NASA AERONAUTICS BOOK SERIES

# Thinking Obliquely

## Robert T. Jones, the Oblique Wing, NASA's AD-1 Demonstrator, and its Legacy

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### Bruce I. Larrimer

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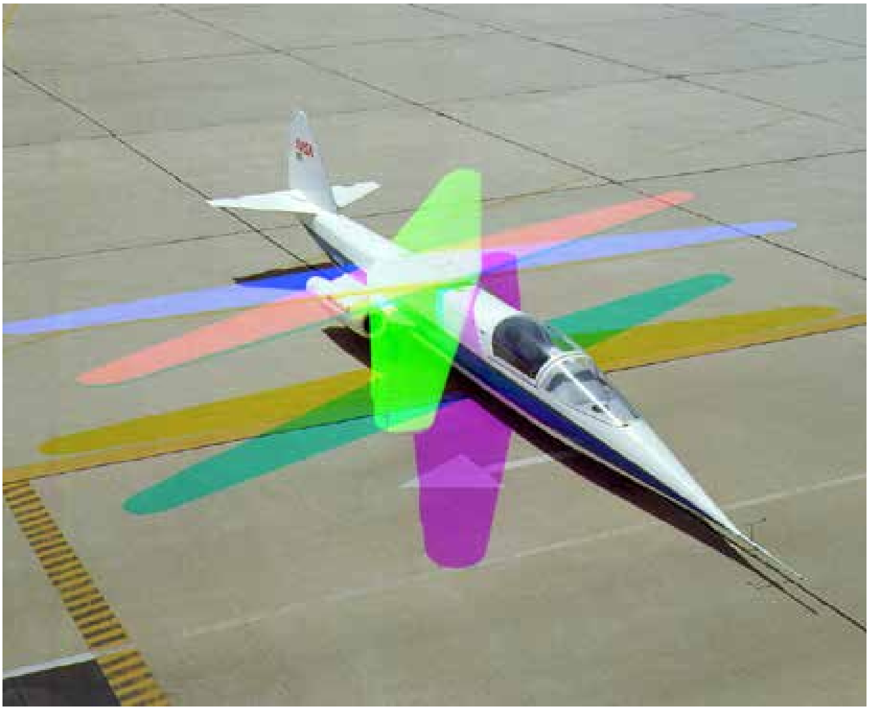

This time-lapse photograph shows three of the various sweep positions that the AD-1's unique oblique wing could assume. (NASA)

# Introduction

On December 21, 1979, the National Aeronautics and Space Administration (NASA) AD-1 Oblique Wing Research Aircraft (OWRA) took off from the main runway at Edwards Air Force Base (AFB), CA, for a 45-minute checkout flight. It marked the world's first flight of a piloted oblique-wing airplane. This historic flight, which was flown with the airplane's wing at its "straight" (0-degree angle) position, was soon followed by flights at wing angles of 15 degrees, 20 degrees, 45 degrees, and finally on April 24, 1981, at the 60-degree-angle design goal, thus proving the aerodynamic concept of an airplane with an oblique-wing configuration. This initial oblique-wing program, which ran from 1976 through 1982, was a joint effort between NASA's Ames Research Center and Dryden Flight Research Center, CA, thus giving rise to the aircraft's name—Ames-Dryden AD-1 Oblique Wing Research Aircraft.[1] Extensive research, wind tunnel and computer-code testing, and model-building and testing projects were undertaken at Ames, and flight simulation, flight testing, and flight evaluation were conducted at Dryden. While the concept of the oblique wing was developed during World War II, and the landmark wind tunnel tests of John P. Campbell and Hubert M. Drake were undertaken just following the end of the war, most aeronautical attention in the postwar era concentrated on the continuous refinement of symmetrical point-forward swept-wing aircraft.

Serious attention, however, once again turned to the oblique wing in the 1970s, resulting in the research activities discussed in this book. Chapter 1 reviews the life of NASA aerodynamicist Robert T. Jones and his path to the oblique wing. Chapter 2 covers the extensive wind tunnel, model, computer-code, and simulation testing, first at Langley and later at Ames, as well as a number of NASA industry design contracts undertaken by Boeing and Lockheed. Chapter 3 reviews the design and fabrication of the AD-1 Oblique Wing Research Aircraft and its subsequent proposed use as a joined-wing demonstrator. Chapter 4 describes the flight testing and flight evaluation of the AD-1. Chapter 5 reviews the supersonic F-8 followup oblique-wing program. And, finally, chapter 6 reviews the subsequent oblique-wing plans and proposals. Appendices present the physical characteristics of the AD-1 aircraft, a detailed description of it, and a summary flight log of its flight research program.

Writing the history of the AD-1 proved both a challenge and a pleasure. I am very grateful to all who have assisted me in this endeavor. A listing of those who were particularly helpful follows the appendices.

Bruce I. Larrimer
Columbus, OH
March 12, 2012

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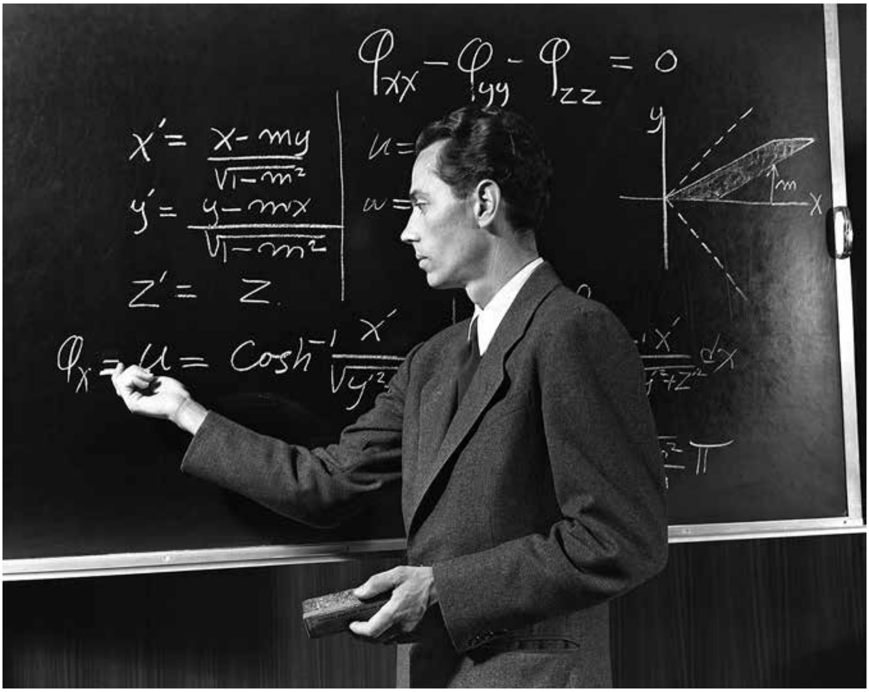
1. From September 27, 1959, until March 26, 1976, NASA Dryden was known as the NASA Flight Research Center. From March 26, 1976, until October 1, 1981, the Center was known as the NASA Hugh L. Dryden Flight Research Center. From October 1, 1981, until March 1, 1994, the Center was part of NASA Ames and was known as the NASA Ames-Dryden Flight Research Facility. On March 1, 1994, the Center once again became a separate operational entity and since then has used its previous designation as the NASA Hugh L. Dryden Flight Research Center, being more simply known as the NASA Dryden Flight Research Center, which is how it is referred to throughout this book.



NACA-NASA research scientist Robert T. Jones. (NASA)

# CHAPTER 1

# *American Genius*

## R.T. Jones's Path to the Oblique Wing

Robert Thomas "R.T." Jones was born on May 28, 1910, in the farming community of Macon, MO, and died on August 11, 1999, in Los Altos Hills, CA. In the intervening 89 years, Jones more than fulfilled the definition of genius, and his lifetime in aeronautics constituted a particularly productive and well-lived life. In his progression to distinction, Jones resembles far more the 17th century's largely self-taught and broadly interested "natural philosopher" than the rigorously educated, university-trained STEM (science, technology, engineering, and mathematics) über-specialized professional of the modern era.[1]

Jones's lifelong consuming interest in aviation started at an early age when he built rubberband-powered model airplanes and assembled airplane models with scaled drawings from the Ideal Model Airplane Supply Company. In his rural Macon, MO, high school, Jones acquired an interest in mathematics from his math teacher, Iva Z. Butler, who guided him "along the intricate path through exponents, logarithms, and trigonometry."[2] Following the nationwide increase in interest in aviation resulting from Charles Lindbergh's nonstop transatlantic flight in 1927, Jones was readily able to purchase the magazines *Aviation* and *Aero Digest* in his hometown of Macon. These publications contained technical articles, which Jones read with great interest, as well as notices of Technical Reports (TRs) of the National Advisory Committee for Aeronautics (NACA, the forerunner to NASA), which Jones was able to purchase from the Government Printing Office for as little as 10 or 15 cents. In regard to his interest in aviation, Jones noted that he must have puzzled his high school English teacher with all the essays he wrote on aeronautics-related subjects. After graduation, Jones attended the University of Missouri to study engineering but left college after the first year because the university did not offer courses in aeronautics and he "found the other subjects rather uninteresting."[3] In dropping out of college after a year, Jones followed in the footsteps of his father, who also had quit after 1 year, and then read the law and passed the bar examination to practice as an attorney in Missouri.

