NASA AERONAUTICS BOOK SERIES

Beyond Tube-and-Wing

The X-48 Blended Wing-Body and NASA's Quest to Reshape Future Transport Aircraft

Bruce I. Larrimer

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On the cover: The X-48C reveals its distinctive manta ray–like planform as it flies low over Rogers Dry Lake, California. NASA

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Prologue

This book reviews the remarkable efforts to develop a new aircraft configuration known as the Blended Wing-Body (BWB). While the blended wing is an offshoot of the flying wing, there are significant differences. The flying wing, or all wing, airplane encompasses its entire payload within the wing structure, while a blended wing-body smooths, or blends, a fuselage upward into the wing. Both, however, are tailless aircraft that represent a significant design difference from the conventional wing, tube, and tail design of current passenger and cargo airplanes. They likewise represent significant stability and control challenges posed by tailless aircraft.

In 1988, the National Aeronautics and Space Administration (NASA) challenged the U.S. aeronautics industry (and the dominant design paradigm) by asking if there was a potentially revolutionary renaissance for the long-range airplane, or had industry reached a plateau after which designers would only marginally improve upon the design and hence performance of contemporary "tube-and-wing" airliners and transports such as the Boeing 747, McDonnell Douglas MD-11, and Airbus A320. The McDonnell Douglas Corporation (MDC, which subsequently merged with the Boeing Company) accepted the challenge and, in the early 1990s, initiated studies to determine if this new configuration could bring about significant advantages over conventional sweptwing, streamlined tube, and swept-tail designs that echoed Boeing's trendsetting B-47 bomber built 50 years earlier. The McDonnell Douglas engineers who led this effort noted that anyone familiar with the B-47 bomber would readily recognize in its lines and features the basic structural layout of contemporary large jet passenger and transport airplanes.

McDonnell Douglas' initial studies identified both the significant advantages of the blended wing and the challenges in designing, fabricating, and flying a BWB aircraft. Early issues identified and eventually solved included designing a very large pressurized passenger or cargo cabin lacking the hoop-tension strength of a cylinder-shaped conventional tube and tail airplane. These studies led first to additional comparisons of various design concepts and to further development of the BWB configuration, and then to the follow-on design and construction of a dynamically scaled small-size BWB Technology Demonstrator—the X-48B, which was later modified and designated as the X-48C.

As a followup to the initial studies and designs, Stanford University, with McDonnell Douglas' assistance, built and flew some radio-controlled (R/C) models, including a 6-foot-wingspan R/C model designated the BWB-6, and later designed, built, and flight-tested a 17-foot-wingspan remotely piloted BWB testbed—the BWB-17. At this point, McDonnell Douglas hoped to build a piloted, twin-engine, 24-percent-scaled BWB technology demonstrator. However, on August 1, 1997, just days after the completion of the Stanford BWB-17 flight testing and just prior to the beginning of MDC's efforts to build a prototype, McDonnell Douglas merged with the Boeing Company, thus raising the possibility that Boeing might simply abandon the BWB effort.

But Boeing undertook a detailed review of MDC's work, and afterward, with NASA's encouragement, recommendations, and support, the company agreed to continue the BWB effort. Additional Boeing studies further perfected the BWB concepts and designs and addressed important flight control issues, including the development of the flight control laws and angle of attack and sideslip limiters required for tailless aircraft. The follow-on Boeing/NASA project started with NASA Langley Research Center's plan to design and build a 14-percent small-scale BWB Low Speed Vehicle later designated the X-48A by the U.S. Air Force. This first effort was abandoned, but the BWB continued with the follow-on X-48B project. As reviewed in this book, the X-48B project built upon the earlier BWB work, but with extensive aerodynamic testing and the design and fabrication of two 8.5-percent dynamically scaled test vehicles. The X-48B flew 92 test flights before modification into the X-48C; then it flew an additional 30 flights under the auspices of NASA's Environmentally Responsible Aviation Program. These efforts, while proving the viability of the BWB concept, still represent a work in progress, for the fullest promise and international future of the BWB concept is still unfulfilled as of this time.

Bruce I. Larrimer
Columbus, Ohio
September 22, 2020

The Northrop N-9MB of the early 1940s constituted an ambitious if premature effort to exploit the flying wing configuration, a predecessor to the blended wing-body. Here, the then sole surviving N-9MB is flying over Fox Field, Lancaster, CA, in March 2014. Unfortunately, it subsequently crashed on April 22, 2019, at Chino, CA, killing pilot David Vopat. (United States Air Force [USAF])

CHAPTER 1

Seeking "An Aerodynamic Renaissance"

> A blended wing configuration is characterized by an overall aircraft design that provides minimal distinction between wings and fuselage, and fuselage and tail. The blended wing configuration closely resembles a flying wing configuration but concentrates more volume in the center section of the aircraft than does the traditional flying wing.
>
> —*Timothy Risch, NASA Dryden Flight Research Center (DFRC) X-48 project manager*

Dennis Bushnell Poses a Challenge

In the fall of 1988, in a letter inviting McDonnell Douglas representatives and some other interested aeronautical engineers and aerodynamicists to attend a Langley workshop, Dennis Bushnell of the NASA Langley Research Center (LaRC) asked the following question: "Is there an aerodynamic renaissance for the long-haul transport?" Bushnell specifically questioned the evolutionary pace of transport aircraft design, noting that revolutionary development as typified by the Boeing 707 and Douglas DC-8—the first-generation sweptwing jetliners that revolutionized international air commerce—had been succeeded by later designs following a more cautious, incremental, and evolutionary pattern.[1]

Bushnell's challenge initially received a cautious, and even skeptical, reaction from McDonnell Douglas aerodynamicists, who, since the 1930s, had pioneered a "DC Revolution" in aircraft design that had led to such notable—and in some cases, breakthrough—designs such as the legendary DC-3, DC-4, DC-8, and DC-9. However, following a brainstorming session with several aerodynamicists, they conceptualized a three-phased study approach:

- prepare a baseline array of airplanes using both an evolutionary (i.e., derivative) and revolutionary (i.e., breaking with the past) philosophy,
- define a revolutionary design with unconstrained technical optimism, and
- compare the results of the two design approaches.[2]

This was the beginning of the remarkable effort to design, develop, and flight-test the blended wing-body concept.

Responding to Bushnell, in the spring of 1989 almost two dozen leading Government, industry, and academic aeronautical engineers and aerodynamicists gathered at NASA Langley Research Center in Hampton, VA, to discuss possible new aircraft configurations. The attendees represented NASA Headquarters; Langley; NASA Ames Research Center; NASA Lewis Research Center (now NASA Glenn); McDonnell Douglas (now Boeing); Lockheed Georgia; AeroVironment, Inc.; Stanford University; Princeton University; the U.S. Navy; and Systems Technology, Inc.

Bushnell was looking for a revolutionary leap in air transport aerodynamic efficiency, rather than simply another evolutionary step forward as seen since the advent of the jet airliner with Britain's De Havilland Comet in 1949.[3] Indeed, what was surprising was how relatively unchanged jet airliner aerodynamic efficiency had been since the introduction into service of the sweptwing Boeing 707 and Douglas DC-8, which had revolutionized global air travel. A Boeing study tracing jetliner aerodynamic efficiency from the era of the narrow-body 707 and DC-8 through the initial wide-bodies—the Boeing 747-100, Lockheed L-1011, and Douglas DC-10—and on through the second-generation wide-body Boeing 747-400, 767, Airbus A300, and McDonnell Douglas MD-11 found that efficiency, as measured by Mach number times lift-to-drag ratio (expressed as ML/D) was "almost flat."[4]

Most attendees presented their vision of possible new configurations. McDonnell Douglas' Robert H. Liebeck presented the blended wing-body. The Navy's Harvey R. Chaplin presented a symmetric spanloader; NASA Ames' legendary R.T. Jones presented an oblique wing; independent conceptualizer Steve Crow presented his ideas relating to personal air vehicles, and NASA Langley's Werner Pfenninger presented a truss-braced wings configuration. The group then summarized their findings and established priorities for further consideration. The approaches presented by Liebeck, Jones, Chaplin, and Pfenninger were all thought to be "game changers" with major performance improvements. Overall, the workshop was informal, and apparently there was no formal agenda, proceedings record, or written reports ever filed.[5]

Attendees at the spring 1989 NASA Langley Research Center meeting on future aircraft configurations. *First row, left to right:* Bruce J. Holmes, NASA Langley; Richard S. Shevell, Douglas Aircraft and Stanford University; Robert T. Jones, NASA Ames; Werner Pfenninger, NASA Langley; Harvey R. Chaplin, U.S. Navy (David Taylor, Model Basin); and Steve Crow, independent. *Second row, left to right:* Seymour M. "Boggy" Bogdonoff, Princeton University; Coleman D. Donaldson, consultant; Dennis M. Bushnell, NASA Langley; Richard T. Whitcomb, NASA Langley; Hewitt W. Phillips, NASA Langley; Paul McCready, AeroVironment, Inc.; and Ilan Kroo, Stanford University. *Third row, left to right:* Unidentified; Louis Williams, NASA Langley; Randolph A. Graves, Jr., NASA Headquarters; Richard Weldon, NASA Lewis; Duane T. McRuer, Systems Technology, Inc.; Cornelius "Neil" Driver, Boeing; Robert H. Liebeck, McDonnell Douglas (subsequently Boeing); Roy H. Lange, Lockheed Georgia; and Percy J. Bobbitt, NASA Langley. (NASA via Dennis Bushnell)

Aircraft Design: Some Historical Perspective

In a 1988 paper delivered at the Aerospace Technology Conference and Exposition in Anaheim, CA, University of Kansas Professor Jan Roskam addressed the factors and "severe and/or novel design requirements" driving aeronautical engineers to evolve new design concepts. As background for comparison, Roskam defined a "conventional" configuration "as one with which the designer and user community have some degree of familiarity and confidence," adding as an example "the classical wing/fuselage/tail design used by over 90 percent of all airplanes." He pointed out that what engineers consider to be unique "depends to some extent on their background," adding that "[a]fter being around a 'unique' configuration for some time, it ceases to be unique!"[6] He used the Boeing B-47 Stratojet as an example. While its configuration—a

The first production Boeing B-47A Stratojet (SN 49-1900) while on loan to the National Advisory Committee for Aeronautics (NACA) High-Speed Flight Station, Edwards Air Force Base (AFB), CA, for comparative flight trials, in September 1953. Note the six podded jet engines, quickly adopted for large long-range sweptwing jet airliners such as Boeing's 707 and Douglas' DC-8. (NASA)

The Avro Vulcan, a four-engine delta-winged strategic bomber, represented a very different design approach—and, for its time, equally radical—to long-range strategic bomber design from Boeing's B-47. (National Museum of the United States Air Force [NMUSAF]) high-fineness-ratio fuselage combined with a high-aspect-ratio sweptwing and pylon-mounted podded jet engines—made it unique when first flown, the B-47 ceased to be unique after its features became commonplace.

Similar design and mission requirements, however, do not necessarily drive designers toward a single configuration choice. For example, Roskam noted that while the roughly contemporaneous Boeing B-47 and British Avro Vulcan jet bombers were both designed for similar missions, each had a unique configuration, one being a sweptwing aircraft with relatively thin wing and tail surfaces (and podded engines), the other being a thick delta with its engines buried in its wing roots.

Roskam noted further that "when a designer tries to meet certain extreme or novel design requirements with a 'conventional' configuration, it may be that a satisfactory design solution cannot be found. In such a case the result may very well be a 'unique' airplane configuration." This could include the designer confronting various requirements not previously integrated into an airplane design, or the designer facing extreme design requirements that cannot be achieved by a conventional aircraft configuration. (As an aside, the former is exemplified by Robert Woods' Bell XS-1 (X-1), which first exceeded the

The Bell XS-1 (later X-1) no. 1 (SN 46-062) on its historic flight through Mach 1 on October 14, 1947, piloted by Capt. Charles E. "Chuck" Yeager. The air-launched XS-1 had a bullet-inspired shape, thin wings and tail surfaces, a modest aspect ratio, an adjustable horizontal tail, and rocket propulsion. (USAF)

The Lockheed Blackbird, the world's first production Mach 3+ aircraft, represented a radical departure in both configuration and design, and it incorporated blended wing-body shaping that both enhanced its aerodynamic performance and reduced its radar cross-section (RCS). Here is YF-12A SN 60-6936, one of three proposed interceptor variants of this elegant and challenging design. (USAF)

speed of sound in October 1947, and the latter by Kelly Johnson's Mach 3+ Lockheed A-12 Blackbird strategic reconnaissance aircraft.)

Roskam identified six classification requirements driving aircraft design:

1. Mission requirements, consisting of *Performance requirements* (such as payload-range; loiter and/or endurance; speed and altitude; field length for takeoff and landing; climb rate and/or gradient, time-to-climb; acceleration and/or deceleration; and maneuvering); and *Operational requirements* (for example payload type and arrangement; provisions for survivability such as ejection seats and armor shielding; operating surface, for example land, sea, or ice, and flight qualities such as high angle-of-attack capability).
2. Airworthiness requirements (regulations set by government) including:
   - *Performance regulations*, including: minimum speed(s) and reference speed(s); minimum climb rate and/or gradient with all engines operating and with one engine inoperative; and field length for takeoff and landing.
   - *Stability and control regulations*, including: minimum stability and controllability; minimum maneuverability; and stall-spin behavior.
   - *Structural regulations*, including: minimum design load factors; fatigue life; fail safe; crash survivability; and flutter and steady state aeroelasticity.

A McDonnell Douglas MD-11 used by NASA to investigate aircraft control by propulsion lands at Dryden Flight Research Center (now Armstrong) on November 30, 1995. (NASA)

  - *Other regulations* such as: escape and emergency exit regulations; and systems regulations (fuel, electrical, hydraulic, etc.).

3. Environmental requirements (set by the government), including airport and community noise and internal noise; and emissions.
4. Cost requirements (often dictated by the customer), including minimum design and development cost; minimum manufacturing cost; minimum operating cost; minimum life-cycle cost; maximum return on investment; and design to net-worth.
5. Manufacturing requirements (set by the manufacturer and/or the customer), including design to existing manufacturing capability; design to future manufacturing capability; design to existing or new material; and design to minimize parts count and/or minimum throughput time in assembly.
6. Maintenance and accessibility requirements (set by the customer and/or the manufacturer), including engine access and removal requirements; equipment access and removal requirements; and inspectability for cracks in primary structure.[7]

A decade later, Robert H. Liebeck, Mark A. Page, and Blaine K. Rawdon—the three principal developers of the BWB concept that led to the Boeing X-48B Technology Demonstrator—reviewed the evolution in aircraft design, noting a startling break at the mid-20th century. For comparison, they examined the Wright 1903 Flyer, a canard biplane with pusher propellers; the Boeing B-47

Stratojet sweptwing, turbojet-powered bomber; and the McDonnell Douglas MD-11 three-engine wide-body jetliner (an outgrowth of the earlier DC-10).

Looking just at these three examples, it was clear that in the four decades following the 1903 Wright Flyer, airplane design had radically changed, going from the era of the externally braced wood, wire, and fabric biplane to the all-metal, propeller-driven monoplane; and thence on to the era of the jet-propelled, sweptwing transonic airplane with external podded jet engines, exemplified by the B-47, which first flew on December 17, 1948, ironically the 45th anniversary of the Wrights' first flights at Kitty Hawk, NC.

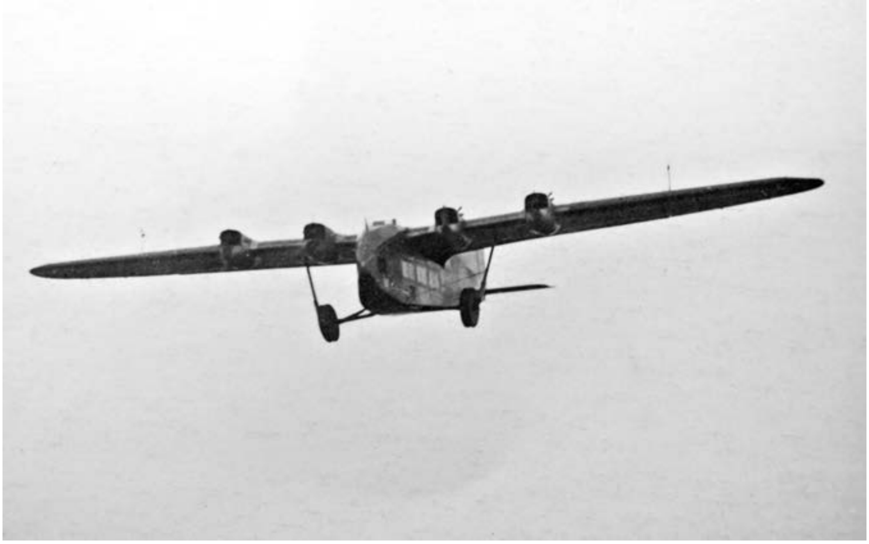
But in the four decades after the B-47, few if any configuration changes to large jet airliners had occurred; rather, aircraft as varied as the Boeing 767, the MD-11, and the Airbus A300 still largely emulated features introduced with the B-47, leading Liebeck, Page, and Rawdon to conclude that "embodied in the B-47 are most of the fundamental design features of the modern subsonic jet transport: swept wing and empennage and podded engines hung on pylons beneath and forward of the wing."[8]

The Allure of the Gigantic

During the early 1990s, the global aerospace community debated the case for very large passenger aircraft, possibly capable of carrying up to 800 passengers, effectively doubling the capacity of conventional wide-body aircraft of the time. As summarized by Boeing senior engineer John H. McMasters and Stanford University professor Ilan Kroo in a seminal 1998 American Institute of Aeronautics and Astronautics (AIAA) paper, industry engineers asked:

- How much larger can practical passenger airplanes of the sweptwing tube-and-wing 707/747 configuration be?
- What alternatives exist for going beyond this configuration?
- What existing or innovative technological elements might be synergistically integrated "to resolve or ameliorate very large subsonic airplane problems?"[9]

This steadily growing interest in larger aircraft followed upon progressive evolution of existing "jumbo" aircraft of the 1980s that resulted in the Boeing 747-400 (which made its first flight on June 30, 1989); the continued refinement of the U.S. Air Force's Lockheed C-5 Galaxy airlifter (first flown on June 30, 1968), which could carry over 130 tons of cargo; the even larger Ukrainian Antonov An-124 *Ruslan* (first flown on December 26, 1982), which could carry over 165 tons of cargo; and the larger still Antonov An-225 *Mriya* (first flown on December 21, 1988), which could carry an incredible 275 tons of cargo. And, of course, there was the gigantic double-deck, 850-passenger (in all-economy seating) Airbus A380 (the development of

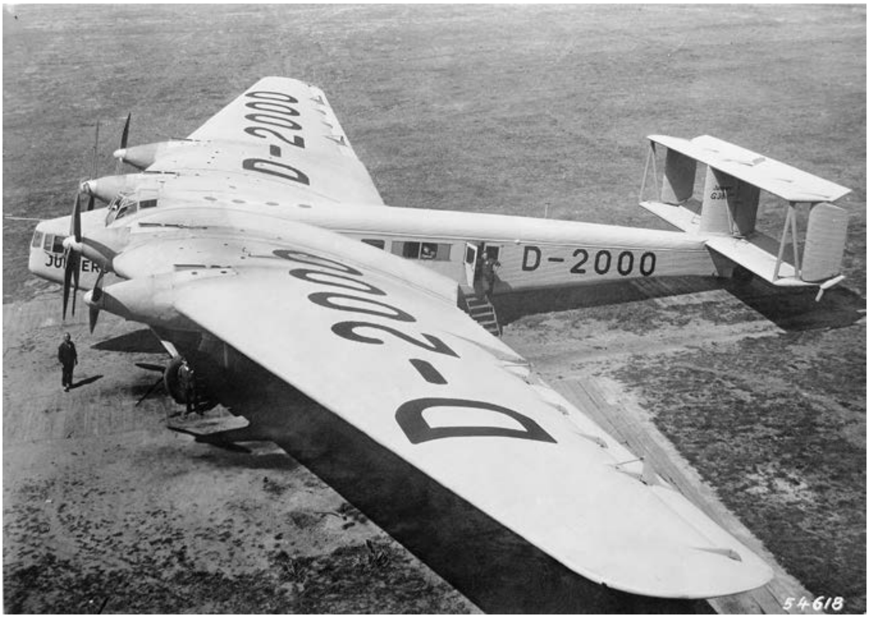


Adolf Rohrbach's astonishing E.4/20 of 1920—which flew just 17 years after Kitty Hawk—featured advanced aerodynamic shaping, a broad-span cantilever wing, and all-metal structural design, thus anticipating air transports of the 1930s. Sadly, Allied occupation authorities ordered its destruction. (Library of Congress)

which began in 1988), which made its first flight in 2005 and entered airline service in 2007.[10]

"Each of these giants [was] a reasonable evolutionary extrapolation of the basic configuration for such aircraft established fifty years ago by the Boeing B-47 bomber and characterized by a cylindrical fuselage mated to a high-aspect-ratio wing with pod-mounted engines distributed across its span and an aft-mounted empennage," wrote McMasters and Kroo, noting, "Everything else being equal, the economics of flying devices tend to improve in direct proportion to their increasing size," and asking pointedly, "Is this basic, fifty-year-old configuration paradigm really the appropriate (or best) one for an airplane substantially larger than a 747?"[11]

Actually, this fascination with "bigger is better" was nothing new in aeronautics and represented instead the latest resurgence of interest in aircraft much larger than contemporary practice. In the interwar years, building on a wartime fascination with *Riesenflugzeuge* ("Giant Aircraft"), German designers Adolf Rohrbach, Hugo Junkers, and Claude Dornier built what were, in their time, the largest passenger airplanes in the world: the four-engine Zeppelin-Staaken E.4/20 and Junkers G 38 landplanes, as well as the 12-engine Dornier Do X flying boat.



The four-engine Junkers G 38 of 1929 was an early attempt to develop a BWB airliner; while visually impressive, it was underpowered and not a great success. (Library of Congress)

Rohrbach's streamlined 18-passenger E.4/20 of 1920, a brilliant all-metal cantilever design, was well over a decade in advance of the contemporary aeronautical state of the art and might have dramatically transformed the interwar history of air transport save for having been destroyed by the vindictive Inter-Allied Aeronautical Control Commission, then determined to suppress German aeronautics. Though imaginative, neither the later G 38 nor the Do X was a great success, though, interestingly, with its very thick cantilever wing, the G 38 constituted an imperfect attempt to achieve a blended wing-body configuration reflecting Junkers' personal interest in eventually developing pure *nurflügel* ("wing only," i.e., flying wing) aircraft.

After the Second World War, various American and British manufacturers contemplated equally unsuccessful behemoths, most notably the Air Force's Consolidated Vultee XC-99 (a two-deck cargo and passenger derivative of the B-36 bomber), the Navy's Lockheed XR6O-1 Constitution (another double-deck design), and Britain's eight-engine (in four paired units) Bristol Brabazon.

The 1960s and 1970s brought the wide-body airlifter and jetliner, made possible by the development of the powerful high-bypass-ratio turbofan engine. First was the Lockheed C-5A Galaxy, which flew in 1968; the next year brought the Boeing 747-100, the world's first civil wide-body jetliner. Both entered

Convair designed the six-engine XC-99—essentially a large-capacity fuselage grafted onto the wings and tail surfaces of the company's B-36A bomber—to meet anticipated postwar military and civil transport needs. But the military and civil market envisioned for such a gigantic aircraft never materialized, and thus only one ever flew, serving with the Air Force into the mid-1950s. (Air Force Flight Test Center History Office)

Lockheed hoped that its four-engine XR6O-1 Constitution, another giant of its time, might secure airline orders, but only built two, both briefly flying for the Navy. Here is one at a postwar air show held at California's Alameda Naval Air Station in 1949. (Naval History and Heritage Command)

Bristol hoped that its massive Type 167 Brabazon airliner, an eight-engine design (two coupled engines in each of four nacelles) would regain postwar British leadership in civil aeronautics. But the plane proved too large and expensive to compete with cheaper and more plentiful American aircraft such as the Lockheed Constellation, Boeing 377 Stratocruiser, and Douglas DC-4. First flown in 1949, the Type 167 met an ignominious fate, going to the scrappers in 1953. Here it is at the September 1950 Society of British Aircraft Constructors (SBAC) show at Farnborough, dwarfing all other aircraft around it. (Photograph courtesy of Nick Stroud and *The Aviation Historian* quarterly journal)

service in 1970, quickly revolutionizing global military and civil air mobility. The 1980s brought the Antonov An-124, and the turn of the century witnessed the advent of the world's largest passenger jetliner, the 850-passenger (if using all-economy seating) Airbus A380, which had fully 50 percent greater internal floor space than the 747, though it subsequently found few airlines receptive to operating such a giant.

Since the A380, interest in building "mega" airplanes has declined due to an uncertain market and the likely significant developmental and operational costs for such aircraft. In the case of Boeing, its leadership downsized studies for an 800-passenger blended wing-body in favor of a 450-passenger one, as subsequently discussed in chapters 2 and 3. Still later, it emphasized the BWB as a cargo carrier or refueling tanker rather than as a passenger airliner.

The Lockheed C-5A Galaxy has been the mainstay of U.S. heavy military airlift since the Vietnam War and played a decisive role in saving Israel from catastrophic defeat in the 1973 Yom Kippur War. Here is a C-5A (SN 70-0451) of the Air Force Reserve Command's 433rd Air Mobility Wing delivering humanitarian relief to Honduras in November 2015. (USAF)

The Boeing 747 revolutionized civil air transport, launching the age of mass (and relatively cheap) global air transport. Here is NASA 905 (N905NA), an ex–American Airlines 747-100, that NASA acquired as a mother ship aircraft for the Rockwell Space Shuttle Orbiter *Enterprise*'s Approach and Landing Tests (ALT). Before those, however, it flew on a highly significant air safety investigation of trailing vortices and their impact on following airplanes. It is shown flying on one such trial in 1974. (NASA)

Ukraine’s Antonov An-124, once the largest airlifter serving the former Soviet military, now furnishes contract heavy airlift around the world, even to former rivals. Here one departs Moffett Federal Airfield (formerly Moffett Naval Air Station) with urgent cargo for Afghanistan in April 2007. (USAF)

The Airbus A380, a truly gigantic aircraft, entered civil airline service in 2007. Though praised by passengers, it has not achieved the widespread airline adoption its supporters envisioned. Here is Lufthansa’s A380-800 (D-AIMA) *Frankfurt-am-Main*, photographed at Frankfurt airport in August 2013 after having flown from America. (Richard P. Hallion, hereafter RPH)

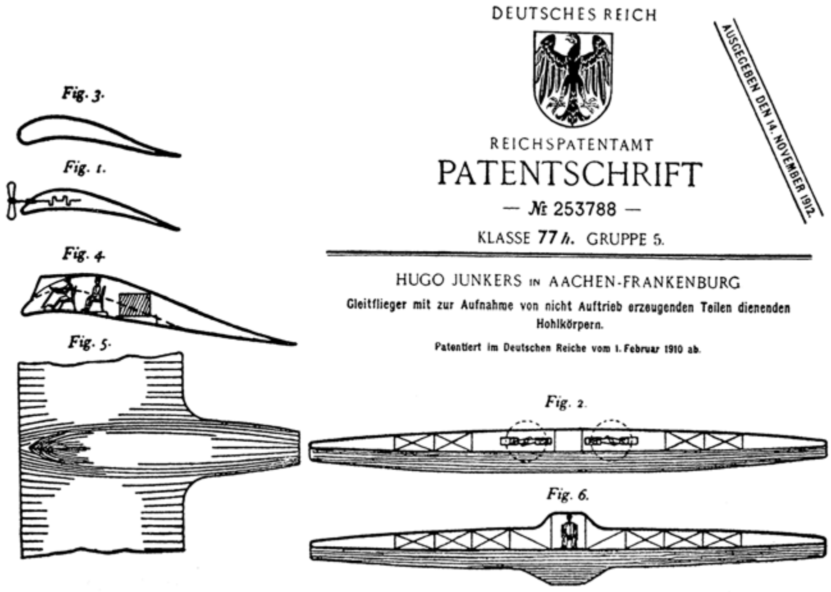
Flying Wings, Tailless Aircraft, and Notable Influences on the BWB

To the untutored eye, blended wings, flying wings, and tailless aircraft might seem identical. In fact, they are technological cousins, not siblings. Thus, while the Boeing team conceded that the blended wing-body is "an offshoot of a popular concept called the flying wing," they also pointed out some important differences.

Robert Liebeck noted that "[f]lying wings, whether they're swept or unswept, look a lot like a big plank [but] Blended Wing-Body airplanes have a center similar to the fuselage of a traditional airplane."[12] Accordingly, a BWB airplane configuration falls between a classic tube-and-wing (for example, a Boeing 787) and the flying wing (for example, the Northrop Grumman B-2A Spirit stealth bomber).

Technically, the flying wing and blended wing are both "spanloaders," that is, the flight loads of the aircraft are distributed across the span, from wingtip to wingtip, not shared with a fuselage and tail group.

The idea of the flying wing, or tailless airplane, dates to the earliest days of aviation.[13] Germany's Hugo Junkers envisioned as early as 1910 a pure



DEUTSCHES REICH

REICHSPATENTAMT

PATENTSCHRIFT

— № 253788 —

KLASSE 77 *h*. GRUPPE 5.

AUSGEGEBEN DEN 14. NOVEMBER 1912.

HUGO JUNKERS IN AACHEN-FRANKENBURG

Gleitflieger mit zur Aufnahme von nicht Auftrieb erzeugenden Teilen dienenden Hohlkörpern.

Patentiert im Deutschen Reiche vom 1. Februar 1910 ab.

In 1910, Hugo Junkers—best remembered for his succession of corrugated-skin all-metal transports—patented a pure flying wing design concept. Note the buried engines and cabin. (Library of Congress) all-wing, all-metal cantilever design with engines and crew "buried" within the wing itself.

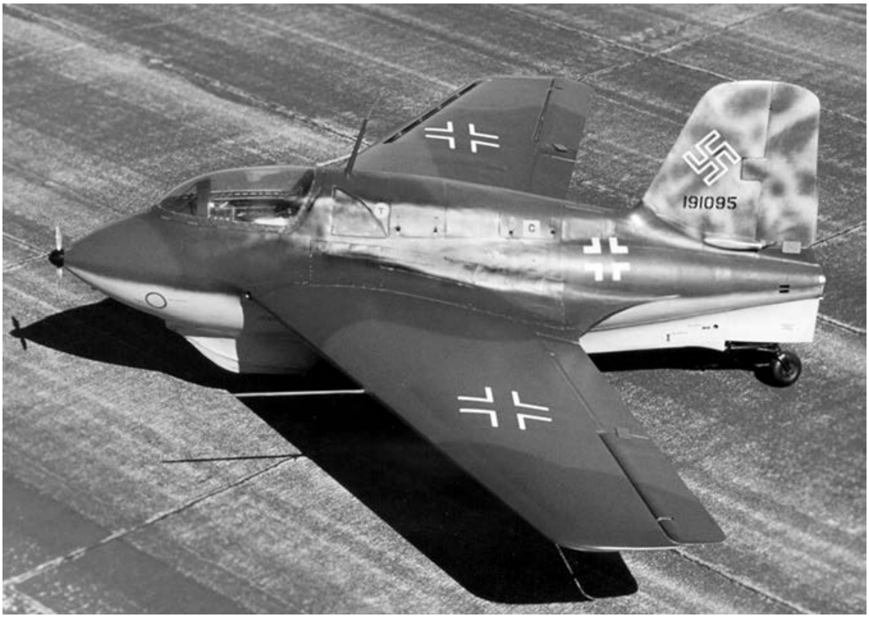
Early experimentation by Scotsman John William Dunne led to Anglo-American tailless gliders and powered "pusher" biplanes, several of which served the American military in training and familiarization roles at the time of the First World War.

In the 1930s, pioneers in various countries experimented with tailless aircraft, using modestly sweptwing planforms to impart a degree of self-correcting longitudinal stability. Most notable of these were Germany's Alexander Lippisch and brothers Reimar and Walter Horten; between Lippisch and the Hortens, Lippisch was most successful, his ideas culminating in the wartime tailless sweptwing Messerschmitt Me-163 *Komet* rocket-propelled fighter, a flashy, highly dangerous, and ultimately ineffectual warplane.

Attempts to develop generally similar designs for military fighters and cruise missiles after the Second World War generally met with disappointment or outright failure.

During the 1950s, various manufacturers proposed large delta-wing or pure flying wing air transports, but in every case authorities rejected these in favor of more conventional wing-body-tail designs. Best known are the small and large flying wings of John Northrop, culminating in the giant XB-35 four-engine piston-powered flying wing and its jet-powered derivatives, the eight-engine

An American Burgess-Dunne AH-7 Flying Wing trainer at Pensacola Naval Air Station circa 1916. Though pleasant to fly, the Burgess-Dunne designs in Navy (and Army) service did not enjoy great success and were replaced by more conventional biplane designs. (Naval History and Heritage Command)



A rocket-propelled Messerschmitt Me 163B-1 *Komet* (Werk Nr 191095) interceptor captured at the end of the Second World War and now on display at the National Museum of the U.S. Air Force. Already hampered by a limited fuel supply that constrained its flight duration and, hence, operational value, the *Komet* had serious transonic buffeting and trim changes that, together with dangerously unstable hypergolic (self-igniting) propellants, made it more dangerous to the pilots who flew it than to Allied airmen. (USAF)

At the time of its first flight in 1948, the Vought XF7U-1 Cutlass (BuNo 122472), a twin-engine sweptwing tailless fighter (shown at the NACA's Langley Memorial Aeronautical Laboratory, later NASA Langley Research Center, in December 1948) seemed highly promising. But in naval service, production Cutlass fighters proved disappointing and dangerous, and they soon disappeared, replaced by conventional designs. (Naval History and Heritage Command)

First flown in October 1947, the Northrop YB-49A experimental jet bomber exemplified the classic pure flying wing even more than its later stablemate, the contemporary Northrop Grumman B-2 Spirit stealth bomber. Unlike the fly-by-wire B-2, however, the YB-49 manifested serious performance, stability, and control limitations, which, together, contributed to the loss of the second prototype in June 1948. Here is the first YB-49A (SN 42-102367) at Northrop's Hawthorne, CA, plant, on December 23, 1948. (USAF)

YB-49 and six-engine YRB-49 of the late 1940s and early 1950s. A variety of deficiencies, along with their basic unsuitability for military service, resulted in the cancellation of military production contracts and plans to build a large passenger-carrying wing with the passengers located within the wing rather than a conventional fuselage, as well as various concepts for freight- and cargo-carrying flying wing logistical transports.[14]

All of these latter aircraft suffered from degraded performance as they entered regions of compressible flow, which led to mission-limiting, and in some cases dangerously divergent, longitudinal pitching, accompanied by combined roll-yaw directional instability. Only after the advent of digital electronic flying control technology was it possible to damp divergent motions rapidly enough to permit the design of practical transonic flying wing aircraft, exemplified by the Northrop (later Northrop Grumman) B-2A Spirit stealth bomber, which made its first flight in 1989, followed by introduction into operational service in 1997.

Since the time of the B-2A, other countries have designed and flown smaller fly-by-wire-dependent "drone" flying wings for various military purposes.

The first Northrop B-2A Spirit stealth bomber (SN 82-1066), whose first flight in 1989 heralded the age of the practical transonic flying wing. (USAF)

Even so, given their long history of development, few tailless aircraft of flying wing, blended wing, or just wing-body combinations have flown. "One may be puzzled by the fact that we see so few tailless airplanes," Ilan Kroo has written, adding:

> Although the tail[s] of commercial transport aircraft constitute 25–35 percent of the wing area and pushes down with as much as 5 percent of the aircraft weight (~100 passengers with baggage), the horizontal tail has remained a prominent feature of modern aircraft design and despite over thirty years of technical progress, the 707, rolled out in about 1954[,] and the A340[,] first flown in 1991, look very similar. This is not simply a reflection of aircraft manufacturers' conservatism, but an indication of the fact that horizontal tails are an efficient means of satisfying the requirement for longitudinal trim and control.[15]

The advent of practical computer-controlled flight removed the major obstacle to the development of large flying wings, other spanloader designs, and, particularly, blended wing-bodies. As Daniel P. Raymer has written:

> The Blended Wing-Body is basically a flying wing with a delta-shaped wing/fuselage in the center, large enough for a passenger cabin [and] the center section is blended into the wing panels. This concept reduces the total wetted area [the area of the aircraft in contact with the external airflow] of the airplane and, with its deep center section, improves structural efficiency. The BWB has about half of the root-bending stresses of a conventional configuration. The wing-tip mounted vertical tails also act as winglets to reduce drag due to lift. BWB requires relaxed static stability and an automated flight control system to fly efficiently, optimize span loading, and avoid the need for a tail. The BWB optimizes at a wing loading of about 100-psf (488 kg/sqm), much less than the 160-psf (781 kg/sqm) of most airliners….[16]

Blaine K. Rawdon, Boeing Technology Fellow and one of the three principal formulators of the BWB concept, noted that "[c]ontrary to what one might expect, when we get a new project we don't go and research all of the relevant airplanes to understand them and use them as a foundation. A better analogy, for me at least, would be that everything we have ever seen…is dumped into a big stew in the backs of our heads. Some of us store this as pictures, some as numbers, some as relationships between geometry and numbers. So when we start a new airplane we rummage around in the stew for a place to start."[17]

Rawdon noted that two of the airplanes in the "stew" were John Northrop's flying wing and Robert Jones' oblique airplane concept. Both the flying wings and the oblique wing, however, were unsuitable for commercial airliners because they both suffered from the same problem—insufficient passenger headroom. Another airplane in the "stew" was the Canadian Car and Foundry-Burnelli CBY-3, an abortive twin-piston engine design from the mid-1940s that Rawdon saw in the New England Air Museum at the Windsor Locks, CT, airport. Designed by Vincent Burnelli (an early pioneer who worked on the fringes of the mainstream aeronautical industry, notably with two remarkable eccentrics—Alfred Lawson and William Christmas) for cargo operation, the CBY-3 built on earlier Burnelli work to manufacture aircraft with lifting fuselages that would augment the lift produced by their wings. It had twin booms with a cowled radial piston engine at the front, tapering aft of the wing trailing edge into a very thin vertical cross-section that became the craft's twin vertical fins and rudders. The horizontal tail, in the fashion of Lockheed's P-38 Lightning, joined the vertical fins together, with a portion of the horizontal tail extending beyond the boom. Outboard of each boom was a smoothly tapered conventional wing, while between them was an almost grotesquely thickened airfoil-profile center-section that doubled as its fuselage, cabin, and cockpit.[18]

The Canadian-built CCF-Burnelli CBY-3 Liftmaster, shown here at Baltimore's Friendship Airport in May 1961, attempted to gain the benefits of a blended wing-body design by having wings attached to a fuselage shaped like a very thickened airfoil. Despite the seeming logic of the idea, the drastically differing lift-and-drag properties of the thin-wing/thick-fuselage combination negated any benefit, and the CBY-3 never saw production, though it flew for nearly two decades. (American Aviation Historical Society)

The sole CBY-3 flew in 1944, and thereafter operated off and on until the early 1960s. However, as Rawdon added tellingly, "although this airplane was in the stew it was more an example of what not to do," being a "non-starter due to the severe discontinuity in lift distribution—this is very inefficient." Rawdon also acknowledged that the British Avro Vulcan bomber was, likewise in the mix.[19]

There were also two Douglas precedents for the team's work. Designed by a team led by Derek MacWilkinson and Richard Cathers, one was a very-high-aspect-ratio flying wing with a body in the center. The judgment of the BWB team was that this airplane "had way too much aspect ratio (long skinny wings) and that the concentration of the payload at the center did not take advantage of span-loading [distribution of the payload weight in spanwise direction with the benefit of reducing wing bending moment and wing structural weight]. In addition, the configuration had much smaller passenger capacity than the BWB team desired. The second Douglas project was a NASA-funded hydrogen-powered flying wing study for which Rawdon did the configuration work, though he subsequently noted that the design "ended up looking somewhat like the Space Shuttle with way too little aspect ratio."[20]

Evolutionary and Revolutionary Development—The First-Phase Study

Following the NASA Langley meeting, McDonnell Douglas received a $90,000 NASA contract to conduct a very preliminary study. The study compared both evolutionary and revolutionary airplane design concepts to answer Dennis Bushnell's challenge. This was the start of what became the X-48 program. Jerry T. Callaghan, Manager of Product Definition for the MD-12X program, and Robert H. Liebeck, a McDonnell Douglas Technical Fellow, summarized their study results in a paper presented at the Aerospace Technology Conference and Exposition in October 1990. Callaghan and Liebeck stated at the start of their presentation that the "classic aerodynamic figure of merit for a subsonic transport airplane is Mach number times lift-to-drag ratio [adding that] advanced airfoils, a high aspect ratio, advanced high-lift systems, and boundary-layer modifiers such as laminar flow control (LFC) and riblets [imply] an all-new airplane—even if it is a conventional/evolutionary configuration."[21]

The two aeronautical engineers started their performance improvement analysis by examining the evolutionary derivative approach to the development of large transport aircraft using the DC-10 as the baseline for comparison purposes. This baseline was used to compare three successive derivative options and then to address revolutionary as opposed to derivative configurations. The first comparison was between the baseline DC-10 and the follow-on MD-11. Callaghan and Liebeck noted that aerodynamic changes for the MD-11, including the modification of the wing's trailing-edge camber,[22] the addition of winglets, and a smaller advanced aerodynamic horizontal tail, resulted in a significant reduction in wetted area (hence producing a notable reduction in form drag), along with a fuel management system that reduced trim drag. Also, the MD-11 had advanced technology engines, a new cockpit with a flight crew of two instead of the three required for the MD-10, and an 18.6-foot fuselage extension. These changes increased payload (62 more passengers) and range (by 1,200 nautical miles) and resulted in a 33-percent reduction in fuel burn per passenger. Callaghan and Liebeck concluded that "this is a vivid (and real) example of why derivative airplanes are so popular."[23]

Next, Callaghan and Liebeck examined the evolutionary change that could result from taking the MD-11 up to a Super Stretch Advanced Derivative (AD) configuration with an all-new wing and high-lift system. This new wing would have an aspect ratio of 11, as well as advanced airfoils that would increase the cruise speed to Mach 0.85. The AD configuration also included the possible use of a laminar flow control boundary-layer modifier and Very-High-Bypass-Ratio (VHBR) engines. The changes increased the design range to 8,500 nautical miles and the payload to 368 passengers (a 30-percent increase). Callaghan and Liebeck pointed out, however, that the changes would result in a takeoff gross weight increase to 738,000 pounds. The improved performance would be due primarily to the new wing and the increased size of the aircraft. They added that this would not be a high risk technologically. A higher degree of risk would probably occur with improvements resulting from LFC and riblets and that the VHBR engines could be 10 years away from being operational.[24]

The final derivative configuration addressed in the evolutionary chain was the Synergistic Technology Transport (STT) that used a "synergistic combination or all technologies that were envisioned to be available in the year 2000," as shown in the following table:[25]

Table 1-1. Synergistic Technology Transport (STT) Improvement Percentages Reflecting Advanced Technology

Technology	Percentage of Improvement
Aerodynamics (Lift/Drag) • High aspect ratio, turbulent drag reduction, etc.	35
Propulsion (Specific Fuel Consumption, SFC) • VHBR, materials, aerodynamics, etc.	40
Propulsion (Weight) • Improved materials	20
Structural (Weight) • Improved materials	40
Systems (Weight)	
• Distributed avionics (using optics)	50
• Hydraulics	25
• Mechanical controls	80
• Environmental (ducts, pumps/auxiliary power units [APU])	65
• Landing gear	10
• Furnishings	15
• Operating items	10
Maintenance	25

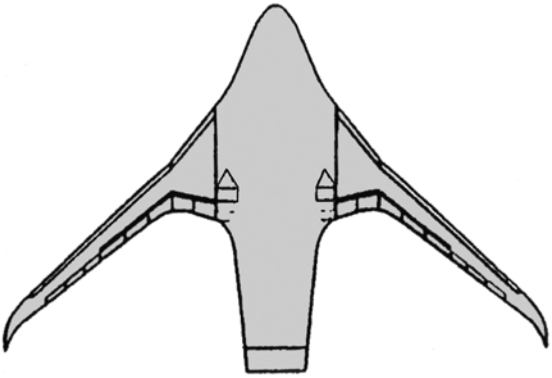
Note: Measures of merit are in parentheses after each technological element.

