separate these as much as possible. However, some of the information presented in all sections will point to other design aspects.

2. Potentials and Challenges of the Blended Wing Body Design

2.1. Aerodynamic Considerations

During a great portion of the first century of aviation, industry efforts focused on efficiency improvements of the classical tube-and-wing configuration. However, with a growing demand for environmentally friendly and aerodynamically efficient aircraft which could carry a large number of passengers over a long range and having reach the limits of conventional design, NASA prompted [17] studies that renewed the interest in alternative aircraft configurations.

The first major blended wing body design study, by Liebeck [26], focused on the design of a commercial airliner to carry 800 passengers over a 7000 nm range at a cruise Mach number of 0.85 and was projected to enter service in 2020. Due to the blended nature of the airframe and lower wetted area, the design featured increased aerodynamic efficiency, resulting in a 20% higher lift-to-drag ratio, 27% lower fuel burn, and total installed thrust. However, the aspect ratio was low, resulting in faster induced drag increase with lift coefficient, generating a very low optimum lift coefficient [27]. The cross-sectional area was uniformly distributed among the span to minimize wave drag [28,29].

The lack of horizontal and vertical stabilizers also reduced corresponding friction and induced drag penalty, further increasing aerodynamic efficiency [30]. Through the use

of (then) advanced composite materials in the fuselage, the takeoff weight (TOW) was reduced by 15% and the operating empty weight (OEW) by 12%, compared to similarly sized conventional aircraft.

The development of the BWB concept by the same team resulted in a series of follow-up studies [18,28,31], which culminated in the development of the Boeing BWB-450 commercial aircraft concept. The model underwent successful, full-scale Reynolds number wind-tunnel testing, with excellent agreement with simulations regarding aerodynamic characteristics. In a collaboration between NASA and Stanford University, the BW-17 radio-controlled model was built, which demonstrated good handling qualities despite the lack of a vertical tail. This comprised the first wave of BWB studies, which happened in the United States between the 1990s and early 2000s and consisted of NASA-Industry-Academia collaborations.

The BWB is a highly integrated aircraft configuration, with strong coupling between aerodynamic design, structural design and manufacturing, stability and controls, performance, and passenger comfort. The early tradeoffs pointed to the necessity of multidisciplinary optimization, where the focal point of the design (i.e., optimal aerodynamic performance) was achieved at a compromise of other design characteristics.

The superior aerodynamic qualities were indeed the driving aspects behind the development of the BWB configuration over conventional aircraft. Roughly a decade after the beginning of developments in the U.S., parallel research studies conducted in the EU and UK elaborated on superior aerodynamic performance and weight savings of the configuration through design optimization algorithms.

As early as 2000, a study [32] at Cranfield University proposed a baseline BWB similar in configuration to the Boeing BWB-450. Subsequent efforts focused on the design optimization, such as the MOB—multidisciplinary optimization of a blended wing body [33,34], which integrated aerodynamic, structural, aeroelastic, and flight mechanics modelling through low and high-fidelity analysis tools. The algorithm allows for the optimization of range for a constant MTOW, which depends on the lift-to-drag ratio and structure weight.

The VELA projects [35], which focused on the development of a large passenger aircraft with requirements similar to [26], reported a 10% lower TOW and 4–8% improvement in aerodynamic efficiency [27]. A study by TsAGI, in Russia, presented an optimal blended configuration with a lift-to-drag ratio of 25 at Mach 0.85 [30]. Lower total drag and improved aerodynamic efficiency were also reported in further studies [36,37].

Design constraints included a higher thickness-to-chord ratio to accommodate for passengers and cargo, as well as a cruise deck angle of less than 3 degrees for passenger comfort—a higher angle would result in inadmissible reduction of the passenger cabin [30]. The cruise deck angle requirement demands the use of positive aft-cambered airfoils [38,39]. This generates a nose-down pitching moment, however, increases the trim requirement [18,40]. To further illustrate the highly coupled nature of the BWB design, it is worth mentioning that sweep and trim are commonly used to set control surface deflections and minimize trim drag, also affecting deck angle requirements [41].

Usually, aircraft design strives for an elliptical lift distribution for optimal aerodynamic efficiency [42]. However, the BWB is aimed to operate in the transonic regime, where wave drag, rather than induced drag, is dominant. A research study [36] found that the elliptical lift distribution creates a strong shock at the outer wing due to local lift, resulting in increased wave drag and reducing aerodynamic performance.

In a further research study, the same authors proposed an averaged elliptical/triangular distribution [43] (shown in Figure 6) to reduce shock strength while maintaining superior aerodynamic performance. A purely triangular distribution is preferable if the design goal is to minimize wing bending loads. A moderately loaded outer wing [18] is also useful to optimize wetted area while reducing the wing bending moment and thus structural weight.