## The Evolution of a Practical Engineer-Scientist

After leaving college, Jones returned to Macon, working for the Marie Meyer Flying Circus. In exchange for odd jobs, such as fueling its Curtiss JN-4 Jenny aircraft and patching its often-damaged fabric-covered lower wingtips, Jones received free flying lessons—although it would take another 50 years before he would make his first solo flight and subsequently receive his pilot's license. In 1929, at the age of 19, Jones was hired as the chief and only engineer of the Nicholas-Beazley Airplane Company, Inc., of Marshall, MO, after Charles Fower, a friend of Jones's, told Russell Nicholas that Jones "knew everything there was to know about airplanes." Jones obtained this engineering position due to the departure of Walter Barling, who had been the principal designer of the company's NB-3 of 1928, a low-wing, single-engine, two-place, open-cockpit monoplane of straightforward design that enjoyed brief, modest commercial success. Later, the company hired Thomas Kirkup, a certified engineer from England who taught Jones how to undertake stress calculations. At its peak production, Nicholas-Beazley, which Jones noted was well-placed to become the center of small airplane production in the United States, was producing an airplane per day, but the company failed during the Great Depression and Jones soon found himself back in his hometown of Macon. During this time back in Macon, Jones continued his self-study by reading books on aeronautics, including Max M. Munk's *Fundamentals of Fluid Mechanics for Aircraft Designers*, his introduction to an individual who was himself a towering figure in aeronautics and who would have a profound effect upon Jones's life and work.[4]

During the depth of the Depression, Jones, desperate for work, hitched a ride to Washington, DC, with some neighbors. Once in Washington, he immediately visited his local Congressman, who secured for him a position as an elevator operator in the House Office Building. Jones took advantage of this welcome security to further his study of mathematics by studying books from the Library of Congress and attending evening classes in aerodynamics taught by Max Munk at Catholic University. A decade previously, Munk had introduced modern scientific airfoil development to America. Munk was born in Hamburg, Germany, in 1880. He studied under Dr. Ludwig Prandtl, was a contemporary of Theodore von Kármán, received two doctoral degrees from the Göttingen University, and moved to the United States in 1920 to join the National Advisory Committee for Aeronautics's Langley Memorial Aeronautical Laboratory (now NASA Langley Research Center). After a productive if tempestuous time with the NACA, Munk left the agency to take up a teaching position at Washington's Catholic University and to serve as technical editor of the magazine *Aero Digest*.[5] Soon after arriving in Washington, Jones paid a visit to Munk and informed the professor that he had read his book on fluid dynamics for aircraft designers. Listening to Jones, Munk, a brilliant if irritable personality, was impressed to the point of promptly inviting his young visitor to take his course in aerodynamics. When Jones modestly demurred, stating that he lacked an undergraduate degree, Munk challenged him to define a derivative of a function. When Jones promptly did so, Munk equally promptly admitted him to the course.

Jones realized that in order to become a successful engineer, he would need to know more about mathematics. Fortunately, his status as a congressional employee, coupled with the close proximity of the House Office Building to the Library of Congress, readily enabled Jones to obtain works on various branches of mathematics. He read Hermann Grassmann's *Die Ausdehnungslehre*, one of the most influential texts in the history of mathematics, written by an individual who was, in his broad range of interests and largely self-taught abilities, very much like Jones himself, though, sadly, unrecognized for his contributions in his lifetime.[6] In particular, Jones became fascinated with the "time plus space" theory of quaternions (four-element multiples of real numbers consisting of a scalar [time] element and three vector [space] elements), first derived by the Anglo-Irish mathematician Sir William Hamilton, which contributed much of the underpinning of quantum theory.[7] Jones credited the scholarship of both men with helping him during his years with the NACA.

In addition, while at the Library of Congress, Jones made the acquaintance of Dr. Albert F. Zahm, a physicist and influential aerodynamics researcher who had established America's first wind tunnel–equipped research laboratory at Catholic University in 1901 and, later on, helped found another at the Washington Navy Yard. By the time he met Jones, Zahm was managing the Library's aeronautics collections, though he still undertook some research and maintained a determinedly future-focused mindset. One of the topics he pursued was the challenge of upper-atmospheric near-space flight, and he invited Jones to assist him.[8] Impressed, he subsequently furnished Jones a contact who was to help the young Midwesterner obtain his job with the NACA—Congressman David J. Lewis. Lewis took to Jones for, like the young man, he had achieved his own success without formal education, and he was likewise fascinated with mathematics. Subsequently, Jones tutored Lewis in mathematics, impressing the Congressman with his extraordinary knowledge. Having impressed Munk, Zahm, and Lewis, Jones had no difficulty securing their recommendations to obtain, in 1934, a temporary 9-month appointment as a Junior Scientific Aide at the NACA's Langley Aeronautical Laboratory under a Roosevelt-era employment program.

The temporary appointment lasted until Jones's supervisors were able to make it permanent. At Langley, Jones first worked under Fred E. Weick, a well-known engineer who in the 1930s continued earlier work on inherent stability undertaken by Jerome C. Hunsaker and E.B. Wilson. Weick was also interested in designing an airplane with a simplified "two-control" (independent pitch control but interlinked roll and yaw control) pilot operation, and Jones was given the task of making the dynamic calculations. Jones's calculations indicated that Weick's two-control operation, subsequently employed on Weick's two-control Erco Ercoupe that Jones enjoyed flying in later years, would be better achieved by placing primacy upon the ailerons instead of the rudder as the principal control device driving directional changes. Weick, according to Jones, also realized that a two-control system would need dynamically stable landing gear, driving his development of a tricycle gear with fixed wheels behind the center of gravity and a steerable nose wheel ahead.

While Weick was not the first to develop such a configuration—for example, it had appeared before the First World War in the pusher designs of Glenn Curtiss—the Ercoupe certainly encouraged its use and almost universal subsequent adaptation. As for Jones, his work on two-control flight control systems later influenced his wartime work on guided weapons.[9]

Once Jones's 9-month appointment expired, the Langley staff found a way to retain Jones by skipping him a grade above junior engineer, which required a college degree, to the next higher professional engineering position, which already assumed that the candidate had a college degree and thus failed to list a degree as a position requirement. This led to Jones's long career with the NACA and NASA.

William R. Sears, himself a noted aeronautical engineer, noted of Jones that during his long civil service career, Jones had become "one of the world's leading aerodynamicists, [who] made discoveries that have changed the history of aeronautics, and received important honors."[10] In 1947, the Institute of the Aeronautical Sciences (one of two professional societies—the other being the American Rocket Society—that merged to form the American Institute of Aeronautics and Astronautics [AIAA]) awarded Jones its 1946 Sylvanus Albert Reed Award "For his contributions to the understanding of flow phenomena around wings and bodies at speeds below and above the speed of sound."[11] In 1971, Jones was awarded an honorary doctorate degree by the University of Colorado for his contributions to aeronautics, and in 1973, he was elected to the National Academy of Engineering. Jones received the Prandtl Ring award from the German Aeronautical Society in 1978. In 1981, the Smithsonian Institution selected Jones to receive its prestigious Langley Medal (named for Smithsonian Institution Secretary and pioneer astrophysicist Samuel Pierpont Langley, himself a notable pioneer of flight), which is awarded for "especially meritorious investigation in the field of aerospace science."[12] The Langley Medal was awarded to Jones in recognition of his "extensive contributions in theoretical aerodynamics, particularly with regard to development of the swept

The first production Ercoupe, at its College Park, MD, plant, 1939. (NASM)

wing, supersonic area rule and, more recently, the oblique wing."[13] In 1981, Jones received the President's Award for Distinguished Civilian Service, which read in part as follows: "Of major consequences are his triangular wing concept, the independence principle for the three-dimensional boundary layers, and the concept of the oblique wing boom-free supersonic airplane."[14]

## Jones's Other Interests

In addition to aeronautics, R.T. Jones had a wide range of other areas of interest and expertise, again reflecting, to an almost uncanny degree, Hermann Grassmann and Sir William Hamilton, whose work had furnished so much insight for his own work. Jones's polymath tendencies are evident in at least nine reports prepared while at the NASA Ames Research Center and at least four reports prepared at the Avco-Everett Research Laboratory, MA, during his approximately 7 years of voluntary absence from NASA. At NASA Ames, these reports covered such varied topics as:

- modified Gregorian and Cassegrainian mirror systems,
- time calculations for interplanetary travel,
- work on lenses and telescopes of an unusual optical design,
- extending the Lorentz Transformation by characteristics coordinates,
- a review of some selected space-science problems and accomplishments,
- analysis of accelerated motion in the theory of relativity,

- conformal coordinates associated with uniformly accelerated motion, and
- conformal coordinates associated with space-like motions.

His studies at Avco-Everett Research Laboratories included the following topics:

- wide-angle lenses with aspheric correcting surfaces,
- motions of a liquid in a pulsating bulb with application to problems of blood flow,
- a theory of synchronous arterio-arterial blood pumps, and
- studies of blood flow (as a followup, he undertook a study of fluid dynamics of heart assist devices).

Even in leisure and family pursuits, Jones could not resist the opportunity to study and learn new things—and then to improve upon them. When his daughter developed an interest in violins, Jones even built a number of violins, making a detailed acoustical study of each. In testing two of the violins, Jones concluded that "It will be noted that the second violin has accentuated overtones in the 2000 to 3000 Hz [hertz] range, the main body resonance is at 450 Hz, and the air resonance peak is somewhat lower in amplitude," adding (with just a touch of obvious pride), "This violin is preferred by musicians who have tried both."[15]

Jones, however, never left his lifelong interest in aeronautics. He returned to NASA Ames in 1970 and worked there until his retirement in 1981. During this time period, Jones concentrated mostly on his oblique-wing concept and its potential development as a high-speed transport. After retiring from NASA, Jones joined the faculty of Stanford University, where he served until 1997 as a consulting professor in the Department of Aeronautics and Astronautics while, at the same time, maintaining an informal relationship with NASA Ames. While at Stanford, Jones's work on the oblique-wing concept moved toward developing a pure oblique flying wing, an idea he had long nurtured. After Jones's death in 1999, Walter G. Vincenti, a veteran NACA-NASA engineer and distinguished historian of technology, noted in his *Biographical Memoir* of Robert T. Jones (written for the prestigious National Academy of Sciences) that

> [t]hose who worked with R. T. marveled at how he arrived at his ideas, seemingly intuitively and frequently in terms of physical models and analogies. He could use highly sophisticated mathematics deductively when necessary, but he did so mostly to support his ideas and explore their consequences. In the initial report on his concept of sweepback he began conventionally with a mathematical derivation followed by three physical arguments and explanations. Events at the time suggest that the mathematics

Robert T. Jones at home, making a violin. Note the oblique-wing radio-controlled model airplane and a reflector telescope, also made by Jones, July 30, 1982. (Photograph © Roger Ressmeyer/Corbis Images)

> actually came to R. T.'s mind after the physical concepts and had been put into the report in response to editorial-committee objections. Whatever the situation, the fact is that things that seemed clear and obvious to him in his physical explanations often caused the rest of us difficulty and struggle to master.[16]

## Jones's Early Work at Langley Aeronautical Laboratory

Jones established his reputation between 1936 and 1946, when he worked on a number of different engineering assignments and wrote entirely or coauthored at least 21 NACA reports, notes, and studies covering a wide range of topics. Taken together, they constitute a prodigious output and extraordinary technical and scientific accomplishment. If he had done nothing else, this work, culminating in his enunciation of the thin, high-speed slender delta wing and the swept wing, would have on its own sufficed to secure his place in aviation history.