Callaghan and Liebeck found that realizing improved performance, together with sizing the STT airplane for the same payload and range as the Advanced Derivative aircraft, "yield[ed] somewhat spectacular results" and added:

> This is a vivid example of the effects of combining technological advances—a nonlinear result in, for once, a very positive direction. One might well be skeptical as to whether this performance could be achieved by the turn of the century. Developing an airplane that offered half of the performance increments would be remarkable…. Referring to the STT as a derivative may be regarded as stretching the definition of that class of airplane development. However, it certainly qualifies as evolutionary. At the airport, it would be indistinguishable from a 30-year[-]old DC-10 with a fresh paint job to the average person.[26]

They next directly addressed Dennis Bushnell's challenging question—"Is there an aerodynamic renaissance for the long-haul transport?"—by examining a blended wing-body spanloader concept utilizing an extension of the B-2 stealth bomber technology, assuming that technology base would be well established by the turn of the century. The proposed configuration concept, designated as the MD-BWB, called for a fully augmented control system and two VHBR engines embedded within the wing-body structure. The BWB airplane was sized for the same mission as the AD and STT evolution concepts reviewed above. Laminar flow controls and riblets were included on both the upper and lower surfaces of the aircraft.[27]

Callaghan and Liebeck concluded their initial study by noting that "[t]he airplanes that resulted from both concepts [evolutionary and revolutionary] offered performance improvements over existing transport airplanes which



The initial blended wing-body concept sketched out by Dr. Robert H. Liebeck and colleagues at McDonnell Douglas following the NASA Langley design workshop triggered by Dennis Bushnell's challenge to make revolutionary, not evolutionary, advances in transport configuration design. It was this shape, offering to raise transport lift-to-drag ratios from 17 to near 28, that catalyzed NASA's interest in the BWB configuration. (NASA)

Table 1-2. The Synergistic Technology Transport (STT) Compared with the MD-BWB

Characteristics	STT	Blended Wing-Body
Design in Nautical Miles	8,500	8,500
Passengers	368	368
Cruise Mach	0.85	0.85
Engines	3 VHBR engines	2 VHBR engines
Thrust (each)	30,600 pounds	30,900 pounds
Wingspan	188 feet	260 feet
Length	236 feet	167 feet
Wing Area	2,020 square feet	4,500 square feet
Aspect Ratio	17.5	15.0
Total Weight	367,200 pounds	338,800 pounds
Operating Empty Weight	192,700 pounds	195,300 pounds
Lift/Drag	23.1	33.3
Fuel Burn Per Seat at 3,000 Nautical Miles	Base	–25.7 percent

support a definite 'yes' to the NASA question" and that, based on this very preliminary study, a potential exists for an aerodynamic renaissance for the long-range subsonic airplane. Furthermore, they added that substantial aerodynamic improvement is "clearly demonstrated" for the Advanced Derivative and the Synergistic Technology Transport configurations and, by extrapolation, the MD-BWB configuration. In addition, combining these improvements with the "projected improvements offered by the other technologies has shown that a revolutionary improvement in airplane performance could be available shortly after the turn of the century."[28]

However, Callaghan and Liebeck advised that, while they had illuminated the potential benefit from the blended-wing configuration, "the depth of the present study was insufficient to offer this result with a high level of confidence [but that] various classes of revolutionary configurations should be examined in future, more thorough studies."[29] Indeed, they offered an additional note of caution regarding evolutionary versus revolutionary airplane development, at least for the near term:

> The market demand for large transport airplanes is projected to grow well beyond the turn of the century. Thus, it is likely that the

> evolutionary development cycle will prevail. The results could still be quite spectacular as indicated by the STT. Technical progress will be paced by return on investment commercially, the perceived military threat, and environmental and energy requirements. As mentioned earlier, the environmental and energy requirements may initiate serious development of the revolutionary configurations.[30]

They also conceded that incorporation of new technologies required for a new airplane would represent a substantial cost, estimated as being in the range of $4 billion (in 1990 dollars) with a total "cash bucket" in excess of $6 billion in 1990 monies. They added that cost "is one of the reasons that derivatives of existing airplanes are so popular. New technology must provide required capability and it *must* [emphasis in original] be guaranteeable. Clearly, cost is the fundamental consideration."[31]

While they selected the BWB concept for this study, Callaghan and Liebeck recognized R.T. Jones' oblique-wing concept (demonstrated by the NASA Ames-Dryden AD-1 Oblique Wing testbed), which was one of the designs considered at the 1989 Langley workshop, noting:

> Another candidate [for revolutionary airplane development] would be R. T. Jones' classical yawed wing-concept. Future environmental and energy considerations may point to the use of liquid hydrogen fuel, and both the Blended Wing-Body and the yawed wing could become even more attractive.[32]

While Blaine Rawdon agreed that the oblique all-wing configuration was "in play" at the start of the BWB program, a 1994 NASA-sponsored study that Rawdon directed found that the oblique all-wing concept had a "fundamental conflict between the passenger's desire for headroom and the airplane's desire to be thin (shallow) and high aspect ratio. The square cube law[[33]] favored very big versions of this airplane," but the point at which it started to look good was too big compared to the BWB, so Boeing did not pursue the oblique all-wing concept. The BWB, instead, solved the passenger problem by "making the payload region thick with a lot of chord and mak[ing] everywhere else as slender as possible."[34]

The Key BWB Concept Developers

The three aeronautical engineers generally credited as the principal developers of the blended wing-body concept that led to the X-48 BWB airplane are Robert H. Liebeck, Boeing Senior Technical Fellow; Blaine K. Rawdon, Boeing

The diminutive Ames-Dryden AD-1 Oblique Wing Testbed (NASA 805) demonstrating controlled flight at 60-degree wing sweep during a 1980 research mission. (NASA)

Technical Fellow (advanced design); and Mark A. Page, Chief Scientist, Swift Engineering and formerly with McDonnell Douglas.

All three worked on the development effort as a very close team working at one location at McDonnell Douglas. Liebeck and Rawdon transferred to Boeing following the August 1997 merger of the two companies. While the three worked as a team, each had a primary specialty area. Liebeck served as the team lead specializing in research aerodynamics and airplane design and, according to Rawdon, provided the "big picture view and made the large-scale decisions." Page's specialty was aerodynamic stability and control, as well as sizing, performance, and Multidisciplinary Design Optimization (MDO). Rawdon's specialties were overall configuration, system architecture, drawing, and integration. Rawdon described the working relationship as follows:

> My mode of operation was to work at the CAD [computer-aided design] tube and develop the airplane's form. Bob and Mark would frequently come by and provide welcome guidance. Drawings were plotted and distributed for analysis.... In the early stages of design, [a] team is very small—just a few people—and the integration is tight and boundaries between disciplines are porous. The team was of Douglas Aircraft Company heritage. Its

> culture is open and honest. Technical arguments were common but not acrimonious. Such arguments are very helpful in getting to the core of an issue and forming a solution.[35]

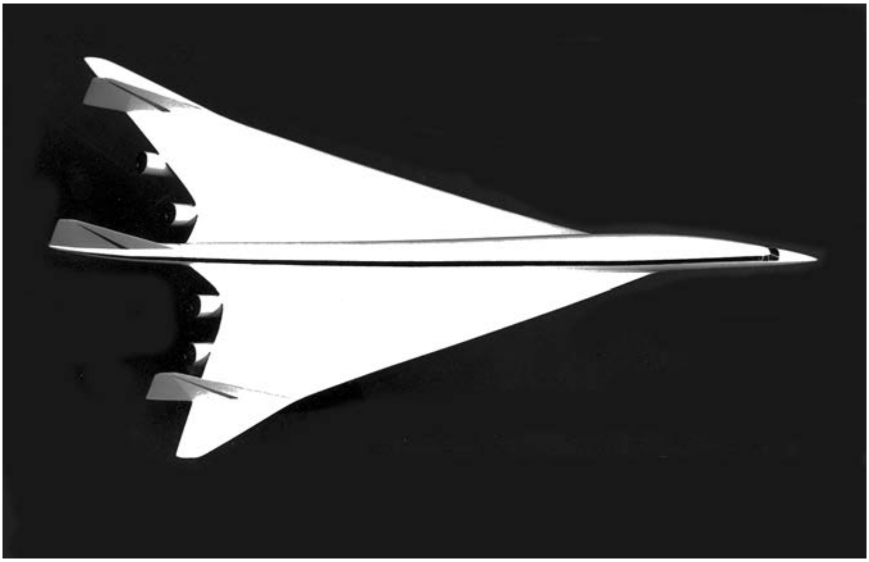
The AIAA 1998 Dryden Lecture: Bushnell Updates His Challenge

Writing nearly 10 years after issuing his challenge to develop a new configuration, Dennis M. Bushnell, by then NASA Langley's Chief Scientist, noted in his 1998 Hugh L. Dryden Lecture to the American Institute of Aeronautics and Astronautics that much of the progress in the previous 50 years had been made under the "dominant metric of higher, faster and larger is better and [had been] a continuation of aeronautical developments since the early 1900s." He added, however, that today and for the foreseeable future the "new" metrics would include "AFFORDABILITY (initial, life cycle), productivity (aircraft, air space), safety and environment (noise, pollution)."[36]

Bushnell added that the reasons for this were increasing global economic competition, increasing demand for shorter-term air travel, increasing environmental regulations, and the increasing (if just emerging) competition from the telecommunications revolution "wherein business travel in particular may become increasingly replaced by 'virtual' interpersonal interaction via (eventually) 3-D technology."[37]

Satisfying these metrics, he said, "almost universally involve[s] incremental/evolutionary technological improvements to the existing paradigms coupled with revolutionary reductions in design cycle time and 'manufacturability' improved in the context of an 'integrated product team.'" What was missing from these approaches "are any major attempts to satisfy these metrics via the complementary approach of inventing, developing, and deploying farther term/advanced technologies, in particular advanced configurations or systems, with revolutionary performance improvements."[38]

Importantly, Bushnell added that as of 1997, "much of the major aeronautical improvements over the past 40 years, particularly in the long-haul arena, has been the result of propulsion technology, primarily higher bypass and turbine inlet temperature, which provided much of the technology for the near tripling of seat miles per gallon." Missing from these efforts, for the most part, have been the in-depth investigation and implementation of advanced configuration concepts. He qualified this statement by noting that the "military has been much more proactive in this regard." Bushnell then presented some examples of advanced concept approaches that could "provide revolutionary changes and opportunities," adding, however, that there are no "magic bullets"—meaning concepts that "require no R&D, have no problems, require no research and provide guaranteed (huge) benefits."[39]



NASA's SCAT family of possible configurations for SSTs included some remarkably futuristic shapes. Here is SCAT 15F, which, while not a blended wing-body in the fullest sense, incorporated elements of body blending with an elegant cranked-arrow delta planform. (NASA)

By comparison, in an earlier 1960s NASA study program for Supersonic Commercial Air Transports (SCAT), Agency personnel examined over 20 new configurations, including some with blended wings. As noted by former Langley historian James R. Hansen, "Nearly everybody who had been thinking about the SST [Supersonic Transport] had their own prized aerodynamic shape to champion: fore and aft tails, outboard tails, canards, fixed-delta and double-delta wings, arrow wings, cranked or M-shaped wings, blended wing-fuselage combinations, all manner of translating and variable-sweep wings, and much more."[40] Each of the proposed SCAT designs had a number. SCAT 15, Hansen noted, "was an innovative 'blended wing' concept developed by A. Warner Robbins, an aerodynamicist in Langley's Low-Speed Tunnels Branch…. It was an especially intriguing configuration because it was a direct outgrowth of the new high-speed digital computer integration program developed by Boeing and NASA."[41] This was, of course, very different from the kind of shaping pursued later for the blended wing-body.

The National Research Council Vision 2050 Study

At the request of NASA and the Federal Aviation Administration (FAA), the National Research Council (NRC) established the Committee on Aeronautics Research and Technology for Vision 2050 to assess the long-term visions and technological goals for U.S. civil aviation. The committee issued a letter report on August 14, 2002, and a full report in 2003, concluding that aircraft performance was critical in achieving necessary improvements in the air transportation.

The committee identified significant measures of aircraft productivity, for example multiplying an aircraft's payload by block speed (the average gate-to-gate speed) and calculating the ratio of productivity to maximum takeoff weight (MTOW), with gains in design efficiency being reflected in lower MTOW. They also identified other productivity and efficiency factors, including aircraft availability (the daily, weekly, or monthly average number of operating hours), utilization time (actual number of hours that a particular aircraft is operated), and operational range and fuel consumption. The committee noted that advances in aerodynamics, materials, structures, and "other disciplines that improve performance parameters such as lift-to-drag (*L*/*D*) ratio, ratio of empty weight to MTOW, and specific fuel consumption" could greatly improve aircraft productivity and efficiency. Technological approaches to achieve the above goals included "the use of boundary layer control to reduce profile drag and parasite drag and the use of new materials, such as modern carbon-based or metal matrix composites, to reduce structural weight fraction."[42]

The committee concluded that aircraft performance through 2025 should involve research leading to continued evolutionary improvements in aircraft performance. However, looking to 2050, the committee added that "large gains in aircraft performance are unlikely to be achieved without innovative long-range research leading to new aircraft concepts and technologies."[43] As an example of the time taken to develop a new aircraft, the committee noted that the technologies used to launch the Boeing 777 were developed over 20 years prior to its rollout.[44]

While the committee reviewed a number of potential aircraft configurations, they identified the blended wing-body and the strut-braced wing as being "concepts of particular interest." The committee added that two major airlines had expressed interest in the BWB aircraft, but the committee cautioned that expressed interest does not always result in a commercially successful product, giving as an example the General Electric GE 36 contra-rotating open fan engine that consumed 35 percent less fuel but that airlines declined to buy due to concerns over "life-cycle costs, noise, blade loss, and the possibility that airline passengers might be put off by the appearance of the engine's external blades."[45]

Among the areas that the committee recommended for development were the following:

- "Nontraditional aircraft configurations, including but not limited to (1) the blended-wing-body and (2) the strut-braced or joined wing,

to improve aircraft productivity and efficiency and reduce noise and emissions."
- "Passive and active control of laminar and turbulent flow on aircraft wings (laminar flow to increase cruise efficiency and turbulent flow to increase lift during takeoff)."[46]

Robert Liebeck Assesses Challenges for the BWB

In a 2002 AIAA paper, Liebeck identified eight "issues and areas of risk," noting that they were extracted from a Douglas Aircraft Company memorandum written in the 1950s about moving from the piston-engine, straight-wing, firmly subsonic DC-7 to the jet-powered, swept-wing, and transonic DC-8. The challenges ranged from systems development through performance and handling qualities, and on to the social—namely, would the flying public accept such a "radical" design:[47]

- Complex flight control architecture and allocation, with severe hydraulic requirements.
- Large auxiliary power requirements.
- New class of engine installation.
- Flight behavior beyond stall.
- High floor angle of takeoff and approach to landing.
- Performance at long range.
- Experience and database for new class of configuration limited to military aircraft.

Liebeck added, "Hopefully our industry will press on, just as Douglas and Boeing did fifty years ago." Now, in an era when Boeing and Douglas were joined in corporate unity, Boeing did move on with more detailed studies leading to the design, aerodynamic testing, and fabrication and flight-testing of the X-48B and its modified X-48C, as subsequently discussed.

Endnotes

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2. Ibid.
3. Robert E. McKinley, "Blended-Wing-Body Low-Speed Vehicle Project Formulation" (Hampton, VA: NASA Langley Research Center, October 9, 2000), p. 3, personal copy of document transmitted to author by NASA Langley Senior Research Engineer Dan D. Vicroy on August 26, 2015. Bushnell's measure of efficiency was Mach number times lift-to-drag ratio.
4. R.H. Liebeck, M.A. Page, and B.K. Rawdon, "Blended-Wing-Body Subsonic Commercial Transport," AIAA 98-0438 (1998), p. 2.
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15. Ilan M. Kroo, "Tailless Aircraft Design: Recent Experiences," in F.Y. Fung (ed.), *Symposium on Aerodynamics & Aeroacoustics: Tucson, Arizona, March 1–10, 1993* (Singapore: World Scientific, 1993), chapter 7.
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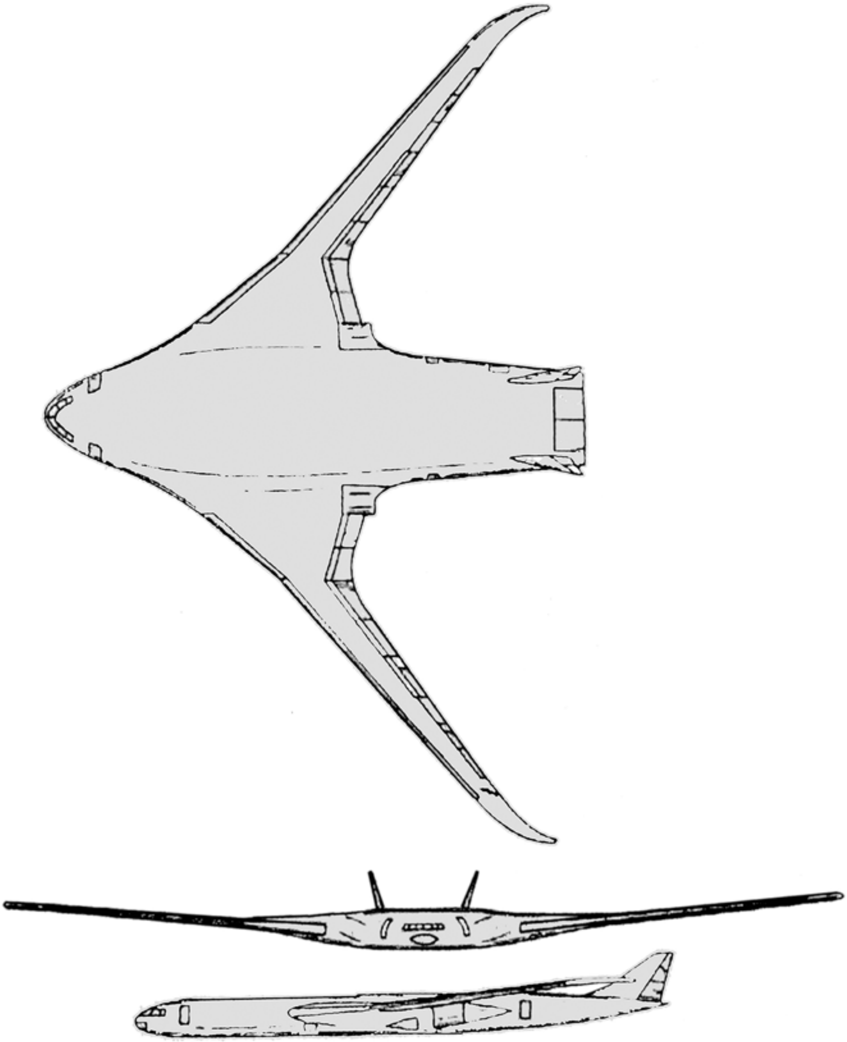
17. Email from Blaine Rawdon to author, June 23, 2015.
18. Richard M. Wood, "The Contributions of Vincent Justus Burnelli," AIAA 2003-0292 (paper presented at the 41st Aerospace Sciences and Exhibit, Reno, NV, January 6–9, 2003), pp. 6–7.
19. Ibid.
20. Ibid.
21. Callaghan and Liebeck, "Some Thoughts on the Design of Subsonic Transport Aircraft for the 21st Century," p. 1.
22. The camber is the curved upper surface of the wing.
23. Callaghan and Liebeck, "Some Thoughts on the Design of Subsonic Transport Aircraft for the 21st Century," p. 3.
24. Ibid.
25. Ibid., p. 5.
26. Ibid.
27. Ibid., p. 7.
28. Ibid.
29. Ibid.
30. Ibid., p. 7.
31. Ibid., p. 1, emphasis in original.
32. Ibid., p. 5. For a detailed review of R.T. Jones' oblique wing work, see Bruce I. Larrimer, *Thinking Obliquely: Robert T. Jones, the Oblique Wing, NASA's AD-1 Demonstrator, and Its Legacy* (Washington, DC: NASA SP-2013-602, 2013).
33. The square-cube law is a fundamental engineering relationship governing the scaling of an object, and it is of profound significance in aerospace design—indeed, all design. Simply stated, when an object increases in size, its new surface area is proportional to the square power of the multiplier, while the new volume of the object is proportional to the cube power of the multiplier. These two relationships for surface area and internal volume are expressed in two equations:
    $A_2 = A_1\ (l_2/l_1)^2$ where A_1 is the original surface area, A_2 is the new surface area, l_1 is the original length of the object, and l_2 is the new length.
    $V_2 = V_1\ (l_2/l_1)^3$ where V_1 is the original volume, V_2 is the new volume, l_1 is the original length of the object, and l_2 is the new length.
34. Exchange of emails between Blaine Rawdon and author, June 23, 2015.

35. Interviews of Robert H. Liebeck (February 25, 2015) and Mark A. Page (June 17, 2015) by author, and exchange of emails between Blaine K. Rawdon and author, June 23, 2015.
36. Dennis M. Bushnell, "Frontiers of the 'Responsibly Imaginable' in (Civilian) Aeronautics: The 1998 AIAA Dryden Lecture" (Reston, VA: AIAA, 1998), pp. 1–20.
37. Ibid., pp. 1–2.
38. Ibid.
39. Ibid., pp. 2–20.
40. James R. Hansen, *The Bird Is on the Wing* (College Station, TX: Texas A&M Press, 2003), p. 157.
41. Ibid.
42. National Research Council of the National Academies, *Securing the Future of U.S. Air Transportation: A System in Peril* (Washington, DC: The National Academies Press, 2003), p. 27, including quotations.
43. Ibid., p. 4.
44. Ibid., p. 27.
45. Ibid., p. 33.
46. Ibid., p. 48.
47. R. Liebeck, "Design of the Blended-Wing-Body Subsonic Transport," AIAA-2002-0002, printed in *Journal of Aircraft* 41, no. 1 (January–February 2004): 10–25.



Following initial conceptualization of the blended wing-body, Liebeck and his colleagues at McDonnell Douglas evolved a proto-first-generation transport configuration that served as a departure point for ever-more-refined derivatives culminating eventually in the BWB-450 that served as the basis for the X-48B. (NASA)

CHAPTER 2

“The Concept Appears to Be a Winner”

> The magnitude of the performance increments of the BWB over the conventional baseline airplane is indeed unusual, if not unprecedented, in the aircraft industry. All of these benefits are due to the BWB configuration itself, rather than specific traditional technologies such as aerodynamics or structures. The configuration is the new technology.
>
> *—Robert H. Liebeck, Mark A. Page, and Blaine K. Rawdon,*
> *the Boeing Company, January 1998*

While the development of the blended wing-body concept represented a revolutionary change in airplane configuration design, the path to the BWB X-48 Technology Demonstrator followed a traditional evolutionary course, played out from 1993 into 1997. It started with initial concept development that led to the more detailed second-phase efforts reviewed below. This second phase in turn generated further study and design iterations and aerodynamic testing that resulted in the fabrication and flight-testing of the X-48B and its X-48C modified version. The combination of additional studies and flight testing, taken together, further defined the rationale and identified component characteristics relating to the BWB concept. Issues addressed included wing sizing, aerodynamics, stability and control, propulsion, interior design, and finally the safety and environmental benefits of the new configuration. This phase ended with a McDonnell Douglas June 1997 plan to proceed with the fabrication of a BWB vehicle, an effort temporarily derailed by the August 1, 1997, merger of McDonnell Douglas and Boeing.

McDonnell Douglas' Follow-On Configuration Studies

Following McDonnell Douglas' initial concept study and development work, the company expanded its analysis in a study conducted between April 1 and December 31, 1993, supported by NASA grant NAS1-18763. Then, in 1994, NASA initiated its Advanced Concepts for Aeronautics Program (ACP). Afterward, at the instigation of Langley Research Center's Joseph "Joe" Chambers, the BWB became the focus of intensive study, a follow-on $3 million, 3-year contract—NAS1-20275—awarded to McDonnell Douglas pursuant to a competition announcement. This follow-on study, conducted from October 1994 through October 1997 (with a time extension for documentation), resulted in a more detailed analysis and comparison of three different subsonic jetliner configurations—a conventional "tube-and-wing," a straight-forward spanloader flying wing, and a blended wing-body. McDonnell Douglas' Phantom Works was the prime contractor and research partner; NASA Langley Research Center was contracting entity and research partner; NASA Lewis Research Center (now NASA Glenn) undertook supporting studies in propulsion; and Stanford University, Clark-Atlanta University, the University of Southern California, and the University of Florida were subcontractors.[1] Over the contract's 3-year period, the BWB concept steadily evolved as reflected in three Configuration Control Documents (CCDs). CCD-1 was the initial baseline configuration, CCD-2 a midterm derivation, and CCD-3 the final configuration generated under this second-phase contract.[2]

The analysis undertaken in 1993 established mission requirements, selected and sized three different airplane configurations, recommended technology initiatives, and assessed the three different configurations leading to McDonnell Douglas' BWB recommendation.

Mission Requirement. The standardized mission requirement for the sizing and design of each configuration consisted of the following:[3]

- An 800-passenger-capacity airplane.
- A range of 7,000 nautical miles.
- A takeoff field length of 11,000 feet.
- An approach speed of 155 knots.
- A cruise speed of Mach 0.85.
- A cruise altitude of 35,000 feet.

The study did not address airport compatibility constraints, and while the team acknowledged that such constraints could become an issue, they added that a promising configuration could be refined to meet airport requirements. By way of example, they pointed to history, noting that if the wide-body DC-10 had been envisioned at the time of the DC-3, "it would have been imponderable to have considered the operation of the 'giant' tri-jet from existing airports."[4]

Selecting and Sizing the Three Configurations. For the three configurations selected for comparison, the conventional cylindrical fuselage plus a simple sweptwing served as the baseline configuration. As already noted, the blended wing-body, which the engineering team acknowledged as the motivation for the study, represented one of the revolutionary design configurations. The third selected configuration was a pure spanloader based on a 1979 Douglas concept, the Model D-3139-SL-2 design, for Air Force Systems Command's Aeronautical Systems Division at Wright-Patterson Air Force Base in Dayton, OH. All three aircraft designs were for standard passenger airplanes with an estimated entry into service by the year 2020.[5]

The team summarized each configuration as follows:

> *Conventional Configuration Development.* The team noted that this configuration was already well defined and represented a challenge to improve. The team's selection of primary features for this design included four wing-mounted engines, double-deck seating, and an upper-deck cockpit to allow for a "hinge-up" nose suitable for cargo versions.[6]
>
> *Spanloader Configuration Development.* This configuration started as a simple constant-chord sweptwing but was changed to a W-shaped planform necessitated by the need to more favorably locate the landing gear and to move the dynamic center of gravity (CG) forward, which also required reducing the effective length of the airplane. The W shape resulted from reversing from aft to forward sweep that solved the center-of-gravity location problem.
>
> *Blended Wing-Body Configuration Development.* This configuration started with a passenger cabin consisting of "several cylindrical pressure vessels tied together in a fashion similar to a conventional 'double bubble fuselage,'" with buried wing-root engines recalling the world's first jetliner, the four-jet modest sweepback (and ultimately tragically unsuccessful) De Havilland Comet.[7] The team abandoned this approach in favor of a less complex cabin structure, from which "a very unique and synergistic blended-wing-body configuration evolved." The BWB would have four engines located aft of the cabin in the main fuselage section, fed by what was termed a "mail slot" inlet ingesting boundary-layer air

> from the forward portion of the fuselage. The team concluded that while highly promising, integrating aerodynamics, propulsion, flight mechanics, and structures to work together in synergistic fashion would pose significant challenges.[8]

Preliminary Sizing. Given the many unknowns involving sizing a blended wing-body vehicle, a subset of critical constraints was determined in order to support a simplified performance analysis of the conventional, spanloader, and BWB designs. These constraints included the following:

- Top of climb lift coefficient ≤ .60 (airfoil drag limit).
- Exposed wing aspect ratio ≤ 10.0 (structural limit).
- Landing approach speed ≤ 155 knots.
- Landing maximum lift coefficient ≤ 3.10.
- Trapezoidal wing taper ratio = 0.30 (historically good for high-aspect-ratio wings).
- Spanloader wing area ≥ 16,327 square feet.
- Spanloader wingspan ≥ 274.8 feet.
- Blended wing-body "fuselage" span = 121.4 feet.
- Conventional fuselage span = 26.9 feet.

In addition to the above constraints, approximate gross-weight relations needed to be developed to account for the effects of lift-to-drag-ratio improvements on takeoff gross weight. Also, two additional constraint problems needed to be addressed to size the wing: adjusting the optimization formula to account for (1) the effect of large wing-area changes on operating weight and (2) initial cruise altitude effects on pressure vessel weight.[9] With these adjustments, the three configurations were considered optimized.

Final Sizing Comparisons. The final sizing procedure varied between the three selected configurations. The conventional configuration received the most refined sizing using the McDonnell Douglas Computer-Aided Sizing and Evaluation System (CASES), not surprising given the decades of experience in dealing with this kind of configuration. Sizing the spanloader proved equally simple. Doing so established the floor area and cabin height required to accommodate the passenger cabin. The wing area was more than ample, thus reducing the sizing to selecting the minimum engine size needed to satisfy mission requirements. Final sizing of the blended wing likewise varied from the preliminary sizing. For example, the lift-to-drag ratio in the final sizing was 27 compared with 21 in the preliminary sizing. It was determined that much of the increase "was due to the accounting for boundary-layer swallowing by the engine, which charged zero skin friction drag for the portion of the upper surface of the centerbody forward of the inlet." The team cautioned that the BWB "is highly integrated compared to a conventional configuration, and a small adjustment in one area can have profound effects on several areas." As a result of this, the final BWB airplane "in the present study is a 'hand built' prototype which is very unlikely to represent an optimum."[10]

Weights. A combination of empirical and analytical methods was used to estimate the weights of the three selected configurations, based on the initial three-view drawings. The study qualified the weight estimates by noting that "these weights must be considered conceptual in nature." Based on the team's estimates, the total maximum takeoff gross weights were 1,149,000 pounds for the conventional configuration; 1,330,000 pounds for the spanloader; and 991,000 pounds for the blended-wing configuration.[11]

Two other major areas that needed to be addressed for comparison purposes were aerodynamics and flight dynamics. The conventional baseline represented a well-understood configuration. A primary flight dynamics task related to this configuration was to specify vertical and horizontal tail volume ratios in order to proceed forward with the drawings and drag estimation. Both the spanloader and blended wing, however, had issues near aerodynamic stall due to the tailless design. The sized vehicles for this study did not require the spanloader or blended wing to fly near aerodynamic stall, but the tailless design made both aircraft susceptible to pitch departures near stall, and one form of pitch departures is post-stall tumbling. According to NASA Langley studies, the spanloader's aspect ratio and stability level would result in post-stall tumbling. Accordingly, the spanloader and the blended wing would require a very robust angle-of-attack-limiting feature to protect against tumbling.[12]

Sizing and Configuration Results. The table below reviews the final sizing results of the three configurations selected for analysis. The numbers for the blended wing and spanloader are relative to the conventional configuration, which is 1.

Table 2-1 summarizes the final sizing results.[13]

Technology Initiatives. The study team acknowledged the challenges of various technology disciplines, including the following:

1. Flight Mechanics
    - Stability augmentation of unstable pitch axis.
    - Engine-out yaw control.
    - Ride qualities, flexibility, and short coupling.
    - Stall characteristics, post-stall tumbling.
    - Aeroelastics of wing pitch-and-roll controls.

Table 2-1. Summary of Final Sizing Results

Measure	Conventional	BWB	Spanloader
Takeoff Gross Weight	1,149,000 pounds	991,000 pounds	1,330,000 pounds
Operating Empty Weight	572,000 pounds	519,000 pounds	594,000 pounds
Fuel Weight	401,000 pounds	296,000 pounds	560,000 pounds
Lift-to-Drag Ratio at Cruise	20.6	27.2	16.1
Reference Wing Area	6,560 square feet	10,432 square feet	19,343 square feet
Wingspan	269 feet	339 feet	290 feet
Total Wetted Area	41,000 square feet	35,600 square feet	47,000 square feet
Wingspan^2/Wetted Area	1.76	3.22	1.78
Wing Loading	176.7 pounds per square foot	95.5 pounds per square foot	68.8 pounds per square foot
Thrust Per Engine	76,100 pounds	55,600 pounds	111,900 pounds
Thrust-to-Weight Ratio	0.265	0.224	0.336
Specific Fuel Consumption	0.530 (pound/hour)/pound	0.578 (pound/hour)/pound	0.530 (pound/hour)/pound
Fuel Burned	364,000 pounds	269,000 pounds	510,000 pounds

2. Structural Design
    - Pressure vessel structural concept.
    - Engine and landing gear structural integration.
    - Wing/centerbody junction.
3. Propulsion
    - Installed performance (thrust/drag bookkeeping).
    - Boundary-layer ingestion.
    - Manifold inlet design.
    - Propulsion inflow distortion.
    - Engine cycle optimization.
4. Aerodynamics
    - Wing aerodynamics, subsonic and transonic.
    - Airfoil and inlet aerodynamic integration.
    - Navier-Stokes computational fluid dynamics (CFD) modeling of boundary-layer ingestion.

5. Configuration Layout
   - Interior layout and cargo handling.
   - Emergency egress.
   - Airport compatibility, gear track, and wingspan constraints.

Assessing the Three Configurations

The team concluded that the conventional configuration was a very good airplane with a high degree of predicted performance, adding that the baselined version indicated that "the 800-passenger 7000-nautical mile mission is a realistic goal."[14]

They considered the cranked-wing spanloader configuration as being "firmly in third place compared with the other two configurations." They added, however, that the spanloader concept "should not be summarily discarded," noting that performance would improve by flying at higher altitudes. This is because preliminary sizing indicated that adding conventional outboard wings to the cabin portion of the vehicle "made its performance competitive with the other concepts" at higher altitudes; otherwise, as originally configured for the baseline mission, it had a much lower lift-to-drag ratio. The cranked-wing spanloader's greatest liability was the need for a very large wing to provide adequate cabin height for the 800 passengers, combined with the need to provide a relatively thin thickness-to-chord ratio to meet the $M = 0.85$ cruise requirement. The spanloader had a lower weight—15,000 pounds less than the conventional design—with a lower aspect ratio and simpler high-lift devices. [15] Overall, the team concluded:

> The cranked-wing concept provides an ingenious and appealing solution to the spanloader design problem. This airplane went together very well, and its simplicity should not be ignored. While it appears that the concept is not ideal for the mission of this particular study, it may be quite viable in other applications, e.g., a long-range cargo airplane with an unpressurized payload compartment and a cruise Mach number of 0.78.[16]

The team was most enthusiastic over the sizing result for the blended wing-body, concluding that it "indicates that the blended-wing-body configuration is the superior performer," with a substantially higher—27.2—cruise lift-to-drag ratio, and noting that "this capability is directly related to the vehicle's wetted aspect ratio that is nearly double that of the other two configurations."[17] The team noted that "For the long-range mission of this study, the high *L*/*D* [lift-to-drag ratio] of the blended-wing-body has resulted in a very low fuel burn and consequent reduction in size and weight of the entire airplane and its engines," adding:[18]

> The concept appears to be a winner. It is believed that this is a consequence of several synergistic effects which were not consciously anticipated at the onset of the study.... The price of this synergism is a highly-coupled configuration where independent variation of most parameters is difficult, if not impossible. Any change such as wing area or cabin volume implies a complete reconfiguration. "Stretching" is not in the vocabulary. [Later studies indicated BWB scalability.] Whether the concept of "multidisciplinary" is popular or not, it will be unavoidable in the development of the blended-wing-body airplane.[19]

The flattened-sphere approach—some called it a "hockey puck"—with added wings, a flight deck, and engines, furnished the original departure configuration for the BWB. It is interesting to note that, roughly a decade earlier, the Northrop (later Northrop Grumman) team working under Irving T. "Irv" Waaland and John Cashen to design the B-2 stealth bomber employed a relatively similar design approach—taking a smooth, very-low-RCS diamond body shape derived in part from Northrop's straight-wing and V-tail Tacit Blue technology demonstrator, and then adding two swept outer wing panels to the diamond to furnish the basic B-2 shape (a change in mission requirements later led to the characteristic three-point B-2 sawtooth trailing edge).[20]

Further Refinement of the BWB Concept

Writing in 1998, Liebeck, Page, and Rawdon updated and further refined their BWB, addressing the rationale and development of the design and then reviewing in greater detail a list of design features and issues, including wing sizing, aerodynamics, stability and control, propulsion, structure, interior layout, safety and environmental issues, and performance.

Rationale and Development. The development of the BWB began with the payload requirements, starting with the passengers. The team noted that for airplane design purposes, "passenger height is discrete, and hence cannot be rubberized." The required minimum cabin height was 82 inches and 10 square feet of floor area per passenger. Accordingly, a capacity of 800 passengers necessitated approximately 55,000 cubic feet of cabin volume.[21] Thus, the problem that remained was "to establish the optimum geometry for packaging this volume." An important component in this calculation was the determination of the total "wetted" area (the area of the aircraft in contact with the external airflow). Using a double-deck approach reduced the aerodynamic wetted area per passenger by a factor of 2. The team illustrated this by calculating that a single deck holding 100 passengers within an 18-percent-thick (i.e., 18 percent thickness/chord ratio) airfoil would require a surface area of 5,500 square feet, or 55.0 square feet per passenger, while a double deck holding 800 passengers would require a surface area of 22,000 square feet, or 27.5 square feet per passenger. Next, the engineers noted that the shape with the minimum wetted area for a given volume is a sphere and that a sphere with a volume of 55,000 square feet would have a surface area of approximately 7,000 square feet.[22]

Streamlining the sphere into "distinct streamlined fuselage concepts" resulted in either a conventional cylinder or a disk, both of which were nearly equal in wetted area. However, placing these fuselage concepts on a wing having a total wetted area of 15,000 square feet and using the disk concept reduced the wetted area by 7,000 square feet, compared with the conventional fuselage concept. Next, by adding the engines, the difference in wetted area increased to 10,200 square feet. Adding the required control surfaces raised this difference to 14,300 square feet. Overall, the reduction in wetted area of the streamlined disk fuselage over the conventional configuration was 33 percent.[23]

The three Boeing engineers added:

> The streamlined disk fuselage configuration as shown [is] a canonical sketch which has been used to demonstrate the philosophy of the germination of the BWB concept. Synergy of the basic disciplines should be clear. The fuselage is also the wing, and inlet for the engines, and a pitch control surface. The verticals provide directional control and act as winglets to increase the effective aspect ratio. Now [the concept] must be transformed into a realistic airplane configuration. This is achieved by blending and smoothing the streamlined disk fuselage into the wing. In addition, a nose bullet is added to offer good cockpit visibility, and at the same time provide increased effective wing chord at the centerline to offset compressibility drag due to the unsweeping of the isobars at the plane of symmetry. Utilizing this design philosophy, the BWB concept has evolved into the configuration shown [below].[24]

Blaine Rawdon later noted in an extensive communication with the author that this summation masked a more complex evolutionary design progression, writing:

The "hockey puck" derivation of the BWB configuration is used to compare components of the BWB and tube-and-wing configurations. But, in my view, this is an after-the-fact explanation. An alternative explanation of the configuration that is in my view more closely aligned with its evolution follows:

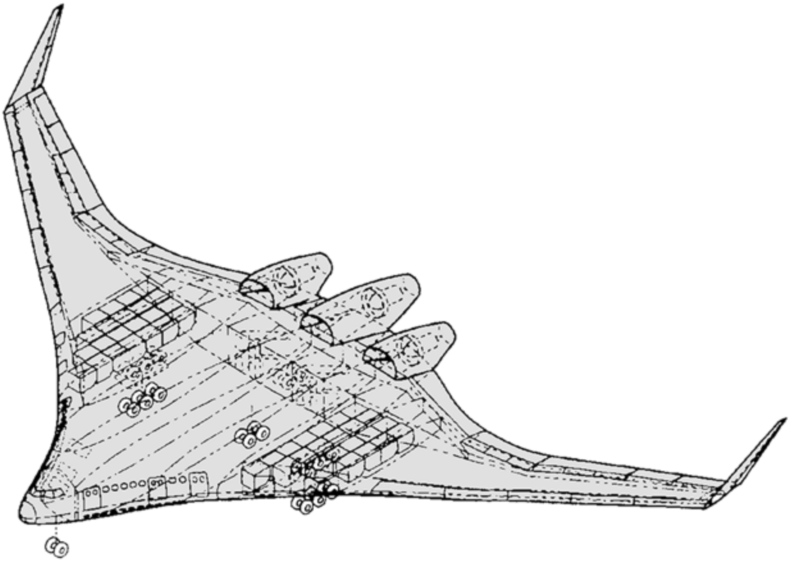
There are a few key objectives for an aerodynamically efficient airplane, taken as a whole: large wing span, minimum wetted area and elliptical lift distribution, arranged to provide pitch trim and stability.

The conventional starting options for flying wings are the "plank" and the swept flying wing. Plank flying wings achieve pitch stability and trim with a forward center of gravity and reflexed camber. Swept flying wings use a forward center of gravity with download at the tips to achieve stability and trim. Planks must have extra wing area because the reflexed trailing edge limits cruise and maximum lift coefficient, increasing parasite drag. Swept flying wings have a poor lift distribution, substantially increasing induced drag.

The BWB configuration adds a smoothly-faired payload volume and wing chord to a swept flying wing as a "center body". The wing is cambered and twisted to provide an efficient elliptical lift distribution. The greater chord in the center body operates at a low lift coefficient, permitting the center body airfoils to be reflexed. This reflex operates on large chords and much area, providing a powerful nose-up moment to counter a stable forward CG and permitting the outboard wings to use favorable aft camber and small chords, reducing wetted area.

The low lift coefficient of the center body also permits the center body to have a high thickness[-]to[-]chord ratio even in transonic flight. This reduces the chord and wetted area of the center body. At the centerline, the center body is unswept, but the chord there is longest and the lift coefficient is lowest, weakening transonic shocks.

Each BWB design is carefully tailored to provide sufficient payload volume, an elliptical lift distribution, and minimum parasite drag by coupled tuning of thickness[-]to[-]chord ratio, chord and sweep angle. The sweep angle (or "shear") of the center body is further tuned to achieve an acceptable center of gravity range.[25]



The BWB configuration as of 1998 represented a careful and synergistic blending of multiple design elements, the overall result being an aircraft of both extraordinary efficiency and beauty. (AIAA)

Liebeck, Page, and Rawdon, while noting that the above configuration was still evolving, identified a number of design features and issues relating to wing sizing, aerodynamics, stability and control, propulsion, and structure of the preliminary BWB configuration. It should be noted, however, that while this first configuration was purely passenger-focused, later configurations moved toward BWB cargo and military carriers as the first potential users. Potential military missions included aerial refueling tankers; cargo carriers; and command, control, intelligence, surveillance, and reconnaissance (C2ISR) platforms. As a refueling tanker, the BWB could be equipped with "three 'smart' booms, two hose/drogue refueling points and automated refueling capabilities.… [A] BWB tanker would be able to accommodate simultaneous air-to-air refueling of multiple conventional aircraft or UAVs."[26] For a BWB used as a C2ISR platform, *Jane's* pointed out the advantages of increased loiter time, increased interior space for battle management, and increased exterior locations for "conformal phased-array antennas for broadband communication with no increase in radar signature."[27] *Jane's* added that the BWB's capabilities likewise make this aircraft configuration suitable for use as a long-range standoff weapons platform.[28]

Wing Sizing. Sizing the BWB wing was based on a variety of factors:

- A minimum takeoff gross weight (TOGW).
- An 11,000-foot runway length.
- A 150-knot approach speed.
- A low-speed trim maximum lift coefficient ($C_{L_{\max}}$) of 1.7.
- A cruise Mach number of 0.85.
- An initial cruise altitude (ICA) exceeding 35,000 feet.

As designed, the wing had an aspect ratio of 10, a span of 280 feet, and a trapezoidal area of 7,840 square feet. Optimized wing loading was approximately 100 pounds per square foot; in contrast, other long-range aircraft typically had higher wing loadings on the order of 160 pounds per square foot.[29]

Table 2-2 shows the salient specifications of this configuration, the BWB-1-1.[30]

Aerodynamics: The team employed various computational methods and codes to design the BWB wing and wing-nacelle combination. Methods and codes used included structured grid Navier-Stokes[31] computational fluid dynamics (CFD) analyses, Computational Fluid Laboratory-3D (CFL3D) computer code, and OVERFLOW (for "OVERset Grid FLOW Solver," a CFD flow solver code), along with NASA's own Constrained Direct Iterative Surface Curvature (CDISC) methodology. They undertook CFD analyses to predict engine mass flow ratio effects, evaluate effects of engine size and location, and compare both isolated and installed inlet duct performance with boundary layer ingestion. The Navier-Stokes analysis indicated that shock wave formation on the outboard wing would be very weak on the centerline, while the subsonic flow behind the shock would benefit the inlet performance of the three turbofan engines.[32]

Stability and Control: The BWB required the alignment of the actual center of gravity with the required center of gravity in order to provide better trim stability for the vehicle by shifting the center of gravity fore and aft. The low effective wing loading of the BWB and beneficial trim effect negated any need for a complex high-lift system except a leading-edge slat on the outboard wing. Trailing-edge devices were thus simple hinged flaps that also served as elevons. Even so, the team concluded, "Flight-critical stability augmentation and envelope protection systems will be required."[33]

Pitch and roll control consisted primarily of outboard elevons because they furnished the largest lever arms around the center of gravity. Operation of the outboard elevons was blended with that of the inboard elevons to decouple pitch and heave; altogether, the full-span elevons provided "substantial" control power. Small Whitcomb-style winglets furnished primary directional stability and control with B-2-like drag rudders to afford control in case of a low-speed

Table 2-2. Specifications of the Boeing BWB-1-1 (800-Passenger Configuration)

External Dimensions	
Wingspan (excluding winglets)	280 feet
Wingspan (including winglets)	289 feet
Wing Aspect Ratio	5.1
Overall Length	161 feet
Overall Height	50 feet
Wing Area	
Wings (trap)	7,840 square feet
Wings (gross)	15,325 square feet
Weights and Loadings	
Empty Weight	369,800 pounds
Empty Weight (equipped)	412,000 pounds
Maximum Payload	231,000 pounds
Maximum Fuel Weight	270,000 pounds
Maximum Takeoff Weight (MTOW)	823,000 pounds
Maximum Zero Fuel Weight	643,000 pounds
Fuel Burn (over 7,000 miles)	213,450 pounds
Maximum Wing Loading	105 pounds per square foot (trap)
Thrust-to-Weight Ratio (T/MTOW)	0.226
Performance	
Normal Cruising Speed	Mach 0.85
Maximum Approach Speed	150 knots (173 miles per hour)
Initial Cruising Speed	35,000 feet
Takeoff Field Length	11,000 feet
Range with 800 Passengers	7,000 nautical miles (8,055 miles)
Engines	3 turbofans, each rated at 61,900 pounds static thrust

engine-out emergency. In partnership with the Boeing team, Stanford researchers led the investigation of the low-speed flight mechanics of the configuration using a 6-percent scale testbed as discussed in greater detail in chapter 4.[34]

Propulsion: Engine integration on a BWB affects aerodynamics, structures, flight mechanics, and weights more directly than on a conventional airplane configuration with podded engines under the wing or off the aft fuselage. The engines were located aft of the centerbody, enabling their inlets to "swallow" the boundary layer (the stagnant airflow immediately over the centerbody forward of the inlets), reducing drag and hence generating a beneficial lower fuel burn rate.[35] "In my view," Rawdon wrote later, "the aft location was selected because we could not figure out a graceful integration of the engines ahead of the leading edge. Such a location would improve balance but is worse from the standpoint of noise reduction (no shielding plus exhaust noise reflection from the lower wing surface) and the potential for laminar flow as well as boundary layer induction. More-forward locations on the wing upper surface are unattractive because the local Mach number is too high there."[36]

The BWB team initially concluded that a three-engine design was best. The team conducted an engine installation "downselect" on several engine-mounting concepts, including pod-and-pylon, buried S-bend (like the center engines of the older Boeing 727 and Lockheed L-1011), and a mid-bifurcated inlet that ingests the boundary layer from both the upper and lower wing surfaces. Researchers at the University of Southern California performed wind tunnel investigations to develop high-recovery/low-distortion boundary-layer ingestion inlets. Testing indicated that fitting the inlets with vortex generators energized the internal flow and greatly improved performance. The team evaluated all engine concepts for center-of-gravity range, ditching implications, emergency egress of passengers and crew, susceptibility to foreign object damage (FOD), airport noise, reverse thrust, landing gear integration, and maintainability.