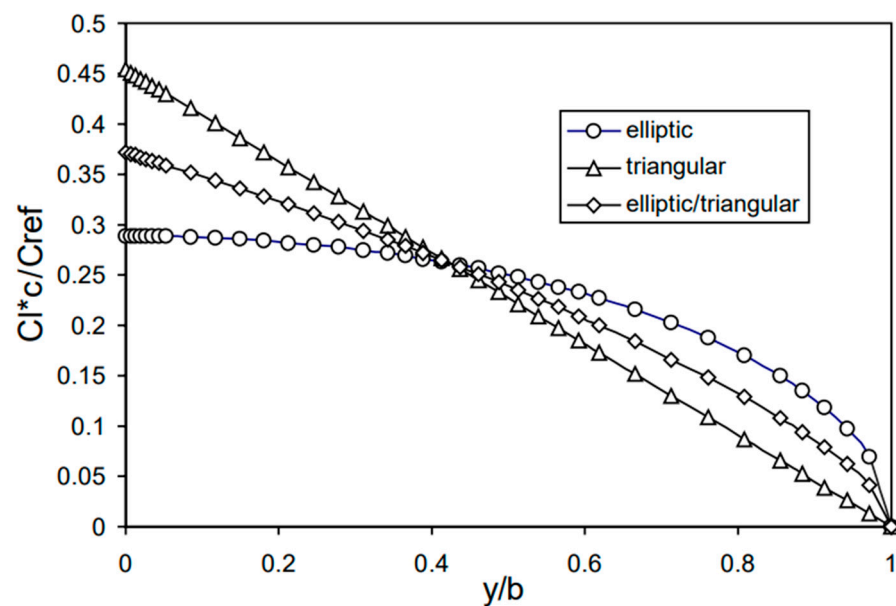


Figure 6. Different design lift distributions for a BWB design. Reprinted from [43], with permission from Elsevier.

A low wing loading configuration contributes to reduced take-off and landing speeds, resulting in decreased required field lengths [20] and improving the aircraft's ability to operate from unprepared airfields. If the engines are mounted on top of the fuselage, the inlets are also protected from foreign object debris (FOD) by the fuselage. These aspects match the requirements put forth by the USAF, as discussed in Section 1.2.

Additionally, low wing loading enables a higher rate of climb. This, in turn, reduces the necessary airspeed to generate supplementary lift for ascending to higher altitudes. Furthermore, low wing loading augments the sustained turn capabilities of a BWB aircraft by enabling it to produce greater lift for a given engine thrust when compared to conventional tube-and-wing aircraft configurations.

The outboard wing is highly loaded, and outboard slats are necessary for stall protection [18]. Outer wing flow remains attached, as well as in the centerbody region, due to significant lateral flow relieving compressibility effects. Ideally, the stall should begin in the centerbody or in the kink region, keeping the ailerons effective and avoiding pitch-up moment during stall [18,28].

In a related investigation [44], the aerodynamic impact of sweep angle variations on a BWB aircraft featuring constant twist and airfoil sections was explored. The study involved adjusting the leading-edge sweep angle of the outer wing from 40° (forward sweep) to 55° (backward sweep). The results indicated that forward sweep mitigates tip stall tendencies but concurrently elevates wave drag, resulting in a diminished lift-to-drag ratio. Conversely, aft sweep generates a nose-down pitching moment, thereby enhancing longitudinal stability, albeit at the expense of increased wave drag.

Varying the sweep angle within the range of 20° to 40° notably enhances the lift-to-drag ratio by up to 80% at the optimized sweep angle of 38.6°, primarily attributable to a substantial reduction in wave drag. However, further increments in aft-sweep angle led to diminishing returns, reducing aerodynamic efficiency and requiring structural reinforcement to withstand elevating heightened bending moments and stress.

Moreover, a significant aft-sweep angle results in the displacement of aircraft weight and center of gravity, resulting in adverse longitudinal moments and subsequent augmented trim drag. The pitching performance, as well as other control and stability characteristics, are explored in detail in Section 2.3.

Aerodynamic Considerations in Light of the NGAS Program

Improved aerodynamic efficiency is a desirable trait in modern aviation. Only in rare circumstances it is not the main driving factor behind aircraft design (i.e., for military applications when speed, maneuverability or stealth are prioritized). The next generation tanker has mission requirements that closely match the performance of current commercial aircraft regarding everything but its payload.

With that in mind, just as in commercial aircraft, the superior aerodynamics of the BWB serves a tanker aircraft well. A recent research study [25] compared the blended wing body tanker to a conventional tube and wing aircraft currently in service (Boeing KC-46 Pegasus). The blended wing body has a better lift-to-drag ratio and significantly lower takeoff weight (28%), fulfilling the same mission while requiring the thrust installed in narrow body aircraft such as the A320 Neo.

The efficiency of the BWB compared to conventional aircraft raises questions as to why the BWB has not become a commercial product thus far. This is likely related to the mission requirements of the projects developed in the 1990s; all major projects in the USA, EU, Russia, or UK required the aircraft to be sized as a long haul, very high-capacity transport. Passenger comfort and emergency egress were also key issues. These will be addressed in Section 2.5.3.

The current landscape of aviation shows a preference for twin-engine, shorter capacity aircraft over multi engine designs such as the Boeing 747 or Airbus A380. This trend was allowed by the development of reliable turbofan engines featuring higher thrust-to-weight ratios and lower specific fuel consumption, decreasing operational and maintenance costs. In the early stages of BWB development, it was speculated that conventional aircraft would be gradually retired as the BWB entered commercial operations. Despite the aerodynamic advantages, the sizing of the aircraft at the time aimed at the succession of the 747/A3XX [30]. The industry ultimately moved in the opposite direction, disproving that claim.

2.2. Structure and Manufacturing

The BWB configuration offers efficient payload distribution and the possibility of over-the-wing engine placement. The centerbody generates lift due to its low aspect ratio, thereby mitigating wing loading. These characteristics serve to minimize wing bending moment and shear forces, resulting in favorable inertia relief and consequently reduced structural weight [45,46]. Additionally, the integration of the fuselage and outer wings reduces the overall wetted surface area, leading to a higher wetted aspect ratio and, consequently, a structurally more efficient wing design [47].