Viewed sequentially to the point just prior to his commencing research on swept planforms, his corpus of accomplishment included:

- Report No. 560 (1936), reviewing a simplified treatment of the application of mathematician and physicist Oliver Heaviside's operational methods to problems of airplane dynamics.
- Report No. 570 (1936, coauthored with Fred E. Weick), analyzing the lateral controllability of an airplane in which both the static rolling and yawing moments supplied by the controls and the reactions due to the inherent stability of the airplane were taken into account.
- Report No. 579 (1936), examining the two-control operation of an airplane.
- Technical Note (TN) No. 586 (1936, with Albert I. Nerken), studying the reduction of aileron operating force by differential linkage;
- Report No. 605 (1937, a Fred E. Weick report to which Jones contributed), examining a resume and analysis of NACA lateral-control research.
- Report No. 635 (1938, coauthored with Henry A. Pearson)—examining the theoretical stability and control characteristics of wings with various amounts of taper and twist.
- Report No. 638 (1938), studying the influence of lateral stability of disturbed motions of an airplane with special reference to the motions produced by wind gusts.
- Technical Note No. 667 (1938), addressing the operational treatment of the nonuniform lift theory in airplane dynamics.
- Report No. 681 (1940), studying the unsteady lift of a wing having finite aspect ratio.
- Technical Note No. 771 (1940, coauthored with Leo F. Fehlner), reviewing the transient effects of the wing's turbulent wake on the horizontal tail of an airplane.
- Report No. 709 (1941, coauthored with Doris Cohen), analyzing the stability of an airplane with free controls.
- Report No. 722 (1941, coauthored with Doris Cohen)—studying a graphical method of determining pressure distribution in two-dimensional flow.
- An article (1941), examining the theoretical correction for the lift of wings having an elliptical planform.
- Technical Report No. 837 (1941), addressing problems involved in the stability and control of tailless airplanes.

- Wartime Report L-464 (1942, coauthored with Milton B. Ames, Jr.), covering wind tunnel testing of beveled trailing edges to reduce the hinge moment of a control surface.
- Report No. 731, (1941, coauthored with Doris Cohen), examining a theoretical analysis to determine the optimum planforms for control surfaces.
- Wartime Report L-233 (1943, coauthored with Joseph W. Wetmore), dealing with emergency measures for increasing the range of fighter airplanes.
- Report No. 798 (1943, coauthored with Harry Greenberg), covering the effect of hinge-moment parameters on elevator stick forces in rapid maneuvers.
- Wartime Report L-651 (1943, coauthored with W.J. Underwood), involving a wind tunnel investigation of a beveled aileron shape designed to increase the useful deflection range.
- Report No. 801 (1943), presenting a method for studying the hunting oscillations of an airplane with a simple type of automatic flight control system.[17]

Jones's NACA activities during this time period included important work in the emerging field of guided weapons research, and it was this work that led him, eventually, to conceptualize the American delta and swept wing. In 1944, he was assigned to work at Eglin Field to help the U.S. Army Air Corps develop guided missiles, including a glide bomb designed to be launched from a B-17. The glider was equipped with a heat seeker developed by Franklin Offner and an autopilot made by Laurens Hammond, designer and manufacturer of electric organs. The initial tests, however, were not very successful because the bomb was guided to its target by rudders, which imparted directional control (yaw control, i.e., left-right control) but still did not ensure sufficient accuracy. Drawing upon his earlier experience with two-control flight control systems with Weick at Langley, Jones recommended using aileron (roll) control, which greatly enhanced delivery accuracy.

In 1944, Jones was detailed to join a U.S. Army Air Force's Air Technical Service Command (ATSC, forerunner of the modern U.S. Air Force [USAF] Materiel Command) team sent to Eglin Field (now Eglin Air Force Base) in Florida to test the pulsejet-powered Republic JB-2 Loon guided missile. An American copy of the Fieseler FZG-76 (better known to history as the infamous Nazi V-1 Buzz bomb—the V standing for Vergeltungswaffe, or "Revenge Weapon," its Nazi propaganda designation—that savaged London in 1944 through early 1945), the JB-2 was America's first jet-age cruise missile.

Unlike the preset V-1 (which could deviate as much as 8 miles over approximately 120 miles), the JB-2 used ground radar tracking and radio-controlled

Republic JB-2 ready for flight. (USAF)

guidance to reduce its course deviation to just one-quarter mile at a range of 100 miles—extremely accurate by the standards of the day.[18] While the V-1 employed a launching sled and steam catapult (with the steam produced by the reaction of concentrated hydrogen peroxide poured over potassium permanganate), the JB-2 was boosted to flight speed by solid-fuel rockets, considered both safer and less complex for the launching team. It seemed a simple matter to modify the missile for rocket boost: simply by aligning the thrust vector of the rockets through the missile's center of gravity, the test team could launch the JB-2 into the air.

But at the time, the JB-2 was in trouble. It took many attempts before the team determined the proper configuration, to prevent the powerful rockets from tearing the missile apart during launch. Initially, only 20 percent of all missiles launched successfully. Thanks in large measure to Jones and a more analytical approach to the missile's launch dynamics, by war's end, the figure had increased to 80 percent.[19] Jones also used gyros from the JB-2 to devise a bilaterally symmetric flight control system to improve the one developed by Hammond for the Northrop Company's rival JB-10 flying wing "flying bomb."

In regard to this wartime service, an Army Air Forces Air Technical Service Command letter commending Jones for his service stated:

> It will be noted that the Air Technical Service Command desires to commend Mr. Robert T. Jones of the Langley Memorial Aeronautical Laboratory for his assistance in the successful initiation of this project. This office also wishes to take this opportunity to commend

JB-2 launch accident. (USAF)

> Mr. Jones for his efforts which resulted in the NACA making very valuable contributions to the success of the JB-2 flying bomb project of the Army Air Forces Air Technical Service Command.[20]

Overall recognition of R.T. Jones's contributions during his time at Langley is found in George W. Lewis's October 14, 1947, letter to Jones (who had transferred the previous year to the Ames Aeronautical Laboratory, now NASA's Ames Research Center) noting the following:

> I am attaching a clipping from the *Washington Sunday Star*, which is very interesting to me because I well remember the day Congressman Lewis of Maryland called on me and said that something must be done about Bob Jones—he must have an opportunity to use his talents in a scientific organization. It was a fortunate day for the Committee, for you and Mrs. Jones have brought credit to the Committee with the many contributions that you have made.[21]

## Jones's Great Discovery: The American Delta and Swept Wing

By the time Lewis penned his note, Jones had contributed two landmark technical studies—his singular greatest and most influential technical accomplishment—that influenced, arguably, what still constitutes the greatest aerodynamic transformation following the invention of the airplane in 1903, which made Jones's name and gave him a truly international reputation: NACA Technical Reports numbers 835 and 863, published in 1946 and 1947, respectively.

They had a remarkable genesis. In 1935, leading aerodynamicists met in Rome for the Volta Congress on high-speed flight. During the prestigious conference, Adolf Busemann, a young German fluid dynamicist, unveiled the concept of using a sweptback wing to delay the onset of high-drag rise afflicting conventional straight wings, thus making the attainment of supersonic flight a practicality. Busemann's paper attracted little notice at the time, perhaps because the modest wing-sweep angles that he presented and the concepts underlying them seemed far less revolutionary than they were. Also, the moderately sweptback wing had been a feature of aircraft design since before the First World War, but it was used for reasons of stability rather than to achieve high-speed flight. (With a moderate sweptback wing, a designer could build a tailless aircraft, several different types of which appeared over the previous quarter century.) Thus the Busemann study dropped out of sight to be resurrected a decade later, when the Allies sifted through the rubble of Germany's wartime aeronautical research establishment, discovering the tremendous investment that the Nazi regime had made in developing jet-and-rocket-powered swept- and delta-wing designs for aircraft and missiles. Only the punishing Allied strategic bomber offensive, coupled with the rapid overrunning of Germany itself in 1944 to 1945, had prevented some of these from entering service.[22]

Jones, in an unpublished autobiography, recounted his own progression to the swept wing, using as a departure point an experimental configuration he was asked to review:

> One day near the end of the war an engineer from the Sikorsky Company stepped into my office with a design for a fighter plane having a narrow wing of triangular planform, proposed by Michael Gluhareff.[23] He had applied Prandtl's theory to calculate the lift and pressures on the sections, but had some misgivings since Prandtl's theory was based on the assumption that the wing was long and narrow in the direction perpendicular to the flight direction [e.g., a high-aspect-ratio planform], so that the flow over the airfoil sections, parallel to the flight direction, could be considered two

> dimensional. He asked if I could think of a better way to determine the characteristics of such a wing, long and narrow in the flight direction [e.g., a low-aspect-ratio planform]. I remembered a paper by my teacher Max Munk in which the flow in planes perpendicular to the flight direction was considered two-dimensional. I also remembered a paper by H. S. Tsien[24] in which it was pointed out that Munk's "slender body" theory remained applicable at supersonic speeds.[25]
>
> All that remained to convert slender body theory to a wing theory was to find a way to impose the Kutta condition. I reasoned that a portion of the wing behind the section of maximum width would develop no lift, since its boundary condition would be satisfied by the wake from sections ahead. At first I thought the assumptions too crude to be of much interest and I put the report in my drawer. Later I found that the results were insensitive to the Mach number, whether subsonic or supersonic. I then collected my formulas and observations in a paper entitled "Properties of Low Aspect Ratio Pointed Wings at Speeds Below and Above the Speed of Sound" (NACA Tech. Report No. 835, May 1945.[26]) *This paper became instrumental in the design of supersonic aircraft.*[27] [Emphasis added.]

Jones added that he recalled an observation by Max Munk "that the air forces on a sweptwing panel would depend only on the component of flight velocity in the direction perpendicular to the leading edge and were independent of the flow in the direction of the long axis."[28] From this, Jones concluded that Munk's independence principle would enable sweeping the wings back within the Mach cone generated by an airplane's passage through the air at supersonic speeds, thus placing the wings within a subsonic and relatively low-drag flow.

As longtime Jones associate Walter Vincenti noted, it followed from Jones's analysis that

> the effective Mach number, on which the air forces depend, decreases continuously with increasing sweep; it follows that, even at supersonic flight speeds, the air forces can be made to have the advantageous properties found at low subsonic Mach numbers simply by introducing sufficient sweepback. In particular, that the enormously increased drag of conventional unswept wings at supersonic speeds can be reduced to subsonic levels. R.T. thus discovered the theory of high-speed sweepback, which William Sears describes as "certainly one of the most important discoveries in the history of aerodynamics." The planform of every high-speed

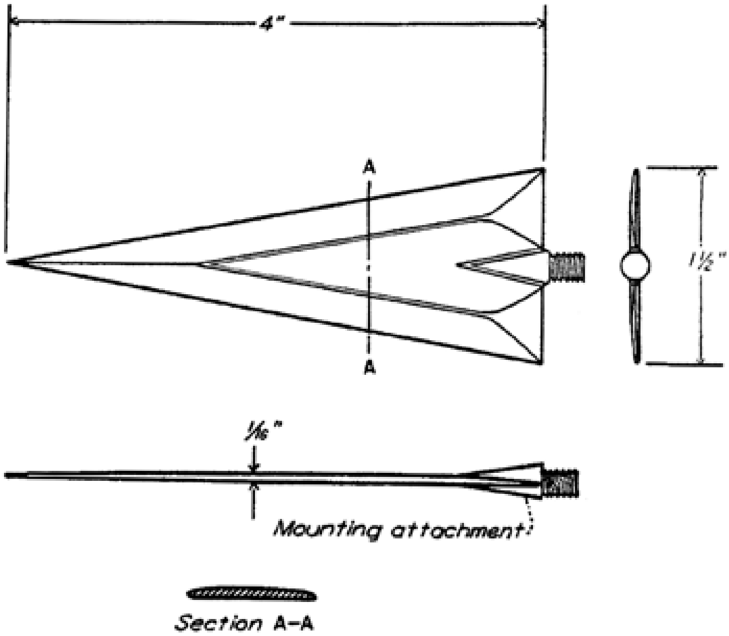


FIGURE 9.—Airfoil tested in Langley model supersonic tunnel.