Placing the engines in pods attached by pylons displaced the thrust line of the engines and thus drastically reduced the permissible range of center-of-gravity travel. It also resulted in an increased wetted area and higher weight. The lower inlet had unacceptable foreign object damage exposure (and the mid-bifurcated boundary-layer ingesting inlet proved to be impractical). In contrast, the shielded inlet upper S-bend with boundary-layer ingestion solved the foreign object damage and airport noise problems and satisfied center-of-gravity range and ditching characteristics.[37]

Structure: The BWB's structure distributed the wing loads from tip to tip, using the passenger cabin structure as a means of optimally distributing the loads. The design had a peak bending moment and shear that was but half that of a conventional tube-and-wing design.[38] But this benefit came only after the team successfully confronted the challenges of designing a centerbody that could both absorb the loads from cabin pressurization and the wing-bending loads. They did so by having the cabin pressure and bending loads carried by a 5-inch-thick sandwich or deep hat stringer structural shell, after investigating alternatives including a potentially more easily manufactured deep skin/stringer design. To facilitate structural analysis, they developed a finite element model to understand more fully the combined pressure and bending loads experienced by the centerbody.[39]

BWB Aircraft Interior: The BWB did not have a conventional passenger cabin such as that found on a tube-and-wing airliner. Instead, the seating was more dispersed laterally, with passenger seating in bays arrayed side by side and occupying two deck levels. The double-deck passenger cabin had ten 150-inch-wide passenger cabin bays with the upper deck being a minimum of 74 inches high (and higher still given the additional space from the upper surface's airfoil curvature) and the lower deck at a nominal 84 inches height. The cabin layout reflected the review of many different potential configurations, including the number of decks, the number of bays on each deck, the length of the bays, and the number of distributed cargo compartments.[40]

Various constraints posed a series of challenges. These included the range of permissible center-of-gravity travel, the maximum possible passenger offset from vehicle centerline without producing unpleasant ride quality, and desired surface area of the pressure vessel encompassing the cabin. The width of a cabin bay was approximately the width of a 3-passenger + aisle + 3-passenger DC-8 jetliner cabin, and the length was approximately the same as that of a DC-9-30 cabin. The partitions between the bays were primary structural items. In contrast to a conventional airliner that had windows on the sides of the fuselage, the BWB had windows built into the leading edge of the wing, and thus at the front of each cabin bay, as were the main cabin doors (the aft doors were in the rear spar). The galleys and lavatories were likewise aft, and a broad "promenade aisle" spanned the front of the passenger cabin on both sides. Altogether, viewed from the front, on each side (right and left) of the BWB's centerline, 13 side-by-side fore and aft rows of passengers faced forward from the centerline to the wing landing gear bay. Cargo compartments were farther outboard still, as were the wing fuel cells even farther beyond the cargo bays.[41]

Safety and Environmental Features. The BWB incorporated various features to enhance safety and improve environmental conditions. The rear engine location afforded better protection for passengers, controls, and fuel tanks in the event of an engine failure. Also, staggering the location of the center and outboard engines reduced the chance of a single uncontained engine failure triggering a cascading sequence of failures of the two remaining engines. The pressure vessel structure surrounding the passengers was immensely strong compared to conventional practice. Since the BWB centerbody is a noncircular pressure vessel, all of its outer surface operated in bending as opposed to the pure tension of a circular or cylindrical pressure vessel. (The interior elements, such as the cabin walls, operated as membranes to restrain the wing skins.) As a result, the pressure vessel surrounding the passenger compartment was considerably more stout than the thin pressure vessel of a conventional airliner. Furthermore, the upper and lower surfaces of the pressure vessel doubled as the wing skins, taking wing-bending loads. Somewhat counterintuitively, this actually added to their strength and, as well, weight. The heavy gauges of the pressure vessel tended to be more resistant to damage and were certainly more resistant to crash loads than those of a conventional tube-and-wing design.[42] As well, the separation of the fuel cells from the passenger cabin greatly enhanced survivability in the event of a crash. Environmental advantages included a low acoustic signature due to favorable engine inlet and exhaust location (the aft exhaust location avoided acoustic reflection from the underside of the wing), and the absence of slotted flaps and supporting mechanisms reduced airstream noise. The substantial reduction in fuel burn per passenger mile provided by the BWB configuration reduced overall flight emissions compared to those of conventional aircraft.[43]

NASA's ACP-sponsored BWB study ended in 1998, coincident with Boeing's decision to scale back the ambitious 800-passenger BWB configuration and move toward the development of a smaller and more practical follow-on BWB 450, a single-deck 450-passenger design. Also, as mentioned earlier, Boeing began examining other applications, particularly military ones including heavy cargo airlift and air refueling. This follow-on effort led to evolving even more design changes and the development and flight-testing of small-scaled BWB vehicles, discussed later in this study.

What Might Have Been: MDC's Proposed Two-Person Demonstrator

Interestingly, in June 1997, McDonnell Douglas' Phantom Works at St. Louis, MO, proposed a piloted two-person, 26-percent-scale experimental technology demonstrator, the BWB-X, to be powered by two small business jet–class turbofan engines, with an anticipated first-flight date of 2000. For a while, it seemed that this might become reality, for the project had high-level support within the MDC hierarchy; the enthusiastic participation of the Phantom Works and the company's BWB's experts, including Robert H. Liebeck, Mark A. Page, John B. Allen, Raquel Girvin, Norman H. Princen, and

George T. Rowland; and a very-well-thought-out management plan. But then it came adrift with the merger of McDonnell Douglas and Boeing not quite two months later, on August 1, 1997, thus bringing an end to the proposed BWB-X piloted demonstrator program.[44]

Boeing Adopts the BWB

Indeed, following its merger with McDonnell Douglas, Boeing was uncertain about proceeding at all with the BWB. At this juncture, NASA played an important role in convincing Boeing's leadership to continue what McDonnell Douglas had started. Dennis Bushnell, now NASA Langley's Chief Scientist, even visited Boeing in Southern California to advocate the merits of continuing the blended wing-body development efforts.[45] NASA also provided Boeing with a small grant to conduct a several-month review of MDC's BWB work in order to determine whether or not to keep the program.[46] Following this review, and NASA's plea, Boeing decided to carry on with the BWB work started by McDonnell Douglas, and the project moved into its next phase.

Endnotes

1. Joseph R. Chambers, *Innovation in Flight: Research of the NASA Langley Research Center on Revolutionary Advanced Concepts for Aeronautics* (Washington, DC: NASA SP-2005-4539, 2005), pp. 80–82.
2. Robert E. McKinley, "Blended-Wing-Body Low-Speed Vehicle Project Formulation" (Hampton, VA: NASA Langley Research Center, October 9, 2000), p. 3, personal copy of document transmitted to author by NASA Langley Senior Research Engineer Dan D. Vicroy on August 26, 2015.
3. Robert H. Liebeck, Mark A. Page, Blain K. Rawdon, Paul W. Scott, and Robert A. Wright, "Concepts for Advanced Subsonic Transports," NASA Contractor Report 4624 (September 1994), p. 1. The coauthors also acknowledged the assistance provided by R.S. Bird (aerodynamic analysis and sizing of the airplanes); P.P. Camacho (assistance in airfoil design); J.K. Wechsler (propulsion system); and William J. Small, NASA Langley Technical Monitor (advice, guidance, and study support).
4. Ibid., pp. 1–2.
5. Ibid., pp. 1–3.
6. Ibid., p. 3.
7. Early De Havilland Comet jetliners fell victim to explosive decompression at cruise altitudes due to a combination of unanticipated factors and (in retrospect) poor design, leading to several tragic and highly publicized accidents. Though redesigned and strengthened Comets served successfully with several airlines and with the United Kingdom's Royal Air Force (RAF) (including a much-loved maritime patrol derivative, the Nimrod), the type never recovered from its early civil stumble (much like Lockheed's later L-188 Electra turboprop, which, after some shocking accidents from structural failure, found its true métier as a naval patrol plane), leaving the jet field largely to the United States with its 707 and DC-8. See Derek D. Dempster, *The Tale of the Comet* (New York: David McKay Co., Inc., 1959), pp. 171–218.
8. Liebeck, Page, Rawdon, Scott, and Wright, "Concepts for Advanced Subsonic Transports," p. 5.
9. Ibid., p. 6.
10. Ibid., pp. 11–12.
11. Ibid., p. 13.
12. Ibid., pp. 25, 28.
13. Ibid., p. 50.
14. Ibid., p. 51.
15. Ibid., pp. 51–53.

16. Ibid., p. 53.
17. Ibid. The large wetted aspect ratio reflected the wide centerbody of the design.
18. Ibid.
19. Liebeck, Page, Rawdon, Scott, and Wright, "Concepts for Advanced Subsonic Transports," pp. 53–54.
20. Conversation with Richard P. Hallion on February 7, 2018, at Shalimar, FL.
21. That is, 82 in = 6.833 ft; therefore, 6.833 ft × 10 ft^2 = 68.33 ft^3, and 68.33 ft^3 × 800 [passengers] = 54,664 ft^3.
22. The volume V of a sphere is $V = 4\pi r^3/3$. Therefore, 55,000 ft^2 = $4\pi r^3/3$, thus 165,000 = $4\pi r^3$; therefore, since $4\pi = 12.566$, $r^3 = 13{,}130.67$, so r = 23.592 ft. The area A of a sphere is $A = 4\pi r^2$. Therefore, since $\pi = 3.1416$, $4\pi = 12.566$, and $r = 23.592$ ft, r^2 is 556.576 ft^2, and A = 6,993.940 ft^2, approximately 7,000 ft^2.
23. R.H. Liebeck, M.A. Page, and B.K. Rawdon, "Blended-Wing-Body Subsonic Commercial Transport," AIAA 98-0438 (paper presented at the 36th Aerospace Sciences Meeting & Exhibit, Reno, NV, January 12–15), pp. 3–4.
24. Ibid.
25. Blaine K. Rawdon, email to author, August 29, 2018.
26. Paul Jackson et al., eds., *Jane's All the World's Aircraft, 2007–8* (London: Jane's Information Group, 2007), p. 312.
27. Ibid.
28. Ibid.
29. Liebeck, Page, and Rawdon, "Blended-Wing-Body Subsonic Commercial Transport," pp. 4–5.
30. Paul Jackson et al., eds., *Jane's All the World's Aircraft, 1997–98* (London: Jane's Information Group, 1997), p. 251.
31. Navier-Stokes equations are five coupled differential equations that must be solved simultaneously and that enable analysis of how the velocity, pressure, temperature, and density of a fluid in motion interact. Independently derived by French and British scientists, the equations are critical to understanding viscosity and viscous effects. Because of their complexity (which before the computer era required engineers to make assumptions, approximations, and simplifications that reduced the accuracy of their results), Navier-Stokes equations are particularly suitable for computational fluid dynamics when engineers can use high-speed computers to determine more accurate approximations. As noted by NASA researchers at Glenn Research Center,

> Navier-Stokes equations consist of a time-dependent continuity equation for conservation of mass, three time-dependent conservation of momentum equations and a time-dependent conservation of energy equation. There are four independent variables in the problem, the x, y, and z spatial coordinates of some domain, and the time t. There are six dependent variables; the pressure p, density r, and temperature T (which is contained in the energy equation through the total energy E_t) and three components of the velocity vector; the u component is in the x direction, the v component is in the y direction, and the w component is in the z direction. All of the dependent variables are functions of all four independent variables. The differential equations are therefore partial differential equations….

(See NASA Glenn Research Center, "Navier-Stokes Equations," at *http://www.grc.nasa.gov/WWW/k-12/airplane/nseqs.html* [accessed on December 30, 2014].)

32. Liebeck, Page, and Rawdon, "Blended-Wing-Body Subsonic Commercial Transport," p. 5.
33. Ibid., p. 5.
34. Ibid., pp. 5–6.
35. Ibid., p. 6.
36. Blaine K. Rawdon, email to author, 29 August 29, 2018.
37. Liebeck, Page, and Rawdon, "Blended-Wing-Body Subsonic Commercial Transport," p. 7.
38. A moment is the product of a force and the distance (the moment arm) from a reference axis.
39. Liebeck, Page, and Rawdon, "Blended-Wing-Body Subsonic Commercial Transport," pp. 7–8.
40. Ibid., pp. 8–9.
41. Ibid.
42. Blaine K. Rawdon, email to author, August 29, 2018.
43. Liebeck, Page, and Rawdon, "Blended-Wing-Body Subsonic Commercial Transport," p. 10.
44. McDonnell Douglas, "BWB-X Blended-Wing-Body Experimental Aircraft: Program Abstract," MDC 97D-006 (Long Beach, CA: McDonnell Douglas Corporation, June 1997), copy from NASA Dryden (now Armstrong) Flight Research Center Library, transmitted to author by Karl Bender on March 3, 2015.

45. Interview of Mark A. Page by author on June 17, 2015, and information provided by Dennis Bushnell on February 11, 2015.
46. McKinley, "Blended-Wing-Body Low-Speed Vehicle Project Formulation," p. 3.

Before the X-48B could embark on its flight research program, Boeing, NASA, and their partners had to undertake extensive research, development, testing, and evaluation activities that would permit the design of this ambitious research vehicle. (NASA)

CHAPTER 3

From Concept to Design

> Development of the Blended-Wing-Body has progressed steadily over the past seven years. Once-apparent "show-stoppers" have been reduced to technical challenges, or in most cases proper solutions. From a distance, the Boeing BWB-450 baseline airplane shows little distinction from the first-generation BWB developed under NASA sponsorship in 1993.[1]
>
> —*Robert H. Liebeck*

The development of the Blended Wing-Body concept occurred over a period of approximately 20 years, and the outcome remains a work in progress. This chapter reviews the follow-on work conducted after the first two study phases, when the BWB went from concept to design, but before the actual fabrication of the X-48B began. This follow-on work represented a third phase advancement to the BWB-450, which became the configuration used for most of the aerodynamic testing and the fabrication of the X-48B/C.

The BWB Development Team and Its Partners

Highly skilled and dedicated people from many governmental, industrial, and academic agencies, organizations, and institutions contributed to the success of the BWB program. First was Boeing, whose "legacy" BWB team members drawn from McDonnell Douglas at Long Beach, CA, and St. Louis—the "first responders" to Bushnell's challenge—formed the vital center of the company's subsequent BWB efforts. Next was NASA, whose scientific and technical cadres at Langley, Lewis (now Glenn), and Dryden Flight (now Armstrong Flight) Research Centers furnished crucial analytical, test, and evaluation support ranging from computational fluid and structural dynamics modeling to wind tunnel testing and finally flight-testing over the Mojave. In Britain, Cranfield Aerospace built the test vehicles under contract to Boeing and furnished vital on-scene test and support personnel during the flight research phase. The U.S. Air Force's Air Force Materiel Command, through its Aeronautical Systems Center (ASC, inactivated in 2012 and absorbed into a new Air Force Life Cycle Management Center, AFLCMC), Air Force Research Laboratory (AFRL), and Air Force Flight Test Center (AFFTC, now Air Force Test Center, AFTC), undertook analytical, developmental, ground, and flight testing at Wright-Patterson, Arnold, and Edwards Air Force Bases. Several universities, including Stanford University, the University of Southern California (USC), and Clark-Atlanta University, supported the BWB effort with studies and small-scale ground-and-flight test programs.

Theirs was truly a joint and combined team effort: "Our present concept of a Blended Wing Body airplane didn't pop up as a crystal-clear vision early on," recalled Boeing Fellow Blaine Rawdon in 2012, adding, "A lot of very smart people have improved on the design over the years. It's been a diverse team of people who have openly exchanged ideas and challenged one another. We've always had open direct communications, and that makes it fun."[2] Rawdon added that the team worked on a series of different BWB iterations for different missions and with increasing sophistication.

Boeing, of course, was the principal program driver. Robert H. Liebeck served as program director, overseeing the development of the outer mold line of the vehicle. Norman Princen, broadly experienced in stability and control and assessing aircraft handling qualities, served as program chief engineer and oversaw the development of systems architectures. Michael Kisska was Boeing's project manager, with primary duties that included seeing that the project met deliverable dates, delivered the project package, and safely executed the flight-test program. Mark Page specialized in stability and control and propulsion-airframe integration, as well as sizing, performance, and Multidisciplinary Design Optimization (MDO). Matt Wilkes followed Page as chief engineer for design, and Derrell Brown, previously McDonnell Douglas' chief engineer for airlift system development, served as the last chief engineer for design. Dino Roman worked on aerodynamic design, and Jonathan Vass served as Boeing test conductor for both the X-48B and X-48C portions of the program and trained two follow-on test conductors. Boeing test pilots Steven McIlvane, Michael Sizoo, Daniel Wells, and Norman Howell flew 99 of the 122 remotely piloted test flights. At any one time, Boeing's project team ranged between 10 and 20 individuals, with the peak reaching as many as 40 people, plus up to 60 others working at times in support of the team's efforts. Mike Kisska, Boeing's X-48 project manager, described the team as "highly dedicated, with a strong attachment to the program that keeps them fully engaged," adding, "It's a very small team doing some very, very extraordinary work."[3]

Transiting the BWB to Boeing and Its Subsequent Development

The merger with McDonnell Douglas had unsettled NASA officials at Langley and elsewhere in the Agency, who feared the merger might derail growing interest in the BWB and the pace of the NASA–McDonnell Douglas BWB design effort, which had just started testing with a subscale flying model, the BWB-17, developed at Stanford by a team of engineers and students working at the direction of Professor Ilan Kroo.[4] Fortunately, such fears proved misplaced, for Boeing embraced the BWB with enthusiasm.

First, the firm launched a months-long in-depth technical analysis of the BWB headed by Michael S. "Mike" Burtle, chief engineer of the company's Boeing 777 production effort. In a meeting held at Boeing's Seattle headquarters on April 15, 1998, Burtle presented the results of his study to a meeting of executives and leading engineers from Boeing and NASA, including Robert Liebeck and NASA's Robert McKinley. "The Boeing team generally accepted the results of the McDonnell Douglas/NASA Research Study," McKinley noted afterward, adding, "No showstoppers were identified. The potential benefits of the concept (in terms of weight, direct operating costs, fuel burn, etc.) were accepted via analysis."[5]

The Burtle assessment effectively "green-lighted" the BWB, which thus successfully transitioned over to Boeing as a development effort and high corporate priority from its legacy days at McDonnell Douglas. Boeing now initiated its own preliminary design study of a BWB transport. Company officials rejected the earlier 800-passenger, 7,000-nautical-mile design mission, deeming it inappropriate for the in-house evaluation of the BWB because of difficulty in making meaningful comparisons with existing airplanes. As well, by now, an 800-passenger-capacity airplane was less attractive. So the Boeing study focused on a smaller 450-passenger design, which accounted for the concept's subsequent BWB-450 designation, deriving a series of baseline mission requirements enumerated in Table 3-1.

Boeing compared the new BWB with its 747, the Airbus A340, and pending A380. The design had a 260-foot wingspan limit, driven by airport compatibility requirements. Unlike the earlier design, with its two-deck passenger layout, the BWB-450 carried all its passengers on an upper deck with the lower deck reserved for cargo. The comparison of the proposed BWB-450 with the proposed A380 indicated a 32-percent lower fuel-burn per seat for

Table 3-1. BWB-450 Baseline Mission Requirements[6]

Payload	468 passengers in three passenger classes
Design Range	7,750 nautical miles
Crew	Standard flight crew of two
Fuel Reserves	International reserve fuel (fuel equal to 5 percent of Block Fuel; 200-nautical-mile diversion to alternate airport; and half-hour hold at 1,500 feet at holding speed)
Constraints	11,000-foot field length; 140 knots approach speed; 2.7 degree second-segment climb gradient; and 300 feet/minute excess power at top of climb

the BWB-450; as well, the lower fuel-burn synergistically worked to dramatically reduce emissions.[7]

Similarities and Differences, Opportunities and Challenges

The BWB-450 drew heavily on experience gained with the 800-passenger variant. The centerbody contained the pressurized cabin, and as well as the wing carry-through structure, thus having to distribute and carry both the pressure loads and the wing-bending loads (which is approximately one-half that of a conventional aircraft). Again, the main challenge with the BWB-450 was developing a light but rugged centerbody structure having high resistance to fatigue failure, which dictated a largely composite structure due to composites' lighter weight than conventional metal structures and greater immunity to fatigue. Thus, the BWB-450 had a composite outboard wing structure and a 5-inch-thick "sandwich," or skin plus 5-inch-deep "hat-section stringers," for the centerbody structural shell. Its designers relied on a finite-element computational structural analysis model for predicting and assessing the combined pressure and wing-bending loads on the centerbody.[8]

The BWB-450 had the same inherent safety features as its larger predecessor. For one, an uncontained engine failure could not impact the pressure vessel, fuel tanks, or aircraft systems. Additionally, the pressure vessel, sized to carry both pressure loadings and wing-bending loadings, was so rugged as to afford great crashworthiness protection. And the BWB-450 benefited the environment in the same fashion as the earlier big wing, for it had a low acoustic signature: the centerbody shielded the forward-radiated fan noise, and the engine exhaust noise was not reflected from the lower surface of the wing, as it is in a conventional transport design. As with the earlier BWB, the lack of a slotted-flap, trailing-edge, high-lift system reduced airframe noise, while engine emissions, as noted earlier, were commendably lower due to the lower per-seat fuel-burn.[9]

Liebeck and his team likewise identified both the opportunities and challenges relating to passenger acceptance of the BWB design. For example, the vertical walls of a BWB passenger cabin would provide a more spacious environment than conventional (and sometimes claustrophobic) curved walls, and the low capacity of each cabin, estimated to carry approximately 100 passengers, provided an intimacy not available on conventional wide-body aircraft. However, while each main door had a window, the separating cabin walls did not. Imaginatively, Boeing engineers planned to use flat-screen displays connected to an array of digital cameras that in effect turned every seat into a window seat.[10]

BWB Design Constraints

The integrated nature of the BWB posed many challenging constraints for the BWB design team.[11] As well as its overall aerodynamic design, which was far more complicated than that of a conventional wing-body combination, these involved volume, deck angle, clean wing trim, secondary power for control surface actuation, landing approach speed, buffet and stall characteristics, propulsion, and manufacturing.[12]

Volume. The most important design constraint was addressing the volume requirement. Since the BWB configuration did not have a dedicated fuselage, the passengers, cargo, and aircraft systems had to be incorporated within the wing. This requirement could lead to a maximum thickness-to-chord ratio of up to 17 percent in the centerbody region, higher than usually associated with transonic airfoils, which typically had thickness-to-chord ratios of 10 percent or less.[13]

Deck Angle. In order to keep the deck angle of the BWB near level, both for reasons of passenger comfort and so flight attendants could easily move heavy service carts back and forth, the centerline wing section required positive aft camber lest the deck angle be too nose-high, typically considered as more than 3 degrees. Doing this increased nose-down pitching moment.[14]

Clean Wing Trim. Because of the increased nose-down pitching moment, the need to meet the deck angle requirement clashed with an equally important need: maintaining cruise clean wing trim, defined as when the wing's center of pressure coincides with the desired center of gravity, with all trailing-edge control surfaces in faired condition.[15] This condition requires that the nose-down pitching moment be minimized, thus restricting the use of positive aft camber that in turn conflicted with the deck angle requirement.[16]

Secondary Power for Control Surface Actuation. For BWB configurations, trailing-edge devices and winglet rudders are required to perform a number of functions, including trim; longitudinal (pitch), lateral (roll), and directional (yaw) control; pitch stability augmentation; and wing load alleviation via distributed lift by selective control surface deflection. Also, due to the size of the inboard trailing-edge devices, the tailless nature of the design, and its great size, the design team had to carefully tailor the airfoil design to minimize control hinge moments. As stated by Roman, Allen, and Liebeck,

> The hinge moments are related to the control surface size by the square/cube law, that is, size increases by the square of the scale whereas hinge moments increase by the cube of the scale. Once the hydraulic system is sized to meet the maximum hinge moments, the power required is only related to the rate at which the surfaces move. The secondary power required can easily exceed that currently available from turbofan engines.[17]

Liebeck, addressing how one solution can impact other related functions, noted that,

> If the BWB is designed with negative static margin (unstable), it will require active flight control with a high bandwidth, and the control system power required may be prohibitive. Alternatively, designing the airplane to be stable at cruise requires frontloaded airfoils, washout and limited (if any) aft camber. This implies a higher angle-of-attack which in turn threatens the deck angle constraint.[18]

Landing Approach Speed. The trailing-edge control surfaces of a BWB, as with those of delta-wing aircraft in general, cannot function as flaps, for there is no tail to trim out the resulting moments. Lacking flaps, the BWB's maximum coefficient of lift was at a relatively high angle of attack, so that as it approached to land, the nose would rise (again, as with all deltas), giving it a pronounced nose-high flight attitude. As well, since the maximum lift coefficient of a BWB aircraft was substantially less than that of a conventional flapped design, the BWB wing loading had to be substantially lower, achievable by a larger lifting planform.[19]

Buffet and Stall Characteristics. The outboard airfoils of BWB aircraft necessarily have chords (the distance from the leading to the trailing edge of the wing, parallel to the fuselage centerline) shorter than the centerbody. Therefore, the outboard airfoils must operate at higher lift coefficients to achieve a reasonable cruise spanloading. Also, at low speeds, as angle of attack increases, the outboard wing sections tend to first experience flow separation, leading to pronounced buffeting and the possibility of loss of lift, leading to a potentially catastrophic wing-drop and departure from controlled flight. The addition of an extensible wing slat to the outboard wing enables the outboard wing sections to maintain a stable attached flow, reducing the magnitude of buffeting and enhancing flight safety. But for the clean airplane in flight, the design team faced pressure to both increase the length of the outboard wing chords and washout (i.e., reducing the angle of incidence of the wing relative to the body from the wing root to the wingtip)—both of which tend to degrade the cruise performance.[20]

Propulsion/Airframe Integration. The three engines on the BWB-450, which Liebeck called a "second-generation BWB," were enclosed in pods on pylons, despite the implications for the thrust moment, which, Liebeck noted, "although undesirable," was deemed acceptable.[21]

Manufacturing. Overall, the BWB was a large wing with an integrated fuselage with the only stabilizing empennage being the winglets/vertical fins, lacking complex wing-to-fuselage or fuselage-to-empennage joints with highly loaded structures intersecting at 90-degree angles, and without the complex drag- and turbulence-reducing fillets found on a conventional design. All its trailing-edge control surfaces had simple hinges without the complex tracks associated with double- and triple-slotted flap designs found on conventional jetliners, and it lacked conventional spoilers for lateral control. (The BWB did use outboard split-aileron spoilers to contribute to the control of drag, yaw, and roll).[22]

Though the inherently complex aerodynamic shape of the BWB posed extremely difficult and expensive manufacturing choices, Liebeck and his aerodynamics team worked diligently toward having smooth, simply curved surfaces.[23] Through their efforts, the BWB configuration had up to a 30-percent reduction in the number of parts compared with a conventional tube-and-wing airplane configuration, reducing potential manufacturing costs.

When the time came to move from design to X-48 demonstrator fabrication, Boeing selected Cranfield Aerospace, a British company specializing in rapid prototyping of advanced technological systems, to build it. While enthusiastic, Cranfield staff were well aware of the integration problem involved with BWB configurations due to both their own BWB studies and work done at Cranfield University, Britain's most respected academic center of aerospace research. As noted below from one of their program studies,

> The design of any classical (Boeing 707 type) configuration civil airliner can be thought of as a number of weakly linked processes such as the design of the fuselage, the design of the wing, the design of the empennage and the design of the propulsion. Whilst this simplifies the design process it does constrain the various systems to, essentially, operate independently of one another. Conversely, the highly integrated nature of the BWB configuration complicates the design process, however, it offers a unique potential for the synthesis of a Systems Configured Vehicle (SCV). The SCV would exhibit an optimal balance between configuration, control system (including TVC [thrust-vectoring control]), propulsion, laminar flow control system, high lift system, secondary power etc.[24]

The complexity involved in addressing the above constraints caused the design of the BWB to be an evolutionary process that transitioned from the "first generation" configuration to what became a follow-on generation. The initial wing design failed to meet most of the constraints. To correct this failure, each subsequent design cycle focused on "better meeting a single unresolved constraint while preserving previous progress." This evolutionary process resulted in many different design iterations.[25]

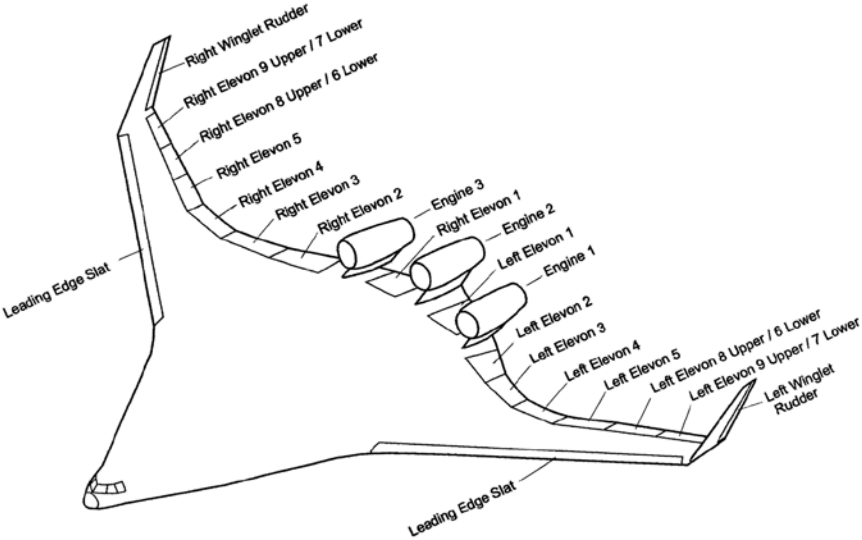
A significant change from the initial configuration involved changing the planform due to lowering the passenger load from 850 to 450 passengers. The planform changes involved increasing the outboard and centerline wing chords. Increasing the outboard wing chords improved the buffet onset level and characteristics. Increasing the centerbody chords reduced their thickness-to-chord ratios and afterbody closure angles. In addition, a new class of airfoils that operate efficiently at transonic speeds were designed, and a more efficient way to package the interior was developed. Also, the BWB wing was trimmed by careful distribution of trailing-edge camber coupled with a "judicious" application of wing washout resulting in a "flying wing aircraft, trimmed at a stable center-of-gravity, with the control surfaces faired, with no induced drag penalty," thus overcoming the induced drag penalty associated with flying wing aircraft.[26] In summarizing the improvements over the initial configuration, Boeing engineers noted:

> Compared to the first generation BWB wing design, today's design delays buffet onset, improves buffet and stall characteristics, allows

> the aircraft to be trimmed at a stable center-of-gravity location, reduces the secondary power demand, and simplifies the manufacturing process. Significantly, these improvements have been incorporated into the design in conjunction with a 16% increase in lift-to-drag ratio…. The new wing more effectively carries the lift with less negative pressure coefficients, leading to compressibility drag reduction. Along with inboard chord extensions, the reduced thickness resulted in significantly smaller airfoil closure angles and a more mild pressure recovery at the trailing edge. This is beneficial for engine installation, putting them in a less accelerated field.[27]

Short-Coupled Controls. Another problem with the BWB was related to short-coupled controls that adversely affected flight control during rotation and landing flare (the landing transition phase between the approach and touchdown and rollout of an airplane, where the pilot raises the nose of the aircraft to achieve a higher lift coefficient, and the wing enters ground effect, defined as an altitude equal to approximately one-half of the airplane's tip-to-tip span, characterized by a cushioning effect that reduces decent rate just before touchdown). (A similar problem existed on the Space Shuttle's initial design, manifesting itself in spectacular fashion during the Shuttle's Approach and Landing Test program).

The BWB's pitch controls had a shorter lever arm to the vehicle's center of gravity than on a conventional aircraft configuration with a long fuselage extending aft of the wing and sprouting a tail group. Abrupt pitch changes could trigger plunging motions, causing the BWB to be pushed down (or to plunge) and then to pitch up to reach the desired angle of attack, introducing an undesirable "sagging" of the BWB's flightpath during takeoff and landing, causing the pilot to have to initiate the takeoff rotation and landing flare earlier in order to reach the same "end state" as a conventional aircraft. The motions were not a classic "phugoid" (an instability mode involving cyclic pitch and speed variation akin to a roller coaster). Rather, it reflected a concept known as "instantaneous center of rotation" (ICR). Airplanes with short-coupled pitch controls (and especially flying wings) have an instantaneous center of rotation that is well ahead of the airplane. A pitch command results in the airplane rotating in pitch about this point. When the point is well ahead of the airplane, the airplane descends as it pitches up until the increased angle of attack enables the airplane to climb. (Conventional airplanes have instantaneous centers of rotation much closer to the airplane, and this effect is much less noticeable. Canard airplanes may have an ICR behind the airplane—they climb as they



The BWB-450 configuration had numerous control surfaces on its trailing edges, including 18 elevons (a combined *elev*ator for pitch control and ailer*on* for roll control) as well as winglet rudders. On the BWB, the winglets furnished not only beneficial minimization of tip vortices, but also directional stability and control. Leading-edge slats on the outboard portions of the wing reduced dangers of loss of control at high angles of attack during low-speed flight. (NASA)

pitch up). This effect is an even greater problem during takeoff because ground effects amplify the loss of lift.[28]

Yann D. Staelens and Ron F. Blackwelder, from the University of Southern California, and Mark A. Page, from Swift Engineering, investigated to determine if a belly flap acting as a pitch control effector for use during takeoff and landing could solve the pitching challenge. Wind tunnel tests in a closed temperature-controlled airflow wind tunnel at the University of Southern California using a 1⁄67-scale generic BWB transport model having a wing planform and thickness distribution patterned after the BWB-450 confirmed that a flap on the bottom of the aircraft near the center of gravity would increase static pressure ahead of the center of gravity and decrease it aft, thus producing a nose-up couple with the resulting moment and lift change helping to rotate the BWB during takeoff and landing. In their final report, the investigators concluded:

> The belly-flap is most efficient when it is totally deployed, this means having a deflection angle of 90°. The belly-flap should have a total span of about 20% of the span of the airplane. With these characteristics an increase of up to 35% of lift-off

> C_L [lift coefficient] and 10% of the total control power in pitching moment available from all of the elevons combined can be expected at low angle of attack with the use of belly-flaps. Those benefits come with an increase of C_D [drag coefficient] of about 10% of lift off C_D.[29]

Following the above study, the team undertook a mathematical simulation, incorporating its findings into the aerodynamic input for a dynamic flightpath model of the BWB airplane. The analytical model indicated that the increase in lift observed during the wind tunnel tests due to the use of belly-flaps would improve the landing field length, takeoff field length, and pitch lagging during go-around. The model also provided a platform for the development of a control law for use in this new type of control surface. Belly-flaps therefore offered a practical solution to poor control leverage of traditional elevons, the team finding that "the surprising level of lift means that belly-flaps are High-Lift devices, and Direct-Lift devices."[30] Staelens, Blackwelder, and Page recommended further study on the effects of belly flaps on the lateral stability of the BWB airplane, suggesting further that the perceived benefits of belly flaps should be verified during actual flight tests with a BWB model thus equipped.

Toward a Family of BWBs for Different Missions

A very significant change from the early BWB studies involved the ability to easily change a BWB airplane design to what Robert Liebeck referred to as "Family and Growth" potential. Early on, it was believed that "any change such as wing area or cabin volume implies a complete reconfiguration…[and that] [s]tretching is not in the vocabulary." Further study, however, indicated that "the BWB concept could be ideal for a family of airplanes with the potential for substantial commonality among its members." This is because stretching occurs spanwise (laterally) as opposed to fore-and-aft (longitudinally), as with a conventional tube-and-wing design (for example, the almost-over-stretched Douglas DC-8-63 derivative of the basic DC-8 jetliner family). Therefore, designers could grow capacity by adding a central bay to the centerbody or, conversely, reduce capacity by removing a central bay from the design. Throughout, Liebeck noted, "wing area and span automatically increase or decrease appropriately with passenger capacity, a quality not offered by the longitudinal stretching of a conventional airplane."[31]

Designing a family of BWB configurations still posed challenges. The outer mold lines had to remain smooth and provide proper aerodynamic performance, and each derivative design had to be individually trimmed and balanced. The cabin cross-section remained identical across the different configurations. While commonality generally afforded benefits in rapid development of different variants, it also constituted a constraint leading to increase in weight. Even so, Liebeck noted that the BWB

> appears to offer the opportunity for an unusual level of commonality while maintaining aerodynamic efficiency via the natural variation of wing area and span with weight. This implies significant reductions in part count and learning curve penalties in manufacturing. Enhanced responsiveness to fleet-mix requirements is also implied. It remains to thoroughly evaluate the trade between airplane cost and performance offered by the BWB family concept.[32]

Boeing's WingMOD and the BWB Design Process

As a new and unique concept, the BWB required a different design approach that departed from what Sean Wakayama and Ilan Kroo, from Boeing and Stanford, respectively, termed the "conventional decomposition of the airplane into distinct pieces."[33] Instead, this new method, known as Multidisciplinary Design Optimization (MDO), integrates together the wing, fuselage, engines, and tail and requires that an "array of requirements must be satisfied with an integrated airframe." Addressing the MDO experience gained during the first 4 years of BWB work, Wakayama and Kroo noted that using the MDO approach has "shown substantial payoffs stemming from the natural ability of MDO to handle the geometric complexity and the integrated design philosophy of the BWB."[34]

The BWB presented any number of challenges for which MDO offered a promising solution, not least of which was that no single design approach or discipline sufficed. Though structures and aerodynamics all historically interplay in aircraft design, that interplay was even more crucial for the BWB, which integrated the fuselage and wing into a single, unified whole. Attaining low drag was difficult due to the very thick airfoil (compared to other jet transports and airliners) required to enclose the payload within the wing. Furthermore, the unique design features of a BWB required higher fidelity modeling than that used for conventional configurations. The flat panels had to support pressure loads over very large spans due to the cabin arrangement. This problem represented a significant challenge for structures and weights disciplines. Also, any tailless design creates stability and control challenges, a combination of trimming and available control power, together with their combined effects on overall spanloadings and drag. Additionally, in this case, the extreme aft-mounted engines posed propulsion and airframe integration issues.[35]

The MDO process in the BWB program involved the use of several computer codes, with most of the work accomplished using Boeing's Wing Multidisciplinary Optimization Design code (WingMOD), originally developed for conventional tailed jetliners. This design code, as Wakayama and Kroo noted,

> performs wing planform, thickness, and twist optimization, with design variables including overall span plus chord, sweep, thickness, and twist at several stations along the span of the wing. It also optimizes skin thicknesses, fuel distribution, spar locations, and control surface deflections. [It] enforces constraints on range, trim, structural design, maximum lift, control power, and balance [and] by performing detailed optimization while attending wide-ranging constraints early in the design process, WingMOD identifies ways to trade and maximize interdisciplinary advantages, generating well-rounded configurations that are usually achieved at great cost with traditional design processes.[36]

As applied to the BWB, the WingMOD code needed to be modified to account for missing characteristics captured in Navier-Stokes CFD codes. Otherwise, without adjusting for this missing information, WingMOD would not generate aerodynamically feasible designs.[37] The Genie (*Gen*eric *I*nterface for *E*ngineering) framework developed at Stanford University provided WingMOD optimization services. Other modifications included add-ons to the Genie framework, additional equations for structures and weights, modifications to address stability and control issues, and modifications to assess center-of-gravity issues. Boeing, under NASA contracts, modified the version of Genie used in WingMOD to handle requirements for several aircraft design optimization tasks. Stability and control issues required additions for "scheduling control surface deflections and observing center-of-gravity issues." In this regard, WingMOD was modified to accept five deflection schedules covering high-speed trim, high-speed control, low-speed trim, low-speed control, and maneuver load alleviation. To address center-of-gravity issues, "WingMOD was modified to track the longitudinal position of structure, fuel, payload and general discrete masses."[38]

Overall, Wakayama and Kroo concluded that while much work remained to be done, "WingMOD optimizations are providing answers that are useful to industry now. While the BWB program has yet to study an MDO-based design in detail, the directions taken by WingMOD in seeking optimal designs have provoked thought, discussions, and conventional studies that have led to improved designs. MDO has gained acceptance in the BWB program as a tool to find ways to improve the design."[39]

In September 2000, Wakayama, writing on behalf of the BWB team, reported on the progress made since the earlier BWB MDO work reviewed above.[40] He noted that the updated BWB optimization took a more careful look at "cabin geometry, balance, stability, and control issues" and that the process could now consider 5 missions, 26 design conditions, 142 design variables, and 930 constraints. WingMOD also could "analyze an aircraft in over twenty design conditions that are needed to address issues from performance, aerodynamics, loads, weights, balance, stability and control."[41]

WingMOD addressed the following five issues:

- Design, primarily to evaluate aircraft range;
- Maximum payload, to evaluate loads and forward balance;
- Minimum payload, to evaluate the aft balance and control limits;
- Empty mission, to check the center of gravity with zero payload to determine if the vehicle meets "tip-over" requirements; and
- Extended range, which checks the aircraft's fuel capacity and balance with less than the design payload, but with extra fuel to reach maximum weight.[42]

WingMOD reviewed 26 design conditions relating to takeoff, beginning cruise, ending cruise, and landing. For each design condition, WingMOD picks up a total weight and payload weight from a mission with which it is associated. Most design conditions are trimmed through the optimizer. Four of the 26 conditions involve takeoff constraints; 2 conditions are examined for takeoff stall; 1 condition is used to check structural loading due to the weight of the vehicle; 8 conditions are examined at maximum weight and maximum payload; 1 condition examines the drag and balance of the aircraft at the start of cruise; 2 conditions examine cruise drag for the design mission; 2 conditions are used to evaluate performance and control at maximum landing weight; 3 conditions evaluate control at minimum flying weight; 1 condition evaluates the balance of the empty aircraft; and 2 conditions are used to analyze for the purpose of constructing the balance diagram.[43]

Overall, the WingMOD analysis used to solve BWB balance problems examined five missions under 26 conditions. Ten optimizations were used to model, calibrate, and optimize the BWB configuration; seven optimizations were used to match different aspects of the vehicle's design; and two optimizations were used to balance the aircraft without changing planform. However, "a final optimization involving 142 design variables and 930 constraints solved balance issues by changing the planform." The BWB team concluded that "by solving certain design problems faster than conventional processes and finding solutions that would otherwise be overlooked, MDO is adding value in industrial aircraft design projects."[44]

Boeing engineers also applied WingMOD to explore the design of BWB configurations at subsonic speeds higher than the Mach 0.85 of the BWB-450 and with increased ranges of between 7,500 and 8,900 nautical miles. For this study, the WingMOD code was calibrated to Navier-Stokes computational fluid dynamics and used to optimize eight BWB configurations at Mach 0.85, 0.90, 0.93, and 0.95. The study indicated that the BWB at Mach = 0.93 "achieved reasonable *L*/*D* and a drag divergence[[45]] Mach number just beyond 0.93." This finding formed the basis for an optimized BWB-6-250B configuration. The Boeing engineers concluded that while "additional CFD work is needed to quantify drag stemming from propulsion airframe interference, the work done so far indicates good potential for creating a BWB that performs well at Mach 0.93."[46]

Boeing's Blended Wing-Body Military Cargo Airplane Patents

By this time, Boeing was looking beyond the civilian world to global military air mobility. On November 21, 2009, the Boeing Company filed a patent application for a blended wing-body airplane that was granted on February 5, 2013. The inventors were listed as Richard C. Odle, Dino Roman, and Blaine Knight Rawdon with the Boeing Company listed as Assignee. The patent, issued as US 8366050, identified the U.S. Government as having certain rights to the invention due to support provided under contract F336 15-00-D3052 granted by the U.S. Air Force. The patent provided the following description of a BWB as well as identifying the configuration differences from a flying wing:

> A BWB is an airframe design that incorporates design features from both traditional fuselage and wing design, and flying wing design. Advantages of the BWB approach include efficient high-lift wings and a wide airfoil-shaped body. BWB aircraft have a flattened and airfoil shaped body (i.e., relative to a conventional aircraft), which produces lift (i.e., in addition to wing lift) to keep itself aloft. Flying wing designs comprise a continuous wing incorporating the functions of a fuselage in the continuous wing. Unlike the flying wing, the BWB has wing structures that are distinct and separate from the fuselage, although the wings are smoothly blended with the body. The efficient high-lift wings and wide airfoil-shaped body enable the entire craft to contribute to lift generation with the resultant potential increase in fuel economy.[47]

The patent noted that conventional military cargo configurations need to address two disparate missions—providing efficient transport of cargo and being able to load wheeled cargo into the aircraft without using ground-based equipment. The patent identified the three following BWB Cargo Airplane primary components that address the above mission requirements: (1) a body section defining a cargo volume, and outer surface of the body section shaped to provide an aerodynamic lifting comprising a lift coefficient increasing smoothly near a center of body section; (2) a cargo door and ramp structure located in the aft end of the body section with an outer shape of the aerodynamic lifting surface shaped to conform with the cargo-door-and-ramp structure and to form a steep upsweep preserving the aerodynamic efficiency of the BWB Cargo Airplane when the door-and-ramp structure is in the closed position; and (3) at least one pitch control surface with a slightly cambered downward shape positioned near an aft end of the cargo door-and-ramp structure such that an efficient lift disturbance is maintained while providing pitch control. The patent pointed out that existing BWB designs do not have airframe designs that can incorporate a rear cargo door and ramp into the BWB configuration without disrupting aerodynamic performance, adding, "Thus there is a need for a rear (aft) cargo door and ramp access for blended wing body airframes that does not reduce aerodynamic performance, stability, and control capability."

Twenty earlier patents were cited by the patent office examiner, including

- two 1946 Northrop Aircraft, Inc.[,] patents for an all-wing airplane and a tailless aircraft;
- a January 1992 all-wing patent applied for by Leon J[.] Croston;
- a 1999 McDonnell Douglas patent for a rib for a blended-wing-body aircraft;
- May 2003 and May 2004 Boeing patents for a variable size blended-wing-body aircraft;
- an August 2005 tailed flying wing aircraft and November 2011 longitudinal flying wing aircraft patents by Faruk Dizdarevic;
- three patents (October 2002, October 2003, and October 2004) for variable size blended wing body aircraft by Mark A. Page; and
- a May 2010 blended wing body unmanned aerial vehicle patent by Williams Aerospace, Inc.[48]

An earlier patent, US 6568632, published on May 27, 2003, provided for an aircraft "having a body that is at least partially constructed from a plurality of longitudinally or laterally extending body structures to provide a family of aircraft with each family member having a different cargo capacity." The inventors were listed as Mark A. Page, Jennifer P. Whitlock, and Mathew W. Wilks, with the Boeing Company listed as the original assignee. The patent listed five "preferred" BWB aircraft cargo configurations.[49]

Proceeding Forward

Boeing Commercial Airplanes' interest in funding the BWB declined as the division was preparing for the introduction of its new 787 Dreamliner. Fortunately, Boeing Phantom Works (now Boeing Research and Technology) agreed to continue funding the X-48 project, although at a reduced level, in order to continue Boeing's efforts to focus on still-unresolved BWB commercial transport issues. The reduced funding, however, forced the BWB timeline to be lengthened.[50] Likewise, NASA continued its BWB work and financial commitment, and the U.S. Air Force now expressed a military interest in the BWB project, resulting in the Air Force assignment of the "X-48B" designation in June 2005 to cover a small-scale, remotely piloted research vehicle. Additional Boeing funding also came from Boeing Integrated Defense Systems (now Boeing Defense, Space & Security), and in 2006 Boeing signed a contract with the U.S. Air Force Research Laboratory at Wright-Patterson AFB. Thus, work continued on the BWB-X-48B project.