The structural design for the earliest versions of the BWB consisted of upper and lower surface panels, rounded leading edge functioning as spar, rear main spar, and outer ribs [18,28], which proved to weigh more than a conventional fuselage. The structure of the outer wing section was similar to that of the wing in a conventional tube and wing aircraft. The inner section, which contains the passenger cabin, must be designed with pressurization and wing bending loads as requirements.

Unlike in a conventional aircraft, where the two loads are separately supported by the fuselage and wing, respectively, the inner section is responsible for both loads simultaneously. Taking pressure loads in a non-cylindrical vessel presents an enormous design challenge due to non-linear stresses which could result in severe deformations under extreme maneuvers or gusts [48–50].

The initial structural concept [31] utilized a thin, arched pressure vessel located above and below each cabin. In this configuration, the pressure vessel skin takes the load in tension independently of the wing skin. Alternatively, the second concept employed a thick sandwich structure for both the upper and lower wing surfaces, with both cabin pressure loads and wing bending loads supported by the sandwich structure.

A potential safety concern arises with the separate arched pressure vessel concept. In the event of a rupture in the thin arched skin, the cabin pressure would need to be sustained

by the wing skin, necessitating that the wing skin be sized to accommodate the pressure load. Consequently, once the wing skin is dimensioned to meet this requirement, the inner pressure vessel theoretically becomes redundant.

The coupling of both pressure and wing bending loads is also concerning as far as fatigue is concerned. Since the pressurized cabin faces its design load on every flight [28], the BWB centerbody must be designed with that requirement in mind, further adding to the weight of the fuselage. Also, deformation of the aerodynamic surface could significantly affect the aerodynamic advantages of the blended design [48]. Preliminary calculations [30] have shown that rather thick upper and lower panels would be necessary to carry both pressure and bending loads.

Early in the design of the first generation BWB aircraft, special emphasis was placed on the problem of containing cabin pressure in blended designs through a simplified, two-dimensional beam-column analysis [49]. In a comparison between elliptical and multi-bubble designs, the latter were found to take internal cabin pressure loads efficiently through balanced membrane stress in inner cylindrical segment shells and inter-cabin walls. Generally, the stresses are one order of magnitude higher than in conventional tube and wing fuselages since internal pressure primarily results in bending stress instead of skin membrane stress [48].

Multi-bubble designs bridge the gap by featuring cylindrical fuselage sections, as shown in Figure 7. The cabin floors and partitions help support the torsion and bending loads [28].

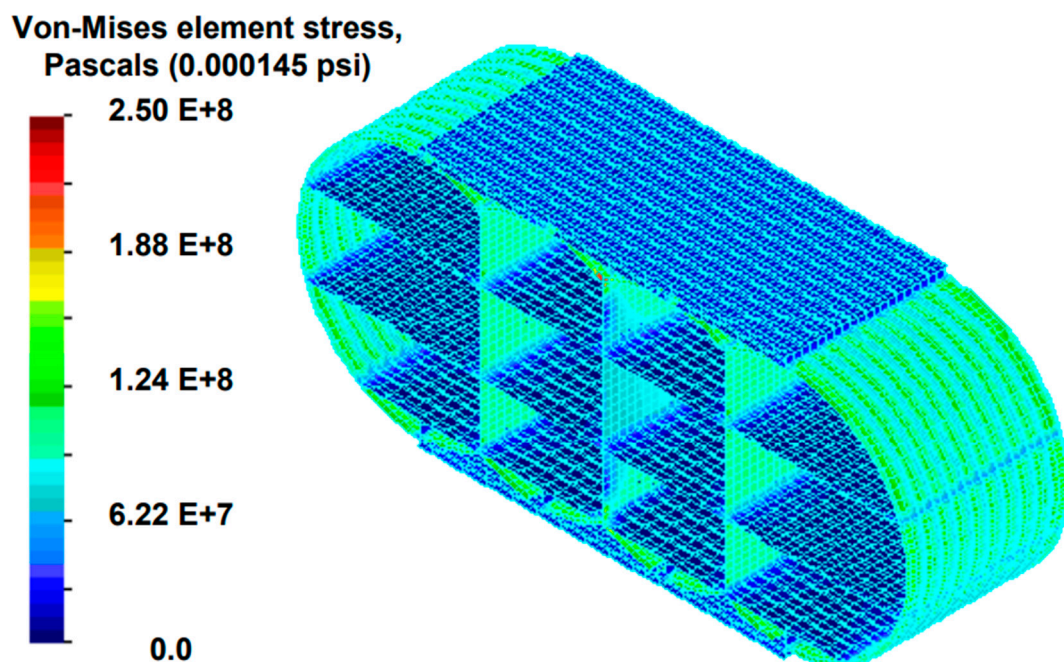


Figure 7. FEA analysis of the multi-bubble concept fuselage (MBF) loaded with cabin pressure and simulated aerodynamic loadings [48].

The outer-ribbed shell prevents buckling due to external resultant compressive loads. The initial results from these approximate finite element analyses indicate progressively lower maximum stresses and deflections compared to the earlier study, but weight is higher than the conventional B777/A380. A slight modification of the multi-bubble concept was investigated by substituting inter-cabin walls for columns, and integrating outer panels to decouple the loads and provide buckling stability [50].

Due to manufacturing concerns with multi-bubble fuselage designs, a Y-braced box fuselage (Figure 8) alternative was developed with special resin-film-injected (RFI) stitched carbon composite with a foam core. This configuration is a hybrid between the multi-bubble

concept and the separate pressure shell concept [31], efficiently taking structural loads while alleviating manufacturing concerns.