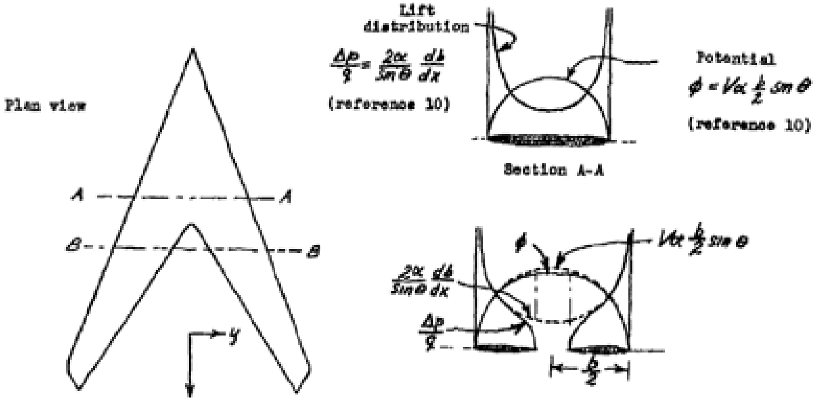
Jones's slender delta, from NACA TR 835, 1946. (NASA)

> transport one sees flying overhead embodies R.T.'s idea. When it became known, it came as a mind-boggling surprise to the rest of us working in aerodynamics.[29]

Jones subsequently built a small test model resembling a dagger, measuring 4 inches in length with a span of just 1½ inches, testing it to Mach 1.75 in a small Langley supersonic tunnel; as predicted, it had much less drag than a conventional higher-aspect-ratio wing. Its configuration is illustrated in the following drawing, from Jones's subsequent technical report.[30]

Jones immediately expanded upon this work, deriving from it a bilaterally symmetric and sharply sweptback Δ-profile wing. Thus, whereas in Germany the discovery of the transonic swept wing had preceded that of the classic delta wing, in the United States the exact reverse was true: the invention of the transonic delta preceded the invention of the transonic swept wing.[31]

Despite the attractiveness of his discovery, Jones did not immediately win converts to the swept-wing cause. Indeed, the results were so controversial that



Jones's sharply swept-back wing, from NACA TN 1033, 1946. (NASA)

Jones encountered official skepticism that delayed dissemination of his ideas. He recalled the following:

> As customary, an editorial committee was appointed to go over my paper and approve it if they found it correct. The committee was composed of experts on compressible flow, who had made complex studies of high-speed flow over straight wings. (It may be remembered that our first supersonic airplane, the [Bell] "X-1" had straight wings). I was no expert on compressible flow, but I had a simple solution to their problem. It is perhaps natural that they did not believe it. Surprisingly, they did believe my slender wing theory and I was encouraged to publish this without reference to the sweep theory. During the course of the meetings, a 1935 paper by Adolf Busemann was discovered by one of the members and brought to the attention of the committee. Busemann had used the independence principle but had not considered wings swept behind the Mach cone where I thought a subsonic type of flow would arise (though he later did so).[32]
>
> As a result of the committee's action my paper on slender wing theory was published (NACA TR no 835, 1945), but my paper on sweep theory, entitled "Wing Planforms for High Speed Flight[,]" was delayed.[33] NACA's Director, George W. Lewis, proposed that we make experiments to see whether the theory was correct. In one such experiment, wings were attached to a balance inside a heavy cylindrical body which was dropped from a high altitude and the balance readings transmitted to the ground. At Mach

> One [the speed of sound], the wings with 45 degrees sweep had less than *one-tenth* the drag of the straight wings!
>
> Earlier, at the end of the war a group of American scientists boarded an Air Force plane to Europe for the purpose of studying the accomplishments of German wartime research. According to George Schairer [a Boeing design engineer subsequently responsible for the swept-wing design of the company's XB-47 Stratojet bomber], one of the group, much of the time on the long flight was devoted to a debate on the merits of my sweep theory. By the time they reached Germany they decided that it was correct. On going through the German research they found that, thanks to Busemann, many experiments had been made on swept wings, although the idea had not yet had time to influence the manufacturers.[34]

In a signed and witnessed statement that apparently was part of his patent submission, Jones stated the following:

> I have discovered a form of construction and a method of determining the correct proportions of airfoils whereby the large increases of air resistance associated with the formation of shock waves is avoided, and whereby an airplane embodying this form of construction will be enabled to fly at speeds greater than those now attained, without undue expenditure of power and thrust. The object of my invention is therefore the improvement of the design of the airfoil surfaces or wings for airplanes flying at high speeds.

Jones added, "An airfoil surface embodying my invention requires also a certain angle of inclination or sweep in planview relative to the direction of flight."[35] His signed statement was typed on March 14, 1945, and the witness acknowledged receipt of the information on February 27, 1945.

Jones's NACA Report 835, published in 1946, spawned American research on thin, sharply sweptback wings, using the example of an extremely slender delta planform (his NACA Report 863, a year later, extended his work to cover sharply swept wings). Jones reviewed previous theories regarding disturbances in two-dimensional potential airflows, including his mentor Munk's thin-airfoil theory and a later compressible-incompressible airflow corrective approximation method, commonly called the "Prandtl-Glauert rule," derived by Germany's Ludwig Prandtl and Britain's Hermann Glauert.[36] The Prandtl-Glauert approximation "reduced the equation for compressible flow to the same form as the equation for incompressible flow"[37] and enabled comparison of the boundary conditions of both as well.

But unlike previous researchers, examining these in relation to conventional high-aspect-ratio wing planforms (wings characteristically having a large span and small, narrow chord such as those on a long-range transport or a light personal airplane) at subsonic speeds, Jones examined instead the case of low-aspect-ratio wings (wings characteristically having a short span and a larger, broader chord such as a supersonic jet fighter) having pointed planforms and at supersonic speeds (that is, at speeds in excess of the speed of sound, Mach 1 in aerodynamic shorthand).

Reviewing conventional wing theory, Jones noted that "At speeds above the speed of sound, application of the [Munk and Prandtl-Glauert] assumptions leads to [Swiss fluid dynamicist Jakob] Ackeret's theory according to which the wing sections generate plane sound waves of small amplitude," adding, "As is well known, the Ackeret theory predicts a radical change in the properties of such wings on transition to supersonic velocities."[38] Examining the properties of low-aspect-ratio wings in compressible flow at transonic and supersonic speeds, Jones concluded in early May 1945 (before Americans had the opportunity to avail themselves of Germany's impressive wartime swept- and delta-wing research) that

1. The lift of a slender, pointed airfoil moving in the direction of its long axis depends on the increase in width of the sections in a downstream direction. Sections behind the section of maximum width develop no lift.
2. The spanwise loading of such an airfoil is independent of its plan form and approaches the distribution giving a minimum induced drag.
3. The lift distribution of a pointed airfoil traveling point-foremost is relatively unaffected by the compressibility of the air below or above the speed of sound.[39]

## The Emergence of the Oblique Wing

The uncovering after the Nazi collapse of the staggering extent of German swept-wing work before and during the Second World War confirmed Jones's work and added greatly to his stature.[40] Edward C. Polhamus and Thomas A. Toll recalled the multinational development of high-speed swept-wing theory in 1981, stating that the "concepts of both fixed-sweep and variable-sweep high-speed aircraft trace their beginnings to aerodynamic research carried out in Germany during the latter half of the 1930s and early 1940s,"[41] adding that,

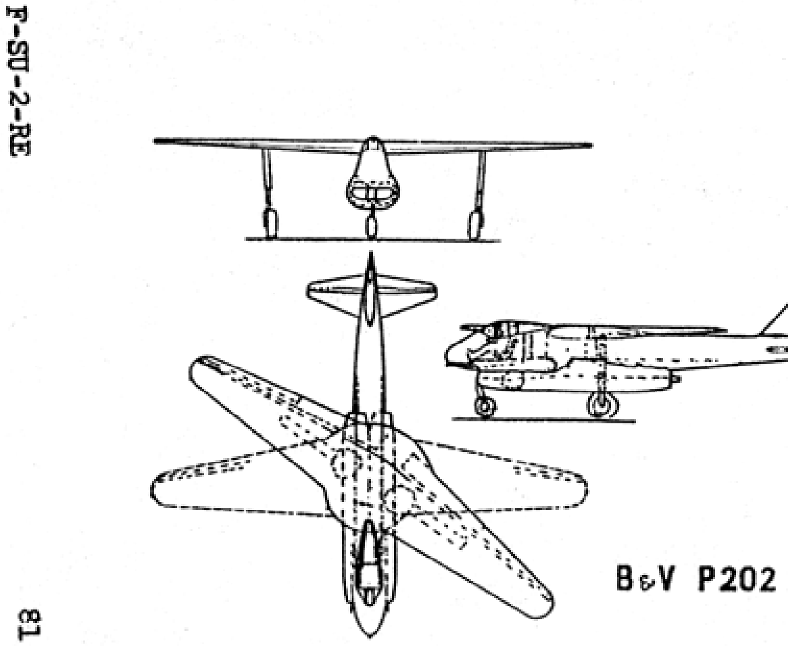
> while the Germans, during World War II, were the first to apply sweptwings to high-speed aircraft and had periodically considered variable sweep, other pressures during the war and the dismantling of their aeronautical industry after the war precluded any serious research relative to variable-sweep aircraft.... [Afterward] aerodynamic researchers in the United States discovered and verified the advantages of sweep independently of the German research, although some five years later, and in 1945 as our research effort was expanding and the German swept-wing results became available, the aerodynamic technology required for successful variable-sweep high-speed aircraft began to evolve."[42]

Independent development likely occurred because aerodynamicists read many of the same papers written by earlier and current experts in their fields and built upon that base of work with their own formulations and concepts, and their work was expedited by the added pressure caused by World War II. As a further indication of independent development, Jones noted in a tribute to Adolf Busemann after the latter's death that

> [d]uring the war years communication with German scientists was lost, and my own somewhat belated discovery of the sweep effect, which emphasized subsonic sweep, was not immediately accepted by American aerodynamicists, including those who had attended the Volta Congress. Consequently, the first American supersonic airplane, the X-1, had no sweep.[43]

R.T. Jones's development of his oblique wing theory followed upon his discovery of the swept-wing concept. The oblique wing is a single continuous wing surface with a central midspan pivot attached to the top of the fuselage. An aircraft with such a wing appears as a conventional straight-wing (i.e., perpendicular to the direction of flight) design during takeoff and landing. But as the pilot increases speed, the wing pivots so that one wingtip (typically the right) advances forward as the other wingtip translates aft. At cruise speed, therefore, an oblique-wing aircraft has the appearance of an open pair of scissors, hence its nickname, scissors wing. The aeroelastic structural behavior and lateral-directional (roll-yaw) stability characteristics of the oblique wing are complex, blending those of the traditional swept wing (for the trailing aft-swept wing) and the more radical forward swept wing (for the leading wing).