However, before moving on to the actual fabrication of the X-48B, two other projects need to be mentioned. The first involved testing many BWB concepts on radio-controlled (R/C) models and a small, remotely piloted BWB Flight Control Testbed with a 17-foot wingspan. This successful Stanford University project, reviewed in the next chapter, ran from 1995 until just prior to the Boeing and McDonnell Douglas merger on August 1, 1997. The second project, reviewed in chapter 5, was an attempt directed by NASA Langley, with assistance from Boeing, to build a subscale, remotely piloted BWB Low-Speed Vehicle. This first effort, which was later designated the X-48A, ended before it took to the air.

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2. William Seil, "Wing of Innovation: The Story of the X-48 Program Is One of Discovery—and Ideas Taking Flight," *Boeing Frontiers* (December 2012–January 2013): 25.
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4. Robert E. McKinley, "Blended-Wing-Body Low-Speed Vehicle Project Formulation" (Hampton, VA: NASA Langley Research Center, October 9, 2000), pp. 5–6, personal copy of document transmitted to author by NASA Langley Senior Research Engineer Dan D. Vicroy on August 26, 2015.
5. Ibid., p. 6.
6. Robert H. Liebeck, "Design of the Blended Wing Body Subsonic Transport," AIAA-2002-0002 (2002), pp. 12–20.
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8. Ibid., p. 10.
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13. Ibid., p. 2.
14. Ibid.
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18. Liebeck, "Design of the Blended-Wing-Body," pp. 5–6.
19. Roman, Allen, and Liebeck, "Aerodynamic Design Challenges of the Blended-Wing-Body Subsonic Transport," p 3.
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32. Ibid., including quotations.
33. Sean Wakayama and Ilan Kroo, "The Challenge and Promise of Blended-Wing-Body Optimization," AIAA-99-4736 (1998), p. 1.
34. Ibid.
35. Ibid., p. 4.
36. Ibid., p. 1.
37. Ibid., p. 5.
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The BWB-17 in flight. Model tests with this aircraft and its predecessors played a crucial role in giving developers confidence to proceed with the X-48 development program. (Photo courtesy of Blaine Rawdon)

CHAPTER 4

Small-Scale Testbeds

> Small-scale research aircraft play an important role in the development of novel full-scale configurations. They are a powerful tool for exploring the operating envelope, discovering unexpected dynamic behaviors, and gathering quantitative time-history data. They encourage a hands-on approach to aerodynamics and controls experimentation that provides intuitive and quantitative understanding of airplane dynamics.[1]
>
> —*Benjamin Tigner*

Tigner and his associates were correct in their judgment: flight research using flying models has been a significant—indeed crucial—aspect of aeronautical research since the beginning of the 19th century. Models pointed the way toward the creation of the Air Age. A century before the Wrights flew at Kitty Hawk, NC, Sir George Cayley experimented with models and gliders. Then, on August 18, 1871, a rubber-cord-powered free-flight model designed and flown by France's Alphonse Pénaud flew 131 feet in 11 seconds during a test flight at Paris' Tuileries Gardens, the first powered flight in aviation history. After this demonstration, there was no question that a powered aircraft could fly; rather, the question was, could a *piloted and controlled* powered aircraft fly? That answer, of course, came on December 17, 1903, with the first powered, sustained, and controlled piloted flight of the Wright brothers' Kitty Hawk Flyer, itself based upon the brothers' experimentation with models, kites, and gliders.[2] Models thereafter became an essential element of aeronautical research, and it was the rare engineer, if any, who worked in the aerospace field without having, at some point, built and flown a model aircraft. For aerospace engineers, models were—and are—an essential element of both personal enjoyment and professional accomplishment.[3]

Model Research and the BWB

Given this legacy of work, it was hardly unusual that fabrication and testing of radio-controlled (R/C) and small-scale remotely piloted testbed vehicles preceded the development of the X-48B Technology Demonstrator. The BWB-17 Flight Control Demonstrator represented the final test-flight vehicle resulting from this project. The project goals were to obtain a better understanding of the low-speed and high-angle-of-attack dynamics of the BWB configuration and to contribute to the development of scale-independent flight control concepts for subsequent BWB aircraft. The tests included basic bench-top measurements, static tests, dynamic ground tests, computer simulations, and ultimately flight-testing; and they completed NASA and Air Force wind tunnel research supporting the program, including free-flight testing of wind tunnel models in Langley Research Center's Full-Scale Tunnel (LFST).[4]

The Small-Scale BWB Vehicle Team

A Stanford University and McDonnell Douglas team—with the assistance of an independent pilot contractor—accomplished the development and testing activities of the R/C models and BWB-17 testbed in slightly less than 2 years. The research team conducted high-speed ground and some flight tests at Moffett Federal Airfield, formerly Moffett Naval Air Station, home to NASA Ames Research Center. The majority of flight-test work took place in the skies over El Mirage Dry Lake, CA, approximately 30 miles southeast of NASA Dryden (now Armstrong) Flight Research Center at Edwards Air Force Base. NASA and McDonnell Douglas (Boeing's heritage company) supported the Stanford program, which ran from August 1995 through July 1997, immediately prior to the absorption of the McDonnell Douglas enterprise and its BWB team into the Boeing corporate fold.[5]

Stanford's Benjamin Tigner, a postdoctoral researcher, undertook the work with NASA sponsorship, under the auspices of Stanford Department of Aeronautics and Astronautics Professor Ilan Kroo. In addition to Kroo and Tigner, the Stanford team included Mark J. Myer (test director support and a graduate research assistant) and Michael E. Holden (ground handler and graduate research assistant). Stanford University had previous experience in this area from their similar participation in NASA's oblique wing-research program. The McDonnell Douglas team included Blaine K. Rawdon (BWB configuration and design and pilot assistant), Mark A. Page (BWB technical manager and deputy project manager), Robert Liebeck (BWB program manager), and Debbie Runion (ground support). McDonnell Douglas likewise furnished William "Bill" Watson, an independent pilot contractor.[6] Altogether, the team

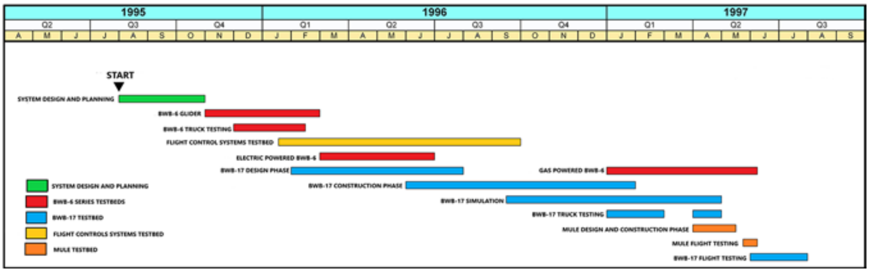
BWB-17 Flight Team from left to right: Mike Holden (Stanford), Ben Tigner (Stanford), Blaine Rawdon (MDC), Mark Meyer (Stanford), Bill Watson (pilot contractor), Debbie Runion (MDC), Mark Page (MDC), and Robert Liebeck (MDC). (Photo courtesy of Blaine Rawdon)

was a mix of veteran old hands and young professionals, all gifted, dedicated, and immensely enthusiastic.

McDonnell Douglas provided technical reviews and advice during the design and construction of the BWB-17, as well as substantial logistical and technical support during the test phase.[7] The BWB-17 was the last blended wing-body design undertaken by McDonnell Douglas prior to merging with Boeing. NASA provided access to Moffett Field for truck testing of the BWB-17, funding the project out of an approximately $300,000 NASA contract to support BWB development, as well as several analytical studies carried out by several Stanford graduate students on aspects of the planned McDonnell Douglas BWB effort.[8]

Project Timeline

Work on the Stanford R/C models and the remotely piloted BWB testbed started in August 1995 with systems design and planning work leading to the BWB-6 and ended on July 29, 1997, with the final demonstration flight of the BWB-17.



Timeline of the BWB-6, BWB-17, Flight Controls Systems Testbed, and Mule Research Vehicle. (Graphic courtesy of Blaine Rawdon)

The research team tested several different iterations of the BWB-6. The first was a glider, followed by an electric-powered version that preceded the final BWB-6 gasoline-powered iteration.[9] They conducted testing of the BWB-6 R/C glider from November 1995 through February 1996. High-speed ground tests of the model mounted on a truck started in December 1995 and ended in February 1996. The BWB-6 electric variant first flew in March 1996 and ended in September 1996. The BWB-6 gasoline-powered variant followed it with tests from January through May 1997.

McDonnell Douglas' design and construction work on the BWB-17 ran from June 1996 through January 1997. The BWB-17 had two flights prior to its final demonstration flight on July 29, 1997, just days before the August 1, 1997, merger of McDonnell Douglas and Boeing. Researchers hoped for a series of experimental flights, but funding issues prevented more than the three flights being performed, especially after risk elements associated with experimentation efforts had to be removed for the final flight. This was necessary in order to lower vehicle flight risk due to the attendance of high-level NASA officials who wanted to see the vehicle in actual flight.[10]

The detailed Stanford project timeline is reviewed in Table 4-1.[11]

The BWB-6

Three variants of the BWB-6 were flown: a small hand-launched glider; an electric-powered version; and a piston-powered, 6-foot-wingspan, single-engine, non-instrumented, radio-controlled (R/C) model.

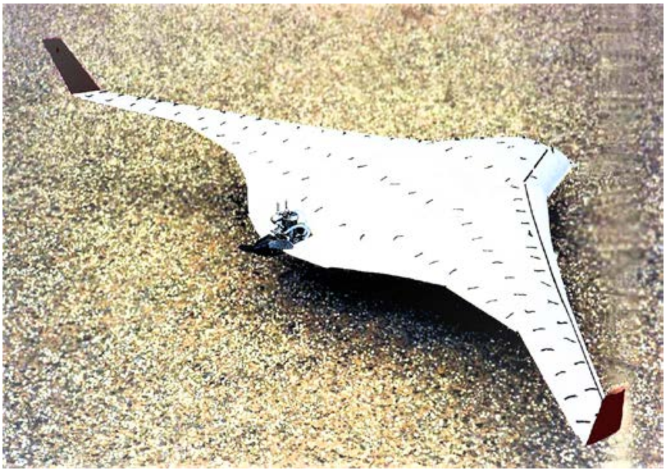
Together, these three undertook preliminary BWB testing prior to actual flight-testing of the remotely piloted 17-foot-wingspan twin-engine BWB-17 testbed. The R/C models were dynamically scaled, weighted, and aerodynamically configured to achieve desired pitch and yaw stability. While the R/C models lacked any stability augmentation system or data acquisition system, the models still furnished insights into the BWB's likely behavior within its

Table 4-1. BWB-17 Developmental Timeline

Tasks	Dates
System Design and Planning	August through October 1995
BWB Glider Testing	November 1995 through February 1996
BWB-6 Truck Testing	December 1995 through February 1996
Flight Control System (FCS) Testbed	Mid-January through September 1996
BWB-6 Electric-Powered Testing	March through September 1996
BWB-6 Gas-Powered	January through May 1997
BWB-17 Design Work	June 1996 through January 1997
BWB-17 Construction Work	June 1996 through January 1997
BWB Simulation	Mid-September 1996 through April 1997
BWB-17 Truck Test	January through April 1997
Mule Aircraft Design and Construction	April through mid-May 1997
Mule Aircraft Flight Tests	Late May through mid-June 1997
BWB-17 Flight Testing	May through July 1997
BWB-17 Flight Demonstration	July 29, 1997

Stanford's initial BWB flight-test work was with this deceptively simple BWB glider. (Photo courtesy of Blaine Rawdon)

The electric-powered BWB-6 flew from March into September 1996, an interim step between the previous glider and the subsequent gas-powered BWB model. (Photo courtesy of Blaine Rawdon)



The final BWB-6 configuration, powered by a gasoline engine, shown against a pebbled surface. Note the wing tufts for analysis of flow patterns, particularly at increasing angles of attack. Tests with this aircraft led to an angle-of-attack limiter subsequently installed on the larger BWB-17. (Photo courtesy of Blaine Rawdon) operating envelope. For example, on one flight, the gas-powered BWB-6 went from stall entry into a pitch-up, causing the team to search for possible solutions that led to the development of the angle-of-attack limiter function for the BWB-17. This in turn was "directly relevant for the full-size aircraft because of the dynamic scaling relationship between the two aircraft." The 6-foot R/C model (BWB-6) likewise assisted in investigating landing and takeoff dynamics. The Stanford–McDonnell Douglas team added that the "difficulty in operating the 6-foot BWB suggested the need for thorough piloted simulation studies and careful numerical analysis of BWB ground effect."[12]

The BWB-17

The most impressive of the models flown was the BWB-17, a remotely piloted, 6-percent dynamically scaled, 17-foot-wingspan, 120-pound blended wing-body Flight Control Testbed with active controls. The vehicle's planform matched that of the planned full-size aircraft, but with airfoil sections redesigned to carry out the vehicle's low-speed flight envelope. The testbed vehicle had simply hinged surfaces along the trailing edge and split-flap drag rudders/brakes on the outer wing panel. The vehicle had twin two-stroke "Super Tigre" engines with propellers designed to produce a similar thrust-to-weight ratio to that of the full aircraft design. The vehicle's airframe, which was fabricated at Stanford, was made from foam blocks that were epoxied to an aluminum frame. The airframe was then covered with fiberglass and several coats of paint. The trailing-edge devices were built from balsa wood, except that the outer-span surfaces consisted of vacuum-bagged fiberglass layups. Onboard digital data acquisition systems recorded roll, pitch, and yaw rates; airspeeds; angles of attack and sideslip; and pilot commands. Stability augmentation was provided by an onboard computer that generated control surface deflections based on nonlinear combinations of pilot commands and sensor inputs. The data acquisition and stability augmentation systems enabled in-the-field evaluation and modification of the systems' control laws.[13]

The research methods developed for the small-scale flight control testbeds included bench-top and static tests, error analysis for mass moments of inertia, and characterization of static engine performance. To conduct this research, the team employed a variety of test techniques, including the following:

- *Highway Vehicle Testing* simulating the dynamics and aerodynamics of flight while avoiding the risks associated with free flight.
- *Nonlinear Piloted Simulation* to support control law design and training.
- *Use of a "Mule" Aircraft* as a "placeholder" in early flight-test practices to prepare for the BWB-17's first flight.

Readying the BWB-6 and BWB-17 for flight required, though on a smaller scale, the extensive preparations associated with conventional piloted research aircraft. The ground tests included bench-top measurements, static engine performance runs, taxi tests, and semiconstrained dynamic highway vehicle tests. Highway vehicle tests simulated the full-scale dynamic and aerodynamic environment of flight without the associated risks. These tests exposed the BWB-6, and later the BWB-17, to a wide range of flight conditions, including varying airspeeds, angles of attack and sideslip, throttle settings, vibration intensity, and wing loadings.

For vehicle testing, researchers mounted the BWB model on a mast several feet above the roof of a Volkswagen Sirocco owned by Ben Tigner. The BWB had an attachment joint at its center of gravity (CG), thus allowing free (but not complete) rotation about all three axes—pitch, roll, and yaw. "The model had a big hole in the bottom with a structural hard point right at the airplane's computed center of gravity location," Blaine Rawdon recalled:

> This point was attached via a spherical bearing to a tall pole that extended from the top of Ben's VW Sirocco. The car and airplane were driven up and down the runway at Ames. The spherical bearing let the airplane "fly." Ben adjusted all of the flight control parameters in the onboard flight control computer.[14]

Research engineers manually controlled angle of attack (AOA) while observing how tufts attached to the upper surface of the wing behaved, thus revealing airflow patterns and flow changes as AOA varied. A safety monitor riding in the car could take control of the testbed in unanticipated situations. The data acquisition system recorded the vehicle's response to command inputs from the pilot riding in a chase vehicle. The research team developed a nonlinear piloted simulation for use in designing control laws and for pilot training. The engineering team noted that "the car-test technique provides intuitive and quantitative understanding of the vehicle dynamics by allowing hands-on experimentation with low-speed aerodynamics and control law behavior," adding that it furnished "an effective tool for measuring and tuning the aircraft's dynamic behavior."[15]

The vehicle's longitudinal controller included an angle-of-attack limiter that constrained the pilot's pitch-up authority to protect against possible stall departure. Researchers tested the limiter by using increasingly aggressive inputs to exceed the angle limit. The test results indicated that the limiter was "highly effective at preventing unwanted angle-of-attack excursions," though it required modification to "compensate for the effects of the flow-curvature around the car."[16]

The BWB-17 during a high-speed road test at NASA Ames Research Center, Moffett Federal Airfield, CA. Behind the vehicle is Moffett's signature airship hangar, a skyline fixture since the days of the great naval airships in the 1930s. (Photo courtesy of Blaine Rawdon)

Flight Training for the BWB-17 via a "Mule" Aircraft

One of the challenges facing the team was simply gaining the flying experience to safely fly the 17-foot BWB on its first flight. The ground pilot used a direct vision approach in the same manner as a hobbyist R/C model pilot and, as noted by Blaine Rawdon, very few people had experience flying R/C models of the BWB's size and weight (let alone, it may be added, its unique configuration and unverified flying and handling qualities).

To better prepare for the first flight, Robert Liebeck had the team build a "Mule" aircraft for practicing flight testing prior to flying the BWB. (A Mule aircraft is a conventional airplane configuration modified to enable testing of some of the handling qualities of a new configuration testbed vehicle. With conventional aircraft flight testing, this is most often accomplished through the use of so-called "variable stability" airplanes to model the new design's flying and handling qualities; some of these "V-Stab" testbeds, such as Calspan Corporation's NT-33A, NC-131H, and F-16D VISTA, have become quite significant and versatile flying research tools in their own right.) In the case of the BWB, the team used a Mule aircraft carefully designed to have the same weight, span, and propulsion power as the BWB vehicle. The high-lift flaps of the Mule aircraft were electronically geared to the elevator controls so as to

The Rawdon Mule on a BWB-17 training flight. (Photo courtesy of Blaine Rawdon)

mimic the BWB's characteristic lift-pitch coupling. As well, the Mule's wingtips had split surface drag devices designed to mimic the BWB's outboard yaw/brake surfaces.[17]

Blaine Rawdon designed the Mule in just 1 week, and Bill Watson, the independent pilot for the BWB-17, built it in 2 weeks. Rawdon and Watson spent several weeks at El Mirage Dry Lake test-flying and getting acclimated to the Mule. Rawdon's evaluation was that the Mule "proved to be a pleasure to fly…our experiences with the model was crucial to the success of the three test flights of the BWB-17."[18]

The Mule was thus a BWB "placeholder" for practice flights to develop flight-test plans for actual BWB flight testing. From this process, the team developed and followed checklists during all Mule and testbed vehicle operations. The team concluded that "[t]he experience during these practice flights was essential in operating the BWB with precision." Mule flights conducted prior to BWB flights also provided important information concerning winds-aloft and radio frequency (RF) interference. Communication protocols were "debugged" during practice Mule flights.[19]

The BWB-17 Aloft

Though originally intended for an extensive test program of its own, the BWB-17 test team flew their elegant creation on only three occasions, the first two basic flight familiarization checkouts, with the third—and consequently the most significant—being a data-gathering flight on July 29, 1997. All flights took place at El Mirage Dry Lake, piloted by Bill Watson. In practice for its initial flight, Watson had "flown" the BWB-17 while it was affixed to a short pole at El Mirage so that he could assess the functioning of the R/C system and the control system of the BWB itself. Ironically, it was growing official NASA interest that helped constrain the program: with such interest came requirements to incorporate risk reduction features that would have constrained data gathering. As Benjamin Tigner recalled, "After high-level NASA officials expressed interest in witnessing the tests, the risk elements associated with experimentation all had to be removed."[20] Along with this were two other factors, a lack of funding in the Agency to further support the program and, of course, the announcement of the Boeing merger with McDonnell Douglas, which briefly put the whole future of the BWB endeavor, model and otherwise, into doubt. July 29, 1997, thus remains both the graceful BWB-17's pinnacle of achievement and also its swansong.

In preparation for the BWB-17's first flight, pilot Bill Watson assessed the radio control and control surface function with the BWB-17 mounted on a pole at El Mirage Dry Lake, CA. (Photo courtesy of Blaine Rawdon)

The BWB-17 cruises over El Mirage Dry Lake on one of its three flights, remotely piloted by Bill Watson. (Photo courtesy of Blaine Rawdon)

The BWB-17 lands on El Mirage Dry Lake. (Photo courtesy of Blaine Rawdon)

Scale Free-Flight BWB Model Testing: An Assessment

Though the direct transfer of technical work from the BWB-17 to the X-48B was necessarily limited, it afforded, as noted by Blaine Rawdon,

> the concrete proof that the concept could be made to fly well…. The expenditure on the relatively modest BWB-17 made the risk of a multi-million dollar X-48B acceptable. Without it, there might have had to be a preliminary proof-of-concept vehicle. So, in essence, that is what the BWB-17 was.[21]

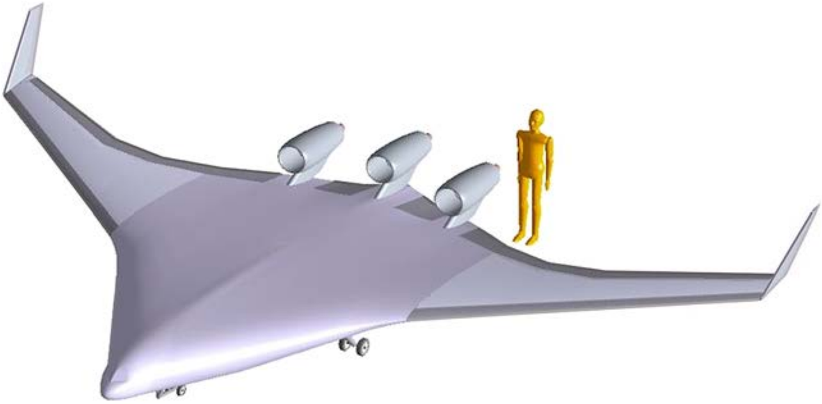
Benjamin Tigner provided his own assessment of the BWB-6's and BWB-17's contributions by noting that their testing confirmed that[22]

- the BWB configuration flies well and can be operated safely across a range of CG positions, including during takeoff and landing;
- takeoff and landing dynamics were as predicted by simulation; and
- ground effect has a significant impact on takeoff rotation.

NASA hoped to follow the BWB-17 with a subscale, low-speed test BWB later designated the X-48A and then by the X-48B (modified subsequently as the X-48C). But the program followed a different path.

Endnotes

1. Benjamin Tigner et al., *"Test Techniques for Small-Scale Research Aircraft,"* AIAA-98-2726 (1998), p. 10.
2. Richard P. Hallion, *Taking Flight: Inventing the Aerial Age from Antiquity to the First World War* (New York: Oxford University Press, 2003), pp. 107, 120–122, 178–210.
3. The definitive reference on NACA-NASA use of models in flight research is Joseph R. Chambers' impressive *Modeling Flight: The Role of Dynamically Scaled Free-Flight Models in Support of NASA's Aerospace Programs* (Washington, DC: NASA SP-2009-575, 2010).
4. Benjamin Tigner, Mark J. Myer, Michael E. Holden, Blaine K. Rawdon, Mark A. Page, William Watson, and Ilan Kroo, "Test Techniques for Small-Scale Research Aircraft," AIAA-98-2726 (1998), pp. 2, 10.
5. Exchange of emails between Ben Tigner and author, July 30, 2015.
6. Tigner, "Test Techniques for Small-Scale Research Aircraft," p. 1, and exchange of emails between Ben Tigner and author, July 30, 2015.
7. Exchange of emails between Ben Tigner and author, July 30, 2015.
8. Ibid.
9. Ibid.
10. Ibid.
11. Ibid., Attachment 1.
12. Tigner, "Test Techniques for Small-Scale Research Aircraft," p. 9, including quotation.
13. Ibid., pp. 1–2.
14. Exchange of emails between Blaine Rawdon and author. Information received on June 23, 2015.
15. Tigner et al., "Test Techniques for Small-Scale Research Aircraft," pp. 2–3.
16. Ibid., pp. 7–8.
17. Ibid.
18. Exchange of emails between Blaine Rawdon and author. Information received on June 23, 2015.
19. Tigner et al., "Test Techniques for Small-Scale Research Aircraft," p. 10.
20. Exchange of emails between Ben Tigner and author, July 30, 2015.
21. Exchange of emails between Blaine Rawdon and author. Information received on June 23, 2015.
22. Exchange of emails between Ben Tigner and author, July 30, 2015.



The proposed BWB Low-Speed Vehicle (LSV) testbed would have differed in size and performance from the X-48B that succeeded it. (NASA)

CHAPTER 5

NASA's First Effort: The Blended Wing-Body Low-Speed Vehicle

> The BWB Low Speed Vehicle (LSV) was envisioned as a small remotely piloted vehicle (RPV) designed exclusively to answer questions about the low speed portion of the envelope. In order to accurately assess flying characteristics of the BWB airframe, the LSV project wished to maintain full dynamic scaling as closely as possible.
>
> —*Albion H. Bowers, NASA Dryden Chief Engineer, BWB-LSV*

The first attempt to fabricate a BWB vehicle following the BWB-17 small-scale Stanford project involved a larger-size Low-Speed Vehicle (LSV) Technology Demonstrator that the U.S. Air Force formally designated the X-48A Experimental Aircraft on October 12, 2001.[1] Originally, there was a plan also to build a High-Speed Vehicle (HSV) that never got beyond some initial planning. The LSV vehicle was planned to be a 14.2-percent scaled representation of a Boeing D3290-450-1L BWB commercial aircraft configuration.[2] The 14.2-percent scale was smaller than the planned McDonnell Douglas 24-percent scaled vehicle plan reviewed in chapter 2, but it was larger than the follow-on successful X-48B program's 8.5-percent dynamically scaled aircraft. The LSV project was led by NASA Langley with NASA Dryden and Boeing involvement. NASA did the preliminary design work for the demonstrator and managed the project. The initial Systems Requirements Review was presented on April 14, 1999, and the Preliminary Design Review was completed in May 2000. The project, however, ended in 2001 before completion. In addition to the work reviewed below, very significant wind tunnel testing was conducted on the BWB LSV concept, as reviewed in chapter 6.

NASA, Boeing, and the Next Steps Forward on the BWB

NASA Evaluates Its In-House RPV Fabrication Capability

In the summer of 1997, NASA Langley executives held a meeting to gauge the capability for the research center to design, fabricate, and test remotely piloted vehicles (RPVs). At this meeting, Langley Director Jeremiah F. Creedon posed the following question: "can LaRC build a research aircraft using in-house resources?" The intended aircraft was a remotely piloted vehicle rather than a piloted airplane. Other than the Director, only one Langley engineer attending the meeting believed that Langley had this capability. Nevertheless, the meeting attendees agreed to charter a "Tiger Team" to investigate RPV construction capability at Langley.[3] A few months later, the team reported back that, in their view, Langley had the capability to undertake such a project. The Tiger Team report, along with Boeing's BWB study team report and followup discussions with NASA, set the stage for the BWB-LSV program to go forward. However, it should be noted that the Tiger Team identified a skill they believed to be missing at Langley—the ability to integrate all of the systems necessary to assemble an operational vehicle. The team thought, however, that the skill could be "grown in-house" or obtained from outside sources.[4]

The Tiger Team report and related followup discussions set in motion the attempt to fabricate a BWB High-Speed Drop Vehicle (HSDV). Followup discussions with Langley's systems engineers, model designers, aerodynamic and design staff, and fabrications units generated consensus among participants that the HSDV was a considerable step beyond what Langley had attempted to accomplish in house, but also that, given adequate support and resources, it was both achievable and attractive. Recalling lessons learned from the X-36 project, the Tiger Team recommended bringing Dryden in as a research and flight operations partner at the beginning of the project.

As a result, Darrel Tenney and Robert McKinley initiated discussions with Dwain A. Deets, Director of the Aerospace Projects Office at NASA Dryden, in May 1998. Tenney and Deets, who were the managers of the Airframe Systems and Flight Research Base Programs, verbally agreed to undertake the HSDV work as a joint project funded by the two base programs. Thereafter, Robert McKinley assembled a project team from both Centers.[5] Following the Boeing and MDC merger, NASA Langley remained committed to continuing BWB configuration development work and, while concerned about the impact of the merger on the project, still proceeded with the Center's work on the BWB concept under the Airframe Systems Base Program. Also, the BWB concept became a "comparative baseline for advanced concepts" within the Center's Systems Analysis Branch.[6]

Boeing Evaluates Continuing McDonnell Douglas' BWB Work

As discussed previously, soon after the merger, Boeing initiated a several-month "in-depth" technical study overseen by Michael Burtle to decide whether or not to continue McDonnell Douglas' BWB work. Burtle presented the team's findings to NASA during a meeting held in Seattle, WA, on April 15, 1998 (one month earlier than the Langley-Dryden meeting regarding the development of a High-Speed Vehicle reviewed above). Boeing attendees included Michael Henderson and Robert Liebeck. NASA attendees included Darrel R. Tenney (Director, Airframe Systems Program Office), Douglas L. Dwoyer (Director for Research and Technology Group), Joan G. Funk (Langley's first LSV project director), and Robert E. McKinley, Jr. (LSV project manager from 1998 into 2000). Finding "no showstoppers," the Boeing study team generally accepted the results of the McDonnell Douglas and NASA research efforts. The team, however, had two concerns relating to the BWB. One was the development of an economically viable noncylindrical pressure vessel, and the other involved the behavior of the vehicle at the edge of the flight envelope. Both concerns were significant factors addressed in the studies reviewed earlier and in subsequent BWB program efforts. Critical areas related to weight, operating costs, and fuel burn.[7]

The team's findings, and the lengthy group discussion among the attendees, emphasized the need to address the issues relating to flying a low-speed BWB aircraft near and at the edge of the flight envelope (entry into stall, engine-out stall, and tumble) as well as the issues related to high-speed behavior such as dive and buffet. Researchers said that "for a BWB configuration, investigation of this behavior is extremely risky…. No one has ever deliberately performed this research" [and that] "[t]his type of research was not performed on the Northrop Grumman B-2" stealth bomber. Instead, wind tunnel models were tested to gather the stability and control data necessary to develop the flight control laws for the B-2. This approach, however, would not be viable for a commercial transport because the entire flight envelope must be well understood and quantified in order to receive FAA certification.[8]

While there appeared to be general agreement that a single vehicle could be built to test both the low- and high-speed regimes, it was noted that such a vehicle would be "extremely" risky and expensive. Following Burtle's presentation, another approach was discussed based on NASA's experience with large, remotely controlled or piloted unpowered drop models of 10-percent to 25-percent scale. If researchers applied proper scaling laws for the flight regime, models could be designed to test the edges of the flight envelope without risking the full-size research demonstrator. For testing the low-speed segment of the flight envelope, dynamic scaling relationships were critically important. These relationships focused on the mass of the vehicle and the corresponding mass moments of inertia relating to pitch, roll, and yaw. For the high-speed part of the envelope, fidelity to Mach number and wing loading was critical.[9]

During the discussion that followed the briefing, participants proposed two drop models. Each would have the same outer mold line, and both would have an approximately 9-percent scale resulting in wingspans of about 22 feet. This sizing and scale were determined based on the size limitations imposed by the drop pylon and available clearance on the NASA Dryden NB-52B launch aircraft. One model would be a high-speed version to address dive and buffet, and the other model would be a low-speed version to address stall and spin/tumble entry. At this time, the consensus was that NASA Langley would design and build the High-Speed Drop Vehicle (HSDV) and that Boeing would design and build the Low-Speed Drop Vehicle (LSDV). The High-Speed Drop Vehicle would be almost entirely metal, would weigh approximately 7,000 pounds, and would be launched from Dryden's NB-52B mother ship from an altitude of 50,000 feet.[10]

By late June 1998, the core of a NASA (Langley and Dryden) and Boeing Phantom Works team was in place, and system planning efforts and vehicle design work continued throughout the summer of 1998. At this time, Robert McKinley proposed forming an aeronautics project unit within Langley, though NASA did not accept this recommendation. As a result, McKinley noted, the cascading effects of this decision led to "struggles for workforce resources and a perception of low priority" for the project.[11]

On August 26, 1998, Boeing, Langley, and Dryden representatives gathered at Dryden for another meeting, this one to coordinate the BWB Drop Vehicle program between them. Based on the meeting agenda, both the LSDV and HSDV were still under consideration: topics covered included drop vehicle technical objectives, program framework, Low-Speed Drop Vehicle overview (presented by Boeing's Norman Princen), and High-Speed Drop Vehicle overview (presented by Langley's Robert McKinley).[12]

NASA and Boeing authorities determined team composition and responsibilities at a followup meeting at the end of fiscal year (FY) 1998, also setting the groundwork for two very important follow-on decisions. First, NASA held discussions concerning Boeing's desire to have a powered low-speed vehicle. Next, the team acknowledged that the low-speed vehicle was the more important of the two vehicles from a research perspective. Finally, at this meeting the principals agreed that with proper management, they could construct and fly a High-Speed Drop Vehicle for approximately $6 million, within approximately 30 months.[13]

However, the situation quickly changed. Boeing's leadership decided that the company could not then invest the necessary funds into developing the low-speed vehicle. Accordingly, Boeing asked NASA to assume the responsibility for the low-speed vehicle and place the HSDV on hold. NASA agreed and, in late January 1999, held a second kickoff meeting at Dryden. At this meeting, important issues raised included a powered versus unpowered vehicle, scale, weight estimates, outer mold lines, and other basic characteristics. The most important decision made at this meeting was the decision to switch from an unpowered drop model (such as the earlier McDonnell Douglas F-15 Remotely Piloted Research Vehicle (RPRV) departure-and-spin research vehicle flown in the mid-1970s) to a powered alternative (such as the Rockwell Highly Maneuverable Aircraft Technology [HiMAT] supersonic RPRV flown in the early 1980s) in order to satisfy Boeing's desire to obtain engine-out stall data from the test vehicle.[14] Furthermore, since some of the desired maneuvers are in a departure envelope area involving takeoff and landing, a powered vehicle, as opposed to drop models, was required.[15]

A NASA meeting summary document identifies a meeting held on January 20, 1999, to establish roles and responsibilities prior to a meeting scheduled for January 26–27, 1999. While the January 20 meeting summary deals mostly with control systems design, analysis, and testing, it does contain the following statement indicating a powered vehicle: "Engine instrumentation is not completely defined, but the Navy contacts indicated that it is cheaper to do in-house rather than asking Williams to do the work (assuming WJ24-8 is used)."[16] The meeting summary also provided the following project challenge and potential use of the LSV:

> There has been much progress over the past two decades in the area of control theory…. However, little or none of these theoretical advances have found their way into day to day design methods for aircraft control law design. A number of these methods have been successfully demonstrated through batch or piloted real-time simulation but not in the actual flight of a test vehicle. These technologies are "stuck" at a Technology Readiness Level (TRL) of 3 or 4. Movement to TRL of 5 or 6 has been thwarted by the lack of a safe, economical and robust demonstration flight vehicle.[17]

Three "challenges" were identified—NASA's Spacecraft Control Laboratory Experiment (SCOLE), NASA's Control Structures Interaction (CSI) Testbed, and a European Group for Aeronautical Research and Technology in Europe (GARTEUR) Program[18] that ran from 1995 through 1997. The GARTEUR Program, which was used as a model, involved efforts to develop automatic flight control systems for a stated set of maneuvers for two different "futuristic" concepts—a transport aircraft and a fighter aircraft. The teams included controls specialists from European universities, industry, and government

Definition of Technological Readiness Levels

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or flight)
TRL 7	System prototype demonstration in a ground or flight environment
TRL 8	Actual system completed and "flight qualified" through text and demonstration (ground or flight)
TRL 9	Actual system "flight proven" through successful mission operations

laboratories. The developed design methods were carried through the program's simulation phase.[19]

NASA intended to expand on the GARTEUR program model by adding actual flight-test capability using the Low-Speed Vehicle. Meeting this challenge would require providing the following:

- A common mathematical model of the vehicle in a nonproprietary medium;
- A set of required maneuvers to be flown;
- A set of evaluation criteria relative to the required maneuvers;
- A common format for each design team to report on its method and results;
- A set of evaluators from industry, universities, and government laboratories.[20]

The proposed timeline is provided in Table 5-1.

The next step was engine selection. Three different engines were under consideration: hobby engines with approximately 50 pounds of thrust that would limit the vehicle scale to 9 percent or less; the Williams International WJ24-8 with 240 pounds of thrust that was suitable for a scale of between approximately 13 percent to 15 percent; and the Williams International F107 (a cruise missile engine) at approximately 700 pounds of thrust that would enable a scale greater than 20 percent. The planned initial instrumentation and systems weight estimates ruled out the 50-pound-thrust hobby engines. The 700-pound-thrust engines were rejected since three would weigh about 6,000 pounds. This left only the 240-pound-thrust Williams International engines.

Table 5-1. Proposed LSV Schedule as of the January 20, 1999, Meeting

Activity	Schedule
Government Design Challenge Management Team Assembled	June 1999
Common Mathematical Model Environment Downselect	July 1999
Challenge Requirements Document, Evaluation Criteria, and Format Completed	December 1999
NASA Research Announcement of Design Challenge	March 2000
Selection of Participants Completed	May 2000
Design Completed and Results to NASA for Evaluation	December 2000
Evaluations Completed by Evaluation Team	May 2001
V&V Completed for Flight Tests of Successful Designs	October 2001
Flight Tests Completed	March 2002
Final Report	September 2002

The selection of these engines resulted in setting the scale for the vehicle at 14.2 percent. The operating empty weight was set at 1,243 pounds, and the maximum landing weight was set at 1,848 pounds. The very rough weight breakdown estimated the airframe weight at less than 600 pounds and the instrumentation weight at approximately 250 pounds; the weight of everything else (fuel, engines, power, wiring, actuators, etc.) was set at approximately 400 pounds. However, no bottom-up weight estimate followed, and many team members recognized that the weight breakdown was very optimistic. Due to this concern, the dynamically scaled weight was made a goal, rather than a requirement.[21]

Overview of BWB Low-Speed Vehicle Project

Planned Vehicle Characteristics and Components

The BWB LSV was planned to have the following component subsystems and responsible authorities: airframe (Langley), propulsion (Langley), communications and tracking (Langley), flight control system (Dryden), power (Langley) audio/video (Dryden), recovery (Boeing), and flight termination (Dryden). The ground support systems included ground communications, a flight station, telemetry and data, and vehicle ground support. System integration areas included vehicle integration (Langley), ground systems integration (Dryden), and vehicle-to-ground integration (Dryden).[22]

The planned vehicle was based on a dynamic scale of 14.2 percent, compared with the 8.5-percent scale ultimately used for the X-48B. This planned vehicle would have resulted in a 35-foot wingspan, compared with the 20.4-foot wingspan for the X-48B. The planned weight ranged between a minimum of approximately 1,200 pounds and a maximum of approximately 1,800 pounds. The trailing-edge control surfaces were to consist of 14 elevons and 2 winglet rudders. The left and right wings each were planned to have two fixed-position leading-edge slats. Each of the three engines would have produced 200 pounds of thrust power. The BWB-LSV was planned to be dynamically scaled, fully instrumented, and remotely piloted for horizontal takeoff and landing. The vehicle would have telemetered data stream, spin recovery, programmable flight controls, and flight termination systems.[23]

In this first effort to build the BWB vehicle, Langley identified a number of benefits and corresponding challenges, including the ones listed below.[24]

Table 5-2. Potential Benefits Versus Known Challenges

Benefits	Challenges
Lower Operating Costs	Structures and Materials
Lower Production Costs	Aero-Structural
Reduce Airport/Airspace Congestion	Aerodynamics
Lower Air Fares	Controls
Reduce Environmental Impact	Propulsion-Airframe Integration
Improve Safety	Systems Integration and Infrastructure

Dynamic Scaling. As pointed out by Dryden's Albion H. "Al" Bowers, dynamic scaling "has a series of implications for the design, construction, and operation of the LSV." For one thing, the structure must be very lightweight in order for a small subscale-size vehicle to maintain a dynamic scaling representation of the full-size airplane. "Time" also must be scaled, requiring "the loop closure of the active control system" to be highly constrained. It is difficult to satisfy these requirements, and at many scale sizes, dynamic scaling cannot be done. The project team considered a number of different scales but ultimately decided on the 14.2-percent scale size for the LSV. This resulted in a 30-millisecond closure requirement in the control system from the sensor to the actuator.[25]

Systems Requirements, Studies, and Identified Risks. The primary requirement for the Low-Speed Vehicle project was to deliver a 14.2-percent dynamically scaled remotely piloted vehicle. The empty weight was 1,193 pounds with a maximum weight of 1,778 pounds. The maximum vehicle speed was set at 145 knots. Planners assessed vehicle fabrication by undertaking two studies, one on skin panel impact on vehicle weight growth, and the second evaluating the practicality of using flat panels in place of a complex structure with custom ribs and bulkheads. Systems risk assessment identified the following potential problems:

- Increased cost and weight.
- Operational flight safety factors—since the vehicle has to actually fly, the design must be optimized for mission weight and maximum strength. (The presentation noted that there was minimum in-house remotely piloted vehicle experience.)
- Dynamic scaling—the final dynamic scaling could not be determined because some vehicle equipment remained unspecified.[26]

Recovery System. The Systems Requirements Review noted that the overall probability of losing the vehicle was less than 10^{-3} per flight-hour; that implies that each system failure probability was less than 10^{-5} per flight-hour. The loss probability influenced whether to have redundant systems or a vehicle recovery system. Based on the Systems Requirements Review, the LSV team decided to develop a recovery system with the following characteristics:

- The recovery system should function across the entire operating envelope;
- The recovery system should restore the vehicle to controllable flight from spin or tumble-out-of-control situations across the entire operating envelopes;
- The maximum altitude loss from time of deployment to steady state descent from the initial condition of maximum flight velocity at 4,000 feet of altitude should not exceed 500 feet;
- The parachute system design and construction should conform to standard aerospace practices; and
- The parachutes should be of an established design with a previous history of successful deployment and operation.[27]

Another critical function to be addressed was the stability and control characteristics of the BWB class of vehicles in free-flight, including assessing the four following issues.

- Stability and controllability about each axis at a range of flight conditions. The review team set forth the following hypothesis regarding the BWB: roll control is good, yaw is poor throughout, and pitch is unstable in various regimes.
- Departure onset and out-of-control modes of motion (tumble and spin).

- Dynamic interaction of control surfaces.
- Asymmetric thrust control requirements.[28]

To assist in addressing the above issues, the team reviewed flight control algorithms designed to provide desired flight characteristics, including the following:

- Assess control surface allocations and blending.
- Assess edge-of-envelope protection schemes.
- Advance the state of the art in control theory through the application of embryonic technologies, especially in areas of nonlinear aerodynamics and during rapid maneuvers.

NASA and Boeing would share in the overall development of the flight control system, with NASA providing the basic operating set and Boeing furnishing the research set, and collaborating on the development of the control laws.[29]

LSV Program Goals

The following primary goals were tentatively set for the LSV program:[30]

- *Characterize departure onset and out-of-control modes of motion.* (The "prime objective" of the BWB-LSV project.)
- *Assess stability and controllability about each axis at a range of flight conditions.* (This goal included conducting a "comprehensive envelope expansion program up to and including the portions of the envelope that are of research interest," including assessing out-of-control modes that represent both technical and material risk. Due to the risk involved, this would come near the end of the flight program.)
- *Assess asymmetric-thrust control requirements.* (A subject of "intense" interest to Boeing reflecting an FAA certification requirement, this sized the directional control requirements for a commercial BWB. These flights likewise would come near the end of the project.)
- *Assess edge-of-envelope protection schemes.* (Another goal very important to Boeing.)
- *Advance the state of the art in control theory via application of embryonic technologies, particularly in regions of nonlinear aerodynamics and during rapid maneuvers.* (This goal was one of the primary drivers of the BWB-LSV's unique control system. The control system would incorporate two separate control laws—one for basic control and one for research—identified as the "genesis of the NASA Control Law Design Challenge" that was planned to follow the test-flight portion of the program.)
- *Assess dynamic interaction with neighboring control surfaces.* (This goal likewise was a high priority for Boeing because dynamic interactions

between the engines/inlets and the nearby control surfaces could significantly impact vehicle performance and involved extensive tunnel tests in the Langley 30-foot by 60-foot tunnel.)

- *Correlate flight measurements with ground-based predictions and measurements*. (This goal formed the basis for most of the project's data deliverables.)

Research Goals. Later, in an October 2000 presentation to the World Aviation Congress meeting held in San Diego, CA, Langley's Dan Vicroy presented the more detailed "research" BWB-LSV program goals reviewed below.[31] These goals represent a good identification of the issues that had to be, and later were, overcome.

- Explore the stability and control characteristics of a BWB-class vehicle in free-flight conditions.
    - Assess stability and controllability about each axis at a range of flight conditions. Hypothesis is that roll control is good, yaw is poor throughout, and pitch is unstable in various regimes.
    - Characterize departure onset and out-of-control modes of motion (tumble and spin).
    - Assess dynamic interaction of control surfaces.
    - Assess asymmetric-thrust control requirements.
- Develop and evaluate flight control algorithms designed to provide desired flight characteristics.
    - Assess control surface allocation and blending.
    - Assess edge-of-envelope protection schemes.
    - Advance the state of the art in control theory via application of embryonic technologies, particularly in regions of nonlinear aerodynamics and during rapid maneuvers.
    - Assess takeoff and landing characteristics.
- Propulsion/airframe integration.
    - Assess inlet conditions and sensitivity.
    - Assess dynamic interaction with neighboring control surfaces.
- Evaluate prediction and test methods of BWB.
    - Correlate flight measurements with ground-based predictions and measurements.
    - Develop the process and associated infrastructure to allow for a seamless transfer of the aircraft to DFRC [NASA Dryden] and efficacious final validation and verification of flight control system.