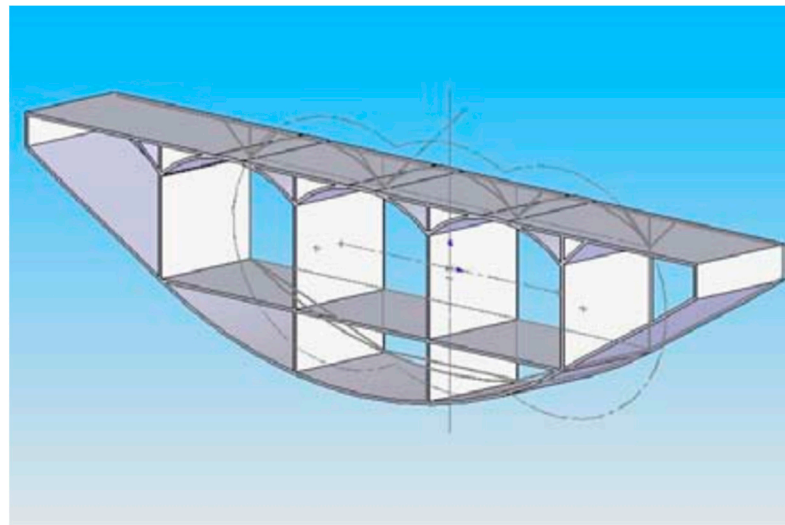


Figure 8. Y-braced box fuselage for BWB vehicles [48].

More recently, attempts have been made to include physics-based mass predictions on shape optimization algorithms for the BWB [47]. Most early research projects assumed extensive use of composite materials in as early as 1996 [28,51], although this assumption was made exclusively for weight estimations. The TsAGI project was more conservative and assumed a fuselage composition consisting of mostly aluminum with minimum use of composites [30]. Later developments [52] indicated the need for substantial improvements beyond aluminum and composite structures. The alternative presented was a unique manufacturing process to exploit the orthotropic nature and unique processing advantages of dry carbon fibers.

As another design alternative, an oval fuselage design [53] consisting of four arcs connected by a prismatic box creates a large, uninterrupted internal space that allows for a flexible cabin configuration while more efficiently taking tension and compression loads.

Structural Considerations in Light of the NGAS Program

The previous section describing the structure and manufacture concerns for the BWB is relatively short for a few reasons. Unlike in tube-and-wing aircraft, where the materials and manufacturing techniques change but both the wings and fuselage are designed in the classical manner, the highly coupled design and odd fuselage shape of the BWB makes the structural design unique for each aircraft.

The BWB tanker aircraft is also unique, even among blended designs, due to its payload; since no passengers are carried, the fuselage (other than the crew cabin) does not need to be sized with the internal pressure loading in mind. This creates immense opportunities for weight savings and simplifies the design process. For the outer wing, we envision a conventional design, featuring ribs and spars. The centerbody must be designed to support wing bending loads as well as the fuel tanks. Due to the distributed weight, we suggest the use of longitudinal beams to reinforce either a truss or monocoque construction.

There is ample opportunity to introduce modern materials in the NGAS structure. For instance, aluminum-lithium alloys could substitute traditional aeronautical aluminum due to lower density, improved mechanical properties, and corrosion resistance [54,55]. The lack of necessity to account for cabin pressure facilitates the use of composite materials to build the fuselage panels, resulting in further weight savings.

Each individual fuel tank needs to be pressurized for proper operation at very high altitude [56]. The crew cabin may be separately designed for a comfortable pressure and mounted on the overall structure.

2.3. Stability and Control

The absence of horizontal and vertical stabilizers makes the BWB configuration unstable and inherently difficult to control [15], also making it particularly sensitive to lateral wind gusts [38,57], as well as other adverse weather conditions [58,59]. Winglet rudders have been proposed as a partial substitute, but the idea was abandoned due to its complexity [24]. The inclusion of regular winglets also causes a decrease in flutter speed, which is also potentially dangerous for aircraft structure [30].

These problems are shared by flying wings, as discussed in Section 1.1. In a conventional aircraft, movement in any of the principal axes is achieved by movement of specific control surfaces and the axes are decoupled. For example, moving the rudder to generate a yawing moment does not cause a significant pitching moment. On the other hand, in a BWB or flying wing, movement of any control surface generates movement in more than one axis, characterizing strong coupling and redundant motion [60–62]. One exemplary control surface arrangement is shown in Figure 9. There are twelve elevons which generate pitch, yaw, and roll motion simultaneously when activated.

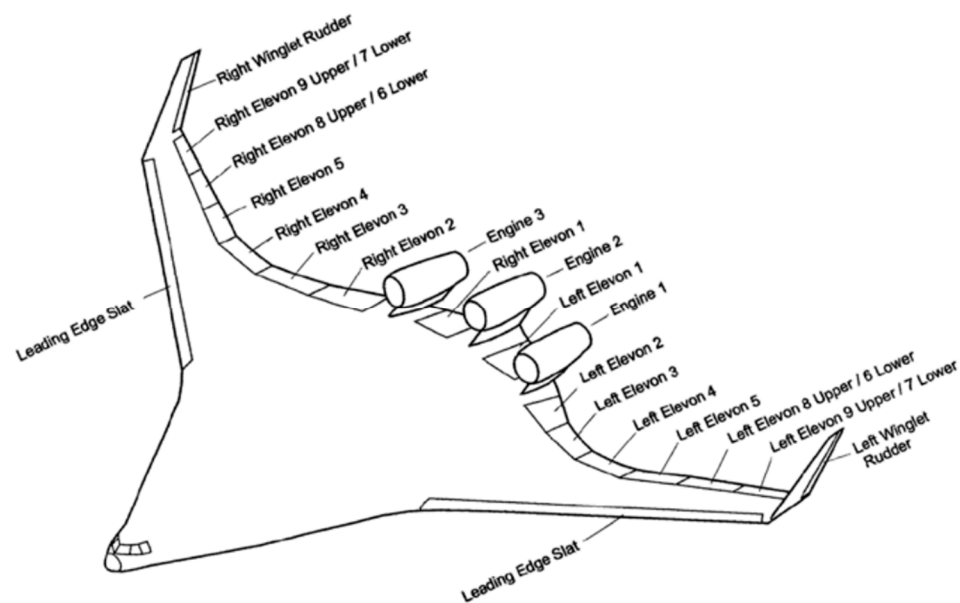


Figure 9. Control surface arrangement for early BWB design [17].