As with the classic V foremost swept wing itself, the concept of the oblique wing appears to have been another example of mutual (if not simultaneous) discovery, once again in both Germany and the United States.



Vogt's Blohm und Voss P 202 oblique-wing-fighter proposal, from USAAF, Foreign Equipment Descriptive Brief, August 1946. (USAF)

In 1942, Richard Vogt, chief engineer of the Abteilung Flugzeugbau of the Blohm und Voss Schiffswerft—the Aircraft Manufacturing Department of Blohm and Voss (BuV] Shipworks—proposed the P 202, a jet fighter having a straight, pivoted variable-sweep wing. At takeoff and landing, it would fly at a 0-degree sweep. But at high-speed, it would pivot to 35 degrees, becoming an oblique swept wing. While concept drawings as well as a number of other references of the proposed aircraft exist, no prototype of the fighter was ever built, and no German Air Ministry aircraft designation was assigned for the BuV project—an indication of its lowly status.[44]

Vogt's proposed BuV fighter airplane had a sweep angle of 35 degrees with the left wingtip forward; a top-mounted wing spanning 39.4 feet when straight and 32.84 feet at a 35-degree sweep; a wing area of 215 square feet; two BMW 003 jet engines enclosed in a bulged lower fuselage, sharing a common intake and nose; and a proposed armament consisting of one MK-103 30-millimeter (mm) and two MG-151 20-mm cannons.[45]

Vogt's penchant for aeronautically unconventional designs was well established, his best known design being an experimental asymmetric observation aircraft, the Bv 141, which had its cockpit mounted in a small pod on the wing separate from the fuselage. (Luftwaffe procurement officials, despite how its technical staff might otherwise have been impressed with his technical acumen, chose a more conventional symmetrical design, the Focke-Wulf Fw-189, instead).[46] Altogether, including the P 202, Vogt and his engineering team came up with as many as 33 asymmetrical aircraft designs between 1938 and 1945. Ironically, of all those generated, arguably it was the P 202 that presented the most logical and worthwhile case for development. But Vogt was not alone in his pursuit of the oblique wing; other so-called sheared elliptical-wing concepts were conceptualized at the Aerodynamische Versuchsanstalt (the Experimental Aerodynamics Establishment at Göttingen) and by German manufacturer Messerschmitt's advanced concepts team under Woldemar Voigt, architects of some of Germany's most radical and advanced future aircraft designs. Their P 1101/XVIII-108 (also referred to as the P 1109) featured two axisymmetrically pivoted oblique wings, one on top and one under the fuselage. At takeoff and landing, the P 1101/XVIII-108/P 1109 would be, effectively, a biplane. But at high speed, the upper wing would sweep its right wingtip forward as the lower wing would sweep its left wingtip forward, producing the planform of a compressed X shape whose legs were swept at 60 degrees. In addition to the two-wing design, there was a single-wing variant with the right wingtip swept forward at maximum sweep. Messerschmitt also explored a fixed X-wing concept using two fixed oblique wings that were axially superimposed, one above the other, with one mounted on top of the fuselage, and the other mounted below.[47]

The leading German aeronautical aerodynamicist, Dietrich Küchemann (who after the Second World War became chief scientific officer and aerodynamics department head for the Royal Aircraft Establishment [RAE] in Farnborough, England, where he pioneered slender-wing research influencing the aerodynamics of the Concorde supersonic transport) noted that,

> [once] the application of sweep was proposed, it became clear that the aerodynamic problems concerned not only the cruise design but also the increasingly unsatisfactory characteristics at low speeds…[and] thus the concept of variable sweep almost suggested itself as a possible remedy.[48]

Erich von Holst, a pioneer in behavioral physiology who undertook extensive research on bird-like ornithopters (flapping-wing aircraft) at Göttingen in association with Küchemann, suggested in an unpublished

1942 paper that a skewed wing was the simplest way of obtaining variable sweep. Küchemann noted that von Holst actually built and flew models to demonstrate "their generally satisfactory stability and flying characteristics."[49] He added that the models "included not only asymmetrical configurations, without and with a fuselage, but also symmetrical arrangements with scissor-like biplanes."[50] Küchemann noted, however, that while Germany's wartime collapse "prevented the completion of an actual aircraft with a slewed wing," in the postwar era, the slewed wing was effectively "invented" again by the NACA's R.T. Jones, tested at Langley by John P. Campbell and Hubert M. "Jake" Drake (who tunnel tested its stability characteristics), and resurrected in the 1970s by R.T. Jones (by then at Ames Research Center), who provided the rationale and justification for possibly applying it to high-speed supersonic transports (SSTs).[51]

## The NACA Commences its Own Skewed-Wing Exploration

While the German efforts existed as intriguing drawings (and perhaps, in the case of Erik von Holst, as hobbyist models), they did not reach the prototype piloted aircraft construction stage. That had to await the independent conceptual and development work of Robert T. Jones. Jones's oblique-wing concept was being wind tunnel tested by John P. Campbell and Hubert M. Drake at Langley as early as 1945 (as discussed below). As with his other swept-wing and delta-wing research, Jones's work resulted in extensive study, wind tunnel testing, and model building, and it finally led to the design and fabrication of a proof-of-concept jet-propelled aircraft—the Ames-Dryden AD-1 Oblique Wing Research Airplane, which to date remains the only piloted oblique-wing aircraft ever flown.

Walter G. Vincenti, who knew Jones well and worked with him over a period of years, has addressed the independent oblique-wing concept development issue and Jones's role in influencing Campbell and Drake to undertake their wind tunnel investigation of an oblique-wing model. Vincenti stated that

> [w]hether the concept of the oblique wing was original with R.T. is not clear. The idea was current in the sweep developments in Germany during the war. The first mention in the United States is in a NACA report, dated in mid-1946, by John P. Campbell and Hubert M. Drake on stability-and-control tests of an oblique-wing airplane model in the Langley low-speed free-flight wind tunnel (Campbell and Drake 1947). The report states in typical NACA impersonal fashion that 'it has been proposed' that such

> an airplane be flown, but R.T. has confessed that he promoted the tests, though somewhat secretively from Langley management. Whether he had heard of the German work before these tests we do not know. In any event, the idea was—and is—startling because as R.T. wrote, "Artifacts created by humans show a nearly irresistible tendency for bilateral symmetry."… A large body of work has grown up concerning the oblique-wing airplane in the past half century, much of it at Ames and Stanford under R.T.'s inspiration.[52]

Wind tunnel model testing of the oblique-wing concept started at NACA Langley shortly after the end of the Second World War, blending the conceptual development work of R.T. Jones with the methodical tunnel research of John P. Campbell and Hubert M. Drake. This work was followed by a series of other tests, first at NACA Langley and later NASA Ames, the results of which were well documented by the NACA and NASA in future references that served as building blocks for continued study and testing, which, in fact, is still in progress today. The wind tunnel tests validated the anticipated aerodynamic performance of the oblique-wing concept, thus encouraging further study. Specific areas covered included wing-body tests, lift-to-drag (L/D) ratio assessment, and airfoil and planform studies. Aircraft industries, universities, and conceptual studies (undertaken by R.T. Jones and other aeronautical engineers with NASA) analyzed these findings and further refined the oblique-wing concept. These efforts led to the fabrication of the AD-1 oblique-wing demonstrator and, later, in followup designs and proposals, including one to modify an obsolete U.S. Navy jet fighter as a potential transonic low-supersonic test bed (the F-8 Oblique Wing Research Aircraft program covered in chapter 5) and more recent design applications for potential high-speed civil air transport aircraft (reviewed in chapter 6).

NASA engineer-historian Joseph R. Chambers has noted that "virtually every technical discipline studied by the NACA and NASA for application to aerospace vehicles has used unique and specialized models, including the field of aerodynamics, structures and materials, propulsion, and flight controls.… The most critical contributions of aerospace models are to provide confidence and risk reduction for new designs and to enhance the safety and efficiency of existing configurations."[53] There are two major categories of aeronautical modeling techniques: physical wind tunnel test models and computer models and codes. Both were used in the AD-1 Oblique Wing Research Aircraft program. In addition, there are remotely piloted models or vehicles, such as the oblique-wing model used by R.T. Jones to demonstrate the oblique-wing concept. A physical model generally refers to the model used in experimental analysis of a larger full-scale vehicle. Wind tunnel models are routinely used in many applications, including aerodynamic data gathering for the analysis of full-scale aircraft designs, proof-of-concept demonstrators for analysis of aeronautical concepts, and problem-solving exercises for vehicles already in production. Physical wind tunnel models are generally classified as either static or dynamic depending on their configuration and testing purpose. Static models of aircraft are used to obtain detailed aerodynamic data for analysis of their full-scale versions under specified flight conditions. Static tests are normally conducted with the model fixed to an internally mounted, force-measuring device known as an electrical strain gauge, which in turn is mounted to a sting support system. Dynamic model investigations represent an extension of conventional static tests to include the effects of vehicle motions assessed in free flight (hence the term dynamic). The primary objective of free-flight testing is to evaluate the inherent flight motions of a configuration and its response to various control inputs. Computer models and codes consist of various computer programs and combinations of programs designed to model various design concepts and vehicle performance. All of these techniques were used in the development and flight testing of the AD-1 Oblique Wing Research Aircraft.