Management and Oversight

Program Organization and Staffing

NASA's overall BWB program fell under the Agency's Aerospace Technology Enterprise, which directed the Advanced Vehicle Systems Technology (AVST) program out of NASA Langley and the Flight Research Program out of NASA Dryden. The AVST program, which promoted the science and technology of flight, delegated direct control of the BWB Low-Speed Vehicle project to the Revolutionary Airframe Concepts Research and Systems Studies (RACRSS) unit. This level of responsibility included the addition of Boeing BWB involvement.[32] The objective of RACRSS "is to mature and develop advanced vehicle concepts," hopefully "building blocks for future advanced aircraft."[33]

Langley had responsibility for (a) overall project management and for serving as the lead for science development; (b) the design, development, and fabrication of the BWB vehicle's structural airframe, instrumentation, and related electronics; and (c) initial ground testing and support equipment. Dryden had responsibility for (a) project operations, (b) safety and assurance, (c) control law design and validation, (d) ground support testing, and (e) the remotely piloted vehicle lab. Boeing served as a co-principal investigator and had responsibility for vehicle configuration requirements and simulation model design. Old Dominion University was a partner for tests conducted in the 30- by 60-foot wind tunnel that NASA had turned over to the university.[34]

As of November 1999, approximately 76 individuals were involved in the BWB-LSV program, including 32 from Langley, 27 from Dryden, 2 from NASA Ames, 14 from Boeing, and 1 from the engine contractor.[35] Joan G. Funk was Langley's first LSV project manager, succeeded by Robert E. McKinley, Jr., who was, in turn, followed by Wendy Pennington. Frank Cutler served as Dryden project manager; Kurt N. Detweiler served as project chief engineer; Albion Bowers served as Dryden chief engineer; Dan Vicroy served as project principal investigator; and Norm H. Princen served as Boeing project manager. The leads were Mike Langford (airframe development), Bob Antoniewicz (flight systems and controls and project software), Bruce Cogan (range and facilities), Dan Vicroy (ground correlation testing), Dave Groepler (operations), and Herb Kowitz (instrumentation). Robert E. Cummings served as Dryden crew chief.[36] Warren Beaulieu served as principal investigator for Propulsion Airframe Integration (PAI).

Each titled position had assigned duties and responsibilities. The project manager was responsible for identifying project goals, verifying project objectives, managing the development and execution of the project, negotiating for commitments of project resources, and ensuring the successful completion of the project within time and budget allocations. Both Langley and Dryden had project managers, with overall project management planned to switch from Langley to Dryden once the BWB-LSV vehicle was delivered to Dryden for flight testing. The principal investigator was responsible for defining research plans and objectives, translating objectives into performance parameters, and ensuring that project research aligned with NASA Aeronautical Enterprise goals. The chief engineer was responsible for ensuring that flight vehicle and flight experiments aligned with research and technology objectives and goals and for focusing on all technical aspects of the project.[37]

Projected Budget and Schedule Timeline

Spending Plan. The near-term spending plan (FY 1999) was considered well defined at a total $1.77 million. This included $890,000 for payload electronics; $100,000 for research; $280,000 for design; and $500,000 for fabrication. The fiscal year 2000 spending plan, which was to be detailed as the effort was more clearly defined, totaled $2.145 million. This amount included $680,000 for payload electronics; $295,000 for research, $70,000 for design; and $1,100,000 for fabrication.[38]

Project Schedule. The planned timeframe for the project ranged from late January 1999, with receipt of the geometry definition from Boeing, to the first flight scheduled for late June 2001. The preliminary design review was set for November 1999, with the critical design review planned to take place by March 30, 2000.[39]

Table 5-3 represents the projected timeline.[40]

Proposed Test Flight Plan and Operational Procedures

Ground Support and Operations. On March 29, 2000, Dryden presented its Preliminary Design Review for the conduct of ground support and operation activities for the LSV project. In addition to a review of the ground equipment that would be needed, David Groepler identified the extensive operations activity planned for the flight center. The ground test plan included weight and balance checks; ground vibration tests using external shakers and accelerators; mass moments of inertia checks to verify pitch, roll, yaw, and cross coupling inertia; low-speed and high-speed taxi tests; and spin chute deployment tests.[41]

Although neither completed nor flown, the BWB-LSV (a.k.a. the X-48A) had a detailed flight plan that incorporated Dryden's past remotely piloted vehicle flight-test experience and that, no doubt, influenced the successful follow-on X-48B and X-48C vehicles' flight operations. Naturally, the authors of the flight plan assumed that the Systems Requirements Review, Preliminary Design Review, Critical Design Review, Flight Readiness Review, and Airworthiness

Table 5-3. Projected Timeline (as of July 7, 2000)

Task	Projected Date
First Bending Mode Study	September 2000
Update finite element analysis (FEA) Model	September 2000
RPV Cockpit Critical Design Review	October 2000
Project Plan Signed Off	November 2000
14 × 22 Wind Tunnel Data Delivery	November 2000
Preliminary Design Review	December 2001
Airframe Critical Design Review	March 2001
FCS (Flight Control System) Bench Tests Start	May 2001
Vehicle Critical Design Review	June 2001
Integration Load	September 2001
System Hardware Delivery	September 2001
FCC (Flight Control Computer) Delivery	September 2001
Centerbody Shell Delivery	October 2001
Pre-Closure Integration Start	October 2001
Wind Tunnel Load	February 2002
Post-Closure Integration Start	March 2002
Structures Proof Tests Start	May 2002
Systems Function Tests Start	July 2002
Flight Load	July 2002
30 × 60 Wind Tunnel Test	November 2002
Deliver to NASA Dryden	December 2002
Vehicle Integration Tests Start	December 2002
First Flight	December 2003

Flight Safety Review Board would all be completed and the "proceed to the test flight" phase approved, which, of course, did not occur.[42]

Al Bowers, who served as chief engineer for the BWB-LSV project (subsequently becoming the Armstrong Center's Chief Scientist), identified several predecessor programs that, together, afforded a knowledge base for flight-testing

The NB-52B-launched unpowered McDonnell Douglas F-15 RPRV, designed to investigate the departure and spin behavior of the F-15 then under development, constituted a milestone in remotely piloted aircraft design and operations. (NASA)

the BWB-LSV. These included the McDonnell Douglas F-15 Remotely Piloted Research Vehicle (RPRV), the Ames-Dryden AD-1 Oblique Wing demonstrator, the Rockwell International HiMAT program, and the Boeing X-36 Tailless Fighter Agility program. All of these were remotely piloted, save for the AD-1, a small piloted twin-engine design.

Bowers noted that the Rockwell HiMAT of the early 1980s was the closest match for operations of the BWB-LSV making use of Dryden's infrastructure, even though the HiMAT was air-launched from NASA's NB-52B and thus could not take off on its own. The F-15 RPRV, also air-launched though unpowered, pioneered the Remotely Augmented Vehicle (RAV)[43] system uplink. The X-36 was similar to the BWB-LSV in that it had retractable landing gear for horizontal takeoff and landing and closely resembled lakebed operations by the aircraft crew. Finally, the AD-1 had similar engine systems that were close to the complexity level of the BWB-LSV.[44]

The flight operational concept included a number of tasks starting with meetings and simulations to review the research maneuvers planned for each flight. These planned maneuvers would be assembled into a set of flight cards for use by the pilot in practicing for each flight. The flight-test engineer would select the most efficient flow for conducting the flight, and the research engineers would inform the pilot and flight engineer of any special requirements.

The Ames-Dryden AD-1 Oblique Wing demonstrator was a small twin-engine piloted testbed having the fuselage, tail, and oblique-wing design of a proposed supersonic transport. Highly successful, it offered a clear example of how such a simple research aircraft could contribute to large aircraft design. (NASA)

Finally, a card review would be made by key project personnel to finalize the card set. Approximately 3 days prior to each flight, a "Mini Tech Brief" would be scheduled to review data from the previous flight and to advise senior-level managers with the "technical objectives of the proposed flight, a review of requirement elements and skills, schedule, safety assessment, and accepted risks." If the tech brief was accepted by senior management, the project team would then proceed with flight preparations. The flight systems personnel

The Rockwell HiMAT, an ambitious NB-52B-launched RPRV designed to assess the behavior of a highly agile and radically configured design blending several leading state-of-the-art technologies, furnished important lessons for NASA in how to approach risk reduction and operate what was, for its time, a very complex little airplane. (NASA)

The Boeing X-36 tailless research testbed required sophisticated flight-test management and execution, furnishing useful experience, some of which was applicable to flight-testing the X-48B/C. (NASA) would load the proper flight control software before preflight tests began. Functional checks of the research instrumentation would follow; the aircraft crew would ballast the aircraft to the appropriate weight, center of gravity, and inertia values; and research engineers would ensure that the wing slats were in proper position for what the particular research flight required. After each component was completed and sealed by the aircraft crew, logged by the aircraft crew chief, noted by the operations engineer, and witnessed and noted by quality assurance staff, the aircraft system would be made ready for flight. This process would usually take several days to complete.[45]

A crew briefing would be scheduled 1 day prior to flight. At this briefing, the pilot would review (a) the timeline for control room staffing, pilot entry, engine start, takeoff, and landing; (b) the operations numbers and assigned frequencies; (c) chase plane activity; and (d) the weather report. The aircraft crew would report on the aircraft readiness and any changes to the aircraft since the last flight. The chief engineer would report on essential personnel required to complete the research mission. The technical information engineer would report on the control room and range readiness. Finally, the pilot would brief the flight cards from takeoff through landing.[46]

Due to atmospheric conditions, the test flights generally would be flown early in the morning. The flight was planned to last 1 hour, and most of the flights would be flown in the north lakebed unmanned aerial vehicle (UAV) area. The maximum takeoff gross weight was planned at 1,840 pounds. A typical flight would not exceed an altitude of 10,000 feet mean sea level and a speed of 145 knots. A postflight briefing would be held about 1 hour after landing. In this briefing, the pilot would explain what had occurred during the flight and each disciplinary engineer would explain any observations they had. The operations engineer would give a postflight inspection assessment, and the project manager would provide a summary, along with future plans.[47]

Flight Day Operations Schedule. Assuming that a "quiet" atmosphere existed, the test-flight day routine would start at 2 a.m. with a planned completion time of 7:30 a.m., pursuant to the following schedule:[48]

0200	Crew reports for duty
0430	Low-Speed Vehicle deployed to lakebed
0500	Control room staff reports for duty
0600	Pilot enters Remotely Augmented Vehicle (RAV) Lab cockpit
0620	Engine start
0630	Takeoff
0730	Landing (1 hour planned for typical flight)
0730	Crew recovery

Accomplishments, Issues, and Termination

The BWB-LSV project made significant progress through October 2000 with completion of the following tasks:[49]

- Systems Requirements Review (FY 1999).
- Outer Mold Line delivered and mold programing started (FY 1999).
- Remotely piloted vehicle cockpit Systems Requirements and Preliminary Design Reviews completed (FY 1999); Critical Design Review completed (October 2000).
- Low-Speed Vehicle landing gear delivered, assembled, and tested (FY 2000).
- Centerbody and wing lower skin manufacturing molds completed (FY 2000).
- Preliminary Design Review completed May 2000.
- Spin tunnel tests completed FY 2000.
- 3-percent model delivered to 12-foot tunnel and testing completed (June 2000).
- 3-percent model testing in 14×22-foot tunnel started in October 2000.
- Flight Control Actuator test stand designed and built.
- Four engines-assembly and acceptance test completed.

The above progress, however, was not enough to overcome issues that soon led to the termination of the project.

Preliminary Design Review Hints at Problems

NASA conducted a BWB-LSV Preliminary Design Review at Langley on May 2–4, 2000. A poll of the panel members indicated that the "project had a well-organized package and presented the proper subject matter for the majority of the technical and management areas necessary to address the requirements of a PDR." The panel, however, identified the three following concerns for the "fiscal and performance success of the project":[50]

- Lack of an aircraft design (or alternative design) that meets all requirements for the BWB-LSV.
- The mass properties of the design as presented were significantly over budget and there was no clear solution.
- The project must close very quickly on a design that meets all requirements or descope the requirements. Delay in reaching this position threatens cost and schedule.

The panel added that there was "a lack of a single technical position that can make the technical and tradeoff decisions spanning all partners for the project."[51]

Termination of the LSV (X-48A) Program

A combination of different factors contributed to the decision to cancel the BWB Low-Speed Vehicle in 2001. Various reasons for project termination have been given by a number of different sources. Joseph R. Chambers, writing for NASA, stated:

> The LSV Program encountered major problems as flight control development had to be put on hold when commitments to other programs changed the agency's priorities and resource allocations…due to higher priority program commitments…the program had successfully completed a preliminary design review of the vehicle's airframe, an initial round of structural material coupons and elements testing, structural design of proof-of-concept wing box testing, and fabrication/assembly of the centerbody and wing molds for the composite LSV.[52]

The editors of *Jane's All the World's Aircraft*, in a much later update to the BWB X-48B program, provided the following overview of the earlier LSV project:

> Construction began in 2000, at which time it was still known as the BWB-LSV, but it was subsequently assigned the experimental X-48A designation shortly before the end of 2001. Production and assembly of the X-48A was expected to have been completed by the end of 2002, with a lengthy series of ground testing planned for most of 2003, leading up to flight trials in 2004. In [any] event, the X-48A was quietly cancelled, among the reasons cited being difficulties encountered with the flight control system and budgetary considerations on the part of NASA.[53]

But as well, a number of program participants noted the impact on the LSV development effort of the loss of the experimental X-43A supersonic combustion ramjet (scramjet) testbed over the Pacific Test Range following launch on its first flight test on June 2, 2001. The X-43A stack, air-dropped from Dryden's Boeing NB-52B Stratofortress mother ship, consisted of the Micro Craft X-43A scramjet Hyper-X Research Vehicle (HXRV), the interstage adapter, and Orbital's modified Pegasus winged booster; taken together, the combination was known as simply the "stack." The root cause of the loss of the X-43A was a flight control failure. Simply put, the control system was unable to maintain stack stability during transonic flight. That caused the stack to enter a pitching oscillation so severe that the Pegasus booster lost its right elevon, at which point the stack went totally out of control and was destroyed by range

The ill-fated first X-43A Hyper-X launch stack under its NB-52B at Dryden in March 2001. Note the small Micro Craft X-43A scramjet test vehicle and the large modified Orbital Pegasus booster. The right elevon that separated is visible at the rear of the booster. (NASA)

safety. Contributing to the loss were inaccurate analytical models that did not properly address the flight conditions encountered on the vehicle's planned boost trajectory. The investigation was complex and required a significant commitment of time and resources before NASA's leadership cleared the X-43A to return to flight.[54] (Thereafter, the second and third X-43A's did attain their program objectives, including a last flight to beyond Mach 9.) Some of the LSV project participants believed that the increased time and resources needed to fix the ailing X-43 program caused NASA to divert funding and resources from the LSV, thus contributing to its demise.

As well, the LSV (X-48A, as the Air Force had designated it) was encountering its own technical problems, particularly weight growth. Blaine Rawdon (one of the Boeing liaisons for the program, along with George Rowland) pointed out that "the problem with a small version of an optimized large airliner is that achieving the needed light weight is very difficult…. To succeed, each discipline needs a sharp focus on the vehicle's weight and there must also be an overarching focus" because there can be a tendency of engineers working in each separate discipline to focus their attention on the function of their particular component rather than on the overall function of the airplane.[55] Boeing's concerns regarding increasing weights, which were noted by Rawdon and others, most likely played a role in the project's cancellation. In any event, Boeing became increasingly convinced that the overall likelihood of success and the high cost of continuing had the potential to derail the BWB program and that it was time to plan for an alternate, smaller, and lower-cost demonstrator.[56]

NASA Langley's Robert McKinley, in his October 9, 2000, overview report noted:

> On 5 October 2000, all work on the BWB-LSV Project was stopped until the NASA Project and Program Offices and Boeing management can agree upon some specific design requirements. Boeing is aggressively lobbying for a vehicle that can meet the dynamic-scaling goal for engine-out stall (i.e., define the asymmetric minimum control airspeed, V_{MCA}) in flight. The BWB-LSV principals at NASA…agree that this is a noble goal; however, the physics will likely rule out defining this point in flight.[57]

McKinley went on to address overweight issues with the LSV, noting that the current design LSV Operating Empty Weight (OEW) was 2,300 pounds, while the OEW weight should not exceed 1,600 pounds. He added that when all of the vehicle systems, flight envelope limits, and structural margins were set, the original OEW goal of 1,243 pounds still was not feasible. Furthermore, even with the major weight reduction efforts that the team had made, McKinley believed that reducing the OEW below 2,000 pounds was highly unlikely. Finally, McKinley made the following overall project observation:

> This situation has precipitated the work stoppage noted above, pending resolution of the requirements by the project partners. If an acceptable compromise can be reached, the project may continue to Preliminary Design Review (PDR) and the associated Commitment Review (CR) in late 2000 or early 2001. If a compromise is not feasible, work on the LSV itself will likely end.[58]

McKinley also connected the overweight issue with the reallocation of resources noted above, adding:

> The conflict over vehicle weight and other related issues is also being waged inside NASA. Resources, both workforce and financial, are under attack at NASA-LaRC and at NASA-DFRC. Dryden is an integral partner in this activity, especially in terms of the flight control system, operations, and the actual flight research. Funding under the original "handshake" agreements…

> is now at risk due to other pressures, and workforce is needed for space-related activities at Dryden. At Langley, the workforce is needed to support a variety of other activities. Both Centers will (hopefully) re-enlist their support at the CR following the PDR. Current estimates place the final net cost of the BWB-LSV at around $16M with a first flight around December 2003.[59]

There are indications that, due to a combination of the issues noted above, the program might simply have ended "quietly," as noted by *Jane's All the World's Aircraft*, by NASA not including funding in the following year's budget. No formal termination order or termination report could be located.

McKinley held out a glimmer of hope for saving the project or at least providing significant test data for use in any follow-on efforts. He noted that ending the LSV project would not terminate BWB research at Langley because the BWB Remotely Piloted Vehicle was only one component of a larger set of research activities. This was because all of the activity was directed toward developing a piloted simulation of the full-scale vehicle and that, in the absence of the actual vehicle, a flight simulation could still be created around wind tunnel, computational fluid dynamics, and analytical data. McKinley added that "if funds and workforce at Langley were not tied up in the RPV, it is likely that some high-speed wind-tunnel efforts, including aeroelasticity, would be undertaken instead."[60]

The BWB Program Survives and Moves Forward

Even though the LSV "first effort" program was not completed, BWB work resumed later on a smaller X-48 version, which the U.S. Air Force officially designated the X-48B on June 16, 2005.[61] The program continued after the Boeing Commercial Airplane Division agreed to provide some funds for continuing the BWB work. Boeing, however, did not want to build the vehicle in-house. They decided to scale the X-48 down to a 20.4-foot-wingspan subscale vehicle and to contract out the fabrication work to Cranfield Aerospace. The continued efforts, which are reviewed in the remaining chapters of this book, resulted in the X-48B and its modification to the X-48C.

Endnotes

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2. Robert E. McKinley, Jr., "BWB Envelope Limit Vehicle Project; Systems Requirements Review," April 14, 1999, System Requirements Section, presented by Kurt N. Detweiler, Systems Manager, p. 24.
3. A "Tiger Team" is a NASA term for a special team formed to investigate an important issue or problem.
4. Robert E. McKinley, Jr., "Blended-Wing-Body Low-Speed Vehicle Project Formulation," NASA Langley Research Center, September 26, 2000, p. 9.
5. Ibid., p. 9, including quotations.
6. Ibid., p. 6.
7. Ibid.
8. Ibid.
9. Ibid., p. 8.
10. Ibid.
11. Ibid., p. 10.
12. Meeting notes and agenda provided to author by Dan Vicroy on August 26, 2015. Dan Vicroy attended the meeting.
13. McKinley, "Blended-Wing-Body Low-Speed Vehicle Project Formulation," p. 10.
14. Ibid.
15. Al Bowers, "Blended Wing Body Low Speed Vehicle Operational Concept Document," NASA Dryden Flight Research Center, February 14, 2000, p. 3.
16. Author not identified, "Summary of NASA Meeting, 1/20/99," January 21, 1999.
17. Ibid., p. 3, quotation credited to Jim Batterson.
18. GARTEUR (Group for Aeronautical Research and Technology in Europe) was formed in 1973 by France, Germany, and the United Kingdom. The Netherlands joined in 1977, Sweden in 1991, Spain in 1996, and Italy in 2000. The organization's mission "is to mobilise, for the mutual benefit of the GARTEUR member countries, their scientific and technical skills, human resources and facilities in the field of aeronautical research and technology…." See *http://www.garteur.org/* (accessed on September 18, 2015).
19. Author not identified, "Summary of NASA Meeting," p. 4.

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22. McKinley, "BWB Envelope Limit Vehicle Project; Systems Requirements Review," Vehicle Configuration Requirements Section, presented by Norman Princen, pp. 15–17.
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24. Dan D. Vicroy, "NASA's Research on the Blended-Wing-Body Configuration," October 10, 2000, p. 8.
25. Bowers, "Blended Wing Body Low Speed Vehicle Operational Concept Document," pp. 1–2.
26. McKinley, "BWB Envelope Limit Vehicle Project; Systems Requirements Review," Systems Definition Section, pages not numbered.
27. Ibid., pp. 2–3 of Recovery System Section, pages not numbered.
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33. Ibid., pp. 2, 5.
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36. Wendy F. Pennington, "Preliminary Design Review: Project Plan," NASA Langley, May 2–4, 2000, p. 2.
37. Untitled document attachment emailed to author by Wendy F. Pennington on August 10, 2015.
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39. Ibid., p. 4.
40. Pennington and Detweiler, "Blended Wing Body—Low Speed Vehicle Project: Project Overview," p. 14.

41. Dave Groepler, "Preliminary Design Review: Ground Support & Operations," March 29, 2000, pp. 8–10.
42. Bowers, "Blended Wing Body Low Speed Vehicle Operational Concept Document," p. 4.
43. Remotely Augmented Vehicle (RAV) capability uses ground-based computers to supplement or replace onboard control and display systems.
44. Bowers, "Blended Wing Body Low Speed Vehicle," p. 4.
45. Ibid., p. 5, including quotation.
46. Ibid., pp. 5–6.
47. Ibid., pp. 6, 11.
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51. Ibid.
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53. Paul Jackson et al. (eds.), *Jane's All the World's Aircraft, 2007-8* (London: Jane's Information Group, 2007), p. 312.
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56. Email exchange between Blaine Rawdon and author. Reply received on June 23, 2015.
57. McKinley, "Blended-Wing-Body Low-Speed Vehicle Project Formulation," p. 11.
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A 5-percent scale free-flight model of the BWB-450-1L configuration “flying” in the historic NASA Langley Research Center Full-Scale Tunnel. (NASA)

CHAPTER 6

Aerodynamic Testing and Vehicle Fabrication

> There is a high degree of uncertainty associated with many aspects of the vehicle's aerodynamics, stability and control. As a highly cost-effective method of risk reduction in these areas, the [Cranfield] programme incorporates the design and manufacture of a flying test-bed to evaluate and explore the aerodynamic characteristics of the configuration.[1]
>
> —*John Fielding and Howard Smith*

Fittingly, given NASA Langley's role in initiating the BWB development effort, aerodynamic testing of the blended wing-body concept started in August 1997 at the Center. The aerodynamic work fell into three phases:

- Initial concept development testing done in the mid- and late 1990s.
- Follow-on work leading to the X-48B and thence to the X-48C.
- Continuation research after X-48B and X-48C flight testing.

Boeing, the University of Southern California (supported by Swift Engineering), and the U.S. Air Force's Arnold Engineering Development Center (AEDC) also did important BWB testing. The aerodynamic testing blended traditional wind tunnel research with computational fluid dynamics (CFD) and analytical tools including the Constrained Direct Iterative Surface Curvature (CDISC) and Multidisciplinary Design Optimization (MDO).

Langley Tunnel Testing and Computational Methods

Langley BWB testing employed the 12-Foot Low-Speed Tunnel, the 20-Foot Vertical Spin Tunnel, the 14- by 22-Foot Subsonic Tunnel, the National Transonic Facility (NTF), the Transonic Dynamic Tunnel, the Unitary Plan Wind Tunnel, and, in the case of the free-flight test, the Langley Full-Scale

Tunnel (the famed NACA-NASA Langley 30- by 60-Foot Tunnel) operated by Old Dominion University.[2]

Dynamic Tunnel Testing Techniques: A Review

Langley used dynamic test techniques to conduct research into the flight dynamics of the BWB vehicles. These techniques included "dynamic stability measurements, simulation verification, control law design, aerodynamic modeling, spin/tumble prediction, spin/tumble recovery systems, and flying qualities assessments."[3] The research techniques fell within three categories:[4]

- *Captive.* This category consisted of forced oscillation and rotary balance tests to measure the damping and rotary derivatives. Researchers used these measurements, along with those from static tests, to develop the mathematical model (known as the aero-model) representing the BWB's aerodynamics.
- *Wind Tunnel Single Degree-of-Freedom.* This category included free-to-roll and free-to-pitch testing used as intermediary steps to free-flying tests. Researchers assessed unsteady aerodynamic effects on the motion of the model to obtain a rapid assessment of unsteady aerodynamics. The models did not require dynamic scaling.
- *Wind Tunnel Free-Flying Vehicles.* Researchers used dynamically scaled and instrumented models, for a series of free-flight and spin tests, complementing the Stanford research on the BWB-6 series and BWB-17. Free-flight models investigated BWB flying qualities and control law effects up to a desired maximum trim angle of attack, or until the BWB model departed from controlled flight. The spin tests evaluated post-stall, equilibrium spin, and tumble modes and supported design of spin/tumble recovery systems.

Langley aerodynamicists noted that

> By adhering to the appropriate scaling rules, these model techniques enable accurate prediction of flight dynamics across a wide range of flight phenomena that are difficult if not impossible to ascertain in any other way. Therefore, an aircraft program can use this battery of dynamic test techniques for a comprehensive assessment of the aircraft flying qualities.[5]

Design Methods—CFD and CDISC Analysis

Richard L. Campbell, a senior research engineer at Langley, reviewed the use of computational fluid dynamics and the Constrained Direct Iterative Surface Curvature method in the aircraft design process, noting that advances in computational fluid dynamics, which provide accurate and detailed flow solutions, generated interest in integrating CFD code into automated aerodynamic design methods. These methods include two general categories—inverse methods using inverse solvers and predictor/corrector methods using direct flow analysis in an iterative manner. Aerodynamicists found that "[t]he predictor-corrector methods can be coupled with any flow solver and hence take advantage of the advances in Computational Fluid Dynamics."[6]

Computational Fluid Dynamics. By 1998, the use of CFD methods had "become an integral, perhaps even dominant, part of the aircraft aerodynamic design process."[7] Campbell added that the reason for the increased reliance on CFD was due to

- improvements in computer hardware and flow solver algorithms,
- improvements in grid generation methods, and
- improved accuracy in the use of Navier-Stokes codes with new turbulence models.

These three factors have greatly reduced the time needed to perform Navier-Stokes analysis and have reduced the time needed to develop grids around nearly complete aircraft configurations. Campbell stated that "even though CFD has produced some results that rival the accuracy of wind tunnel data, it has not replaced the wind tunnel and is not likely to do so in the near future."[8]

Campbell added, however, that

> [w]hile CFD has not replaced the wind tunnel, it has been elevated to a partner status in the design process…[and w]hile expert aerodynamics in the past certainly did produce configurations with good performance using cut-and-dry approaches in the wind tunnel, the automated CFD design methods available today can produce significantly improved configurations in much less time,[9]

thus adding more tools for aerodynamicists to achieve their goals.

He listed the following desirable attributes of a CFD analysis of design method:

- Quick set-up time;
- Robustness;
- Short turnaround time;
- Accuracy; and
- Ease in interpreting the results.[10]

CDISC—Hong Hu, of Hampton University, described the CDISC method as follows:

> The Constrained DISC method (CDISC method) is an extension of the basic DISC method. The DISC method employs a pressure-based predictor-corrector design procedure, where the calculated surface pressure distribution is compared with a target distribution and the correction to surface geometry is then made to achieve the target pressure distribution. In more detail, the DISC method starts with an initial surface geometry and flow condition at design point, a flow analysis is used to generate surface pressure distribution. The calculated pressure distributions are then compared with the target distribution and the difference gives the correction to the surface geometry through a design module. A new geometry is obtained and the flow analysis code is used to generate a new surface pressure distribution until the target pressure distribution is achieved.... The Constrained DISC method specifies desirable characteristics of the target pressure distribution. The target pressure is automatically generated and updated at each step based on the specified characteristics—the constraints. The typical flow constraints are lift, drag, pitching moment and pressure gradient. The typical geometry constraints are airfoil maximum/minimum thickness and leading edge radius, and so on. Including geometry constraints in the design process will yield an airfoil/wing/rotor blade that not only satisfies target pressure distributions but also will be practical to build. In CDISC design method, constraints are easily included in the design process to satisfy various design requirements.[11]

Constraints in CDISC fall into three major categories:

- *Global* (covers multiple design stations such as spanload distribution).
- *Section* (covers values on both surfaces of an airfoil, such as section lift or pitching-moment coefficient).
- *Surface* (applies to a single aerodynamic surface such as shock strength or pressure gradient).

To address all of these requirements, multiple passes are made through the flow constraints. Furthermore, researchers can prioritize the constraints so that optimization can be simulated by over-constraining a given value and enabling the CDISC module to adjust to the minimum value, thus allowing the higher-priority constraints to be satisfied.[12]

NASA and industry researchers have employed CDISC for evaluating complex configurations using large Navier-Stokes grids. Boeing employed it to address nacelle integration issues for the BWB transport configuration. Campbell added that as of 1998, "significant reductions in wave drag have been obtained and flow separation issues associated with propulsion/airframe integration are currently being addressed."[13] Finally, Campbell pointed out that "[t]he modular approach to CDISC has allowed it to be coupled with a variety of flow solvers and gridding approaches, and thus provides the option of choosing an analysis method that is already part of a company's inventory and that can most easily meet the modeling requirements."[14]

First Phase: Configuration Evolution

Writing in 1997, McDonnell Douglas aerospace engineers Mark A. Potsdam, Mark A. Page, and Robert H. Liebeck noted that while a blended wing-body design had advantages over conventional designs, these advantages had to be verified through the investigation of the "detailed aerodynamics of the BWB using Computational Fluid Dynamics (CFD) and Constrained Inverse Design methods (CDISC)" developed by NASA Langley Research Center.[15] However, at the start of the project, no CFD validation data existed for the BWB class of aircraft. Accordingly, researchers planned wind tunnel tests in Langley's 14- by 22-Foot and National Transonic Facility (NTF) to address this issue. The CDISC design method work performed at Langley addressed two separate constraints—aerodynamics pertaining to pressure distributions and spanloads, and geometry pertaining to surface smoothness and enclosure of the passenger or cargo cabin.[16]

Many critical problems unique to the BWB required analyses and solutions so that the BWB could advance from concept into the preliminary design phase. These critical areas included the inboard wing design, wing kink region design, and cruise trim. As noted earlier in this work, the inboard portion of the wing containing the passenger cabin and cargo areas had a thickness-to-chord ratio of approximately 18 percent, and the cabin-height leading-edge doors and rear spar necessitated maintaining the thickness along a considerable length of the chord.[17] Also, deck angle limits were a consideration, and shock strength represented a major concern for the centerbody. Finally, the McDonnell Douglas engineers noted that "supersonic flow on the lower surface is uncharacteristic of conventional wing designs and must be investigated [and that p]illowing of the pressurized outer skin results in modified aerodynamic shapes." ("Pillowing" refers to the bulging of the noncylindrical pressure vessel skin between the frames and stringers. Though molded in a smooth shape, under pressure and aerodynamic loads the not-so-thick skins bulge outward from their edge supports, somewhat like ravioli.)[18]

Design problems in the "kink" region, which is the portion of the wing that blends the thick, inboard airfoils and the thin, supercritical, outboard wing, "include[d] surface smoothness, lift carry-over from the centerbody, shock strength and sweep with possible separation, and buffet tailoring."[19] Cruise trim likewise is a critical factor for the BWB configuration. The BWB aircraft required trimming in the midcruise configuration at the nominal center-of-gravity limits with minimal control deflections.[20] The McDonnell Douglas engineers added that "detailed pressure distribution design on the centerbody and outboard airfoils, planform layout, and determination of optimal span loading are important." In making their initial analysis, Potsdam, Page, and Liebeck stated that "the synergistic nature of the BWB necessitates simultaneous input from several disciplines" but noted that the initial focus of their study was on wing aerodynamics and that propulsion, structures, stability and controls, and consideration of weights were not initially addressed, except as they related directly to the wing cruise aerodynamic design. Very importantly, they acknowledged that their objective was "not to demonstrate the absolute performance of the BWB but to illustrate the design process, technical challenges, and application of current CFD and inverse design methods on a novel aircraft configuration."[21]

The BWB team analyzed wing design in two phases starting from an initial "Configuration 0" base design from which the initial step was to produce a first-effort workable design focusing on the inboard and kink regions. The changed shape resulting from this initial work was Configuration 1. A follow-on phase, designated Configuration 2, addressed some shortcomings detected while testing Configuration 1. The initial planform resulted from the interaction between engineers from numerous disciplines, including structures, stability and control (S&C), propulsion, weight, performance, and aerodynamics. Emergency egress, landing gear placement, balance, spar placement, and airport compatibility were among the factors investigated in regard to the cabin and planform layouts. The definition of the baseline blended wing design was derived from a "proof-of-concept work which mated thick, front loaded airfoils inboard with advanced, supercritical, blunt trailing edge airfoils outboard CFD analysis of the initial Configuration 0."[22] This testing "indicated that the kink region would be separated in cruise due to the small chords and a strong shock with unsweeping tendencies…." Correction of this problem required a 15-percent chord extension as well as increased blending in this transition region in order to eliminate the separation. Balance considerations also required an aft shear of the centerbody.[23]

Configuration 1

This configuration represented the "first detailed viable, aerodynamic design of the BWB."[24] Spanloading for this configuration was derived from MDO analysis. Application of the MDO method to the BWB involved examining factors and critical flight conditions in addition to cruise aerodynamic efficiency to produce a configuration having minimum gross takeoff weight. The first step in developing Configuration 1 was to "smooth the geometry and integrate the winglets"; next, "extensive cruise, off-design, buffet, and low speed CFD analyses were performed."[25] After completion of the CFD testing, the results compared with data from wind tunnel tests at Langley. Analysis of Configuration 1 identified various problems, including the following:[26]

- The configuration required control deflections for trim;
- The centerbody and kink shock Mach numbers were below acceptable levels;
- A shock also existed on the inboard lower surface;
- High lift and icing issues drove need for an outboard slat; and
- CFD cruise results indicated high-profile and induced drag from poor spanloading and wave drag.

The three engineers also described two findings regarding the analytical methods:

- "The MDO code was underestimating centerbody drag due to thickness and compressibility while neglecting 3D relief effects."
- "Closer attention to spanwise surface smoothness in the inverse design is necessary."[27]

These identified shortcomings "resulted in *L*/*D* [lift-to-drag] values based on CFD calculations that are lower than the expected improvement over conventional configurations at Mach 0.85."[28] An important Configuration 1 lesson learned was that "it is important to pay attention to shock strength and the tendency to use additional thickness to gain lift on the centerbody."[29]

Configuration 2

This second configuration addressed a number of the problems identified in Configuration 1. Changes made included the following:

- Scaling the airfoils to reduce thickness, especially in the leading edge.
- Uncoupling the aerodynamics and structures in the multidisciplinary optimization.
- Utilizing wing load alleviation to enable more efficient spanloading.
- Selecting a blending factor to yield acceptable tailoring of the critical buffet location.
- Retwisting the airfoils to produce the desired spanload.
- Allowing the kink airfoils to "wash out."

- Applying aerodynamic constraints to improve the pressure distributions.[30]

In addressing the above issues, Potsdam, Page, and Liebeck concluded that

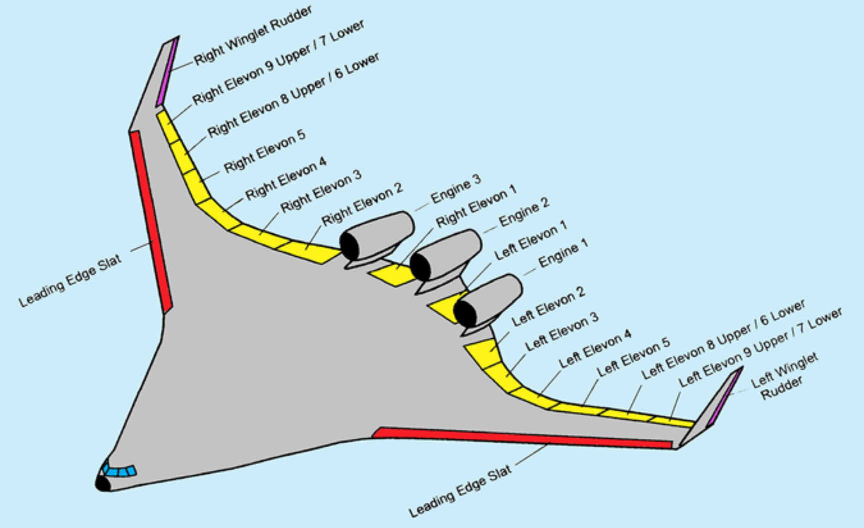
> Inverse design Navier-Stokes codes have been successfully applied to the development of a new aerodynamic configuration. The Blended Wing Body (BWB) is an unconventional aircraft layout compared with transonic transport aircraft of the last 40 years. The design is highly integrated and offers performance improvements of significant proportions. CFD analysis and design methods have been used to study the preliminary detailed aerodynamic design of the BWB, including inboard kink, and outboard wing design. In the centerbody region, thick airfoils must efficiently wrap the cabin and cargo areas and have minimal profile drag due to thickness and wave drag from strong, unswept shocks. The outer wing is a more typical supercritical design. The kink region must blend smoothly between inner and outer wing panels.[31]

Second Phase: BWB Configuration and Wind Tunnel Models

Following BWB studies conducted in the late 1990s, NASA acquired eight wind tunnel models for aerodynamic testing in its tunnels; NASA technicians at Langley fabricated five of these, two came from Boeing, and one came from Tri-Models, Inc., of Huntington Beach, CA (a firm specializing in wind tunnel model fabrication), built to NASA requirements. These models were smaller-scale versions of the Boeing BWB geometry and represented full-scale aircraft satisfying airport constraints and providing better comparisons with existing tube-and-wing commercial transport aircraft. Early in the aerodynamic testing program, researchers decided to maintain the same BWB geometry throughout the various wind tunnel tests to furnish better test-to-test and ground-to-flight correlation.

This basic BWB tunnel configuration had 18 elevons distributed along the trailing edge (two of the outboard elevons were split—that is, they formed both an upper surface panel and a lower surface panel, with twin actuators, so they could serve both as elevons for pitch-and-roll control and as drag rudders), rudders located on each winglet, and leading-edge slats. The configuration had three pylon-mounted engine nacelles located on the upper aft center body.[32]

Table 6-1 reviews the types, scales, dimensions, and owners of eight models used for tunnel testing, all based on the Boeing BWB-450-1L design.[33]



The 18-elevon BWB-450-1L configuration used as the basis for NASA and other wind tunnel model studies. (NASA)

Table 6-1. BWB-450-1L Model Types, Scales, Dimensions, and Owners

Model Type	Scale	Manufacturer	Owner
0.5% Stereo Lithography	0.005	NASA LaRC	NASA
1% Free Spin/Tumble Model	0.011	NASA LaRC	NASA
2% Rotary Model	0.020	NASA LaRC	NASA
2% National Transonic Facility Model	0.020	Tri-Models, Inc.	NASA
3% Multipurpose Low-Speed Model	0.030	NASA LaRC	NASA
5% Free-Flight Model	0.050	NASA LaRC	NASA
8.5% X-48B BWB Demonstrator	0.085	Boeing	Boeing
8.5% X-48C BWB Demonstrator	0.085	Boeing	Boeing

The Wind Tunnel Tests

NASA's first series of wind tunnel tests employed models based upon Boeing's original BWB-800 configuration. Langley researchers conducted their first test in April 1997 at Langley's National Transonic Facility (NTF). Two low-speed static aero tests followed, using a 4-percent model in the 14- by 22-foot tunnel with Daniel "Dan" Murri serving as principal investigator. The first of these tests occurred in August 1997, and the second test was in February 1998. The remaining tests, listed in the table below, used the BWB-450-1L configuration.[34]

Table 6-2. BWB-800 and BWB-450-1L Testing Supporting Development of the X-48B/C

Date (Mo/Yr)	Test	Test Model	Facility	Principal Investigator
4/1997	NTF Test	BWB-800	NTF	—
8/1997	Low-Speed Static Aero	4% BWB-800	14- × 22-Foot Tunnel	Dan Murri
2/1998	Low-Speed Static Aero	4% BWB-800	14- × 22-Foot Tunnel	Dan Murri
10/1999	Free-Spin	1% Scale Free/Spin Model	20-Foot Spin Tunnel	Mike Fremaux
1/2000	Rapid Prototype	0.5% Stereo-Lithography	Basic Aerodynamic Research Tunnel (BART)	Mike Logan
1/2000	Rotary Balance	2% Rotary Model	20-Foot Spin Tunnel	Mike Fremaux
4/2000	Free-Tumble	1% Scale Free/Spin Model	20-Foot Spin Tunnel	Mike Fremaux
5/2000	Elevon Interference	3% Scale Model	12-Foot Low-Speed Tunnel	Dan Murri
9/2000	Low-Speed Static Aero	3% Scale Model	14- × 22-Foot Tunnel	Dan Murri
12/2000	Low-Speed Large Angle	3% Scale Model	14- × 22-Foot Tunnel	Dan Murri
5/2001	Forced Oscillation	3% Scale Model	14- × 22-Foot Tunnel	Dan Murri
10/2001	Elevon Interference	3% Scale Model	12-Foot Low-Speed Tunnel	Dan Vicroy
8/2004	Ultra-Efficient Engine Technology (UEET)	2% Scale Model	NTF	Dick Campbell
3/2005	Static Test Free-Flight	5% Free-Flight Model	LFST	Dan Vicroy
9/2005	Free-Flight	5% Free-Flight Model	LFST	Dan Vicroy

Table 6-2. (continued)

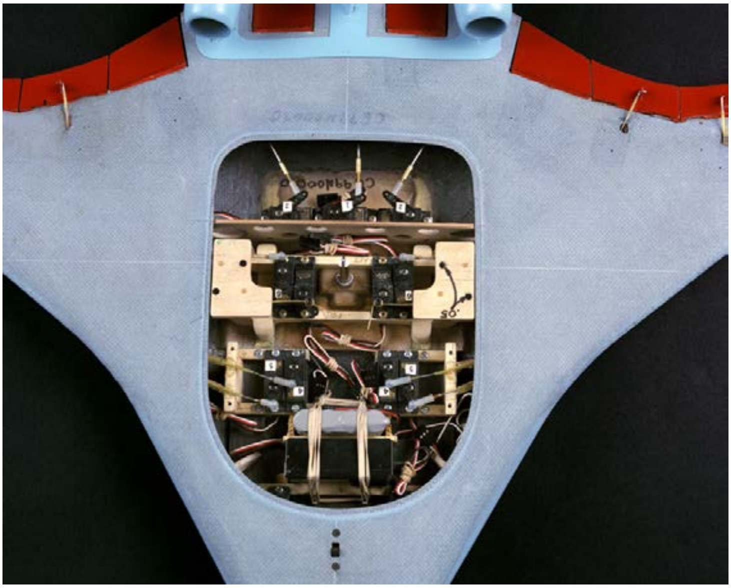
Date (Mo/Yr)	Test	Test Model	Facility	Principal Investigator
12/2005	Ground Effects	3% Scale Model	Swift Aero Tunnel	Boeing
4/2006	Static Test of X-48	8.5% Ship 1	LFST	Boeing
5/2006	Stability and Control	2% NTF Model	NTF	Melissa Carter
—	Stability and Control	2% NTF Model	AEDC 16	Melissa Carter

As noted above, the wind tunnel tests conducted at Langley included spin-and-tumble, rotary, low-speed baseline aerodynamics, large-angle, forced-oscillation, ground effects, free-flight, and the final actual wind tunnel test of the X-48B Ship 1 in the Langley Full-Scale Tunnel (LFST).