Since all control surfaces are part of the wing, activation increases drag and reduces lift, characterizing strong coupling between stability, control, and aerodynamic characteristics. For example, activation of the elevons to increase the angle of attack causes substantial loss of lift, causing the aircraft to plunge before reaching the desired angle of attack [63].

Early in the history of BWB design, it was assumed that the airplane would be statically unstable in order to assume high cruise efficiency [28]. In the initial designs, control surfaces consisted of elevons and drag rudders, all located in the trailing edge, an arrangement identical to that of Northrop's flying wings of the 1940s [30]. Inboard control surfaces consist of plain hinged flaps and generate mostly pitching moment, and rolling moment to a lesser degree; outboard control surfaces consist of elevons and drag rudders, which generate significant rolling and yawing moments [60,64].

Due to short moment arms, the BWB has low pitch and yaw authority [65,66]. The design is also subject to high yaw rates and auto-rotation tumble [32]. Providing sufficient yaw control is especially difficult in the one engine inoperative regime, and research has

shown that winglet rudders are insufficient [61]. The use of drag rudders or crocodile flaps is preferable for yaw control [31].

Early in the development of the BWB, it was known that a complex flight control system, consisting of multiple, rapidly moving control surfaces [18,28], would be necessary. The trailing edge elevon chord fractions are determined by wing spar location, characterizing a structural–control coupling. Trailing edge surfaces should be as large as design considerations allow [60].

Control laws need to efficiently allocate control surfaces to minimize actuator rate, hinge moment, and horsepower requirements [28,31], and the BWB relies on a full authority digital flight control system for stabilization, control, and trim. The BWB pilot does not directly control any surfaces during flight [60]. The main control goals are roll mode damping, coordinated turn, and roll response shaping. An open loop analysis shows that traditional SISO design faces fundamental limitations [67].

There are no dedicated trim devices. Pitch stability is usually achieved through a combination of wing sweep, the use of reflexed airfoils in the centerbody section, and cambered airfoils in the outer wing section [38]. These design choices, when combined with proper wing twist, also generate an optimal lift distribution. A design featuring aft-mounted engines may be chosen to generate additional nose-down pitching moment. The use of positive, aft-cambered airfoils, associated with the cruise deck angle requirement, generates a nose-down pitching moment, increasing the trim requirement [18,40].

Trim stability can be partially achieved through proper wing twists, although the magnitude of washout necessary to stabilize the aircraft may be quite high, ranging from 8 to 10 degrees [68]. This greatly affects the designed lift distribution, supporting the fact that an elliptical lift distribution is not necessarily optimal for a BWB.

There is strong coupling between fuselage design, aerodynamic performance, and handling characteristics. A study comparing different fuselage shapes with respect to moment characteristics [30] found that blended designs with large front chord extension have unsatisfactory moment characteristics, as shown by design FW-103 in Figure 10. Interestingly, JetZero's BWB design resembles design FW-102, with reduced centerbody span, which features satisfactory moment characteristics over the operational envelope.

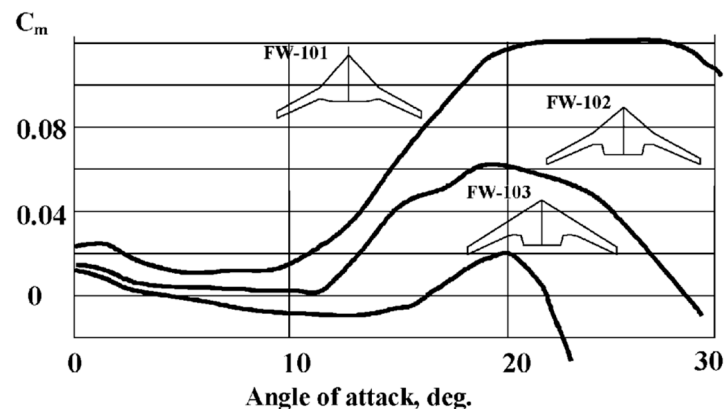


Figure 10. Moment behavior of select blended wing body configurations. Reprinted from [30], with permission from Elsevier.

Performance investigations for the static stability margin by the TsAGI group [30] indicated a degree of static stability close to zero ($C_m^{C_L} \leq 0$) during takeoff and landing, while the instability in cruise flight should be limited by $C_m^{C_L} \leq 0.3$. In tube and wing configurations, a specific static margin can be achieved simply by selecting a wing position relative to the fuselage [28], which is not an option for the BWB design. The most obvious alternative is to change the placement of the engines. The static margin varies greatly with geometry design. Past designs feature static margin values ranging from -15% degrees [28]

to slightly positive [27]. In general, for alternative aircraft designs, a positive static margin from 5 to 15% is desirable [69].