In a 1981 survey of variable-sweep research, Edward C. Polhamus and Thomas A. Toll noted:

> By combining information from various sources—the theoretical findings of Busemann and Jones, the German experimental data at subsonic and supersonic speeds, and the NACA transonic data—a perspective of the benefit of wing sweep was developed. [As a result] [t]he conclusion drawn by many in the United States during 1945 and 1946 was that the best of all worlds would involve having straight-wing characteristics at low speeds and swept-wing characteristics beyond the point where compressibility effects began to appear.[54]

Polhamus and Toll added, however, that: "The oblique-wing (or skewed-wing) concept was a somewhat different matter, since there were widespread reservations about the flying qualities of highly unsymmetrical aircraft, and a free-flight investigation of an oblique-wing model was undertaken during March 1946."[55]

## Phase One: The Campbell-Drake Trials of 1947

This wind tunnel testing of an oblique-wing airplane model was conducted in the free-flight tunnel at the Langley Memorial Aeronautical Laboratory (LMAL, now NASA Langley Research Center [LaRC]) by John P. Campbell and Hubert M. Drake. Their findings were published as NACA Technical Note 1208 in May 1947, and the model they tested is shown in the following drawing.

In undertaking their tests, Campbell and Drake noted that

> [i]n order to gain the advantages of sweep at high speeds without experiencing the difficulties introduced by sweep at low speeds, it has been proposed that an airplane be equipped with a wing pivotally attached to the fuselage so that it can be set at right angles to the fuselage for take-off, landing, and low-speed flight and at some angle of sweep for flight at high speeds. In one suggested design the wing is skewed or pivoted as a unit so that one side of the wing is swept forward and the other side swept back.[56]

Their tests consisted of in-flight tests, force tests, and damping-in-roll tests of a model with an oblique wing that could be set at various angles of skew ranging from 0 degree to 60 degrees. In undertaking the tests, the two NACA engineers noted that the investigation was a "preliminary and qualitative indication or whether such a design could be flown" and that the tests did not represent a "complete and comprehensive"[57] discussion of the stability and control problems involved in skewed- (oblique-) wing designs. To address those problems, Campbell and Drake indicated that higher-scale tests on skewed-wing models more representative of high-speed aircraft designs would probably be needed in order to obtain an accurate and detailed analysis.

The flight and force tests were conducted in the Langley free-flight tunnel using an inclined airstream to enable a continuous gliding flight. Force tests were made on the free-flight tunnel balance, which measured forces and moments about the stability axes. The values of the damping-in-roll derivatives were determined by rotation tests in the Langley 15-foot free-spinning tunnel. Controls for the model were actuated by electrical pulses through a flexible trailing cable, as with all Langley spinning-test models.

The model itself weighed between 4.73 pounds (lb) and 5.03 lb. It had a wing area of 2.67 square feet; a wingspan of 4 feet at a 0-degree skew, 3.07 feet at a 40-degree skew, and 2 feet at a 60-degree skew; an aspect ratio of 6.0

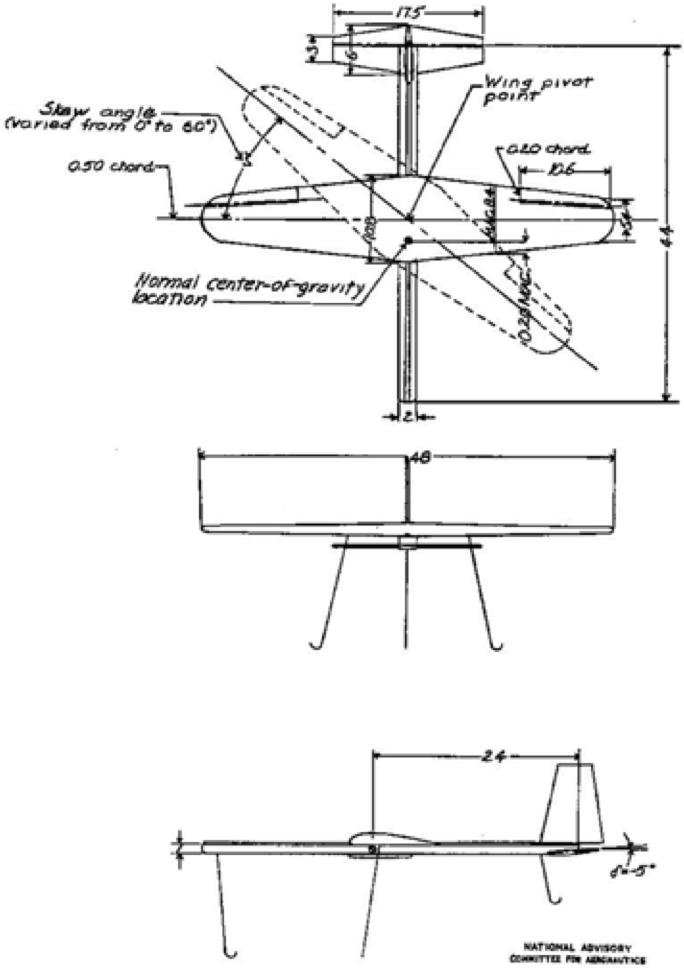


Figure 3.-Three-view sketch of model used in adjustable-skewed-wing investigation. (All dimensions in inches.)

Configuration of Campbell-Drake oblique-wing wind tunnel model, from NACA TN 1208, 1947. (NASA) at a 0-degree skew; and a mean aerodynamic chord of 0.70 feet at a 0-degree skew, 0.91 feet at a 40-degree skew, and 1.40 feet at a 60-degree skew. The ailerons were of the plain type with an area of 0.19 square feet. The horizontal tail had an area of 0.53 square feet, an aspect ratio of 4 feet, and a tail length (hinge line to center of gravity) of 2 feet. The vertical tail had an area of 0.4 square feet, an aspect ratio of 2 feet, and a tail length (hinge line to center of gravity) of 2 feet.[58]

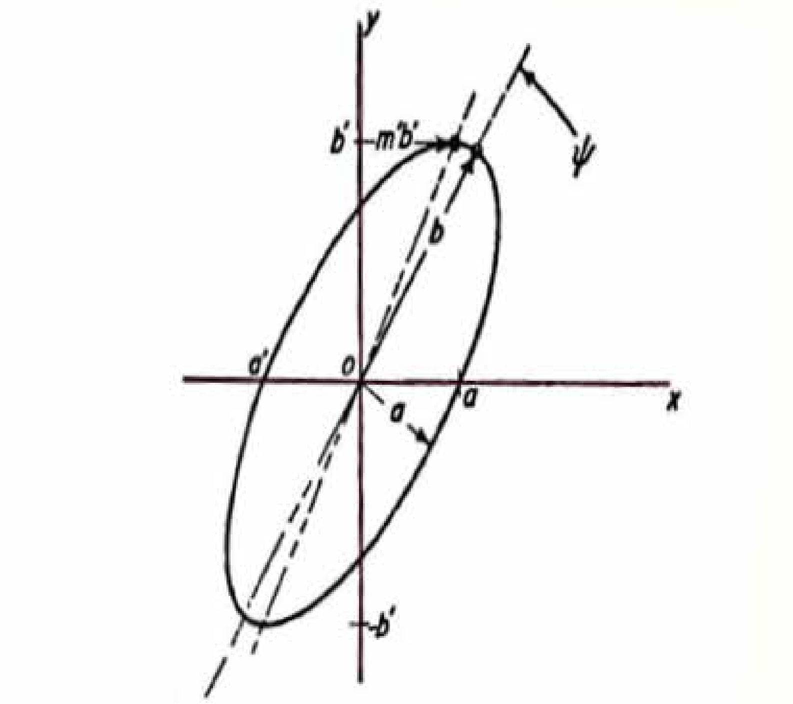
The wind tunnel testing included force tests for longitudinal (pitch) and lateral (roll) stability and control and rotational tests for evaluating its spin characteristics. Afterwards, Campbell and Drake reported, encouragingly, that:

1. In general, the results indicated that an airplane wing can be skewed as a unit as great as 40° without encountering serious stability and control difficulties.
2. Longitudinal stability and control:
    (a) The longitudinal stability and control characteristics were satisfactory in flights made with 40° skew over a lift-coefficient range from 0.3 to 1.0 even for very low values of static margin.
    (b) Only a slight change in longitudinal trim occurred with increasing skew, but an appreciable increase occurred in the glide angle required at a given lift coefficient.

> 3. Lateral stability:
>    (a) The values of effective dihedral for the wing skewed as a unit were considerably less than those encountered on wings with large amounts of sweep-forward or sweep-back.
>    (b) Skewing the wing caused sizable changes in the lateral trim which varied with lift coefficient and skew angle.
> 4. Lateral control:
>    (a) The aileron control effectiveness was only slightly reduced by skew for angles less than 40° because the damping in roll decreased approximately the same amount as the aileron rolling moments. At 50° skew, however, the aileron control effectiveness was noticeably reduced, and at 60° it was so weak that sustained flights could not be made.
>    (b) The force tests indicated that for the 40° skew angle the ailerons produced large pitching moments. In the flight tests, however, no pitching tendencies were observed in aileron rolls, apparently because the lift forces on the wing produced by rolling introduced pitching moments that were equal and opposite to the aileron pitching moments.[59]

The positive impact of Campbell and Drake's tests are evident not only from the findings outlined in the resulting NACA Technical Note, but also in the numerous citations by R.T. Jones and other experts in subsequent writings and oblique-wing designs over the next 50-plus years. Campbell and Drake's wind tunnel tests, however, did not bring about an immediate effort to develop oblique-wing aircraft. Instead, primary attention was directed toward further work on symmetrical variable-sweep development. Wind tunnel study at Langley, however, resumed later under the direction of Charles J. Dolan, using a modified X-1 research airplane model with a fixed pivot point on the fuselage centerline to conduct sweepback tests at 0-degree, 15-degree, 30-degree, and 45-degree angles.[60] The initiation of Campbell and Drake's wind tunnel tests appears to have immediately followed or overlapped the wind tunnel testing of the swept wing. In a March 14, 1945, letter to R.T. Jones, George W. Lewis, the committee's legendary Director of Aeronautical Research at NACA's Washington Headquarters on H Street NW, stated that

> [t]he result of your theoretical analysis in arriving at the correct principle of design of a supersonic, or transonic, wing I consider most important….Mr. Crowley [John "Gus" Crowley, a Lewis associate at NASA Headquarters who specialized in flight testing and flight research] was in the office today and I mentioned your



Jones's depiction of an oblique-wing elliptical planform, 1952. (AIAA)

> letter to him. He said that he had discussed this matter with you and that he had suggested you prepare a memorandum, which is to be followed later by some tests.[61]