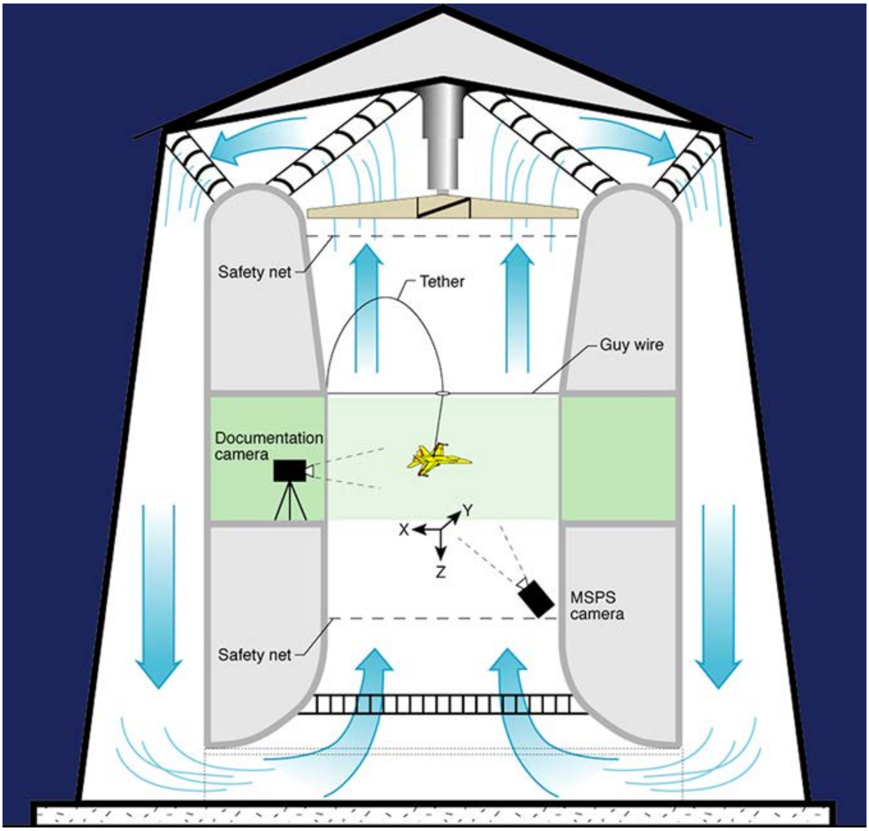
Spin-and-Tumble Test. The 1.1-percent dynamically scaled model spun and tumbled in Langley's 20-Foot Vertical Spin Tunnel. The objectives of this test "were to quantify the steady state spin and tumble modes, explore recovery control combinations, and [for later, higher-risk flight testing outside of the normal operating envelope] develop an emergency single parachute spin and tumble recovery configuration."[35] The test results indicated that the best arrangement for a spin-and-tumble recovery parachute system "was a small parachute with a very short towline attached to a rigid boom extending off the rear of [the] model along the centerline."[36] The short towline enabled the chute to clear the aft end of the model, and the boom increased the drag forces produced by the parachute. These findings led to a scaled-up boom-mounted recovery system for the X-48 flight-test vehicles.[37]

Norm Princen with a BWB spin model he built with Blaine Rawdon to explore spin recovery methods and locate the spin chute anchor point. They built the model in Rawdon's garage using hot-wired expanded polypropylene (EPP) foam on a carbon fiber skeleton with 0.003″ drafting Mylar skins. It was intended to take much abuse in the tunnel, and it did. (Photo courtesy of Blaine Rawdon)

The 1-percent BWB-450-1L spin-test model being evaluated in the NASA Langley Spin Tunnel. (NASA)



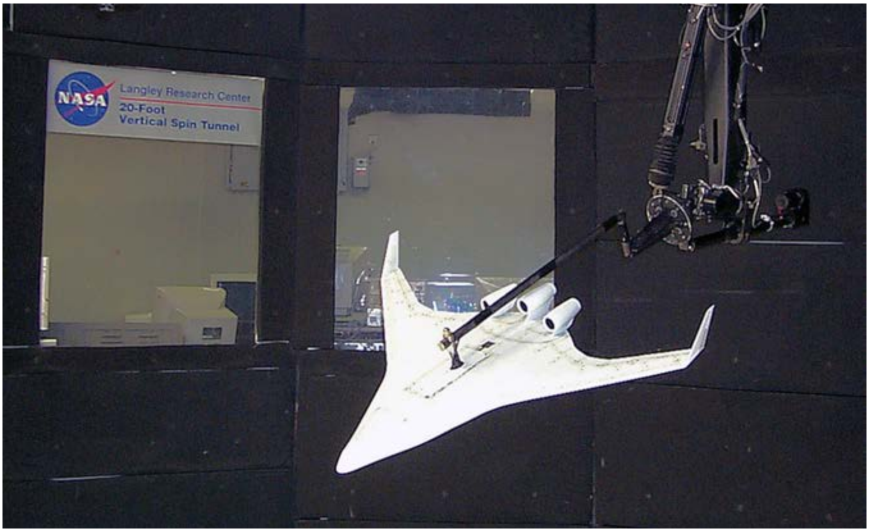
The complex control assemblies of the 1-percent BWB-450-1L spin-test model. (NASA)



The Langley Spin Tunnel is a vertical wind tunnel enabling researchers to assess spin departure and recovery modes. (The reference model shown in this graphic is an F/A-18A Hornet.) (NASA)

Rotary Test. Rotary balance wind tunnel testing followed the completion of the spin-and-tumble tests. The 2-percent model also used Langley's 20-Foot Vertical Spin Tunnel. The test objective was "to measure forces and moments under steady rotation for a large range of angle of attack, sideslip, and rotation rate." Data covered an angle-of-attack range of ±90 degrees and sideslip range of ±30 degrees at nondimensional spin rates of up to 0.67 in both directions. The data from the rotary balance tests were used to analyze subsonic rate-damping characteristics and spin prediction and to conduct spin modeling in high-fidelity simulations.[38]

Low-Speed Baseline Aerodynamics Test. The 3-percent scale multipurpose model furnished most of the low-speed baseline aerodynamic testing in the



The 2-percent Rotary Model in the Langley Spin Tunnel. (NASA)

Langley 14- by 22-Foot Subsonic Wind Tunnel. Tests included "individual and combined control effectiveness, slat geometry effects and ground effects."[39]

Some of the more significant results were as follows:

- "With the slats retracted, the configuration exhibits an unstable pitch break over the angle of attack range where the outboard wing section begins to stall prior to the inboard and center body sections."
- "The stall of the outboard wing sections which are aft of the moment reference center results in a nose up pitching moment change."
- "Deflecting the slat delays the stall of the outboard section and eliminates the unstable pitch break."
- "The deflected slat also increases the maximum lift coefficient as expected."[40]

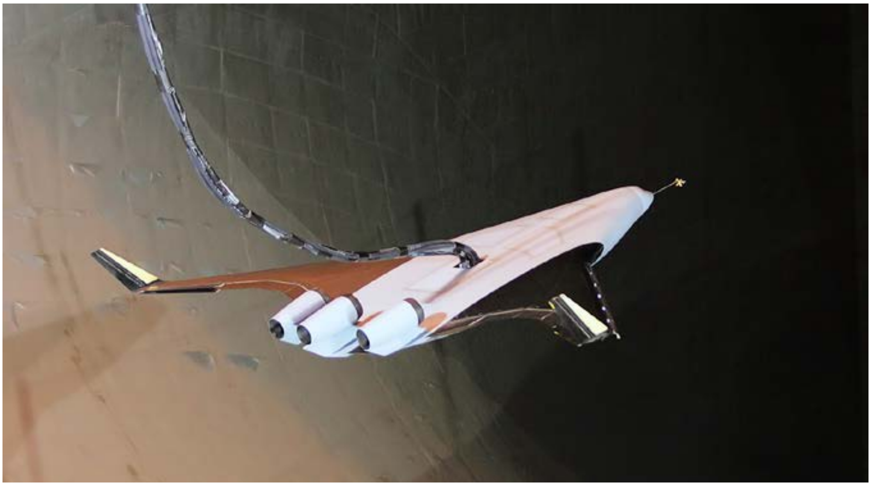
Large-Angle Test. This test also used the same 3-percent scale model used for the low-speed baseline aerodynamics test in the Langley 14- by 22-Foot Tunnel. The test evaluated the low-speed static stability and control characteristics of the configuration over the full angle-of-attack flight envelope (±180 degrees) and sideslip (±90 degrees). The test data fed simulation studies of the edge of the envelope and potential out-of-control flight characteristics. The test covered a limited set of combined deflections for both the slat-extended and slat-retracted configurations.[41]

The 3-percent BWB model in the Langley 14- by 22-Foot Tunnel, with leading-edge slats extended and landing gear down. (NASA)

Forced-Oscillation Test. This represented the third test conducted using the 3-percent model and likewise used the Langley 14- by 22-Foot Tunnel. Researchers evaluated a number of combined control deflection positions, with the wing slats in both extended and retracted mode. They also examined the influence of extended landing gear and doors, the three engine nacelles, and Whitcomb-style wingtip winglets on the design's yaw-damping characteristics.

Ground Effects Tests. Initially, researchers conducted ground effects tests in the Langley 14- by 22-Foot Tunnel, but the data obtained were of dubious value, given possible flow distortion caused by the large post mount supporting the model. Accordingly, researchers conducted followup tests in a Swift Engineering 8- by 9-foot tunnel that had a "rolling road ground belt with a top mount telescoping blade strut that allowed the angle of attack and height above ground belt to vary." They also investigated use of the "belly flap" discussed previously in this work for improved lift and pitching moment during takeoff and landing, the tests pointing to a 35-percent increase in takeoff and lift coefficient and a 10-percent increase in pitching moment at a 90-degree belly-flap deflection when compared with the baseline configuration.[42]

Free-Flight Test in the Langley Full-Scale Tunnel. Researchers employed the 5-percent model for tethered flights in the Langley FST. This model had a 12-foot wingspan, making it the largest model ever free-flight-tested in the



The 5-percent BWB Free-Flight Model airborne in the LFST, historically one of the world's most important aerodynamic research facilities. (NASA)

FST at that time.[43] The objectives of the free-flight tests were to "characterize the BWB 1g departure characteristics including the asymmetric thrust minimum control speed and evaluate the effectiveness of center engine lateral thrust vectoring."[44] Langley's Dan Vicroy pointed out that the roll inertia requirement was especially challenging because every ounce of material added to the wingtip required approximately 2 pounds of additional model weight for balancing the inertia and maintaining the center-of-gravity location.[45]

X-48B Test in the LFST. The final test in the low-speed wind tunnel series used the first of two X-48B 8.5-percent dynamically scaled vehicles, tested in the Langley Full-Scale Tunnel. This test was to calibrate the vehicle's air data system and to measure the control surface hinge moments, as well as collecting static baseline aerodynamic data. This represented a rare opportunity to obtain wind tunnel data on an actual flight-test vehicle so that a direct comparison could then be made with the follow-on atmospheric flight results.

The tests outlined above "generated an extensive full-envelope database for flight simulation and ground to flight correlation."[46] Langley senior research engineer Dan Vicroy noted the following lessons learned from the tests:

- "This configuration does have sustained spin and tumble modes of motion but only with pro-spin or tumble controls."
- "The configuration has limited directional control authority. Center engine thrust vectoring can help to augment directional control authority in an outboard-engine-out condition."

The 8.5-percent scale X-48B being readied for testing in the Langley Full-Scale Tunnel. (NASA)

- "Control interference effects can be significant with multiple trailing edge control deflections and should be accounted for in the aerodynamic simulation model."
- "Wind tunnel installation effects on pitching moment can be large for BWB configurations with significant center-body lift contribution."[47]

Overall, Vicroy concluded that "to date no BWB flight dynamics 'show stoppers' have been identified from these tests and the associated analyses."[48] He added: "The BWB research focus is transitioning from BWB enabling technologies, such as structures and flight controls, to BWB benefiting technologies, such as boundary layer ingestion."[49]

Additional Aerodynamic Tests for BWB Takeoff and Landing Configuration

An engineering team including Yann D. Staelens and Ron F. Blackwelder from the University of Southern California (USC), as well as Mark M. Page—who, after the Boeing–McDonnell Douglas merger, had moved on to become chief scientist for Swift Engineering, Inc., of San Clemente, CA—undertook additional aerodynamic tests on the BWB-450-1L, using a USC wind tunnel and a BWB-450-1L model built by Swift Engineering. NASA supported their research under a cooperative agreement (NCC-1-02043), and, as well, the three engineers drew upon a research award from the National Institute of Aerospace of Hampton, VA.[50]

The USC wind tunnel was a classic closed-return design with temperature-controlled airflow, with a 9- by 18-foot cross section. It had a moving ground plane with a maximum speed of approximately 78 miles per hour, synchronized with the speed of the airflow. The tunnel also employed boundary-layer suction to remove the tunnel wall boundary layer, and researchers could draw upon a computer program using Laboratory Virtual Instrument Engineering Workbench (LabVIEW) routines that sampled the free-stream velocity to ensure that it was constant. The system worked well, keeping the velocity in the test section uniformly within 1 percent.[51]

One of the challenges created by the BWB's unique configuration was short-coupled controls: the elevons, when controlling pitch, had an inherently short lever arm (two to three times shorter than the pitch control lever arm of a conventional tailed aircraft) to the center of gravity. The three engineers noted that "this adversely affects flight path control during rotation and landing flare since pitch changes are accompanied by an unwanted initial plunging," adding that in comparison with a conventional jetliner, "an equivalent pitch change requires a larger down-force from the control surface on the BWB since the moment arm is smaller."[52] They noted that the large and abrupt loss of lift

> causes the BWB first to be pushed down or plunge and then pitch up to reach the desired angle of attack. This phenomenon will introduce an unwanted "sagging" of the BWB's flight path and landing. The pilot will need to initiate the rotation and flare earlier to reach the same end-state as a conventional airplane…. This effect is even more problematic during takeoff since ground effects amplify the lift loss. A particular concern in the landing flare is gear-plunge. It's possible that the nose-up command will actually increase the sink-rate at the main gear. This is a form of control reversal for the flare task, since the pilot is trying to manage the impact at touchdown.[53]

The USC study undertaken by the engineering team contributed to resolving the above problems by employing a rectangular belly-flap as a pitch control effector for takeoff and landing.[54] The inboard edge of the belly-flap was on the wing's centerline. The advantage of the belly-flap over elevon effectors was that "the creation of enhanced pitching moment with belly-flaps does not come with a large lift loss as in the case of flying wings that use trailing edge devices to create a pitching moment."[55] Test data confirmed that a belly-flap deflection of 90 degrees furnished the highest increase in lift as well as a good increase in favorable pitching moment for rotation. Increasing the span of the belly-flap resulted in an increase to the lift and pitching moment up to a length for the belly-flap of 22 percent of the half-wingspan. At that point, the increase in lift begins to flatten out and decrease at a higher angle of attack because, at higher angles of attack, a long belly-flap causes the wing to form a stall region.[56]

The study team concluded:

> From all of the variables studied so far the optimal location of a rectangular belly-flap for a BWB-airplane seems to be when it has no sweep, a longitudinal rigging of about 60–65% of the root chord and no gap left between the inboard edge of the belly-flap and the center line of the BWB-airplane. The belly-flap is the most efficient when it is totally deployed, this means having a deflection angle of 90°. The belly-flap should have a total span of about 20% of the span of the airplane.[57]

U.S. Air Force Testing

During 2007, researchers at the U.S. Air Force's Arnold Engineering Development Center (AEDC) located at Arnold Air Force Base, TN, undertook additional testing supporting X-48B/C development, using the center's 16-foot Transonic Wind Tunnel and a Langley-built 2-percent model of the BWB-450-1L vehicle. The tests, sponsored by the Air Force Research Laboratory (AFRL), were a cooperative effort between the Air Force, Boeing, and NASA and expanded an aerodynamic database started earlier at Langley using the same wind tunnel model. Air Force First Lieutenant Ezra Caplan, who served as AEDC project manager, noted that "this was a team effort in every sense of the word—in both planning and test operations, we were operating on a limited schedule and Air Force Research Laboratory (AFRL) and NASA were operating under a tight budget." He added that "Project Engineer Randy Hobbs and his team worked very closely with the NASA engineers to ensure" accomplishment of the program objectives.[58]

A 2-percent BWB-450-1L model tested in the Arnold Engineering Development Center's 16-Foot Transonic Wind Tunnel, Tullahoma, TN. (USAF)

The primary objective was "to provide external aerodynamic data to evaluate the flight characteristics of the BWB at higher Mach numbers than those applied to the same model" tested earlier by Langley.[59] Langley engineer Dan Vicroy noted that while the team subjected the model to some subsonic flows, most of the tests addressed transonic speeds. NASA research engineer Melissa Carter pointed out that researchers started with a clean wing (no engine nacelles or winglets), then progressed to winglets and finally with pylons and engines. The staged approach enabled the team to determine what each component added to the drag (Carter said researchers were "looking for both the cumulative and incremental effects on drag for this aircraft") and, ironically, followed a style of "drag clean-up" research pioneered at Langley with notable drag-reduction studies on full-size fighter and other aircraft beginning in the 1930s and continuing through the Second World War.[60]

Cranfield Aerospace, Ltd., Fabricates the X-48B and X-48C

Boeing contracted out the actual fabrication of the two dynamically scaled X-48 vehicles. After evaluating proposals from AeroVironment, Inc., and U.K.-based Cranfield Aerospace, Ltd., Boeing chose the latter firm because it wanted to strengthen its global relationships and because Cranfield had been working on its own version of a BWB design. Boeing also wanted Cranfield to decide largely on its own how to fabricate the X-48B; otherwise, Boeing would have needed to follow its own in-house procedures, which would have taken longer and cost more.[61]

Cranfield Aerospace, Ltd., is a for-profit subsidiary of Cranfield University.[62] Located in Bedfordshire, England, Cranfield University is Great Britain's premier aerospace academic education establishment, created in 1946 as "a post-graduate college of aeronautical science" to reinvigorate British aeronautical engineering education, thus ensuring a steady supply of exceptionally qualified graduates for the British aviation industry.[63] Initially known simply as the College of Aeronautics, it came to be largely through the efforts of Professor H. Roxbee Cox, subsequently elevated to a peerage as Lord Kings Norton, one of Britain's most distinguished engineers, who had served as wartime Deputy Director of Scientific Research and who had contributed significantly to the development of the first jet engines.

Cranfield Aerospace's affiliation with Cranfield University thus provided the firm with crucial access to the university's intellectual and physical resources. As well, the university participated in the joint European Multidisciplinary Optimization of a BWB (MOB) consortium (discussed subsequently) providing additional knowledge and experience shared with Cranfield Aerospace. This background, together with Cranfield Aerospace's own efforts to fabricate a small-scale BWB demonstrator vehicle, made the Boeing contract a perfect match for the company's own strategic plan. Cranfield likewise had an interest in building the X-48B demonstrator because the project fit nicely into the company strategic plan "to reduce the cost and time to obtain high-quality aerodynamic and flight control data by combining its rapid prototyping and unmanned aircraft capabilities."[64] Cranfield's work research included initial design studies for its own development of a BWB testbed sized between the Stanford small-scale BWB and NASA's planned (thought never completed) 35-foot-span X-48A.[65]

Subsequently, Cranfield's Unmanned Air System team, directed by Gordon Dickman, oversaw the X-48B construction effort, fabricating two BWB dynamically scaled vehicles and delivering them to Boeing. Vehicle 1 went to Langley for tunnel testing and Vehicle 2 to Dryden for flight testing.

(Vehicle 1 also served as a test-flight backup vehicle in the event of loss of the flight-ready X-48B.)

The wind tunnel model accounted for more than 400 test hours in the 60- by 30-foot wind tunnel at an average tunnel wind speed of 64 miles per hour, covering an equivalent travel distance of approximately 25,600 miles.[66] The second X-48B flight-ready aircraft flew a total of 92 flights, breaking the record for a remotely piloted "X"-series vehicle.

Cranfield continued to assist NASA and Boeing during the flight-test phase, even sending team members to Dryden, and made the subsequent modifications that reconfigured the X-48B into the follow-on X-48C. Cranfield also supported Boeing's programs under NASA's Environmentally Responsible Aviation (ERA) project with a team of leading British academic specialists in aviation environmental and operational issues. This included a 9-month study of some of the primary environmental issues with a special focus on remotely piloted aircraft operations and integration.[67] David J. Dyer, Cranfield's manager for UAV systems, noted, "We are providing Boeing with a research tool in which to test their flight control system software."[68] Ian Poll, founder of Cranfield Aerospace, a former director of Cranfield's College of Aeronautics and past president of the Royal Aeronautical Society, added, "We are giving them the complete thing—two 8.5%-scale aircraft, a ground control station, support equipment and spares."[69]

The Boeing-Cranfield Relationship, Responsibilities, and Results

Boeing provided Cranfield with the X-48 planform and the computer control system software. While Boeing developed the computer controls, Boeing engineers still needed to test the system on the subscale Cranfield X-48 testbed. Also, Cranfield received additional assistance from Norman Princen, Boeing's chief engineer for the X-48 program, who spent months at Cranfield and, when back home, remained in frequent telephone contact with Cranfield representatives. David Dyer served as Cranfield's program manager; David Swain was the company's chief technical officer; and Alan Stevenson served as Cranfield's chief project engineer. Work progressed on a short timeline. Boeing met with Cranfield representatives in October 2001; work started in January 2002; and the two held a Preliminary Design Review in December 2002.[70]

Dynamically scaling the vehicle proved far more challenging than simply geometrically scaling an airplane. For one thing, the subscale X-48 had three times faster flight dynamics on landing than the full-size vehicle would have, thus making it harder for test pilots to handle. (Engineers considered the quickness a potential problem for the test pilots while remotely landing the vehicle, but in actual flight testing the pilots said that it did not represent a significant issue.) Boeing overcame the potential problem by scaling up the data for use in the X-48 flight simulator to provide control responses more closely resembling those of a conventional aircraft.

Ian Poll pointed out that the moments of inertia were scaled (which is not normally done), adding that the short-period oscillation was a function of the scaling parameter and thus not the same as on the full-size vehicle. Dynamic scaling also placed a premium on weight reduction and mass distribution. To reduce weight, the X-48B used a carbon fiber airframe fabricated by Lola Composites, a Cranfield subcontractor (and member of the Lola Group, a corporation with a distinguished history in international motor sport). Regarding the center of gravity, Dyer noted that "[a]s you move away from the center of gravity, mass is much lower than normal, and in places the skin is just one laminate thick." To solve this problem, Boeing did an "enormous amount" of finite modeling with Cranfield.[71]

The small-scale size capability significantly reduced cost, for Cranfield could use some components from the model airplane hobby industry. For example, the company was able to use three small 50-pound-thrust micro-jet engines that provided the 392-pound vehicle with a maximum airspeed of 118 knots, an altitude capability of 10,000 feet, and an endurance of 1 hour. The X-48B had 20 control surfaces along its trailing edge, each driven by Kearfott Guidance and Navigation actuators originally developed for AAI Corporation's RQ-7B Shadow unmanned aerial vehicle (UAV), a joint-service

An AAI RQ-7B Shadow unmanned aerial vehicle takes off at Idaho's Orchard Combat Training Center, October 2, 2016. The X-48B used the same Kearfott guidance and navigation control actuators as the RQ-7B. (U.S. Army) tactical intelligence-surveillance-reconnaissance (ISR) system widely employed in the post–September 11, 2001, global war on terror.[72]

Cranfield used its CATIA software to design the X-48B based on the outer mold line of the Boeing 450-1L BWB study configuration, and it designed the avionics system so that Boeing could upload its software that was subject to International Traffic in Arms Regulations (ITAR) export restrictions. The X-48B's salient characteristics are presented in Table 6-3.[73]

Table 6-3. Boeing–Cranfield Aerospace X-48B Vehicle Characteristics

Scale	8.5 percent
Wingspan	20.4 feet
Wing Area	100.5 square feet
Maximum Weight	523 pounds
Static Thrust	162 pounds
Maximum Airspeed	118 knots
Maximum Altitude	10,000-foot Mean Sea Level (MSL)
Load Factor Limits	+4.5 g's to –3.0 g's
Flight Duration	30 minutes + 5 minutes' reserve

Cranfield and the European MOB Consortium BWB Studies

While Boeing, NASA, the Air Force, and various universities and corporations partnered on BWB development work in the United States, the European aeronautical community partnered to support Airbus in any future BWB efforts. Clearly, Bushnell's challenge to industry had now gone international as well.

Cranfield University's Own BWB Research and the BW-98 Project

In September 2000, Howard Smith of Cranfield University noted that "the Cranfield baseline BWB configuration is similar to the Boeing concept in configuration, and currently represents the only UK National project of its scale,"[74] adding:

> In the case of novel configurations, it is essential to proceed to at least the preliminary design phase before any reasonable conclusions may be drawn. Furthermore, in the light of this lack of experience many potentially show stopping design challenges may be

> hidden in the detailed design. These challenges cannot be further researched, or designed around, until they have been identified.[75]

Smith identified the need to reduce risk through the development of a small-scale vehicle, adding that the Cranfield BWB program, which started in early 1998, was intended to have a fully optimized design study completed and a subscale demonstrator performing its initial flight testing by early 2002.

Researchers examined both civil and military applications. The initial studies indicated that the BWB was well suited for a high-capacity civil transport and for a cargo carrier. This was due to the high efficiency and flexible volume as well as the BWB's capability for meeting the increasing demands of the air transportation market while minimizing the impact on the environment. Likewise, the high degree of flexibility for volume for payload applications would provide a feasible solution over a wide range of weight packaging. The study indicated that the BWB long payload flight range makes the configuration a strong contender for military applications. The BWB airplane would provide an intrinsically stealthy shape, and its low ground stance would aid in the loading and unloading of cargo. Also, its use as a refueling aircraft would provide benefits including stealth and payload range advantages. In addition, "the BWB finds applications from the larger strike aircraft, through the more compact Unmanned Combat Air Vehicle (UCAV) down to the smallest unmanned aerial vehicles (UAV)."[76]

The basic requirements for Cranfield University College of Aeronautics' BW-98 configuration included the following:

- an alternative cabin accommodating a maximum of 960 passengers;
- a design range of 7,650 nautical miles;
- a cruising speed of Mach 0.85 with 656 passengers and baggage; and
- compatibility with existing airports and facilities.[77]

Researchers examined two different approaches for the center wing-body, one using aluminum alloy and classical frames and stringers, and another using composite materials. The study recognized that the full potential of the BWB configuration could only be obtained through the application of advanced technologies including "the application of laminar flow technology, control configured vehicle technology combined with a fully integrated propulsion system."[78] Finally, the Cranfield study team concluded early in the project that human factors represented the dominant issue in designing the BWB for civil transport, largely because of the necessarily large windowless cabin volume and the limited exit locations. The BWB taxed existing assumptions about access and safety, both in the boarding of passengers in such a large capacity aircraft and then in meeting the formidable requirement of demonstrating that all of them could evacuate the airplane in the event of an emergency within

90 seconds. (To address the latter concern, Cranfield, at Boeing's request, both undertook extensive studies and fabricated a full-size mockup of the BWB cabin, running experiments with actual people with "very favorable" results.)[79] On top of this, the BWB faced all the traditional vicissitudes of civil air transport development, including Government certification (made more difficult whenever inspectors encountered a radical new configuration) and meeting established airworthiness and crashworthiness standards.[80]

John Fielding and Howard Smith of Cranfield University noted in their 2002 presentation to the International Congress of Aeronautical Sciences both the potential advantages and actual challenges presented by the BWB configuration, as outlined in Table 6-4.[81]

Before starting their BWB design phase, the Cranfield University BWB team had to develop the tools, knowledge, and overall understanding necessary to evaluate a BWB configuration, especially its applicability to high-capacity civil transports (HCCT). This effort consumed a total of 80,000 engineer-hours including input from British Aerospace (BAE) Systems and Rolls-Royce.[82] This preliminary effort set the following objectives:

> To complete a detailed design study of a fully optimised BWB configuration with integrated propulsion system, incorporating all appropriate technology (e.g. laminar flow) within a rigorous framework of constraints to ensure that it can be successfully and profitably manufactured and operated and to the benefit of passenger appeal and safety. This will provide a considerable degree of confidence that all major design problems have been identified and addressed.[83]

To carry through with the above objectives, the Cranfield team planned to take the following incremental approach:[84]

- The creation and continued development of design tools;
- Development of appropriate design methodologies;
- An incremental programme of detailed design studies;
- The design and manufacture of a subscale flying demonstrator; and
- Detailed studies within identified Key Technology Areas feeding back into the tools and methodologies above.

Fielding and Smith also commented on the then-ongoing effort leading to a plan to fabricate a small-scale BWB vehicle as follows:

> Cranfield University together with BAE Systems and Rolls-Royce has made significant progress in the exciting UK National BWB project, without benefit of direct Government funding. The

Table 6-4. Potential Advantages and Challenges of the Blended Wing-Body Concept

Factors	**Advantages**
Aerodynamics	Low wetted-area-to-volume ratio Form conducive to low interference drag
Structures	Efficient deep sections Favorable spanloading
Human Factors	High volumetric capacity Flexible cabin layout potential
Systems	Potential for highly integrated airframe/engine Ideal configuration for application of laminar flow technology Significant advantages from control configuring the vehicle
Economics	Particularly suitable for high-capacity applications Significant reduction in direct operating costs should be achievable
Factors	**Challenges**
Systems	Design of fully integrated and novel propulsion systems Design and integration of possible laminar-flow systems Control allocation
Operations	Span/wheel track limits Airport passenger handling
Manufacturing	Manufacture/assembly of very large components (probably composite)
Aerodynamics	Drag of thick airfoils and the achievement of laminar flow
Structures	Unconventional layout Noncircular cabin Aeroelasticity Major cutouts for exits
Human Factors	Embarkation time Passenger comfort and appeal No windows Emergency evacuation Pilot workload
Airworthiness Requirements	Safety Evacuation Stability augmentation
Conceptual Design	Tools Methods

> current work has, as planned, isolated many challenges of such concepts, as well as offering some solutions. This progress will continue in the remainder of the current 4 year programme and will utilize Cranfield University's whole-aircraft design, manufacture and operational capability…. The sub-scale BWB flying demonstrator will build on the expertise already demonstrated on the A1 Eagle, the A3 and Eclipse unmanned vehicles and will provide valuable data for future aircraft.[85]

The MOB Consortium and Challenges to Europe's Aviation Industry

The Multidisciplinary Optimization[86] of a BWB (MOB) consortium, which studied the BWB concept from 1999 into 2002, included three aerospace companies, four research institutes, and eight universities located throughout four countries in the European Union. The U.K. members included Cranfield University, QinetiQ (formerly the Defense Evaluation and Research Agency, and earlier still the historic Royal Aircraft Establishment, RAE), British Aerospace (BAE) Systems, and the Council for the Central Laboratory of the Research Councils. German participants were the *Deutsches Zentrum für Luft- und Raumfahrt e. V.* (the German Center for Air and Spaceflight, or DLR), Daimler-Chrysler Aerospace AG, Military Aircraft (European Aeronautic Defence and Space Company, or EADS), *Technische Universität (TU)*-Berlin, *TU*-Braunschweig, *TU*-München, Siegen *Universität*, and Stuttgart *Universität*. Swedish participants included Saab AB and the *Kungliga Tekniska Högskolan* (the Royal College of Technology, or KTH). The Netherlands furnished the *Technische Universiteit (TU)* Delft and Stichting *Nationaal Lucht- en Ruimtevaartlaboratorium* (National Air and Spaceflight Laboratory, or NLR).[87] The Computational Design Engine (CDE) developed by the various partners enabled the software and computers of the consortium members to be linked together at the members' respective sites. This amounted to an international four-nation "plug and play" approach useful at any stage in the design process.[88]

The European Union funded the MOB consortium largely out of concern for the future economic security of Europe's aeronautical industry. One danger was the "clear problem" that aircraft pose to the environment, generating pressures constraining the design freedom and initiatives of industry. Another involved potentially limited oil resources and concomitant high fuel consumption rates triggering high costs. A third—but hardly new—was global market competition, with the European aerospace industry confronting a mix of international challenges from both long-established and newly emergent competitors. Then there was a growing scarcity of technically competent aeronautical engineers. Facing these, Cranfield University's A.J. Morris argued that

Europe's aviation leaders needed to pursue new and novel responses involving innovative designs that could achieve market penetration and long-term success in the global marketplace, particularly designs that could combine low design and manufacturing costs with low in-service operational costs.[89]

Like Boeing's initial thinking on its own BWB-600 and -450, MOB started with a base concept design for a large civil passenger transport aircraft but evolved toward the development of a "freight" aircraft, with design requirements emphasizing cargo payload, operating range, Mach number, altitude, and overall operational envelope. Saab, BAE Systems, and *TU*-Delft furnished critical assistance and input.[90] Phase One focused on defining the functionality and capability of the CDE to facilitate the development of an initial prototype and a follow-on advanced system. The CDE would "create a system allowing both co-operative and innovative design to be undertaken by a distributed design team employing their own specific design tools and methods."[91] NASTRAN and PATRAN, both traditional aerospace design models, furnished structural analysis, but the consortium's members furnished all other tools and programs.[92]

MOB Project Objectives

The overall project objective was "the development of tools and methods to facilitate the design of large scale and complex aeronautical products by distributed teams employing a variety of discipline-based programs and approaches."[93] A secondary goal was applying the CDE to BWB analysis, since the BWB was regarded as a potential A380 competitor and also had possible relevance to future large-capacity military aircraft design. Morris added subsequently that "satisfaction of this second objective validates the CDE tool set and forms a team of European aeronautical engineers able to support the design of a BWB aircraft should Airbus decide to fully explore this concept."[94]

The project's primary and secondary objectives were:

- To develop a Computational Design Engine based on multi-level, multi-disciplinary design and optimization methods for designing aircraft in a distributed environment;
- To introduce a new way of working to integrate teams working on a common design across a number of different sites and in different organisations, using different tools; and
- To design a BWB aircraft using CDE tools and distributed specialist teams.[95]

"Lower level" objectives required users:

- To employ their own proprietary or in-house software and packages;
- To bring their own CFD, structural etc. models to the design process;

- To be able to use any software on any computer within the Co-operative; and
- To enter and use the system without being an MDO specialist.[96]

As an ending summary, Morris added that "finally the objective for the project with respect to the design of the BWB is to ensure that the tools being assembled into the CDE are used to validate the BWB as a serious competitive design to current conventional shapes or otherwise!"[97]

Summary Accomplishments and Next Steps Forward

Following the completion of the 80th X-48 flight, Cranfield noted that its engineers had "demonstrated true rapid prototyping technology in support of the Boeing Blended Wing Body Programme" and further noted the following design, fabrication, and testing accomplishments:[98]

- Turnkey design/build/flight of world-leading aircraft concept.
- Extreme innovation.
- Carbon composite structures.
- Flight control technology.
- Complete aircraft integration, build, and ship.
- Support to full-scale wind tunnel trials.
- Short timescales and rapid development.
- Integral part of the Boeing Research & Technology flight-test team.
- Current program of conversion to X-48C.
- 8.5-percent scale model with 6.4-meter wingspan.
- MTOW 180 kilograms.
- Accurate scaling of mass and inertia characteristics.
- 80 successful flights to date.

Fittingly, on December 11, 2008, the Royal Aeronautical Society—the world's oldest and most distinguished scientific aeronautical organization, dating to January 1866[99]—awarded Cranfield Aerospace, Ltd., the Society's Silver Award for the advancement of the aerospace art, science, and engineering, citing

> work of an exceptional nature, leading to major advances or contributions in aerospace [recognizing Cranfield's] involvement in the design and construction of Boeing Phantom Work[s'] [now Boeing Research & Technology] subscale Blended Wing Body technology demonstration aircraft.[100]

Cranfield Modifies the X-48B into the X-48C

The test program of the X-48B and X-48C—totaling 122 flights, 92 by the X-48B and 30 by the X-48C—is detailed more completely in chapter 7 and the appendix. However, as a quick introduction, following the completion of its 92 test flights, the X-48B returned to Cranfield for modification into the X-48C. Originally, planners had desired a new-build, separate X-48C vehicle but then opted to simply reconfigure the X-48B into the X-48C, much as, years before, Martin Marietta had reconfigured its X-24A lifting body into the significantly different X-24B.[101] Modifications to the X-48B included refitting the vehicle with twin gas turbine engines, making additional changes in the control surface configuration, and adding a more powerful flight control system designed and built by Cranfield. The X-48C then underwent its own Phase Two flight-test program in support of NASA's Environmentally Responsible Aviation (ERA) program.[102] The modified X-48C evaluated "the low-speed stability and control of a low-noise version of a notional, future Hybrid Wing Body (HWB) aircraft design," completing 30 research flights before being retired itself.[103]

But that is getting ahead of the story. Following Cranfield's completion of the X-48B, Boeing and NASA were now ready to evaluate it in the most challenging laboratory of all: the harsh blue skies of the Mojave.

Endnotes

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80. Ibid., pp. 114.6–114.7.
81. Fielding and Smith, "Development of Environmentally-Friendly Technologies and Configurations for Subsonic Jet Transports," p. 8.

82. Ibid., p. 6.
83. Ibid.
84. Ibid., pp. 6–7.
85. Ibid., pp. 9–10.
86. "Multidisciplinary Optimization" more accurately refers to multidisciplinary design optimization (MDO), which uses numerical optimization theory and algorithms to design complex systems composed of subsystems crossing multiple-discipline subsystems and seeks to achieve maximum efficiency of the entire integrated, interacting system. If done properly, MDO can achieve multiple benefits, including improved design, reduced development time, and reduced development costs. See Joaquim R.R.A. Martins and Andrew B. Lambe, "Multidisciplinary Design Optimization: A Survey of Architectures," *American Institute of Aeronautics and Astronautics Journal* 51, no. 9 (September 2013): 2049–2075.
87. A.J. Morris, "MOB: A European Distributed Multi-Disciplinary Design and Optimisation Project," AIAA 2002-5444 (paper presented at the 9th AIAA/ISSMO Symposium on Multidisciplinary Optimization, Atlanta, GA, September 4–6, 2002), p. 3.
88. Ibid., p. 1.
89. Ibid., p. 2.
90. Ibid., p. 3.
91. Ibid., p. 2.
92. Ibid., pp. 1–3.
93. Ibid., p. 2.
94. Ibid.
95. As quoted from ibid., p. 3.
96. Ibid.
97. Ibid.
98. Cranfield Aerospace, "Boeing Blended Wing Body X-48B," available at *http://www.cranfieldaerospace.com* (accessed May 14, 2015).
99. Royal Aeronautical Society, *The Royal Aeronautical Society, 1866–1966: A Short History* (London: Royal Aeronautical Society, 1966), p. 1. For over its first half century, it was known simply as the Aeronautical Society, but King George V granted the Society the distinction of a Royal prefix in 1918.
100. Cranfield Aerospace, "Cranfield Aerospace Receives Prestigious Royal Aeronautical Society Silver Award," media release, March 11, 2009; "Cranfield Aerospace: X-48B Flight 92 Complete, Now Onward As X-48C," February 18, 2011, available at *http://www.cranfieldaerospace.com/news/2009/* (accessed December 2, 2014).

101. Interview of Timothy Risch by author on November 18, 2014.
102. Cranfield Aerospace, "Cranfield Aerospace: X-48B Flight 92 Complete, Now Onward As X-48C," February 18, 2011, and "X-48B Celebrates Successful Completion of 80th flight," April 15, 2010, both available at *http://www.cranfieldaerospace.com/news/2010/* and */2011/* (accessed December 2, 2014).
103. Cranfield Aerospace, "NASA's Futuristic X-48C Hybrid Wing-Body Plane Takes Flight," August 8, 2012, available at *http://www.cranfieldaerospace.com/news/2012* (accessed December 2, 2014).

The X-48B lands at the end of the first Block 2 research mission, a 33-minute flight, on April 4, 2008. (NASA)

CHAPTER 7

The X-48B and X-48C Take to the Air

> The challenge was to test the flight mechanics of the Blended Wing Body concept and prove we could maintain stability and control. We thoroughly addressed these issues with the X-48B and got excellent results.[1]
>
> —*Robert H. Liebeck*

The X-48 research team undertook flight research with the X-48B and X-48C at NASA's Dryden (since renamed Armstrong) Flight Research Center (DFRC) at Edwards Air Force Base, CA, between July 20, 2007, and April 9, 2013. The two vehicles completed a total of 122 remotely piloted flights—92 flights by the X-48B and 30 by the X-48C. Additionally, the X-48B completed three High Speed Taxi (HST) ground tests undertaken in June and July 2007 and a followup HST test conducted on March 31, 2008. The duration of each flight generally ranged between 30 and 35 minutes.

The flight-test program was a joint effort by NASA, the U.S. Air Force, the Boeing Company, and Cranfield Aerospace. NASA project funding came from the Subsonic Fixed Wing Project under the Aeronautics Research Mission Directorate's (ARMD's) Fundamental Aeronautics Program. Pursuant to a February 2006 Memorandum of Agreement between NASA Dryden and the Boeing Company, the two parties had the following flight test responsibilities:

- Boeing would furnish (and operate) two X-48B vehicles and qualified support personnel.
- Dryden had responsibility for facilities and support equipment; the accomplishment of designated Dryden tasks; back-shop support, including meteorological services, video and photo support, and other professional and technical services; range and telemetry services; and range safety.

Boeing agreed to reimburse NASA $863,000 for Dryden-provided facilities and services. Boeing also assumed the risk of loss, damage, or destruction of the X-48B vehicle.[2]

Originally, planners envisioned a three-phase X-48B flight-test program consisting of six separate test blocks. Subsequently, however, they added more test blocks for the X-48B and then further test flights after the X-48B evolved into the X-48C. The first two blocks were for envelope expansion "to define the overall flight capabilities away from stall regimes and to discern the general stability and flight handling characteristics of the aircraft." The second phase included "more aggressive maneuvers to assess the aircraft capabilities under more demanding flight conditions, such as stalls and limited engine power." This second phase would take the X-48 to the limit of controlled flight. The third phase covered departure limiter assaults to test the capability of the vehicle to prevent entry into uncontrolled flight regimes. The outcome of testing conducted in this phase validated software algorithms for computerized flight control systems designed to prevent entry into uncontrolled flight regimes.[3]

Structuring the X-48B/C Flight-Test Program

The objectives of the flight-test program, the various test elements, the duties and responsibilities of the flight-test personnel, the types of tests conducted, and the test results and accomplishments of the flight-test program are below. A list of acronyms and details of each X-48B and X-48C flight are in the appendix (page 213).

Flight-Test Objectives

The X-48B/C was but a part of a much larger and more complex enterprise composed of various other elements. These consisted of a Ground Control Station (GCS) with the remotely piloted flight controls and simulator used by the test pilots, a propeller-driven NASA Beech T-34C Turbo-Mentor two-place chase plane, and the services of numerous Dryden and Air Force ground personnel.[4]

The chase plane provided an additional source of situational awareness for the pilot. In addition, the chase aircraft enhanced safety by providing X-48B position and trajectory information to the range safety officer. The chase pilot was in direct contact with the X-48B remote pilot throughout the flight and could relay information such as position and general characteristics of the X-48B vehicle and, on selected flights, could provide photographic and video coverage of the vehicle.[5]

The X-48B's flight test objectives were as follows:[6]

- Demonstrate controllability throughout the entire envelope.
- Resist "departures" of any kind. This was particularly important because researchers feared—quite rightly—that a BWB aircraft might

NASA 865, the two-place Beech T-34C Turbo-Mentor trainer, used by Dryden as a general mission support airplane, proved an ideal chase aircraft for the X-48B/C. Here it is flying over the Mojave on June 20, 2005. (NASA)

have the same dangerous departure characteristics as the classic flying wing. The BWB's low-speed behavior was of great concern, triggering extensive tests on stalls, departures, asymmetric thrust effects on aircraft stability and control, and flight control responsiveness.

- Possess satisfactory low-speed handling qualities.
- Validate Boeing's advanced Flight Control System (FCS) and collect data to refine the analytical models used as the basis for the FCS.
- Compare wind tunnel results obtained from the first X-48B with flight data from tests of the second X-48B at Dryden.[7]

Flight testing provided FCS risk reduction and was necessary, in the words of Gary B. Cosentino (Dryden's Lead Flight Operations Engineer on the program) "to ensure BWB configuration is as safe as a conventional airplane."[8] He grouped the flight objectives into three categories:

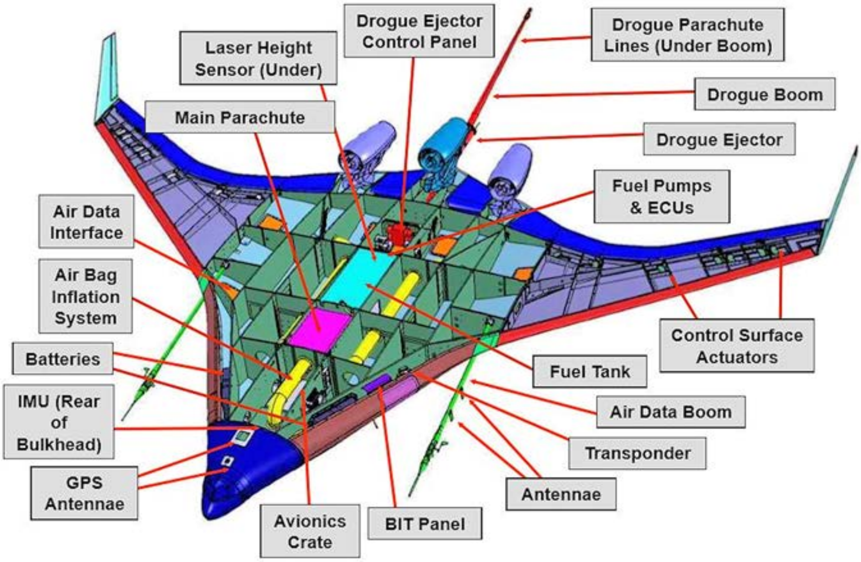
- Explore the stability and control characteristics of a BWB-class vehicle to better understand the unique flight control issues.
- Develop and evaluate flight control algorithms.
- Evaluate prediction and test methods for BWB-class vehicles.

The tri-jet Boeing-Cranfield X-48B on Rogers Dry Lake, CA, October 24, 2006, before commencement of its flight research program. (NASA)

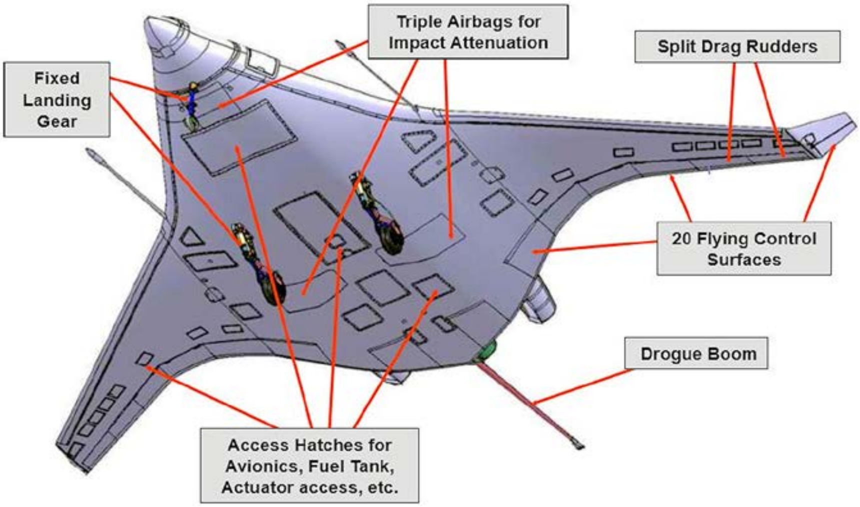
The X-48B Described

The X-48B was an 8.5-percent dynamically scaled version of the proposed 240-foot-span Boeing BWB-450-1L. As discussed previously, a dynamically scaled vehicle has the same weight distribution as the full-size aircraft and enables the simulation of the "same moments, inertias and forces as the full-scale vehicle." This allows flight testing of the 8.5-percent scaled version of the X-48 to "substantiate the stability and control and the low-speed handling qualities of a 240-foot wingspan blended wing-body aircraft."[9]

Engines and Fuel System. The X-48B had three JetCat USA P200 gas turbine engines and Engine Control Units (ECUs). Each engine produced 54 pounds of thrust at sea level. Each engine had its own throttle, fuel control circuit, and fuel pump. The JetCat engines had a single-stage compressor and single-stage turbines mounted on a common shaft.