The fuselage configuration does not impact roll and yaw stability, which are preferably achieved through continuous motion of the outer wing surfaces, the elevons, and drag rudders. Attempts to improve lateral stability include the use of belly flaps, which also enhance rotation at takeoff and landing [63]. Differential control surfaces, located in the lower centerbody, were tested with positive results [38]. Morphing, seamless trailing edge devices were also investigated to substitute traditional drag rudders [61], providing reduced drag while providing both crocodile flap and aileron modes at the same time. The use of split drag rudders is not new in flying wings, being a design feature of both the B-2 Spirit bomber (Figure 11) and of the upcoming B-21 Raider.



Figure 11. Split drag rudders on B-2 Spirit. Courtesy of the U.S. Air Force.

The structure of the morphing trailing edge device consists of composite outer skin layers and stringers and inner middle skins. On the one hand, the outer skins need to be deformable in order to achieve required flap deflections, but on the other hand they need to have sufficient stiffness in order to prevent lateral deformations under cruise air loads, increasing design complexity.

In a BWB, the stability and control design group must decide if the airplane can sacrifice control surfaces originally intended for roll to be pitch effectors [60]; the simultaneous activation of control surfaces is a problem. Activating surfaces for pitch leaves no elevons available for roll or yaw control. Morphing trailing edge devices may help alleviate this issue.

An important requirement for the BWB operation is control in the one engine out regime, which exacerbates the already existing control challenges. The use of split drag rudders as outboard elevons provides extra yaw control in the low-speed engine-out condition [30], in addition to providing speed brakes for low-speed flight.

Thrust vectoring as a means to enhance control was not incorporated for the complexity [40], despite promising results in pitch motion [70], as well as because critical sizing conditions for control surfaces occur during idle engine conditions and thrust vectoring would be insignificant in that operational regime [60]. Additionally, FAA certification requirements also impose that aircraft control should not be impaired after any single failure of the stability system [60].

The BWB requires advanced control allocation algorithms which typically assume linear control surface effectiveness [62]. Wind tunnel experiments have shown that the angle of attack and surface deflection have the strongest effect on control moment nonlinearities. The center-section planform, leading edge sweep, and relative size of the front and rear chord extensions greatly influence the behavior of moment characteristics at high angles of attack [30].

Losses at maximum deflection angles and control surface interaction effects are significant, therefore, the authors recommended the inclusion of control allocation selection and performance evaluation in early design stages to avoid costly redesigns. The inclusion of control considerations in preliminary design also helps alleviate hydraulic power consumption. The BWB features significant hinge moments due to large control surface areas, combined with high deflection rates in order to safely control the longitudinal instability, which may result in actuator mass penalty [57].

Stability and Control Considerations in Light of the NGAS Program

Stability issues are inherent to the BWB configuration, and a design effort must be made to compensate for the obvious absence of vertical and horizontal stabilizers. Overall, there is no one-size-fits-all control allocation algorithm, and the system must be fine-tuned to each blended wing body configuration. The goal is to design a system that provides sufficient control authority while minimizing the size of the elevons and, therefore, the hydraulic power.

Previous research placed important emphasis on the range for the center of gravity of the aircraft [30], which directly affects the trim. A very unique feature of the BWB tanker helps alleviate static stability and trim problems: its payload, comprised of fuel. During ferry flight, the aircraft's own fuel consumption can be drawn strategically from certain fuel tanks to keep the aircraft trimmed and stable.

The same idea applies to the refueling operations. In operating regimes where there is not enough fuel in the tanks to achieve this effect (such as the aircraft's return to base after the fuel payload has been transferred), the aircraft weight is significantly lower, resulting in increased authority of the existing control surfaces. Most advanced military aircraft feature multiple fuel tanks and advanced fuel transfer systems [56].

One specific development greatly facilitates the development of the control system for the NGAS BWB: the partnership between JetZero and Northrop Grumman, which designed and manufactured the only flying wing currently in service, the B-2 Spirit bomber. It must be noted that Northrop Grumman successfully designed a control system for a flying wing with 1990's technology. The design of its successor, the B-21 raider, is currently ongoing, which will most likely prompt a major update in the control system. The use of a similar technology for the NGAS will likely reduce development costs.

2.4. Noise

The original blended wing body features reduced a lower acoustic signature due to the centerbody shielding the engine noise [18,71]. An experimental study featuring a scaled model reported reductions in the noise that radiated downward into the forward sector between 20 and 25 dB [72]. For the chosen configuration, featuring engines mounted with nacelles in the aft section of the fuselage, it was observed that noise associated with the exhaust radiates into the sector directly below the model downstream, reducing shielding efficiency.

Despite the early promise, studies specifically regarding the noise generated by the BWB configuration were scarce, even in the early 2000s. The earliest studies [73,74] investigated a noise-driven design featuring integrated Propulsion-Airframe-Aeroacoustic (PAA) technologies, which resulted in noise benefits at the compromise of performance.

Most specific studies focused on acoustic emissions started after 2006 [75], as part of the "Silent Aircraft Initiative" (SAI) by Cambridge, MIT, and NASA. As mentioned in Section 2.1, the BWB is a highly integrated design, and prioritizing one design aspect compromises the others. Overall, an optimized aircraft for reduced noise emissions tends to have a blended nature [76].

When a BWB airframe was designed with noise as the primary target [4,40], the aircraft noise at an airport perimeter was found to be 62 dBA, near the background noise level for a highly populated area. The design features engines partly buried within the fuselage, resulting in imperceptible takeoff and landing, and presenting a significant environmental

benefit. The SAI was driven by the aggressive requirements set by the NASA N+2 program, aimed at developments regarding environmentally responsible aviation [77]. Despite the focus on noise, the culminating design of the SAI, the SAX-40 still featured a 25% improvement in fuel burn compared to conventional aircraft.