It is not clear whether this letter referred only to the swept-wing testing or to both the swept-wing tests and Campbell and Drake's investigation of the oblique wing. As reviewed above, however, Walter Vincenti stated that "R. T. [Jones] has confessed that he promoted the [oblique-wing] tests, though somewhat secretively from Langley management."[62] In reviewing the early history of the oblique-wing concept, Ilan Kroo, a Stanford University professor of aeronautics, also signaled Jones's role in the undertaking of Campbell and Drake's study, noting, "He [Jones] built balsa wood models of oblique wings while at Langley field in 1945 and inspired the first published wind tunnel tests of the concept by J. Campbell and H. Drake."[63]

## Phase Two: Jones's Progression to the Oblique Wing, 1946–1958

Between 1946 and 1958, R.T. Jones steadily expanded his studies on swept- and delta-wing aerodynamics, making notable contributions to understanding the relationship between planform choice and aerodynamic performance and contributing notably as well to studies of wing-body effects, a subject of vital importance in the early years of transonic aircraft design. Initially, whatever other interest he might have had in Vogt-like skewed wings, Jones was firmly committed to the study of bilaterally symmetric swept-wing shapes. Thus, for example, a 1946 paper entitled "Thin Oblique Airfoils at Supersonic Speed" was not, as the title might seem to imply, a paper on the skewed AD-1-style oblique wing but, rather, a paper extending his research (enunciated in his TR 835 issued that same year) on bilaterally symmetric swept wings.[64]

But in 1952, Jones deviated from the bilaterally symmetric path to address the case of the elliptical wing. The elliptical wing is one of the oldest and most pleasing aerodynamic shapes, and if inevitably associated with the Supermarine Spitfire of Reginald Mitchell (whose wing was, in fact, a broken rather than pure ellipse), its origins actually date to the First World War. In the prewar era, it appeared in its purest form on the interwar Bäumer Sausewind light aircraft, which inspired Heinkel's (Germany's manufacturing company) later He 70 Blitz. Earlier in his career, Jones had studied the conventional elliptical wing, and now, in the early supersonic era, he returned to study it, finding that the drag of an elliptical wing set at an oblique angle not only had a highly desirable uniform lift distribution, but a greatly reduced drag as well.[65]

Jones continued his pursuit of the elliptical oblique wing, and in a conference on high-speed aeronautics held at the Polytechnic Institute of Brooklyn in January 1955, he presented his views on the future of high-speed transport airplanes, noting that the "wing of elliptic planform" had "especially simple mathematical properties at supersonic speeds" with a uniform distribution of lift "over whatever elliptical area is allotted."[66] He added that an elliptical wing "yawed behind the Mach cone"—that is, flying forward but presenting an oblique planform when viewed from above, such as on the AD-1 demonstrated a quarter century later—"enables the requirements of minimum pressure drag and minimum friction drag to be satisfied simultaneously."[67] He concluded,

> At large angles of sweep or yaw the drag due to lift becomes in a large measure independent of the exact distribution, but depends primarily on the span b and the length l [report references] of the wing[, thus the] minimum drag occurs when both the lengthwise and spanwise loadings are elliptical.[68]

> For supersonic speed we thus require the maximum span b and the maximum length l, together with the minimum of exposed area. *These conditions determine the oblique, elliptically loaded lifting line as an ideal limiting form for the supersonic wing.* It seems unfortunate that a bilaterally symmetrical form, such as a swept wing or a V-shaped lifting line could not satisfy the requirement. *However if we bend the lifting line at the middle to form a V it is seen that the wave resistance increases considerably.*[69] [Emphasis added.]

Thus, a decade after enunciating the bilaterally symmetrical swept planform—whether a slender delta or a bent V-planform wing—Jones was now enunciating the pure simplicity of the straight elliptical wing, skewed obliquely to the line of flight, effectively acting as an aircraft with both a forward-swept and aft-swept wing. Ten months after his Brooklyn presentation, Jones spoke before an international aerodynamics conference held, fittingly, at Göttingen. There he presented his findings on the benefits of the oblique elliptical planform, noting as well the contributions of his mentor Max Munk to his analysis of induced drag reduction.[70]

Model aircraft have a long and distinguished history of contributing to the development of aeronautics, from Alphonse Pénaud's rubberband-powered model of 1871, which demonstrated that a powered aircraft could successfully fly through the inherently stable steam-powered Aerodromes of Smithsonian Secretary Samuel Langley, and numerous other examples in the 20th century. Virtually all aeronautical engineers began their careers in flight by building flying model airplanes in their youth. Thus, it was natural that when Jones sought to validate his ideas regarding an oblique wing, he turned to the elegance and deceptive simplicity of the traditional balsa-wood model airplane, demonstrating the concept of an oblique flying wing with a balsa-wood glider that he flew at the first International Congress of the Aeronautical Sciences (ICAS), held in Madrid, Spain, in September 1958. In recalling this in a 1972 paper for the American Institute of Aeronautics and Astronautics, Jones said, "Some years later the present writer demonstrated the rather surprising stability of the slanted wing by flying models at the first ICAS meeting in Madrid."[71] The "surprising stability" that Jones referred to was likewise implicit in the findings of Campbell and Drake, which Jones described as "Perhaps the earliest experiments to test the flight stability of such an arrangement."[72]

In his 1958 paper, Jones reviewed the state of contemporary supersonic design, noting at the outset that

> [i]n its earlier development the subsonic airplane showed a great variety in the arrangement of airfoils, bodies, and other parts.

> For the past 15 or 20 years, however, those airplanes which have passed the tests of experience have shown little alteration in basic form. The aerodynamic principles which have determined this form seem now to be well understood and agreed upon.[73]
>
> The situation is different in the case of the supersonic airplane. Here the aerodynamic rules seem more complex. No clear direction toward a specific form is evident. Our theoretical investigations have taken a rather wide range—seeming in some cases rather far removed from practical questions.[74]

Jones added that in this paper he was going to "review some of the recent theoretical and experimental work in supersonic aerodynamics with its practical application in mind."[75] Central to his review was a comparison of yawed and swept wings. In making this comparison, Jones noted:

> With planar wings the wave drag is reduced as the lift distribution is extended in the flight direction, while the vortex drag is reduced by extending the span. At the same time the friction drag is reduced by diminishing the exposed area of the wing. At subsonic speeds the last two considerations are effective and they lead to wing forms approaching a lifting line perpendicular to the flight direction. At supersonic speeds the added condition on the length leads to a long, narrow wing placed at an angle of yaw.[76]
>
> It is interesting to analyze the yawed lifting line in terms of its area of entrainment. The forward and reversed Mach waves are simply circular cones drawn from the ends of the line. At subsonic angles of yaw the cones are displaced laterally so that the contour of their inter-section, which outlines the equivalent jet, is an ellipse. The area of this ellipse vanishes rapidly, however, and disappears completely as the lifting line approaches the Mach angle. The area of entrainment is zero and the wave drag given by the theory is infinite at supersonic angles of yaw.[77]

Jones then noted that if a yawed wing is converted into a swept wing (by bending the wing at the middle), its length in the flight direction is reduced to about one-half, thus increasing the wave drag "*so that the potential lift-drag ratio is invariably smaller for the bilaterally symmetric arrangement*."[78] (Emphasis added.)

In understanding Jones's quest to reduce supersonic drag, the perspective of the great Hungarian aerodynamicist Theodore von Kármán affords a useful insight, offered near-contemporaneously with Jones's oblique-wing work:

> Even before any manned aircraft had pierced the sound barrier, it was apparent from a theoretical point of view that the most important factor in the design of a supersonic plane is the new source of drag, which we aerodynamicists have come to call "wave drag." This type of drag is analogous to a phenomenon which is familiar to every motorboat operator. At low speed the boat's keel rides deep in the water. As the operator increases the speed, the boat encounters greater resistance, which arises from the waves created by the boat. Similarly, in the case of flight, as indicated earlier, the resistance of the air rises appreciably when the airplane begins to approach the speed of the air waves created by it. Once the plane goes through this speed, the flow around it smooths out to some extent.
>
> The difference between the motorboat and the airplane lies in what one can do to overcome this new resistance. A speedboat can rise on its "step," and move along in the water with most of the boat in the air, so a great part of the water drag is lessened. But an airplane cannot move on the step; it is already operating in three dimensions….Other means have to be found to reduce the new resistance arising out of the high speeds.[79]

It may be said that Jones's progression toward the oblique-wing configuration certainly represented just such an "other means."

## Endnotes

1. See, for example, Frederick L. Nussbaum, *The Triumph of Science and Reason, 1660–1685* (New York: Harper & Row, Publishers, 1953), 7–8; Thomas P. Hughes, "From Deterministic Dynamos to Seamless-Web Systems," in *Engineering as Social Enterprise*, ed. Hedy E. Sladovich (Washington, DC: National Academy Press, 1991), 7–24.
2. For insights into Jones, see his Robert T. Jones, "Learning the Hard Way: Recollection of an Aeronautical Engineer," unpublished autobiography, copies in NASA Dryden Flight Research Center Library, NASA Ames Research Center Archives, and Stanford University Library Special Collection no. 876 (Papers of Robert T. Jones); Walter G. Vincenti, "Robert T. Jones, 1910–1999: A Biographical Memoir," *Biographical Memoirs* 86 (2005); Walter G. Vincenti, "Robert T. Jones, One of a Kind," *Annual Reviews of Fluid Mechanics* 37, no. 1 (2005): 1–21; William R. Sears, Introduction to the "Collected Works of Robert T. Jones," NASA Technical Memorandum (TM) X-3334 (February 1976), vii–xii; James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917–1958,* NASA Special Publication (SP)-4305 (Washington, DC: NASA 1987); and Robert T. Jones, "My Adventures in Aeronautics," undated and unpublished draft of autobiography, Department of Special Collections, Stanford University Libraries, box 11, folder 11.
3. Ibid.
4. Max M. Munk, *Fundamentals of Fluid Dynamics for Aircraft Designers* (New York: The Ronald Press Co., 1929).
5. For the Prandtl-Munk connection, see Michael Eckert, *The Dawn of Fluid Dynamics: A Discipline Between Science and Technology* (Weinheim, Germany: Wiley-VCH Verlag, 2006), 73–76, 102–105. For Munk at Langley, see the previously cited Hansen, *Engineer in Charge*, 72–95.
6. Hermann Grassmann, *Die Ausdehnungslehre: Vollständig und in Strenger Form Begründet* (Berlin: Enslin Verlag, 1862); for Grassmann's extraordinary work, despite contemporary lack of appreciation, see Gert Schubring, *Hermann Gunther Grassmann: Visionary Mathematician, Scientist and Neohumanist Scholar* (New York: Kluwer Academic Publishers, 1996).
7. For Hamilton, see Thomas L. Hankins, *Sir William Rowan Hamilton* (Baltimore, MD: The Johns Hopkins University Press, 1980); see

also W.W.R. Ball, *A Short Account of the History of Mathematics* (New York: Sterling Publishing Co., 2001 ed.), 472–474.