The internal layout of the X-48B as seen from a dorsal perspective. (NASA)



The ventral perspective of the X-48B. Aside from its technical merits, altogether, the X-48B was one of the most graceful aircraft ever flown. (NASA)

Table 7-1. Specifications for the JetCat USA P200 Gas Turbine Engine

Thrust	54 pounds (0.24 kilonewtons)
Weight	5.53 pounds (2.51 kilograms)
Diameter	5.12 inches (130 millimeters)
Revolutions Per Minute (RPM) Range	33,000 to 112,000
Exhaust Gas Temperature	750 °C (1,383 °F)
Fuel Consumption	25 ounces/minute (max power)
Fuel Type	Jet A1, 1-K kerosene
Lubrication	Approx. 5% synthetic oil mixed in fuel
Maintenance Interval	25 hours

The planned flight duration ranged between 30 and 35 minutes due to the limited size of the fuel tank (12½ gallons). The Basic Integrated Test panel on the side of the vehicle furnished access to the battery switches, laptop computer interface for data download, Flight Termination System status and servicing, and transponder access. Exhaust gas temperatures and rotation speeds were the only measurements taken from the engine.[10]

Electrical System. The X-48 used two 32-volt battery packs and one 6-volt battery. One 32-volt battery pack powered the avionics subsystem, including onboard flight control computers, GPS receivers, and inertial measurement units. The other 32-volt battery pack powered the actuators subsystem, including flight control actuators except for the rudder, which was powered by the 6-volt battery pack.[11] The 32-volt subsystems were powered by an external power supply when the X-48B was trailer-towed or stationary on the ground and by onboard lithium battery packs when in flight or in a taxi mode.[12]

Navigation System. The X-48 used two GPS units—one blended with a single inertial measurement unit (IMU) to provide attitude information and navigation, and a separate stand-alone GPS unit that provided position information to the range safety officer.[13]

Avionics and Sensors. The X-48B contained a complete avionics package necessary to fly the vehicle. High-quality sensors collected information for X-48B control and post-test data analysis. An onboard Command Receiver and an onboard Telemetry Downlink Transmitter operated in the L-band frequency spectrum. Nose camera video and onboard audio relayed to the Ground

Control Station via an S-band. An air traffic controller transponder identified the vehicle and its position for the Air Force Flight Test Center's Space Positioning Optical Radar Tracking (SPORT) system. There were 20 control surface sensor inputs to the Flight Control Computer. Two air data booms measured total pressure, static pressure, static temperature, angle of attack, and angle of sideslip.[14] A laser altimeter cued control law mode changes during takeoff and landing as well as providing the pilot with height-above-ground readings at heights below 70 feet. An IMU provided real-time enhanced-accuracy vehicle position and orientation with navigation enhanced by reliance on satellite-derived Global Positioning System (GPS) data. In addition to the primary GPS receiver, there was an independent secondary GPS source incorporated into the avionics pallet.[15]

Flight Control System (FCS). As mentioned, BWB configurations do not have the long-coupled control surfaces and stabilizers found on the conventional aft tail aircraft and therefore must rely on full-authority digital fly-by-wire (DFBW) flight control systems for stability, control, and routine trimming in flight. Therefore, as developed, the X-48 demonstrator required a DFBW flight control system, one with an efficient control allocation scheme to minimize actuator rate, hinge moment, and horsepower requirements. The control system must move the control surfaces in response to pilot input, in-flight changes in aircraft configuration (for example, trimming an aircraft when the landing gear extends or retracts), and external factors such as gusts and turbulence. Douglas Cameron (engineer/scientist) and Norman Princen (BWB Low-Speed Vehicle Project Manager) with the Boeing Phantom Works addressed the control challenges and requirements for the blended wing-body configuration.[16]

Three independent pitch, roll, and yaw augmentation systems worked together with the control allocator:

- Longitudinal Stability and Control Augmentation System (LSCAS).
- Roll Stability and Control Augmentation System (RSCAS).
- Directional Stability and Control Augmentation System (DSCAS).

A deficiency in any of the control laws would compromise the performance and stability of the entire system. Furthermore, if the systems demand more control power than physically possible, then the control allocator will not be able to command enough control surface deflection, thus compromising the control and stability of the complete system.[17] The activities accomplished by the control allocator included

- commanding control surfaces obtaining uncoupled pitch, roll, and yaw moments demanded by the stability and control augmentation systems;

- generating the minimum accelerations required to meet all stability and control surface maneuvers;
- providing simultaneous roll rate and pitch acceleration capabilities for maneuvers requiring simultaneous execution, such as recoveries from stalls, which could involve simultaneous pitch and roll inputs to restore the aircraft to controlled flight;
- upholding stability and control-demanded control surface prioritization; and
- minimizing effector rate and position limiting during augmentation control.

The allocator did not command effector positions or rates greater than physically possible.[18]

Flight-Testing the X-48B's Flight Control System. Early analysis of the BWB aerodynamic characteristics identified the potential for sustained spins and nose-up tumble postdeparture modes, both historic concerns with flying wing and tailless aircraft, and this threat caused Mike Burtle to stress that potential BWB behavior had to be evaluated at the low- and high-speed edges of the envelope, including stall behavior as well as potential tumble, dive, and buffet (a combination of all of these had destroyed a Northrop YB-49A decades earlier).[19] This evaluation required the X-48B flight-test program to demonstrate robust angle of attack[20] (AOA) and sideslip[21] limiters that "would provide departure resistance and allow aggressive maneuvering up to $C_{L_{\max}}$ and sideslip limit equivalent to a full-scale normal landing in a 35 knot crosswind."[22]

Researchers employed the standard windup/wind-down turn method for angle-of-attack limiter testing, at constant airspeed, increasing AOA (and thus normal acceleration) turn at fixed power. After reaching the target angle of attack or normal acceleration limiting condition, the windup turn transitioned into a wind-down turn, a constant normal acceleration/deceleration to "corner speed," with a reduction in AOA.[23] The maneuver consisted of six segments:

- *Initial Condition.* The pilot selects an airspeed that can provide limit normal acceleration at less than limit AOA. A coordinated turn (zero yaw angle) is initiated.
- *Windup.* The pilot steadily increases bank angle while maintaining coordinated flight. AOA and normal force (g's) increase with bank angle. Airspeed is held constant by regulating descent rate.
- *Normal Acceleration Limit Segment.* When the bank angle that provides the normal acceleration limit is reached, the pilot stops increasing the bank angle. This condition marks the end of the "wind-up."

- *Constant Normal Acceleration Wind-Down Segment.* The airspeed, which has been constant to this point, is now gradually slowed to increase AOA while maintaining a constant bank angle at the normal acceleration limit.
- *Corner Speed.* As the airspeed diminishes at constant bank angle, AOA increases until it reaches its limit. Now the airplane is at the corner of the V-n diagram where the airplane is simultaneously at limit g's and limit AOA.
- *Constant AOA Wind-Down Segment.* In this segment, the airplane is flown at the limit AOA while gradually reducing bank angle and airspeed. The end of this maneuver is reached at zero bank angle, 1.0 g and limit AOA.[24]

The X-48B's subsequent tests indicated that the AOA limiter functioned satisfactorily.[25]

To test the sideslip limiter, the pilot used abrupt full-rudder pedal inputs both with slats retracted and with slats extended.[26] Subsequently, X-48B sideslip testing indicated that "sideslip limiter performance was considered excellent at all conditions tested, with typically less than 0.5-deg overshoot [and] the limiter also demonstrated excellent compensation during sideslip limit changes as AOA varied."[27]

Boeing engineers concluded afterward that

> The AOA and sideslip limiter system developed for the X-48B demonstrated acceptable performance at all conditions tested, including slats extended and retracted, forward and aft cg [center of gravity], and low and high assault rates. The incorporation of state-dependent damping improved the limiter performance by decreasing the AOA and/or sideslip overshoot at high assault rates. The limiter is now part of the baseline X-48 control laws and will be used for envelope protection in subsequent flight tests.[28]

The BWB configuration had to be as safe as a conventional transport, including demonstrating that the BWB vehicle is controllable in the post-stall region, an area where, historically, flying wings and tailless aircraft have typically experienced tumble or spins. To accomplish this, Boeing designed a control law concept based on the Versatile Control Augmentation System (VCAS) architecture like the one used on the McDonnell Douglas X-36[29] tailless canard remotely piloted research aircraft program.[30]

The X-48B had 20 flight control surfaces ganged (coupled) together into roll, pitch, and yaw control effectors. The control surface prioritizations were as follows:

- Inboard control effector 1: pitch control.
- Inboard control effectors 2 through 5: shared by both pitch and roll control, with pitch control having priority.
- Outboard control effectors 6–9: shared by yaw, roll, speed brake, and spoiler control, with yaw control having priority over roll control and roll control having full priority over speed brakes and partial priority over ground spoilers.
- Outboard winglet effector 10: dedicated to yaw control.[31]

Subsequently, tests of the X-48B's flight control system indicated that

> The X-48B flight vehicle's maximum sideslip and power-off high [AOA]-to-post-stall angle-of-attack command tracking performed well. The command tracking performance is predicted by time history analysis using the X-48B's high fidelity non-linear 6[-]degree-of-freedom simulation, which was also used for real-time piloted flight rehearsal testing. Linear analysis of the pitch stick to angle-of-attack and rudder pedal to sideslip transfer functions using the X-48B simulation's 3[-]degree-of-freedom linear models also shows good agreement with FFT [Fast Fourier Transform] modes of flight sweeps.[32]

Both wings had pitch-controlling elevators at the aft end of the fuselage between the engine nacelles, four elevons that acted as combined elevators and ailerons, and two drag rudders that also acted as ailerons and speed brakes. The X-48B's winglets, which served as vertical fins, also had rudders. (On the X-48C version, an angled Vee-tail replaced the winglets.) The pilot used a conventional fighter-style joystick to control AOA, e.g., longitudinal pitch, according to a permissible AOA range specified for each flight in a "day-of-flight" file uploaded to the FCS during preflight procedures. For lateral (roll) control, the pilot used the joystick; the X-48 used a roll-rate command system with a bank-angle hold feature when the pilot was not deflecting the stick laterally. The pilot regulated yaw (directional control) via conventional aircraft-style rudder pedals.[33] The flight control software was based on the software used in the X-36, X-45, and F-15, tailored for use on the X-48.[34]

During flight testing, researchers encountered some unanticipated lateral control behavior. As Norm Princen noted, "[W]e saw some oscillation and sideslip that we hadn't expected…. Directional stability was already very minimal because of the lack of vertical tails, so we have to get that right." To address this situation, Boeing developed new software to improve controllability by changing the schedule (control allocation) of the X-48B's 20 movable surfaces. The new software first flew on test flight 52, a Block 3.25 mission flown on July 15, 2009.[35]

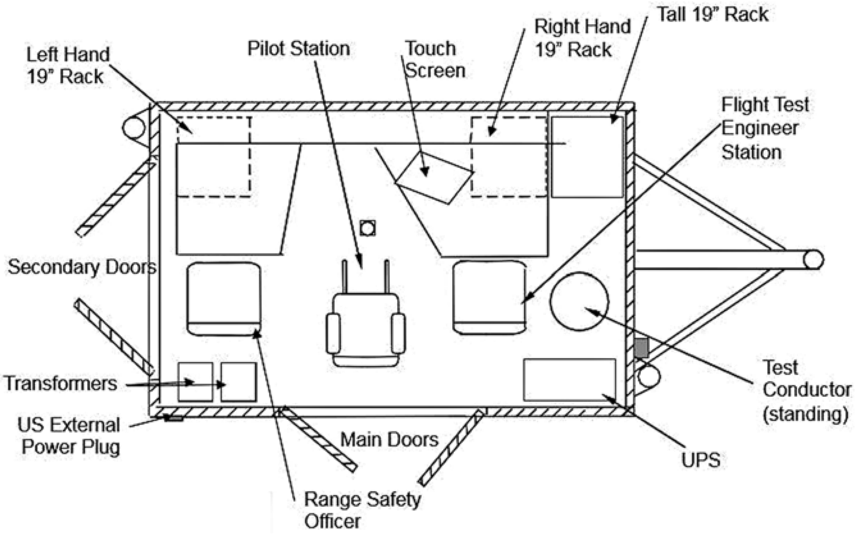
Flight Control and Data-Recording Computer. The X-48B's Flight Control Computer (FCC) processed pilot commands and sensor inputs to command the control surfaces. The control system included a Boeing-developed Vehicle Management System (VMS) that included navigation, guidance, sensor processing, and flight control subsystems. The FCC system recorded approximately 300 critical parameters at 200 hertz for the duration of each flight.[36]

Flight Termination and Recovery Systems. The X-48B had a Flight Termination System (FTS) combining a drogue parachute to terminate the flight and a conventional parachute to lower the craft to the ground, as well as airbags to take the shock of landing. The drogue chute, deployed out of the aft end of the vehicle with riser lines connected to a spin-recovery boom, could be activated by a range safety officer via dual redundant paths—one through the range FTS system and one through a telecommand uplink. Upon activation of the FTS, fuel flow to the engine would cease and the vehicle would adopt a high-drag, slightly nose-down attitude. At this point, a conventional parachute would deploy, as would three airbags (two aft of the main landing gear and one in front of the nose gear) inflated by ducted fans. Following touchdown, the main parachute would separate via a self-contained pyrotechnic line cutter activated by a pressure-pulse touchdown sensor contained inside one of the airbags, preventing the high desert winds characteristic of the Edwards environment from dragging the vehicle along the ground.[37]

Boeing also added a second flight recovery system to further reduce the risk of losing the vehicle. Under this second flight recovery system, if the vehicle control system detected low fuel, Lost Link logic would command the X-48 to circle a predetermined waypoint and then, at a predetermined fuel state, follow a 3-degree descending flightpath landing on Rogers Dry Lake's lakebed.[38]

The X-48B Ground Control Station

The Ground Control Station (GCS) had four operators within the main unit plus three external monitoring stations. The four operators were the pilot, range safety officer, test conductor, and flight-test engineer. The pilot operated the aircraft using conventional stick, rudder, and throttle controls. The three external monitoring stations were for the GCS engineer, vehicle tracking operator, and real-time stability margin engineer. The GCS operated in the following three modes: aircraft flight mode, flight simulation mode, and hardware simulation mode. In the flight mode, the pilot and flight crew controlled the functionality of the X-48B remotely through the telecommand and telemetry systems. The



A schematic drawing of the X-48B's Ground Control Station. Note that the pilot is in the center seat, with the range safety officer on the pilot's left and the mission flight test engineer on the pilot's right. (NASA)

The Ground Control Station as seen from outside. (NASA)

The X-48B's pilot position. Note that among the instrumentation and presentations, the pilot used a conventional control stick and left-hand throttle arrangement, with rudder pedals and a "head down" electronic artificial horizon display. (NASA)

The X-48B Ground Control Station during a research mission. Note that the pilot is using the head-up display with video generated by the vehicle's nose camera. The head-down display is just visible above the pilot's right knee; the range safety officer is at the extreme left of the photograph; and the mission flight test engineer is at the right. (NASA) simulation mode was used to rehearse all flight missions prior to conducting the actual flight tests. The hardware simulation mode was used to verify and validate new software and for hardware integration and validation activities.[39]

The GCS had the following five display types: the pilot's head-up display that used the vehicle's nose camera video; a head-down display that contained similar data but did not use the nose camera video; a map display that provided situational awareness of the vehicle's location and trajectory, including boundaries, runway markers, and predicted impact area in event the emergency parachute recovery was initiated; a dedicated display for warnings, cautions, engine status, fuel status, and battery condition; and an additional touch-screen display that provided buttons for commanding operating modes and programmed maneuvers.[40]

In addition to serving as a remotely piloted control station and flight simulator, the GCS was used for proficiency training. The aero model in the Ground Control Station was based on the actual vehicle's wind tunnel data and had a superior fidelity. This enabled specific power settings and angles of attack to be determined and then repeated with the actual X-48, thus dramatically improving test efficiency. The GCS also had a "playback" function that enabled every mission to be reviewed with the actual screen displays and video. Pilots were able to use this playback function to improve their flight mission reports.[41]

The Real-Time Stability Margin (RTSM) Station. This system contained a desktop computer that ran MATLAB® software (developed by the MathWorks, Natick, MA) that monitored the RTSM system. This system had the capability of processing data collected from the telemetry stream in near-real time. This enabled the station operator to view the results immediately after processing while the aircraft was still in flight.[42]

Chase Aircraft. NASA Dryden's T-34 airplane served as the chase aircraft on selected X-48B test flights, as discussed previously.

Test Range. The X-48B and X-48C flew in the R-2515 Airspace block, the most historic portion of the Air Force's larger R-2508 range complex, within the Remotely Operated Aircraft (ROA) work area on the north side of Edwards Air Force Base. Test flights 1 through 6 took off from runways marked out on Rogers Dry Lake. Test flights 7 through 27 used a paved runway at the North Base Complex—the oldest site of military flight-test activity, dating to the first tests of an American turbojet airplane, the Bell XP-59A Airacomet, in 1942—and North Base remained the preferred runway for the remaining flights. The Air Force Flight Test Center's Space Positioning Optical Radar Tracking (SPORT) facility monitored in-flight operations. Fixed and mobile

The Boeing-Cranfield-Dryden X-48B test team after its 50th flight, April 2, 2009. (NASA)

camera systems acquired video for real-time monitoring and safety purposes, routing it to the Ground Support Station through a digital video switcher; the video was archived in digital video disk (DVD) format.

The X-48B/C Test Team

The NASA Flight Program Team. Gary Cosentino served as NASA's first X-48B flight-test project manager and later as operations lead. Tim Risch served as the second NASA project manager, starting after flight 5 and serving from January 2008 through December 2011. Heather Maliska was NASA's third project manager, serving throughout the X-48C flight-test program. Fay Collier served as principal investigator.

ARMD had overall management responsibility for the flight-test effort at Dryden. Many Dryden Center branches supported the flight-test effort, including the Aeronautics Branch, Simulation Engineering Branch, Range Engineering Branch, Range Operations Branch, Flight Crew Branch, Flight Systems Branch, and Flight Controls and Dynamics Branch.[43]

The Flight and Ground Crews. Boeing furnished test pilots Steven McIlvane, Michael Sizoo, Daniel Wells, and Norman Howell. Frank Batteas, a Dryden veteran with nearly 9,000 total flight hours, was the only NASA pilot involved. Batteas said that the selection of test pilots for each flight was based primarily on their availability and not because of any special mission requirement or other characteristics.[44]

The ground crew included Gary Cosentino (NASA), Dave Westin (Boeing), Ian Brooks (Cranfield Aerospace), Alan Stevenson (Cranfield Aerospace), and David Klassman (NASA). Rod Wyatt was the crew chief, and Norm Princen (Boeing) served as chief engineer. Boeing engineer Jonathan Vass was the main flight-test conductor.

The Flight-Test Routine

Frank Batteas described the flight routine as reviewing the flight-test card and practicing on the simulator the day before the flight; remotely flying the mission; and, afterward, comparing the actual flight with the simulated flight. Batteas noted several problems encountered in flying the X-48, including winds at NASA Dryden and, at times, GPS jamming due to Air Force operations, adding that with the loss of the GPS readings, he had to immediately land the vehicle, accounting for some very short-duration flights. He identified an additional problem related to the very small head-up screen in the Ground Control Station, which only displayed a front view with a small vision field, noting that this made it harder to fly the X-48 for flights that did not have chase planes. Batteas noted the very helpful routine of practicing the test cards on the simulator on the day prior to the actual test flight. He said that approximately 14 to 15 people were present for each flight test. These included the pilot, flight tester, range safety officer, mission director, and sometimes another test pilot, all of whom were in the control trailer. Other people were outside the control trailer observing the flight. Batteas did not recall any vehicle problems while flying the X-48 and stated that there was very little difference between flying the X-48B and the modified X-48C.[45]

Michael Kisska, Boeing X-48 program manager, noted that the test team generally conducted flights on Tuesdays and Thursdays, flying between dawn and 9 a.m., for that was the best time for still atmospheric conditions before desert heating created choppy air and gusty winds. He noted that the small-scale size of the X-48 combined with the aircraft's 20.4-foot wingspan made the vehicle very susceptible to crosswinds. On the Friday (T-4) preceding the Tuesday (T-0) test flight, the test team reviewed the sequence of events and test points outlined on the test cards. The Monday (T-1) before the Tuesday flight included a full briefing of the flight cards followed by a flight rehearsal in the simulator. The test protocol required pilots to have at least 12 hours of rest between flights. The day of the flight started with a 6 a.m. predawn briefing that reviewed the aircraft status, weather conditions, mission requirements, range safety, and emergency procedures. After the flight, the team held a postflight briefing and "lessons learned" session.[46]

All flights followed a carefully structured and scripted flight plan practiced in the ground control trailer. While characteristic of all flight-test programs, this procedure took on significance given the X-48B's limited fuel capacity—a 13.2-gallon fuel tank with ~12.5 gallons usable—which restricted missions to 40 minutes. This limited test time to just 25–30 minutes. Kisska added that the X-48 design team originally envisioned using two engines, but the planned engines were behind production schedule, and so they settled for lower-thrust replacements, forcing the use of three engines. This in turn increased the fuel burn rate, resulting in lower flight time per test, thus necessitating increasing the total number of flights that had to be flown. Also causing a drawn-out schedule was flight area use priority that placed research flights as the third priority after military Research, Development, Test, and Evaluation (RDT&E) missions and higher-priority NASA missions. To support the flight testing, Cranfield Aerospace sent two representatives to the site (one avionics/wiring technician and one engineer).[47]

Boeing engineer Jonathan Vass served as a main flight-test conductor for both the X-48B and X-48C test programs, serving from June 12, 2008, through the completion of the program on April 9, 2013. During this period,

Cranfield Aerospace's Ian Brooks readying the X-48B for another research mission from Edwards' North Base test site. (NASA)

Vass also trained the last two test conductors to participate in the program. Vass described the duties and responsibilities of an X-48 test conductor as execution of the mission and briefings, flight-test preparation, and coordination with agencies. He noted that two lessons he learned from the program were that a robust vehicle "is worth its weight in gold" and being allowed to do things the "right way" is very important.[48]

The X-48B's Research Flights

The X-48B flight-test program had three phases, with each phase consisting of two blocks. The first two blocks were for progressive envelope expansion, totaling 20 flights. The leading-edge slats, increasing lift for takeoff and landing, were set prior to takeoff in either extended or retracted position; all eleven Block 1 flights had extended slats, and all nine Block 2 flights had them retracted. Planned maneuvers during the first phase defined the overall flight capabilities away from stall regimes and discerned the X-48B's general stability and handling characteristics. The second phase included more aggressive maneuvers such as stalls and reduced engine power taking the X-48B to the

With the Tehachapi Mountains behind it, together with NASA's veteran NB-52B mother ship, the X-48B takes off from Edwards AFB's North Base test site. (NASA) limit of controlled flight. The final phase of the flight-test program investigated departure limiter performance to prevent inadvertent entry into uncontrolled flight regimes. Flight-test maneuvering evaluations were largely subjective, based on a simple satisfactory or unsatisfactory judgment from the pilot. Using the information obtained, researchers validated and, if necessary, updated software algorithms for the FCS.[49]

In preparation for first flight, the X-48B test team ran three high-speed taxi (HST) tests on June 23 and 25, and July 19, 2007; the little research airplane, piloted by Boeing's Norman Howell, reached 45 knots (51.8 miles per hour). The day following the last high-speed run, July 20, 2007, Howell piloted the X-48B on its first flight. Following takeoff from Rogers Dry Lake, the X-48B climbed to 7,500 feet mean sea level (MSL) and reached a maximum speed of 70 knots (80.55 miles per hour), remaining aloft for 31 minutes. Afterward, Boeing BWB program manager Robert Liebeck noted that "we've successfully passed another milestone in our work to explore and validate the structural, aerodynamic and operational efficiencies of the BWB concept [and have] begun to compare actual flight-test data with the data generated earlier by our computer models and in the wind tunnel."[50] Robert Krieger, then Boeing's chief technology officer and president of Boeing Phantom Works, added that "the X-48B is a good example of how Boeing also looks much farther into the future at revolutionary concepts that promise even greater breakthroughs in flight."[51] (As noted earlier, at this point in the program, Boeing was investigating the BWB for application to long-range, high-capacity military transports as opposed to commercial carriers.)[52]

Test Blocks 1 and 2—Envelope Expansion

The test goals for Blocks 1 and 2, which included flights 1 through 20 flown between July 20, 2007, and July 25, 2008, included validating the stability and control of the BWB aircraft across a significant portion of the low-speed flight regime, as well as enabling a transition to higher-risk testing. The initial test flights sought to validate prior research on aerodynamic performance and controllability and to compare flight data with the wind tunnel data. Michael Sizoo piloted 13 of these flights; Howell piloted 4; and Steven McIlvane piloted 3. Specific flight maneuvers included climb, approach, and landing. As noted previously, since the pilot could not change slat position in flight, Block 1 flights had slats extended while Block 2 flights had slats retracted.[53]

The Boeing test pilots noted that, in general, the takeoff and landing characteristics were satisfactory and generally matched expectations from the ground control simulator. Envelope expansion maneuvers included steady heading sideslip tests to determine the static roll and yaw characteristics and to expand crosswind landing limits. Dynamic roll and yaw characteristics were evaluated through bank-to-bank maneuvers. Windup turns also were performed to evaluate handling qualities. Finally, frequency sweeps, doublets, and parameter identification (PID) maneuvers collected data for quantitative aerodynamic comparisons between predicted and actual results. The PID test information provided data for aero model updating and flight control effects validation. The Boeing test pilots stated, "all maneuvers were evaluated as satisfactory."[54] Vehicle response and engine response also were determined to be satisfactory. The test pilots concluded:

> Overall, the aircraft performed and handled extremely well in all weight and CG [center-of-gravity] configurations and matched well with the simulator behavior. The image from the "pilot's view" camera out the nose was acceptable, and the sun did not obscure the pilot's vision. Engine thrust response was very good. The speed brake function resulted in symmetric drag with no noticeable directional effects. There was good flight path stability on approach, and the laser altimeter instrument was found invaluable to conduct a proper flare and landing. Auto-pitch-trim and bank angle hold functions were judged acceptable to

Piloted by Boeing's Michael Sizoo, the X-48B banks gracefully on its 12th research mission, a 33-minute flight and the first with the BWB in the "clean wing" (i.e., with slats retracted) configuration. (NASA)

> be used at the pilot's discretion. The tests also proved that the autopilot functioned quite well.... The pilot indicated satisfactory handling at all speed-brake positions when flying near nominal approach speed.[55]

Altogether, this was a heartening and highly encouraging report: The X-48B clearly was a basically satisfactorily flying vehicle, fulfilling the hopes of the BWB team.

For that reason, what happened on Flight 6 came as a shocking hiccup, a reminder that flight-testing always poses its own surprises. Flight 6 was a 34-minute flight flown on August 28, 2007, planned to assess autopilot operation and to include windup turns to 1.9 g's. But after 20 seconds into the flight, the vehicle went into a nose dive when, for some reason, the flight computer reset. The plunge took the X-48B below the altitude at which the flight recovery system could activate. Fortunately, with the computer back and functioning, Norman Howell regained control before it dove into the ground, and he adroitly landed the vehicle.[56] Following Flight 6, the X-48B entered a 4-month break, not returning to the air until Flight 7 on January 18, 2008. During this time break, the X-48 underwent 4 weeks of maintenance and planned modifications to assist the flight team in evaluating the vehicle with slats retracted. In addition, the team updated the flight control software.[57]

Test Blocks 3 and 4

The successful completion of Blocks 1 and 2 resulted in a preliminary flight envelope adequate for transition to higher-risk testing, which led to the next test phase—Blocks 3 and 4. The test goals for Blocks 3 and 4, which included Flights 21 through 72, flown between August 11, 2008, and December 2, 2009, included "precisely characterizing the vehicle handling under conditions just outside of the operational envelope [and] the precise characterization of the vehicle quantitatively through parameter identification maneuvers and qualitatively through pilot feedbacks."[58] Dan Wells flew 23 of these flights; Michael Sizoo piloted 17, and NASA's Frank Batteas piloted 12. Researchers followed a systematic approach such as that used in Blocks 1 and 2 to investigate and expand the angle of attack and sideslip envelopes. The test pilots executed bank-to-bank rolls, steady heading sideslips, frequency sweeps, and PID maneuvers. The test team undertook angle-of-attack expansion in increasing 1-degree increments; at the AOA just below the predicted stall point, the X-48 became relatively difficult to hold steady due to a "sustained and continual pitch bobble" (anticipated from simulation studies). The bobble damped out following an immediate pitch-over down to a lower AOA. The test pilots noted that "at each angle of attack during the expansion [routine] the pitch-over recovery maneuver was performed successfully."[59] Furthermore, they noted that "a limiting angle of attack was reached resulting in un-commanded wing roll offs from the high angle of attack state" and that "[a]t this angle of attack around $C_{L\max}$ [maximum coefficient of lift; the point beyond which the wing stalls] plus two degrees in the slats extended configuration, the pitch bobble subsided and was no longer evident."[60] The data from Blocks 3 and 4 set the final "departure limiter trigger points" in the flight control law.[61] In regard to Block 3, starting with flights 21 and 22, the X-48 was taken to an AOA of 19 degrees, which was within 2 degrees of $C_{L\max}$, and yet the pilots were able to maintain control and good pitch-down recovery. Kisska noted that "although we're right down to the limits at that point, we were nowhere near having the controls saturated yet."[62] Also, in regard to the start of Block 3 testing, Tim Risch stated further that due to fortuitous early-morning calm, the number of flights should increase, adding that "August to November usually is the most favorable flight period."[63]

Test pilots performed a total of six pitch-over recover maneuvers during three test flights with three different pilots. Steady heading was maintained by using outside references provided by the cockpit camera. Level flight bank-to-bank rolls of 15 and 30 degrees were performed, and the initial lateral stick inputs gave the test pilots the expected basic responses. Doublets and frequency sweeps in all three axes (roll, yaw, and pitch) along with PID maneuvers were performed. All maneuvers proved to be successful and provided high-quality data.[64]

Stall testing during Block 3, however, revealed unexpected oscillations and sideslip in lateral control that necessitated the development of a more robust computer control system, requiring retesting of some of the limiter assault test flights. The new tests were flown in two added Blocks designated 3.5 and 4.5. The new software improved controllability by changing the control allocation (schedule) of the X-48B's 20 movable surfaces on the trailing edge that include the rudders on the winglets, ailerons, and elevons (outer pairs are split). All control surfaces operated independently, centrally managed by the flight control system, and were active all the time, much like, say, a high-performance fly-by-wire aircraft such as the General Dynamics (now Lockheed Martin) F-16 Fighting Falcon. Princen, X-48 chief engineer, noted that the flight control system "masks problems up to a point, and you'd only see them when it couldn't handle it [adding that] I'd like to know what happens when the aircraft is five degrees in alpha [α, e.g. angle-of-attack] beyond max lift, and whether the limiter will step in at that point or slightly beyond." The new limiter algorithms would sense the pitch and/or yaw rate and g-forces, thus enabling the control system to reschedule the allocators to address the issues by not allowing the aircraft to exceed programmed envelope limits.[65]

The X-48B shows its unique profile in this left ventral rear-quarter photograph; note the extended wing slats. (NASA)

Test Blocks 5 and 6

The test goal for Blocks 5 and 6, which included flights 73 through 80 flown between February 2 and March 19, 2010, evaluated the functionality of the three limiters (g limiter, angle-of-attack limiter, and sideslip-angles limiters) in both the slats-extended and -retracted positions. Also, one of the objectives was high-angle-of-attack testing in a turn. Sizoo flew five of these flights, Wells flew two, and Batteas flew one. Five of the flights tested the limiters by dynamic approaches to their maximum permissible extent, and the last two evaluated high-AOA stability and control in a turn.[66]

Early analysis of the BWB aerodynamic characteristics identified the potential for sustained spins and nose-up tumble postdeparture modes. Langley spin tests indicated that the BWB-450-1L configuration "has unrecoverable spin and tumble modes," pointing to a "[n]eed to prove that an advanced flight control system will prevent entry into departure regions."[67] This required the X-48B flight-test program to demonstrate robust angle-of-attack and sideslip limiters that "would provide departure resistance and allow aggressive maneuvering up to $C_{L_{\max}}$ and sideslip limit equivalent to a full-scale normal landing in a 35-kt crosswind."[68] Details of each X-48B and X-48C flight are provided in the appendix (page 213).

The last segment of the 92 flights of the X-48B consisted of 12 flights flown between September and November 2010. NASA requested this final phase to focus "on additional [parameter] identification investigations."[69] The first flight in this segment was on September 21, 2010. Wells flew 7 of the 12 flights, Sizoo flew 3; and Batteas piloted 2, including the final on November 24, 2010, a 36-minute flight with retracted slats to 11-degree AOA, bringing the X-48B's total flying time to 49 hours and 56 minutes.

In assessing the X-48B flight-test results, Michael Kisska noted the following successes:

- The X-48B was extremely maneuverable in roll.
- The aircraft very closely matched the simulations for takeoff, flight, and landing.
- The flight control design was very robust.
- Both slats-extended and slats-retracted stalls were flown successfully, demonstrating controllability to a 3-degree α beyond $C_{L\max}$.
- The departure limiter assaults were highly successful.
- Overall, the X-48B flew extremely well.[70]

Boeing test pilots Sizoo and Wells, based on their experiences over six test Blocks, noted that "[t]he most important lesson learned from the X-48 BWB flight test program is that the aircraft flies like an airplane! We do not say that lightly and are willing volunteers to pilot the manned demonstrator version."[71]

Following the completion of the 92 test flights, the X-48B returned to Cranfield Aerospace for modifications to transform it into the X-48C. The X-48C then underwent its own phase 2 flight-test program in support of NASA's Environmentally Responsible Aviation (ERA) program.[72] The modified X-48C was used "to evaluate the low-speed stability and control of a low-noise version of a notional, future Hybrid Wing Body (HWB) aircraft design."[73] "Because handling qualities of the X-48C differed from those of the X-48B, the project team modified the flight control software, including flight control limiters to keep the airplane flying within a safe flight envelope. This enabled a stronger and safer prototype flight control system suitable for further development for potential full-scale commercial hybrid or blended wing aircraft in the future."[74] Cranfield also supported Boeing's programs in support of NASA's ERA project with a team of leading British academic specialists in aviation environmental and operational issues. This work included a 9-month study of some of the primary environmental issues with a special focus on remotely piloted aircraft operations and integration.[75]

The X-48C's Research Flights

The X-48C arrived back at NASA's Dryden Flight Research Center in October 2009 following full-scale wind tunnel testing at NASA Langley that checked out the vehicle's stability and control modifications over the earlier X-48B vehicle. The modifications of the second X-48B vehicle, which began ground checkout in late 2006, included deleting the winglets and replacing their stabilizing function with twin canted tails mounted to the aft deck adjacent to the engine nozzles; replacing the original three 54-pound-thrust micro-gas turbines used on the X-48B with two larger 88.2-pound-thrust AMT Titan gas turbine engines mounted farther forward on the centerbody; and adding an extended deck area underneath and extending aft of the twin engines. Also, due to anticipated changes in handling qualities, modifications were made in the flight control system, including flight control limiters needed to keep the aircraft flying within a safe flight envelope. The noise-shielding modifications reflected NASA's ERA project, the *raison d'être* for the BWB's metamorphosis from the X-48B to the X-48C.[76]

Table 7-2. Specifications for the AMT Titan Gas Turbine Engine

Thrust	88.2 pounds (0.39 kilonewtons)
Weight	10.0 pounds (4.54 kilograms)
Diameter	5.80 inches (147 millimeters)
RPM Range	30,000 to 98,000
Exhaust Gas Temperature	780 °C (1,436 °F)
Fuel Consumption	39.5 ounces/minute (max power)
Fuel Type	Jet A1, JP-4, petroleum
Lubrication	Approx. 4.5% synthetic oil mixed in fuel
Maintenance Interval	N/A

Under the ERA program, Boeing received a $5.29 million contract for a 1-year period starting in December 2010 to conduct a study "to identify advanced concepts for airliners that could enter service in 2025, fly with less noise, cleaner exhaust and lower fuel consumption"—in other words, the X-48C BWB configuration, now known as a Hybrid Wing-Body (HWB). Specific goals were to develop technology to enable future aircraft to reduce fuel burn by 50 percent, with 50 percent fewer harmful emissions, and reduce by 83 percent the size of the geographical areas affected by objectionable noise. The program, which was designated as N+2 for airliners that would be two generations more technologically advanced than today's aircraft, had the key objective of ensuring that the "technological elements proposed for meeting NASA's noise, emissions and fuel burn reduction goals can be integrated on a single aircraft that could operate safely within a modernized air traffic system."

Boeing's Hybrid Wing-Body (HWB) transport concept submitted in response to NASA's Environmentally Responsible Aviation project. (NASA)

The project was part of the Integrated Systems Research Program managed by NASA's Aeronautics Research Mission Directorate.[77]

The X-48C successfully completed its first test flight on August 7, 2012, at Edwards Air Force Base, a brief 9-minute journey piloted by Michael Sizoo. Commenting on this first flight, NASA X-48C project manager Heather Maliska stated, "We are thrilled to get back in the air to start collecting data in this low-noise configuration. Our dedicated team has worked hard to get the X-48C off the ground for its first flight and we are excited learning about the stability and control characteristics of this low-noise configuration of the blended wing body."[78] Boeing's X-48C project manager, Mike Kisska, added, "We are very pleased to begin flight tests of the X-48C. Working with NASA, we've successfully passed another milestone in our work to explore and validate the aerodynamic characteristics and efficiencies of the blended wing body concept."[79]

The objective of the planned X-48C flight tests was to aerodynamically characterize the revised X-48 configuration to validate the vehicle's simulation model. This characterization required the test pilots to fly dynamic maneuvers over multiple centers of gravity to permit verifying the revised elements of the vehicle's control laws.[80]

Researchers planned to test the X-48C in six Blocks, with each Block increasing in risk. Blocks 1 and 2 were for envelope expansion. Block 1 consisted of 12 flights (slats extended), with the first flight flown on August 7,

The X-48C on Rogers Dry Lake, showing the changes to the trailing edge of the wing and the twin-jet, versus tri-jet, installation. The twin canted semivertical fins (somewhat reminiscent of the Beech Bonanza general aviation airplane) acted to shield the noise of the engines from the ground, a highly desirable goal for NASA's ERA team. (NASA)

2012, and the last flight flown on November 20, 2012. Block 2 consisted of five flights (slats retracted) between December 4, 2012, and February 5, 2013. Blocks 3 and 4 were for parameter identification (PID), stalls, and engine-out maneuvering. Block 4, which was flown first, consisted of seven flights (slats retracted) between February 5, 2013, and March 11, 2013. Block 3 consisted of six flights (slats extended) undertaken between March 14, 2013, and April 9, 2013. Blocks 5 and 6, which were planned to include departure limiter assaults and turning stalls, were not required to be flown.[81]

On October 30, 2012, the X-48C flew two separate 25-minute test flights (X-48C Flights 7 and 8). Flight number 8 for the X-48C represented the 100th overall test flight of the X-48 program. Mike Kisska noted that with 100 flights flown, the X-48 had far surpassed the previous record of 40 flights performed by a single unpiloted "X" plane, held by one of the Boeing X-45A Joint Unmanned Combat Aircraft technology demonstrators. Heather Maliska added, "We are thrilled by the success of our flight testing and the useful data that we have collected during the first 8 X-48C flights." Robert Liebeck stated that "earlier flight tests of the X-48B proved that a blended wing body aircraft can be controlled as effectively as a tube-and-wing aircraft during takeoffs and landings and other low-speed segments of the flight regime. With the X-48C, the team has been evaluating the impact of noise-shielding concepts on low-speed flight characteristics."[82]

The X-48C banks over the northern lake shore of Rogers Dry Lake; note the clean wing (slats retracted) configuration. (NASA)

Last Flight

Piloted by Michael Sizoo, the X-48C flew its last test flight on April 9, 2013, a 19-minute excursion terminated early because of heavy turbulence aloft. This was the 30th flight of the modified blended wing-body demonstrator and marked the successful completion of the X-48C flight-test mission that had begun eight months earlier. Commenting on the completion of the flight testing of the X-48C, Heather Maliska stated:

> Our team has done what we do best; flight test a unique aircraft and repeatedly collect data that will be used to design future "green" airliners. It is bittersweet to see the program come to an end, but we are proud of the safe and extremely successful joint Boeing and NASA flight test program that we have conducted.[83]

Robert Liebeck, whose vision had begun the program and whose persistency had ensured that it became more than just an enticing dream, noted:

> Working closely with NASA, we have been privileged throughout X-48 flight-testing to explore and validate what we believe is a significant breakthrough in the science of flight and this has been a tremendous success for Boeing. We have shown a BWB aircraft, which offers the tremendous promise of significantly greater fuel

> efficiency and reduced noise, can be controlled as effectively as a conventional tube-and-wing aircraft during takeoffs, landings and other low-speed segments of the flight regime.[84]

Michael Kisska added, “Our goal was to define the low-speed envelope and explore the low-speed handling qualities of the blended wing body class of tailless aircraft, and we have accomplished that.”[85]

Kisska further identified the following preliminary test results for the X-48C:

- The X-48C remained extremely maneuverable in roll.
- The vehicle, as with the X-48B, very closely matched the simulator for takeoff, flight, and landing.
- Early review indicated that the flight control design was very robust but that further gains could be realized with future software.
- Both slats-extended and slats-retracted stalls were successfully demonstrated (and controllable to 2 degrees beyond $C_{L_{\max}}$ (which was higher for the X-48C).
- Overall, the configuration data appeared to be encouraging and merited additional study.[86]

In reviewing the accomplishments of the X-48 program, Fay Collier, manager of NASA’s Environmentally Responsible Aviation Project and principal investigator for NASA’s Subsonic Fixed Wing Project, stated:

The X-48C test team at the end of the program. (NASA)

The X-48C test team signed the right rear elevator of the X-48C, which is now on exhibit at the Air Force Test Center's museum. The signatures do not reflect all who made contributions to the program but give an inkling of how broad the program became. (NASA)

> We have accomplished our goal of establishing a ground to flight database and proving the low speed controllability of the [BWB] concept throughout the flight envelope.... Both very quiet and efficient, the hybrid wing body has shown promise for meeting all of NASA's environmental goals for future aircraft designs.[87]

Mike Kisska noted further that "Our goal was to define the low-speed envelope and explore the low-speed handling qualities of the Blended Wing Body class of tailless aircraft, and we have accomplished that."[88]

Assessing the potential future development of the blended wing-body airplane, David McBride, Director of NASA Armstrong Flight Research Center, noted:

> It is difficult for a commercial company to accept all of the risk of new technological breakthroughs by building a near full-scale demonstrator on its own. It is simply too risky to bet the company on a new radical aircraft configuration. But a partnership on such a manned X-Plane could deliver that future transport aircraft business to American industry. It is the role of government and NASA to deliver technology ready for use to encourage growth and innovation in the private sector....[89]

Endnotes

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Readying a Boeing Hybrid Wing-Body for tests in Ames Research Center's 40- by 80-Foot National Full-Scale Aerodynamics Complex (NFAC). (NASA)

EPILOGUE
Toward a Full-Size Airplane

> The most important lesson learned from the X-48 BWB flight test program is that the aircraft flies like an airplane! We do not say that lightly and are willing volunteers to pilot the manned demonstrator version.[1]
>
> —*Michael Sizoo and Dan Wells, X-48B/C test pilots*

As the X-48C's two engines whined down to silence after its last flight, its NASA-Boeing-Cranfield research team could take great satisfaction in what they had accomplished, as could the many others at NASA, the Air Force Research Lab, and various universities and subcontractors that had supported the effort. To review briefly, building the new revolutionary blended wing-body aircraft had progressed forward very satisfactorily from its beginnings in Dennis Bushnell's challenge to industry to seek revolutionary, not evolutionary, advancement toward a renaissance in aeronautics. Extensive aerodynamic testing and further refinement of the concept had led to the fabrication and flight-testing of two dynamically scaled demonstrators. The BWB development faced many challenges and technological obstacles over a period of approximately 20 years. There had been challenges, both technical and organizational. McDonnell Douglas had stepped up to Bushnell's call, but when it merged with Boeing on August 1, 1997—coincidentally just days after Stanford University and MDC had flown the BWB-17 remotely piloted vehicle—the future of the program was thrown into doubt. Then Robert Liebeck, driving force for the development of the BWB concept, pressed tirelessly for Boeing to carry on with the BWB work. With NASA's strong support and following a critical internal top-to-bottom review of the program, Boeing boldly pressed ahead with BWB development, defining two configurations—one for an 800-passenger vehicle, the second for a 450-passenger one—suitable for airline operation, later exploring other missions, including military airlift and aerial tanking.

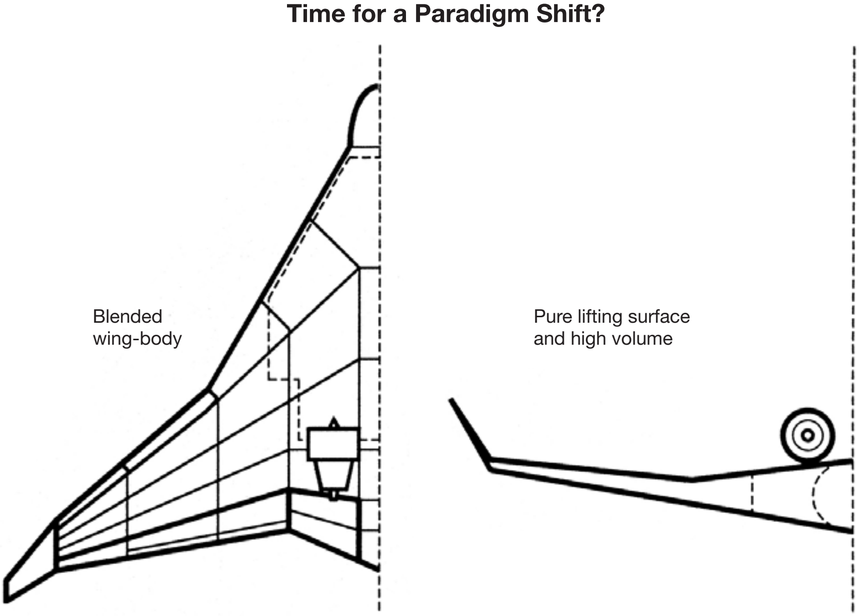
The first BWB development effort, led by NASA Langley and supported by Boeing, focused upon a BWB Low-Speed Vehicle later designated the X-48A. As shown, both parties abandoned this attempt. At this point, the BWB effort again might have ended, just another in aviation history's long list of promising though abandoned projects. Instead, Boeing and NASA forged ahead with the 8.5-percent scaled X-48B. It, too, faced numerous technological hurdles, not least of which was overcoming a tailless aircraft's inherent stability and control issues and designing the flight control laws and limiters necessary to fly the BWB aircraft. Boeing and NASA met this challenge and then, with the creative and dedicated contribution of Cranfield Aerospace, took the project from concept into fabrication, and then into a highly successful flight test program, which, along with continued aerodynamic testing, validated the BWB concept. While no full-size piloted BWB aircraft has yet flown, work continues toward that goal, and the concept has gained wider acceptance from the global aerospace community.