During approach and landing, the airframe generates the most noise, which increases as the approach speed increases [40,75]. Lower approach speeds require lower stall speeds, which in turn generate more drag. The tradeoff between cruise aerodynamic performance, stability, departure characteristics, and noise [39] is exacerbated by the fact that the BWB does not feature trailing edge flaps (since there is no trimming surface to compensate the nose-down pitching moment, resulting in less approach noise [18]), requiring a higher approach angle of attack and resulting in higher induced drag. The SAI included noise assessment methods coupled with extensive use of multidisciplinary optimization tools such as Wingmod [78].

The absence of flaps also negatively affects the departure characteristics [31]. The BWB also has lower wing loading, therefore, the maximum lift coefficient happens at high angle of attack. The higher induced drag is generated by use of the elevons, as well as drooped leading edge slats [30] (which also generate further noise).

The landing gear is responsible for the majority of noise generated during landing, caused by unsteady flow structures [79]. Usually, the landing gears are strategically located in lower velocity regions. The blended shape is such that local velocity under the fuselage is almost the same as free stream; in conventional aircraft, this is only about 80% (generating circulatory flow). Therefore, the BWB landing gear will generate more noise. The slats also pose a significant contribution, and technological developments in the area are proposed to minimize their acoustic signature [77].

During takeoff, the turbulent mixing of the high-speed jet is responsible for the majority of the noise. The BWB features a multi-engine, low specific thrust configuration which allows the fan to operate at part-speed during takeoff. This increases the benefit of a variable area nozzle regarding fan and jet source noise reduction [80]. The SAI proposed a faired undercarriage and smooth lifting surfaces, optimally shaping the centerbody and increasing passive circulation and reducing noise levels. However, the faired undercarriage increases weight [81].

A number of novel noise technologies with potential application for the BWB were investigated, with modest benefits. For instance, the distributed propulsion system in the centerbody enables a substantial amount of acoustic treatment in the exhaust duct, such as the use of extensive acoustic liners [82,83]. Sakaliyiski et al. [84] investigated the potential of perforated drag plates, and Shah et al. [85] proposed the treatment of the trailing edges by the deployment of brushes to reduce airframe self-noise, although the noise reductions were limited to 4 dB [86]. Nozzle chevrons and pylon treatments were also proposed [87].

As part of the Quiet Green Transport (QGT) initiative by NASA, BWB aircraft were shown to be adequately quiet even when featuring open-rotor propulsion [88]. The study reported the design to be quieter than conventional aircraft, though at the time it was speculated that this alternative would face stiff competition by designs featuring future, quieter turbofan engines. Noise studies regarding a BWB powered by hydrogen fuel cells [89,90] indicated that distributing the propulsion system into several engines instead of a few large ones tends to increase the frequency of the engine noise, leading to greater atmospheric attenuation.

Overall, the SAI studies successfully showed that, even when noise is the design priority for a BWB, the aerodynamic improvements over conventional aircraft are still significant. This is achieved through the integration of noise assessment tools [80,91] on the fuselage design methodology. However, some of the technologies proposed by the SAI were then perceived as high-risk [81], including the BWB concept itself, the thrust vectoring system [39], the landing gear design, and the cost of the program.

Additionally, some of the noise-reducing features of the BWB require changes to the operational rules in the terminal area, such as displaced threshold, and use of a variable-

area nozzle on takeoff [75]. The SAI did not publish effective perceived noise level (EPNL) calculation details, which definitely would present a hurdle in the regulatory process.

It is also appropriate to discuss the complexity of performing a noise assessment for the BWB. While multiple noise prediction algorithms exist, such as the fast-scattering codes developed at N.C. State [83,92], these make the consideration of potential flow, neglecting the well-known effects of turbulence on noise generation [93]. Other noise assessment techniques include numerical simulations, experimental data and empirical correlations [77].

Special noise assessments for BWB's lack the possibility of experimental validation. Shielding, for example, can only be assessed through wind-tunnel experiments on scale models. However, even when experimental setups were used [72,92], no attempt was made to simulate the noise emission characteristics of the engines. Overall, at the time of the SAI, noise shielding prediction for full configuration aircraft and realistic conditions were not available.

More recently, a perception-based noise study [94] investigated the flyover of a BWB variant. It has been shown that the blended designs are substantially less annoying than current tube-and-wing long-range aircraft of similar range and mission for take-offs as well as for landings. For the best BWB variant, noise annoyance was reduced by 4.3 units for departures and by 3.5 units for approaches on an 11-point scale. The main reason for these findings seems to be the acoustic shielding by the body of the extended fuselage, which was found to be an important factor in reducing sound levels in the order of 10–20 dB.

Noise Considerations in Light of the NGAS Program

Acoustic emissions are a critical aspect involved in any aircraft designed for low detectability. Given the special emphasis placed by the NGAS on aircraft survivability, it is possible that an attempt will be made to minimize the airframe noise. However, for a tanker aircraft designed to fly at high altitude and Mach number, other stealth elements are likely to be prioritized, such as the radar cross-section and infrared signature. The noise benefits, however, present a significant development regarding the commercial use of the BWB.

2.5. Miscellaneous

2.5.1. Propulsion

At the time of conception, the BWB was seen as an ideal platform to integrate advanced propulsion concepts. Alternative propulsion solutions such as propfan engines [30] and hydrogen fuel cell distributed propulsion [90] were evaluated, with limited potential upside. For propfan engines, the cruise Mach number would be reduced, and the complexity of hydrogen fuel cell design, in addition to added weight, held the concept back. More recently, hybrid-electric propulsion was also investigated for BWB designs [95].