Europe and the BWB

Boeing is not alone in the effort to develop a blended wing-body airplane. The BWB research and development work undertaken by the European MOB consortium and Cranfield University, as well as Airbus' interest in the BWB, reviewed earlier, indicates interest in the BWB concept among European aeronautical industries, universities, and research institutes. European joint efforts continued after MOB as evidenced by follow-on European Commission research programs, including the Very Efficient Large Aircraft (VELA) project; the New Aircraft Concepts Research (NACRE) program, which studied various potential aircraft configurations; and the Active Control for Flexible Aircraft (ACFA) year 2020 project.

VELA

The VELA project, which ran from October 2002 to October 2005, was intended to "stimulate research for innovative, efficient and environmental friendly concepts in [the] air transport sector."[2] Specifically, the project partners addressed the "development of skills, capabilities and methodologies suitable for the design and optimization of civil flying wing aircraft."[3] The project team, which included 17 aeronautical-related companies and institutes, noted that while successful flying wings have been developed for military use, none have been built for civil transport use due to the differences in payload, mission, and airworthiness requirements. VELA "aimed at the development of skills, capabilities and methodologies suitable for the design and optimization of civil flying wing aircraft."[4] To fulfill this aim, the VELA partners conducted wind tunnel testing to measure static and dynamic derivatives; compared these results with predictions made using preliminary design tools; and used aerodynamic derivatives to develop flight control systems. Optimization techniques maximized the efficiency of flying wing configurations. Finite element models addressed pressure cabin issues.



Thanks to the efforts of BWB advocates, by the centennial of the Wright brothers' first flight at Kitty Hawk, NC, in 1903, interest in BWB aircraft had increased greatly. Here is a BWB advocacy drawing from a presentation by Richard P. Hallion at a 2003 National Academy of Engineering symposium. Hallion concluded, "The best way to honor the Wrights and all of those who revolutionized the world through the air is by pushing ahead."[5] (RPH)

NACRE

The NACRE project, which ran from April 1, 2005, to March 31, 2010, was undertaken at a total cost of €30.33 million (then $22.66 million, equal to $25.87 million in 2018).[6] NACRE included 35 partners from 13 countries, including the Russian Federation.[7] Rather than focusing on one specific aircraft concept, the program worked on developing solutions at the aircraft system and subassembly level, including the cabin, wing, propulsion system, and fuselage. The effort focused on four separate work packages (WPs)—novel aircraft models (WP1), novel lifting surfaces (WP2), novel powerplant installation (WP3), and novel fuselage design (WP4). Each work package included discrete tasks. For example, the three tasks for WP2 addressed advanced wings, flying wings, and innovative tail integration.[8]

ACFA

The research conducted under the NACRE program led to the ACFA year 2020 project, a collaborative European Union research project dealing with "innovative control concepts for ultra-efficient 2020 aircraft configurations like the blended wing body (BWB) aircraft."[9] The BWB concept satisfied two major goals of the Advisory Council for Aeronautics Research in Europe (ACARE)—a 50-percent reduction in fuel consumption and related CO_2 emissions per passenger-kilometer and extreme noise reduction by 4 to 5 decibels for short-term operations and 10 decibels for long-term operations. While various wing configurations were studied under the NACRE program, the AFCA 2020 team noted that "Blended Wing Body type aircraft configurations are seen as the most promising concept to fulfil the ACARE vision 2020 goals because aircraft efficiency can be dramatically increased through minimisation of the wetted area and by reduced structural weight."[10]

The project had a startup date of March 1, 2008, with a 42-month planned duration. The European Commission contributed €3.12 million (then $2.34 million, now $2.71 million) of the €4.59 million (then $3.44 million, now $3.98 million) total budget. The consortium had 13 partners, including EADS Innovation Works and Airbus. The "predesign" of the ACFA BWB airplane had a resemblance to the Boeing X-48, including the 450-passenger size. Dynamic models formed the basis for the controller design, and the EADS Innovation Works adaptive-feed forward control concept supported flight tests with DLR's Advanced Technologies Testing Aircraft Systems (ATTAS) aircraft.[11]

NASA Continues Forward

As global interest in the BWB grew, so too did interest by other American airframe manufacturers, typified by Lockheed Martin, which entered the BWB field with a modified Hybrid Wing-Body (HWB) airplane configuration, designed by its famed "Skunk Works" advanced development branch, with funding support from the Air Force Research Laboratory (AFRL). In February 2016, Lockheed completed low-speed testing of a 4-percent scale model in Lockheed's low-speed wind tunnel in Marietta, GA. This testing followed August 2015 wind tunnel testing at Langley's National Transonic Facility (NTF). The wind tunnel tests supported validation of CFD predictions of the HWB performance. As *Aviation Week & Space Technology* reporter

Graham Warwick noted, potential use of the HWB as a military transport and tanker aircraft, as well as a commercial cargo carrier, "raises the possibility that the HWB could succeed in bringing together enough government and industry stakeholders to fund a manned demonstrator—something that so far has eluded both AFRL and NASA on their own."[12] Lockheed also has obtained NASA funding to study a commercial freighter version to see how the HWB performs against NASA's fuel-burn, emissions, and noise targets.

The Lockheed Martin HWB concept had a blended wing and forebody for aerodynamic and structural efficiency, with a conventional aft fuselage and tail, giving it an appearance somewhat like a BWB with the T-tail section of a Lockheed C-5 or Boeing C-17 airlifter. Model testing revealed that having a conventional aft fuselage inflicted less than a 5-percent fuel-burn penalty compared with the pure blended wing. Rick Hooker, Lockheed's HWB program manager, added that "retaining the empennage allows us to flight test more quickly because it will not take us years to develop the flight control laws."[13] Lockheed anticipated that the aircraft could carry oversize cargo currently transported by Lockheed's C-5M Galaxy with a fuel burn 70 percent lower than the smaller Boeing C-17A Globemaster III, due to better aerodynamics, advanced engines, and lighter structures. Like Boeing before it, Lockheed Martin envisioned the HWB fulfilling airlift, tanker/transport, and commercial freighter roles, in each case executing the mission with significant fuel savings compared to contemporary systems.[14]

Back to the Tunnel…

Following the end of the X-48C program, NASA's interest in the BWB also continued, with additional wind tunnel testing undertaken at Langley and NASA's inclusion of the BWB, as well as Lockheed Martin's HWB, in future X-plane considerations. During September 2016, Boeing and NASA resumed wind tunnel testing using the same 6-percent scale model used in the earlier 2014 and 2015 aerodynamic tests conducted in the 40- by 80-foot tunnel at NASA Ames. The new tests, which were done at the Langley 14- by 22-foot Subsonic Tunnel, were conducted to validate testing methodology and to map airflow over the BWB airplane. These tests used lasers and smoke in a flow analysis technique known as Particle Imagery Velocimetry (PIV). John Bonet, Boeing's test director for the BWB, noted that "what we learn from this round of testing will be used to complete the definition of our aerodynamic, stability and control low-speed database—a major milestone in the technology development of the concept."[15] Dan Vicroy added that "testing the same model in two different tunnels gives us data to make our test methods better."[16] The testing, combined with previous X-48B and X-48C BWB aerodynamic and flight testing, prepared the BWB for the "next step in maturing this technology" for a piloted BWB demonstrator.[17]

The 6-percent Boeing BWB undergoes testing in Langley Research Center's 14- by 22-foot Subsonic Tunnel in 2016. (NASA)

Boeing, in early 2017, conducted additional tests to determine that the BWB could successfully operate with an aft clamshell cargo door that would accommodate both cargo and paratroop operations. Researchers undertook flow visualization tests in Boeing's water tunnel in Huntington Beach, CA. (The water tunnel represents a faster and cheaper way to test aircraft concept designs by using 3D-printed small-scale concept models made with dye ports. Water circulating in the tunnel simulates air flow by creating visible streams of colored dye that show how the air would flow over the full-sized airplane.)[18]

NASA Grants Research Contracts for Five Aircraft Configurations

On September 8, 2016, NASA announced the awarding of five contracts, including one for the Boeing BWB, having the objective of assisting NASA "in defining the technical approach, schedule, and cost for proceeding with potential X-plane procurement(s) that support the Ultra Efficient Subsonic Transport Thrust and accomplishment of the Mid-and-Far-term Community Outcomes Awardees."[19] The dollar amounts of the awards were as follows:

- Aurora Flight Sciences Corporation (contract NND16XPO1C), $2,900,991;

- Boeing (contract NND16XPO2C), \$2,572,808;
- Boeing (contract NND16X903C), \$1,871,264;
- DZYNE Technologies, Incorporated (contract NND16XPO4C), \$1,934,254; and
- Lockheed Martin Aeronautics Company (contract NND16XPO5C), \$2,448,092.

The Aurora configuration is the Double-Bubble D8 originally developed for NASA by the Massachusetts Institute of Technology (MIT); the two Boeing configurations are the Blended Wing-Body (BWB) and the Transonic Truss-Braced Wing (TTBW); the DZYNE Technologies configuration is a BWB small airliner/business-class jet; and the Lockheed Martin configuration is their Hybrid Wing-Body (HWB).[20] The contracts for these configurations, which are reviewed in greater detail below, essentially represent the start of the first X-plane phase of NASA's New Aviation Horizons (NAH) initiative.

NASA's New Aviation Horizons Initiative

In 2017, NASA started a 10-year research effort to "accelerate aviation energy efficiency, transform propulsion systems, and enable major improvements in air traffic mobility."[21] For justification of this program, known as the New Aviation Horizons initiative, NASA noted that global aviation is forecast to increase from its current 3.5 billion passenger trips per year to 7 billion by the end of the 2030s and to 11 billion passenger trips by midcentury. While this growth projection would add trillions of dollars from increased manufacturing and operations, with the resulting increase in high-quality jobs, NASA also pointed out the substantial increase in operational and environmental challenges. NASA added that "revolutionary levels of aircraft performance improvements—well beyond today's technology—must be achieved."[22]

To achieve these improvements, NASA set forth a three-prong effort. The first component is to develop "high-speed super computers that can model the physics of air flowing over an object—be it a wing, a rudder or a full airplane." The second component is to put scale models in a wind tunnel "to take measurements of air flowing over the object [and to use the resulting measurements to] help improve the computer model [which in turn] helps inform improvements to the airplane design, which can then be tested again in the wind tunnel." The third component is to fly an X-plane or a full-scale prototype.[23]

The NAH program represents a partnership between NASA, industry, universities, and other Government agencies. This joint effort includes four NASA Centers (Ames, Armstrong, Glenn, and Langley), the principal X-plane builders (The Boeing Company, Lockheed Martin Aeronautics Company, DZYNE Technologies, and Aurora Flight Systems), various U.S. universities, and the

Federal Aviation Administration. The Department of Defense also assists in developing and testing technologies that have potential military applications.

NASA intends the New Aviation Horizons initiative to

- demonstrate revolutionary advancements in aircraft and engine configurations that break the mold of traditional tube-and-wing designs;
- support accelerated delivery to U.S. aviation verified design and analysis tools that support new flight-validated concepts, systems, and technologies;
- provide to appropriate organizations and agencies research results that inform their work to update domestic and international aviation standards and regulations;
- enable U.S. industry to put into service flight-proven transformative technology that will solve tomorrow's global aviation challenges; and
- inspire a new generation of aeronautical innovators and equip them to engineer future aviation systems.[24]

NASA has thus far determined that various X-plane configurations, including the BWB, will be selected for further research and development based on a 10-year phased deployment. This phased approach will start with the technologies and concepts that are already mature enough to proceed with integrated flight experimentations. At the same time, NASA envisions that ground tests and analysis would continue on concepts requiring further maturation. NASA adds that the phased-in approach also should enable a "full competition of ideas among U.S. companies to achieve the highest impact payoffs."[25]

Of the five X-plane configurations, NASA determined that three subsonic X-plane aircraft will be necessary to flight-test the NAH program objectives relating to "the major enabling fuel, emissions and noise reducing technologies."[26] A fourth large-scale transport-class X-plane is planned for testing turbo-electric propulsion during the mid-2020s, and a fifth X-plane "will seek to validate NASA research that shows major hurdles to efficient, low noise supersonic flight can be overcome."[27]

NASA's flight-testing program for the selected aircraft is designed to deliver

- X-planes that integrate advanced concepts and technologies;
- advanced technologies proven through ground and flight tests;
- full understanding of complex, transformational flight systems, including structures, aerodynamics, propulsion, controls (including human factors and autonomy) and flight dynamics interactions.; and
- transformational research aligned with NASA Aeronautics' Strategic Plan.[28]

NASA identified the following possible X-plane configurations, along with their characteristics, for further consideration under the New Aviation Horizons initiative:

- *Hybrid Electric Demonstrator, Single-aisle Turboelectric AiRCraft (STARC)*—large-scale (50 percent); piloted for safe flight in public airspace; and having electric motors attached to turbofan engines, an electric-motor-driven fan in an annular tail cone duct (accelerate the thickened slow-moving boundary layer), and a T-tail to accommodate a tail-mounted fan.
- *Hybrid Electric Demonstrator, Scalable Convergent Electric Propulsion Technology Operations Research (SCEPTOR)*—a small-scale, general-aviation-size, nine-passenger, 500-kilowatt (approximately 700-horsepower) subsonic electric airplane for safe flight in public airspace. The SCEPTOR received the X-plane designation of X-57. NASA engineers added the name "Maxwell" to honor the 19th-century Scottish physicist James Clerk Maxwell who pioneered the field of electromagnetism. The testbed involves replacing the wing on an Italian-built Tecnam P2006T airplane with a new experimental wing with electric motors installed along the entire wing. By using an existing airplane, the engineers can compare the performance of the electric-powered aircraft with the original configuration. NASA Armstrong flew a Tecnam P2006T to obtain baseline performance data on the original configuration. The initial testing has utilized a Hybrid Electric Integrated Systems Testbed (HEIST) that consists of an experimental wing initially mounted on a specially modified truck. Sean Clark, SCEPTOR co-principal investigator at NASA Armstrong, noted that the testbed has been used to measure lift, drag, pitching moment, and rolling moment. Clark added that "by evaluating what we measured, versus what the computational fluid dynamics, or CFD, predicted, we will know if the predictions make sense"; initial testing indicated that "the distribution of power among 18 motors creates more than double the lift at lower speeds than traditional systems."[29]
- *Blended Wing-Body (BWB), also known as the Hybrid Wing-Body (HWB)*—large-scale (50 percent size); piloted for safe flight in public airspace; having a noncircular pressurized fuselage, top-mounted engines to shield noise from the ground, multiple platforms (structures, materials, aerodynamics, flight controls, and propulsion/airframe integration); and designed for initial application as a cargo transport.[30] NASA notes that the X-plane BWB would be a piloted version of the Boeing X-48, effectively marking a return to McDonnell Douglas' abandoned proposal to build a small twin-engine piloted BWB demonstrator. This configuration is the furthest along on the development and testing timeline of the five X-plane concepts. As the most mature of the X-plane configurations, NASA's NAH plan

started with a follow-on preliminary design (FY 2017 into FY 2019), followed by the design and build of the piloted vehicle (FY 2022–23), and then to flight testing starting in late FY 2023 or early FY 2024.[31]

- *Quiet Supersonic Technology (QueSST) Demonstrator*—a planned large-scale (90-foot-long) demonstrator simulating a future 100-passenger supersonic airplane. Lockheed Martin is the lead contractor, assisted by NASA engineers and technicians. Peter Iosifidis, QueSST program manager at Lockheed Martin's Skunk Works at Air Force Plant 42, Palmdale, CA, noted, "Our unique aircraft design is shaped to separate the shocks and expansions associated with supersonic flight, dramatically reducing the aircraft's loudness."[32] In May 2016, NASA Glenn completed its wind tunnel testing of a 9-percent scale model in the Center's 8- by 6-foot Supersonic Wind Tunnel. In June 2017, the QueSST completed its Preliminary Design Review (PDR), and engineers from NASA and Lockheed Martin concluded that the design is capable of fulfilling the planned objectives "to fly at supersonic speeds but create a soft 'thump' instead of the disruptive sonic boom." NASA's David Richwine, manager for the preliminary design effort, stated, "Our strong partnership with Lockheed Martin helped get us to this point. We're now one step closer to building an actual X-plane." The next step is to begin the process of soliciting proposals to build a piloted, single-engine X-plane to be flight-tested as early as 2021.[33]

The above activities are funded under NASA's Aeronautics 10-Year American Aviation Plan, which envisioned that FY 2017 budget projections would represent "the first step in a 10-year plan to achieve the most critical outcomes in NASA's Aeronautics long term vision and strategy, including a bold series of new experimental aircraft or 'X-plane' and technology systems demonstrations."[34] Proposed budget projections for FY 2017 through FY 2026 are as follows:[35]

Table E-1. NASA Proposed 10-Year Budget Projections Supporting Advanced Aircraft RDT&E (in millions of U.S. dollars)

FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26
790	846	1.060	1.173	1.287	1.294	1.308	1.218	830	839

In justifying the NAH effort and funding, NASA pointed out that "[o]nly vigorous and sustained investment in this pursuit will ensure that the United States maintains its continued technological leadership."[36]

NASA, however, did not receive the anticipated FY 2017 or the requested FY 2018 funding levels, reduced from $846 million down to $624 million, which will cause the NAH initiative to move forward at a slower pace than the original timeline for introducing the X-plane configurations at 18-month intervals.[37] Nevertheless, further developments leading to the fabrication of a full-size piloted BWB seem more and more certain to be accomplished: it is just a question of timing. In any case, when the members of the first aircrew are sitting in a BWB at the end of a runway awaiting takeoff clearance, they will be following in the wake of the X-48B/C and all of the hardy pioneers who took the idea of the blended wing-body and transformed it into a flying reality evaluated in the harsh blue Mojave sky.

Endnotes

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APPENDIX

X-48B and X-48C Research Flights at NASA Dryden Flight Research Center

X-48B Research Flights

Flight No.	Date Flown	Flight Duration	Test Pilot	Slats Position	Weight and Center of Gravity (CG)	Flight Description
HST	06-23-07	N/A	Howell	Extended	Mid/Mid	High Speed Taxi to 45 Knots; Completed Low Speed Test (LST) Deck
HST	06-25-07	N/A	Howell	Extended	Mid/Mid	High Speed Taxi to 45 Knots; Completed High Speed Test (HST) Deck
HST	07-19-07	N/A	Howell	Extended	Mid/Mid	Successful Regression High Speed Taxi (35 Knots)
Block 1 Flights						
1	07-20-07	31 min	Howell	Extended	Mid/Mid	First Flight Milestone (70 Knots, 7,500 ft. Mean Sea Level)
2	07-30-07	33 min	Howell	Extended	Mid/Mid	Climbed to 10,000 ft.; Sideslips at 50 Knots and 60 Knots, Parameter Identifications (PID)[1]
3	08-02-07	31 min	Sizoo	Extended	Mid/Mid	Sideslips, Real-Time Stability Margin (RTSM)[2] Sweeps, PID
4	08-08-07	35 min	Sizoo	Extended	Mid/ Forward	RTSM Sweeps, Doublets,[3] Sideslips, Frequency Sweeps (FS)[4]

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[1] Exciting the Flight Control System (FCS) with a time-varying sinusoidal single of increasing frequency, triggering aircraft motions and acquiring data permitting postflight analysis of the dynamic interaction of the FCS upon the aircraft's behavior in individual or combined motions in pitch, roll, and yaw.

[2] An FCS signal input applied to all three axes (roll, pitch, and yaw) simultaneously, furnishing phase and gain margins in all three axes.

[3] Two sequential opposing control inputs beginning from the stick-neutral position; for example, a pitch doublet is a pull-back from the stick-neutral position followed immediately by a push forward through the stick-neutral position, and then a return to the stick-neutral position.

[4] An FCS signal input applied to induce an individual response in pitch, roll, and yaw.

Flight No.	Date Flown	Flight Duration	Test Pilot	Slats Position	Weight and Center of Gravity (CG)	Flight Description
5	08-14-07	36 min	Howell	Extended	Mid/ Forward	PID Impulses and Triplets,[5] Sideslips, Rolls, Stall Recovery, and FS
6	08-28-07	34 min	Howell	Extended	Mid/ Forward	Autopilot—Wind-Up Turns (WUT)[6] to 1.9 g's
7	01-18-08	35 min	Sizoo	Extended	Heavy/Mid	Return to Flight—Airspeed Calibrations (A/S Cal)
8	01-31-08	36 min	Sizoo	Extended	Heavy/Mid	Sideslips, A/S Cal, PIDs, Handling Qualities (HQ)
9	02-08-08	32 min	Sizoo	Extended	Heavy/Aft	PID, RTSM, Lazy 8's, A/S Cal (No Chase)
10	02-29-08	38 min	McIlvane	Extended	Heavy/Aft	Sideslips, PIDs, HQ (No Chase)
11	03-06-08	35 min	McIlvane	Extended	Heavy/Aft	Sideslips, PIDs, HQ
Block 2 Flights						
HST	03-31-08	N/A	Sizoo	Retracted	Light/Mid	High Speed Taxi to 57 Knots
12	04-04-08	33 min	Sizoo	Retracted	Light/Mid	First Block 2 Flight, Clean Wing, Envelope Expansion, RTSM, PID, FS
13	04-17-08	36 min	Sizoo	Retracted	Light/Mid	Clean Wing, PIDs and A/S Cal (No Chase)
14	05-08-08	28 min	Sizoo	Retracted	Light/Mid	PID, Steady Heading Sideslips (SHSS), WUT, A/S Cal
15	06-12-08	35 min	McIlvane	Retracted	Mid/ Forward	Vehicle Management System (VMS) Level 1, 2, and 3 Trials, PIDs
16	06-19-08	34 min	Sizoo	Retracted	Mid/ Forward	Bank-to-Bank (BTB) Turns, WUT, SHSS
17	07-03-08	28 min	Sizoo	Retracted	Mid/ Forward	SHSS, WUT, BTB Turns (No Chase)
18	07-21-08	31 min	Sizoo	Retracted	Heavy/Aft	RTSM, PID, Approach to Stall
19	07-21-08	28 min	Sizoo	Retracted	Heavy/Aft	Cruise "Gait" Maneuver, RTSM, PID, FS
20	07-25-08	32 min	Sizoo	Retracted	Heavy/Aft	High-Speed, SHSS, BTB, WUTs, FS
Block 3 Flights						
21	08-11-08	37 min	Sizoo	Extended	Mid/ Forward	Approach to Stalls, RTSM, PIDs (No Chase)

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[5] Three sequential opposing control inputs to trigger a dynamic response in pitch, roll, or yaw. A pitch triplet is a pull-back from the stick-neutral position followed immediately by a push-forward through the stick-neutral position, and then a pull-back through the stick-neutral position followed by a return to the stick-neutral position.

[6] A turn that the pilot deliberately tightens, becoming progressively steeper (wings approach or reach a 90-degree bank angle), and as it tightens, the flight loads increase, affording a measure of stick force per g over a range of airspeeds.

Flight No.	Date Flown	Flight Duration	Test Pilot	Slats Position	Weight and Center of Gravity (CG)	Flight Description
22	08-11-08	35 min	Sizoo	Extended	Mid/ Forward	Approach to Stalls, 16° α[7] A/S Cal, BTBs, PIDs (No Chase)
23	08-13-08	34 min	Batteas	Extended	Mid/ Forward	NASA Pilot Familiarization Flight (No Chase)
24	09-04-08	38 min	Sizoo	Extended	Mid/ Forward	Stalls to 23° α, PIDs, FS (X-48B Experienced Right-Wing Roll-Off at 23° α)
25	09-11-08	37 min	Batteas	Extended	Mid/ Forward	Repeat Stalls to 23° α
26	09-18-08	12 min	Sizoo	Extended	Mid/ Forward	Block 3 Software (S/W) Regression Cycle
27	09-18-08	36 min	Sizoo	Extended	Mid/ Forward	Block 3 S/W Regression, PIDs at 20° α, FS
28	09-24-08	35 min	Sizoo	Extended	Mid/ Forward	PIDs at 20° α (Revised Gains), Trim in Ground Effect from 15 and 10 ft.
29	10-06-08	35 min	Sizoo	Extended	Mid/ Forward	PID at 20° α (Revised Gains), Trim in Ground Effect to 10 ft.
30	10-06-08	34 min	Wells	Extended	Mid/ Forward	Pilot Familiarization Flight, PIDs to 20° α
31	10-15-08	36 min	Wells	Extended	Mid/ Forward	Stalls to 23° α with Low-Speed Vehicle 1 Slats
32	10-16-08	35 min	Wells	Extended	Mid/ Forward	SHSS at 14°, 16°, and 18° α (No Chase)
33	10-23-08	36 min	Wells	Extended	Mid/ Forward	SHSS at 18° and 20° α—PIDs
34	10-23-08	29 min	Wells	Extended	Mid/ Forward	Single Surface PIDs (SSPIDs)
Block 4 Flights						
35	10-29-08	36 min	Batteas	Retracted	Mid/ Forward	Approach to Stall, 8° α Limiter Verification
36	10-30-08	36 min	Wells	Retracted	Mid/ Forward	Approach to Stall at 6° and 8° α, SSPIDs
37	11-21-08	32 min	Batteas	Retracted	Mid/ Forward	20-Second RTSM Sweeps, SHSS
38	11-21-08	38 min	Sizoo	Retracted	Mid/ Forward	Initial Clean-Wing Stalls
39	11-25-08	34 min	Wells	Retracted	Mid/ Forward	BTBs, PIDs, and Doublets

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[7] α (“Alpha”) = angle of attack in degrees.

Flight No.	**Date Flown**	**Flight Duration**	**Test Pilot**	**Slats Position**	**Weight and Center of Gravity (CG)**	**Flight Description**
40	01-21-09	36 min	Wells	Retracted	Mid/ Forward	Clean-Wing Stalls, PIDs, FS, and Doublets
41	01-28-09	40 min	Batteas	Retracted	Mid/ Forward	Steady Heading Sideslips, FS, and Doublets
42	01-30-09	5 min	Wells	Retracted	Mid/ Forward	Return to Base (RTB) Due to Instrumentation
43	02-04-09	39 min	Sizoo	Retracted	Mid/ Forward	Repeat of Flight 42 Deck—SHSS, FS, and Doublets
Block 3.25 Flights						
44	02-10-09	38 min	Batteas	Extended	Heavy/Aft	Slats Extended; Aft Center of Gravity (CG); Approach to Stalls 14°, 16°, and 18° α
45	02-18-09	30 min	Batteas	Extended	Heavy/Aft	Approach to Stall—18° α
46	03-05-09	38 min	Wells	Extended	Heavy/Aft	Approach to Stall—20° and 21° α, RTSM, 120-Second FS
47	05-05-09	12 min	Wells	Extended	Heavy/Aft	RTB Due to Engine
48	03-18-09	35 min	Batteas	Extended	Heavy/Aft	Accelerations/Decelerations, 5-Second PIDs, Turning A/S Cal
49	03-18-09	34 min	Wells	Extended	Heavy/Aft	Accelerations/Decelerations, 5-Second PIDs, Turning A/S Cal
50	04-02-09	30 min	Sizoo	Extended	Heavy/Aft	5-Second PIDs, Turning A/S Cal
51	06-04-09	35 min	Sizoo	Extended	Mid/ Forward	LST/HST[8]—V40.6 Regression, PIDs, FS, and HQ Evaluation
52	07-15-09	27 min	Wells	Extended	Mid/ Forward	HST—VMS V4.0.6 Regression, SHSS and BTB turns, 7° and 10° α
53	07-6-09	31 min	Sizoo	Extended	Mid/ Forward	VMS V4.0.6 Regression, SHSS and BTB Turns 10° and 18° α, Plus Speed Brake 1
54	07-21-09	36 min	Wells	Extended	Mid/Aft	VMS V4.0.6 Regression, Slats Extended/Aft CG
55	07-30-09	6 min	Batteas	Extended	Mid/Aft	VMS V4.0.6 Regression, Repeat of Flight 54 Deck
56	08-11-09	31 min	Wells	Extended	Mid/Aft	VMS V4.0.6 Regression, Repeat of Flight 54 and 55 Decks
Block 4.25 Flights						
57	08-18-09	35 min	Sizoo	Retracted	Mid/ Forward	VMS V4.0.1.1 Regression

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[8] LST/HST = Low Speed Test/High Speed Test.

Flight No.	Date Flown	Flight Duration	Test Pilot	Slats Position	Weight and Center of Gravity (CG)	Flight Description
58	08-20-09	30 min	Wells	Retracted	Mid/Aft	VMS V4.0.1.1 Regression, Dive Speed (V_{Dive}) to 108 Knots Indicated Airspeed (KIAS)
Block 3.5 Flights						
59	09-01-09	35 min	Batteas	Extended	Mid/ Forward	Stall Characteristics Testing, 20° and 21° α
60	09-01-09	34 min	Sizoo	Extended	Mid/ Forward	Stall Characteristics Evaluation; 22°, 23°, and 23.8° α
61	09-03-09	32 min	Sizoo	Extended	Mid/ Forward	Stall Characteristics Evaluation; 22°, 23°, and 23.8° α
Block 4.5 Flights						
62	09-10-09	33 min	Wells	Retracted	Mid/ Forward	Stall Characteristics Evaluation; 10°, 11°, 12°, 13°, 14°, and 15° α
63	09-10-09	27 min	Batteas	Retracted	Mid/ Forward	V_{Dive} and Clean-Wing Engine-Out Maneuvering
64	09-15-09	31 min	Wells	Retracted	Mid/ Forward	Power-On Stalls to 15° α, Minimum Controllable Airspeed (V_{mca})
65	09-17-09	36 min	Wells	Retracted	Mid/ Forward	V_{mca} Static and Dynamic, PIDs
66	09-23-09	35 min	Batteas	Retracted	Mid/ Forward	PID Matrix
Block 3.5.5 Flights						
67	09-29-09	34 min	Sizoo	Extended	Mid/ Forward	Power-On Stall to 24° α, PID Matrix
68	10-06-09	35 min	Wells	Extended	Heavy/Aft	RTSM, Power-Off/Power-On Stalls to 22° α
69	10-08-09	34 min	Wells	Extended	Heavy/Aft	Power-On Stalls at 22° α, V_{mca} Static and Dynamic
70	10-21-09	36 min	Sizoo	Extended	Heavy/Aft	RTSM, Power-Off/Power-On Stalls to 24° α
Block 4.5.5 Flights						
71	12-02-09	34 min	Wells	Retracted	Heavy/Aft	Power-On/Power-Off Stalls to 15° α
72	12-02-09	31 min	Wells	Retracted	Heavy/Aft	Power-On Stalls to 15° α
Block 5 Flights						
73	02-02-10	24 min	Sizoo	Extended	Mid/ Forward	VMS 4.2.2 Regression, Dynamic Limiter Validation
74	02-20-10	19 min	Sizoo	Extended	Mid/ Forward	RTB Due to Airspeed Anomaly

Flight No.	Date Flown	Flight Duration	Test Pilot	Slats Position	Weight and Center of Gravity (CG)	Flight Description
75	02-23-10	33 min	Sizoo	Extended	Mid/ Forward	Departure Limiter Assaults and FS
Block 6 Flights						
76	02-25-10	33 min	Wells	Retracted	Heavy/ Forward	Departure Limiter Assaults and FS (No Chase)
Block 5.5 Flights						
77	03-11-10	33 min	Batteas	Extended	Mid/Aft	Departure Limiter Assaults and FS
Block 6.5 Flights						
78	03-12-10	32 min	Sizoo	Retracted	Mid/Aft	Departure Limiter Assaults and FS
Turning Stall Flight						
79	03-17-10	33 min	Wells	Extended	Mid/ Forward	30° Turning Stalls—Power-Off 21°, 22°, and 23° α
80	03-19-10	32 min	Sizoo	Extended	Mid/ Forward	30° Turning Stalls—Power-On 21°, 22°, and 23° α
Single-Surface PIDs						
81	09-21-10	33 min	Wells	Extended	Mid/ Forward	Return to Flight, Regression Maneuvers
82	09-28-10	33 min	Wells	Retracted	Mid/ Forward	Clean-Wing Regression, Single-Surface PID (SSPID)—6° α
83	09-29-10	32 min	Wells	Retracted	Mid/ Forward	SSPID—6° α
84	09-29-10	37 min	Wells	Retracted	Mid/ Forward	SSPID—8° α
85	10-06-10	35 min	Sizoo	Retracted	Mid/ Forward	SSPID—6°/8° α
86	10-06-10	32 min	Sizoo	Retracted	Mid/ Forward	SSPID—8° α
87	11-09-10	38 min	Wells	Retracted	Mid/ Forward	SSPID/Walsh Waveforms 6°/8° α
88	11-09-10	40 min	Wells	Retracted	Mid/ Forward	SSPID/Walsh Waveforms 6°/8° α
89	11-16-10	36 min	Sizoo	Retracted	Mid/ Forward	SSPID/Walsh Waveforms 8° α
90	11-16-10	26 min	Batteas	Retracted	Mid/ Forward	SSPID/Walsh Waveforms 10° α
91	11-17-10	37 min	Batteas	Retracted	Mid/ Forward	SSPID/Walsh Waveforms 11° α
92	11-24-10	36 min	Wells	Retracted	Mid/ Forward	SSPID/Walsh Waveforms 11° α (Last Flight of the X-48B)

X-48C Research Flights

Flight No.	Date Flown	Flight Duration	Test Pilot	Slats Position	Weight and CG	Flight Description
1 (93)	08-07-12	9 min	Sizoo	Extended	Mid/Mid	First Flight
2 (94)	08-10-12	29 min	Sizoo	Extended	Mid/Mid	First Flight Deck Continuation
3 (95)	10-09-12	9 min	Sizoo	Extended	Heavy/Aft	RTB Due to Tape Streaming
4 (96)	10-10-12	28 min	Sizoo	Extended	Heavy/Aft	PID, Dynamic Limiter, RTSM, SSSL, Throttle Slap/Chop
5 (97)	10-16-12	28 min	Batteas	Extended	Heavy/Aft	PID, Dynamic Limiter, P_s Mapping, Prac App, Sim Engine Out, A/S Cal at Reference Landing Airspeed (V_{ref}) 75
6 (98)	10-18-12	26 min	Batteas	Extended	Heavy/Aft	Throttle Response, PIDs, SSSL at 6° and 12° α, BTB at 12° α
7 (99)	10-30-12	25 min	Sizoo	Extended	Heavy/Aft	Throttle Response, Climb Characteristics at High Thrust, RTSM, PID, SSSL at 16° α (No Chase)
8 (100)	10-30-12	24 min	Sizoo	Extended	Heavy/Aft	Throttle Response, RTSM, PID, SSSL at 18° α (No Chase)
9 (101)	11-07-12	25 min	Sizoo	Extended	Heavy/ Forward	Throttle Response, PID, FS at 7° α, SHSS at 12° and 16° α, BTB at 12° α
10 (102)	11-14-12	25 min	Batteas	Extended	Heavy/ Forward	Throttle Response, PIDs, FS at 7° α, BTB at 12° α, PIDs at 18° α, SHSS at 18° α
11 (103)	11-14-12	29 min	McIlvane	Extended	Heavy/ Forward	Throttle Response, FS at 14° α, BTB, PIDs, SHSS at 8° α
12 (104)	11-20-12	25 min	Sizoo	Extended	Heavy/ Forward	Throttle Response, PIDs, SSSL at 10° and 14° α, BTB Rolls at 10° and 14° α, Aircraft Specific Energy (P_s) Mapping[9]
13 (105)	12-04-12	28 min	Sizoo	Retracted	Heavy/ Forward	Throttle Response, PIDs and RTSM at 6° and 8° α, SSSL at V_{ref}, Sim Engine Out Approach, Speed Brake Stability
14 (106)	01-16-12	29 min	Sizoo	Retracted	Heavy/ Forward	VMS 1.5.2 Software Regression
15 (107)	01-29-13	30 min	Batteas	Retracted	Heavy/ Forward	RTSM at 10° and 11° α; FS at 7.5° α; Power-Off Stall at 9°, 10°, and 11° α; SSSL at 6° α

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[9] P_s is the specific energy of the aircraft, as calculated by the equation $P_s = V(T - D/W)$ where V is speed, T is thrust, D is drag, and W is weight, which themselves vary according to flight condition, settings, loadings, and maneuvering effects.

16 (108)	01-30-13	28 min	Batteas	Retracted	Heavy/ Forward	SSSL at 7°, 9°, and 11° α; 110 Knots to ¾ Pedal
17 (109)	02-05-13	8 min	Sizoo	Retracted	Heavy/ Forward	RTB Due to Tape Streaming
18 (110)	02-05-13	29 min	Sizoo	Retracted	Heavy/ Forward	Power-Off at 12°, 13°, 14°, and 15° α; Power-On at 11°, 12°, and 13° α; A/S Cal at V_{ref}; BTBs at 6°, 7°, 9°, 10°, and 11° α; PIDs
19 (111)	02-07-13	40 min	Sizoo	Retracted	Heavy/ Forward	Power-On-and-Off Stalls at 13° α; PIDs at 7°, 9°, and 11° α at 110 Knots; BTBs at 110 Knots; A/S Cal at 95; WUT
20 (112)	02-26-13	34 min	Batteas	Retracted	Heavy/Aft	RTSM at 6°, 8°, 9°, and 10° α; PID at 7°, 8°, 9°, and 10° α; SSSL at 6°, 8°, 9°, and 10° α
21 (113)	02-28-13	35 min	Sizoo	Retracted	Heavy/Aft	RTSM at 11° and 12° α; PID at 6° and 11° α; SSSL at 11° α; Power-Off Stalls at 11° to 16° α; Power-On Stalls at 11° to 14° α
22 (114)	02-28-13	29 min	Sizoo	Retracted	Heavy/Aft	Left and Right Power-Off Turning at 11° to 14° α; Power-On Turning at 11° and 12° α; Power-Off Speed Brake at 11° to 16° α
23 (115)	03-05-13	28 min	McIlvane	Retracted	Heavy/Aft	Power-Off Speed Brake at 1°, 11°, and 16° α; Power-Off Speed Brake at 2°, 11°, and 15° α; SSSL at 7° α
24 (116)	03-11-13	26 min	Sizoo	Retracted	Heavy/Aft	Speed Brake at 3°, 11°, and 15° α; Wind-Up/Wind-Down Turns; SSSL at 110 Knots
25 (117)	03-14-13	28 min	Larson	Extended	Heavy/ Forward	RTSM at 19°, 20°, 21°, and 22° α; PIDs at 18°, 19°, 20°, and 21° α; Power-Off at 20° to 24° α; Power-On at 20° α
26 (118)	03-21-13	29 min	Larson	Extended	Heavy/ Forward	PID at 8° α; Power-Off at 20° to 23° α; Power-On at 20° to 22° α; PID at 16° α
27 (119)	04-02-13	27 min	Batteas	Extended	Heavy/ Forward	Power-Off/-On at 21° to 24° α, Turning Stalls at 20° and 21° α; PIDs at 10°, 14°, and 16° α
28 (120)	04-02-13	26 min	Sizoo	Extended	Heavy/ Forward	Wind-Up/Wind-Down Turns, SSSL at 20° and 21° α; PIDs at 12° and 14° α
29 (121)	04-04-13	29 min	Batteas	Extended	Heavy/Aft	RTSM at 19° to 22° α; PIDs at 19° to 21° α
30 (122)	04-09-13	19 min	Sizoo	Extended	Heavy/Aft	Last Flight, Attempted RTSM at 22° α and PID at 8° α; No Cards Completed—Turbulence Aloft

Abbreviations and Acronyms

α	angle of attack (see also AOA)
A/S Cal	Airspeed Calibrations
ACARE	Advisory Council for Aeronautics Research in Europe
ACFA	Active Control for Flexible Aircraft
ACP	Advanced Concepts for Aeronautics Program
AD	Advanced Derivative
AEDC	Arnold Engineering Development Center (USAF)
AFB	Air Force Base
AFFTC	Air Force Flight Test Center (later Air Force Test Center, AFTC)
AFLCMC	Air Force Life Cycle Management Center
AFRL	Air Force Research Laboratory
AFTC	Air Force Test Center (previously Air Force Flight Test Center, AFFTC)
AIAA	American Institute of Aeronautics and Astronautics
ALT	Approach and Landing Tests
AOA or α	angle of attack
APU	Auxiliary Power Units
ARMD	Aeronautics Research Mission Directorate
ASC	Aeronautical Systems Center (U.S. Air Force)
ATTAS	Advanced Technologies Testing Aircraft Systems
AVST	Advanced Vehicle Systems Technology
BAE	British Aerospace Systems
BART	Basic Aerodynamic Research Tunnel
BTB	Bank-to-Bank [maneuver]
BWB	blended wing-body or Blended Wing-Body
C2ISR	command, control, intelligence, surveillance, and reconnaissance
CAD	computer-aided design
CASES	Computer-Aided Sizing and Evaluation System
CCD	Configuration Control Document
CDE	Computational Design Engine
CDISC	Constrained Direct Iterative Surface Curvature
CFD	computational fluid dynamics

CFL3D	Computational Fluid Laboratory-3D computer code
CG	center of gravity
$C_{L\max}$	Maximum Lift Coefficient
CR	Commitment Review
CSI	Control Structures Interaction
DFBW	digital fly-by-wire
DFRC	Dryden Flight Research Center (now Armstrong Flight Research Center)
DLR	German Center for Air and Spaceflight
DSCAS	Directional Stability and Control Augmentation System
DVD	digital video disk
EADS	European Aeronautic Defence and Space Company
ECU	Engine Control Unit
elevon	ELEVator ailerON
EPP	expanded polypropylene
ERA	Environmentally Responsible Aviation
FAA	Federal Aviation Administration
FCC	Flight Control Computer
FCS	Flight Control System
FOD	foreign object damage
FEA	finite element analysis
FFT	Fast Fourier Transform
FRC	Flight Research Center
FS	Frequency Sweep
FST	Full-Scale Tunnel (short for Langley Full-Scale Tunnel)
FTS	Flight Termination System
FY	fiscal year
g	acceleration due to gravity
GARTEUR	Group for Aeronautical Research and Technology in Europe
GCS	Ground Control System; Ground Control Station
Genie	GENeric Interface for Engineering
GPS	Global Positioning System
HALE	high-altitude, long-endurance
HCCT	high-capacity civil transports
HEIST	Hybrid Electric Integrated Systems Testbed
HiMAT	Highly Maneuverable Aircraft Technology
HQ	Handling Qualities
HSDV	High-Speed Drop Vehicle
HST	High Speed Taxi; High Speed Test
HSV	High-Speed Vehicle
HWB	Hybrid Wing-Body

HXRV	Hyper-X Research Vehicle
ICA	initial cruise altitude
ICR	instantaneous center of rotation
ICAS	International Council of Aeronautical Sciences
IMU	inertial measurement unit
ISSMO	International Society for Structural and Multidisciplinary Optimization
ISR	intelligence-surveillance-reconnaissance
ITAR	International Traffic in Arms Regulations
KIAS	Knots Indicated Airspeed
KTH	Royal College of Technology
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LaRC	Langley Research Center
L/D	lift-to-drag ratio
LFC	laminar flow control
LFST	(NASA) Langley Full-Scale Tunnel
LSCAS	Longitudinal Stability and Control Augmentation System
LSDV	Low-Speed Drop Vehicle
LST	Low Speed Test
LSV	Low-Speed Vehicle
MDC	McDonnell Douglas Corporation
MDO	Multidisciplinary Design Optimization
MDS	Mission Design Series
MIT	Massachusetts Institute of Technology
ML/D	efficiency (Mach number times lift divided by drag)
MOB	Multidisciplinary Optimization of a BWB (European project)
MSL	Mean Sea Level
MTOW	Maximum Takeoff Weight
NACA	National Advisory Committee for Aeronautics
NACRE	New Aircraft Concepts Research
NAH	New Aviation Horizons
NASA	National Aeronautics and Space Administration
NFAC	National Full-Scale Aerodynamics Complex
NLR	National Air and Spaceflight Laboratory
NMUSAF	National Museum of the United States Air Force
NRC	National Research Council
NTF	National Transonic Facility
OEW	Operating Empty Weight
OVERFLOW	OVERset Grid FLOW Solver
P_s	Aircraft Specific Energy
PAI	Propulsion Airframe Integration

PDR	Preliminary Design Review
PID	parameter identification
PIV	Particle Imagery Velocimetry
QueSST	Quiet Supersonic Technology
RACRSS	Revolutionary Airframe Concepts Research and Systems Studies
RAE	Royal Aircraft Establishment
RAF	Royal Air Force (United Kingdom)
RAV	Remotely Augmented Vehicle
R/C	radio-controlled
RCS	radar cross-section
RDT&E	Research, Development, Test, and Evaluation
RF	radio frequency
ROA	Remotely Operated Aircraft
RPH	Richard P. Hallion
RPM	Revolutions Per Minute
RPRV	Remotely Piloted Research Vehicle
RPV	remotely piloted vehicle
RSCAS	Roll Stability and Control Augmentation System
RTB	Return to Base
RTSM	Real-Time Stability Margin
S&C	stability and control
S/W	software
SAE	Society of Automotive Engineers
SBAC	Society of British Aircraft Constructors
SCAT	Supersonic Commercial Air Transports
SCEPTOR	Scalable Convergent Electric Propulsion Technology Operations Research
SCOLE	Spacecraft Control Laboratory Experiment
SCV	Systems Configured Vehicle
SFC	Specific Fuel Consumption
SHSS	Steady Heading Sideslips
SPORT	Space Positioning Optical Radar Tracking
SSPID	Single Surface PID
STARC	Single-aisle Turboelectric AiRCraft
STT	Synergistic Technology Transport
T/MTOW	Thrust-to-Weight Ratio
TA	Task Agreement
TOGW	Takeoff Gross Weight
TRL	Technology Readiness Level
TTBW	Transonic Truss-Braced Wing

TU	*Technische Universität*; *Technische Universiteit*
TVC	thrust-vectoring control
UAV	unmanned aerial vehicle
UCAV	Unmanned Combat Air Vehicle
UEET	Ultra-Efficient Engine Technology
USAF	United States Air Force
USARPAC	U.S. Army, Pacific
USC	University of Southern California
V_{Dive}	Dive Speed
V_{MCA}	minimum control [or "controllable"] airspeed
V_{ref}	Reference Landing Airspeed
VCAS	Versatile Control Augmentation System
VELA	Very Efficient Large Aircraft
VMS	Vehicle Management System
WingMOD	Wing Multidisciplinary Optimization Design
WP	work package
WP1	work package—novel aircraft models
WP2	work package—novel lifting surfaces
WP3	work package—novel powerplant installation
WP4	work package—novel fuselage design
WUT	Wind-Up Turns

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