The most extensively studied advanced propulsion concept is the use of boundary layer ingestion (BLI) to reduce ram drag and increase propulsive efficiency at cruise [15,31,49,96,97]. The benefits are offset by lower inlet pressure recovery and increased flow distortion before the compressor stage, in addition to increased fan noise, and it was speculated that some sort of flow control had to be used so that distortion levels were acceptable [75].

As discussed in Section 2.1, minimal aft camber enhances the external pre-compression of upstream flow in the BLI engine configuration [40,98]. This provides uniform flow at the engine inlet, reducing the challenges associated with the use of BLI propulsion. To satisfy these requirements, a multivariate optimization is required to ensure conflicting constraints are satisfied.

Some research has also been performed regarding embedded propulsion systems [75,91], resulting in lower installation weight and lower nose-down pitching moment, as well as improving flow separation and maximum lift coefficient. However, this type of installation is also prone to inlet flow distortions [99].

Despite the number of different propulsion alternatives, JetZero ultimately decided for a conventional design, placing conventional, high bypass turbofan engines on pylons at the rear section of the fuselage (Figure 12). Ultimately, it appears that the benefit of alternative propulsive alternatives is marginal compared to the design hurdles and cost of developing new technologies.



Figure 12. Artist conception of the NGAS during mission. (Courtesy of JetZero).

The only way the authors envision the NGAS aircraft to feature advanced concepts like embedded propulsion, is if the U.S. Air Force places immense emphasis on stealth, like in the B-21 Raider. However, unlike the B-21 (which has to penetrate enemy territory undetected by air defenses), the NGAS will likely operate out of highly contested zones, where allied fighters can provide escort.

Obviously, the NGAS should still feature stealth elements and minimize noise/infrared emissions and radar scattering as much as possible, but embedded propulsion is likely not worth the additional complexity and cost.

2.5.2. Stealth

Flying wing/BWB designs have outstanding radar scattering characteristics due to the blended nature of the airframe [100], as well as the capacity to easily integrate radar absorbing materials [101] on the curved fuselage. Overall, there is enormous potential to reduce the aircraft's radar cross-section (RCS), such as on the B-21 Raider [102].

Some other stealth elements have been previously discussed, such as noise (Section 2.4) and infrared signature. There is a limit to reductions in infrared signature due to engine location. This may make the aircraft vulnerable to the infrared search-and-track (IRST) systems of enemy fighter aircraft [103,104]. It is speculated that modern IRST systems can detect targets at around a 100 km distance [105], placing the enemy fighter well within radar range and beyond-visual-range (BVR) capability for escort fighters.

As explained in the previous section, the increased infrared signature is likely an acceptable compromise considering the design costs associated with burying the engines inside the fuselage.

2.5.3. Aircraft Safety, Passenger Comfort, and Emergency Egress

Compliance with emergency egress rules is a major challenge for BWB configurations due to its shape and fuselage configuration [31]. For example, regulations state that the emergency exits must be above the waterline in case of a water landing [30]. Previous research has shown that the internal configuration of aisle widths, consisting of position, alignment, and format is more important than the aircraft shape [64], and successful emergency egress can be achieved through proper design.

Another issue that cannot be easily alleviated through design is passenger comfort. In a blended configuration, most passengers do not have direct vision over a window.

Additionally, passengers away from the centerline are subject to higher g-loads over turns, deteriorating ride quality [28].

The authors opted to include these challenges to illustrate further design hurdles which contributed toward the BWB not entering commercial service. For a tanker aircraft such as the NGAS, the only “passengers” are the pilots and the refueling boom operator, rendering passenger-related issues a non-factor.

3. Conclusions

In this review paper, we discussed the history of blended wing body designs—from the early days of aviation to the successful B-2 Spirit bomber—highlighting its advantages and challenges and exploring the reasons why the BWB never entered into commercial service.

We firmly believe that the BWB, originally conceptualized as a long-haul transport aircraft, will likely become the U.S. Air Force Next-Generation Air-Refueling system (NGAS). The superior aerodynamic performance of the blended design allows it to fly further while burning less fuel, greatly enhancing refueling operations. The reduced radar signature, noise, and infrared emissions are also particularly interesting for military application in highly contested airspace.

The technical advancements in the past three decades and unique features of tanker aircraft have put JetZero in a great position to address the challenges that prevented the development of the BWB for passenger applications back in the 1990s. For a tanker aircraft, passenger-related issues are a non-factor; the development of new manufacturing techniques and materials greatly reduces the complexity of manufacturing complex shapes for the aircraft structure. Dealing with cabin pressure loads, which created major structural design hurdles in the past, is not necessary.

The last major issue to be addressed is stability and controls of the blended design. New technologies such as artificial intelligence present great potential to reduce design complexity. Also, this problem has been successfully tackled by Northrop Grumman in the development of the B-2 Spirit flying wing. Not so curiously, JetZero partnered with the company to manufacture the BWB tanker prototype. The existing know-how, added to (likely) major control updates for the new B-21 Raider bomber, puts JetZero in prime position to deal with these challenges.

It must be reinforced that the BWB is a highly coupled design, with numerous tradeoffs between aerodynamic performance, stability and controls, structural design, and stealth characteristics, and a complex optimization process is necessary. Ultimately, time will show if the BWB tanker will enter serial production for the NGAS project. Its upcoming first flight, scheduled for 2027, will likely be the deciding factor.

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