8. In his "Aerodynamic Design for Supersonic Speeds," in *Advances in the Aeronautical Sciences Proceedings of the First International Congress in the Aeronautical Sciences, Madrid, September 8–13, 1958* vol. 1, eds. Theodore von Kármán, A.M. Ballantyne, and R.R. Dexter (New York: Pergamon Press, 1959), Jones recollected assisting Zahm by making figures and drawings for Zahm's "Superaerodynamics," *Journal of the Franklin Institute* 217 (1934): 153–166.
9. Jones, "Learning the Hard Way: Recollection of an Aeronautical Engineer."
10. Sears, "Introduction," in "Collected Works of Robert T. Jones," vii.
11. Robert R. Dexter, Secretary, Institute of Aeronautical Sciences, letter to Dr. Robert T. Jones, January 3, 1947, Stanford, box 35.
12. Award Presentation citing January 6, 1981, award signed by President Jimmy Carter, NASA Ames Research Center History Office, Archives Reference Collection, Collection Number AFS1070.8A.
13. Phillip S. Hughes, Acting Secretary, Smithsonian Institution, letter to Dr. Robert T. Jones, February 24, 1981, Department of Special Collections, Stanford University Libraries, box 35, folder 10.
14. Ibid.
15. NASA, "Collected Works of Robert T. Jones," 885–1025. The quotation is on 1022.
16. Vincenti, "A Biographical Memoir," 15.
17. See the R.T. Jones, "Collected Works of Robert T. Jones."
18. Details on the JB-2 are from Kenneth P. Werrell, *The Evolution of the Cruise Missile* (Maxwell AFB, AL: Air University Press, September 1985), 65–67.
19. Indeed, as of November 2011, the remains of one such JB-2 missile fatally damaged during launch are still rusting away amid scrubwood-covered sand dunes at the Sandestin, FL, wartime test location, now the Coffeen Nature Preserve on Florida's Emerald Coast. Information from Dr. Richard P. Hallion, who visited the site and inspected the wreckage on November 16, 2011. Loss statistics are from Werrell, *Evolution of Cruise Missile*, 65.
20. G.W. Lewis, "Memo from NACA to Langley Laboratory," February 14, 1945, Robert T. Jones Papers, Stanford University Libraries, Department of Special Collections, box 35, folder 16.

Jones, "My Adventures in Aeronautics," 10–11.

21. Letter from G.W. Lewis to Robert T. Jones, October 14, 1947, Robert T. Jones Papers, Stanford University Libraries, Department of Special Collections, box 35, folder 16.
22. For this progression, see Richard P. Hallion, "Sweep and Swing: Reshaping the Wing for the Jet and Rocket Age," in, *NASA's Contributions to Aeronautics*, vol. 1, ed. Richard P. Hallion, NASA SP-2010-570-Vol 1 (Washington, DC: NASA, 2010).
23. It is worth noting that on this point, Jones's memory that the Sikorsky engineer came to him with a drawing of a "fighter plane" is incorrect; he came with a drawing of a proposed glide bomb based upon an earlier Sikorsky fighter proposal by Michael Gluhareff. Gluhareff had conceptualized a futuristic delta-wing fighter powered by a pusher propeller. This remarkable concept (more suitable for turbojet propulsion) was not developed, though several years later, it spun off a proposal for a 2,000-lb guided glide bomb, or "glomb." It came to Jones's attention because of his work on guided-weapon issues for the NACA. Richard P. Hallion, who interviewed Jones for his article "Lippisch, Gluhareff, and Jones: The Emergence of the Delta Planform and the Origins of the Sweptwing in the United States," (*Aerospace Historian* 26, no. 1 [Spring 1979]: 1–10)—the first historical examination of Jones's work and the context of swept-wing research in Germany and America—was drawn to Jones's work by discovering a wind tunnel model of the Gluhareff fighter proposal in the collections of the National Air and Space Museum, Smithsonian Institution, in 1976. For a more expanded review and drawing of Gluhareff's proposed 1941 rounded delta planform and subsequent "glomb" missile design, see the previously cited Hallion, "Sweep and Swing: Reshaping the Wing for the Jet and Rocket Age," 8–11.
24. A von Kármán research associate at the Guggenheim Aeronautical Laboratory of the California Institute of Technology (GALCIT), Tsien Hsue-shen undertook significant high-speed research, later concentrating his work in rocketry and hypersonics and, subsequently, became the architect of the People's Republic of China missile program. Two of his papers relating to Jones's interests are: "Two-Dimensional Subsonic Flow of Compressible Fluids," *Journal of the Aeronautical Sciences* 6 (1939); and (with L. Lees) "The Glauert-Prandtl Approximation for Subsonic Flows of a Compressible Fluid," *Journal of the Aeronautical Sciences* 12 (1945).
25. Jones, "My Adventures in Aeronautics."

26. The paper was drafted in May 1945 and published the next year as "Properties of Low-Aspect-Ratio Pointed Wings at Speeds Below and Above the Speed of Sound," NACA Report No. 835 (1946).
27. Jones, "My Adventures in Aeronautics."
28. See Max M. Munk, "Note on the Relative Effect of the Dihedral and the Sweepback of Airplane Wings," NACA Technical Note No. 177 (1924).
29. Vincenti, "Robert T. Jones, One of a Kind," 7.
30. Jones retained this model and used it as a letter opener! When he mentioned this to Richard P. Hallion during Hallion's interview with him, Hallion persuaded him to donate the model to the National Air and Space Museum, and it was subsequently accessioned into the museum's collections.
31. See the previously cited Hallion, "Sweep and Swing: Reshaping the Wing for the Jet and Rocket Age," 13–17.
32. This was Busemann's milestone Volta Congress paper in which he enunciated the theory of high-speed swept wings, printed as "Aerodynamische Auftrieb bei Überschallgeschwindigkeit," *Luftfahrtforschung* 12, no. 6 (October 3, 1935).
33. It subsequently appeared as "Wing Planforms for High-Speed Flight," NACA TR No. 863 (1947).
34. Jones, "My Adventures in Aeronautics."
35. Robert T. Jones, signed statement titled "The Shaping of Wings to Minimize the Formation of Shock Waves," witnessed as explained by Jones on February 27, 1945, and typed on March 14, 1945, NASA Ames History Office, Moffett Field, CA.
36. See Max M. Munk, "Elements of Wing Section Theory and of the Wing Theory," NACA Report No. 191 (1924); Hermann Glauert, "The Effect of Compressibility on the Lift of an Aerofoil," Reports & Memoranda No. 1135, Aeronautical Research Committee (United Kingdom) (1927); Ludwig Prandtl, "General Considerations on the Flow of Compressible Fluids," NACA TM No. 805 (1936).
37. Quote from Hans Wolfgang Liepmann and Allen E. Puckett, *Introduction to Aerodynamics of a Compressible Fluid* (New York: John Wiley & Sons, Inc., 1947), 172. See also R. Giacomelli and E. Pistolesi, "Historical Sketch," in *Aerodynamic Theory: A General Review of Progress Under a Grant of the Guggenheim Fund for the Promotion of Aeronautics,* vol. 1, ed. William Frederick Durand (Pasadena, CA: Guggenheim Aeronautical Laboratory of the California Institute of Technology, 1943 ed.), 383–394; Theodore von Kármán, *Aerodynamics: Selected Topics in the Light of Their*

*Historical Development* (New York: McGraw-Hill Book Company, 1963 ed.), 56–57, 115, 129–30.

38. Jones, "Properties of Low-Aspect-Ratio Pointed Wings at Speeds Below and Above the Speed of Sound," 59. Ackeret's work was published by the NACA as "Air Forces on Airfoils Moving Faster than Sound," TM No. 317 (1925), translated from *Zeitschrift für Flugtechnik und Motorluftschiffahrt* (February 14, 1925).
39. Ibid., 63.
40. Hallion, "Sweep and Swing," 11–13.
41. Edward C. Polhamus and Thomas A. Toll, "Research Related to Variable-Sweep Aircraft Development," NASA TM 83121 (1981), 1.
42. Ibid.
43. Robert T. Jones, "Adolf Busemann: 1901–1986," *Memorial Tributes: National Academy of Engineering* 3, (1989): 65.
44. Headquarters, Freeman Field, Air Materiel Command, "German Aircraft and a List of Foreign Aircraft Brought to the United States," Foreign Equipment Descriptive Brief, archives of the National Museum of the USAF, serial No. 46-6B (August 1946), 1, 8–9.
45. Headquarters, Air Materiel Command, Wright Field, "German Aircraft, New and Projected Types," reprint of British Air Ministry A.I.2(g) Report No. 23, January 1946 (June 1946).
46. William Green, *The Warplanes of the Third Reich* (Garden City, NY: Doubleday & Co., 1970), 83, 192.
47. See Michael J. Hirschberg, David M. Hart, and Thomas J. Beutner, "A Summary of a Half-Century of Oblique Wing Research," a paper presented at the 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 8–11, 2007, AIAA paper no. 2007-150 (2007), 2–3; Hans-Ulrich Meier, ed., *German Development of the Sweptwing, 1935–1945* (Reston, VA: AIAA,[in cooperation with the Deutsche Gesellschaft fur Luft und Raumfahrt Lilienthal-Oberth e.V.], 2010).
48. Dietrich Küchemann, *The Aerodynamic Design of Aircraft* (United Kingdom: Paragon Press, 1978). Quotation from 12. In regard to Küchemann, see Andrew Nahum, "The Royal Aircraft Establishment from 1945 to Concorde," in *Cold War, Hot Science: Applied Research in Britain's Defence Laboratories 1945–1990,* eds. Robert Bud and Philip Gummett (London: Science Museum, 2002), 50–52; Kenneth Owen, *Concorde: Story of a Supersonic Pioneer* (London: Science Museum, 2001), 36–42.

49. Von Holst is not one of the better known interwar aerodynamics and flight control researchers, but in his work one can see the roots of today's interest in insect- and bird-like micro-Remotely Piloted Aircraft (micro-RPA). See his essay (coauthored with Küchemann) "Biologische und Aerodynamische Probleme des Tierfluges," *Die Naturwissenschaften* 29 (1941): 348–362. He was arguably better known among the model aircraft and youth airmindedness movement within the Third Reich; see, for example, his "Tierflug und Modellflug," *Luftfahrt und Schule: Zeitschrift zur Förderung der Luftfahrt und des Luftschutzes an deutschen Schulen* 6, issue 3 (December 1940): 24–26. Reproductions of his remarkable models periodically reappear and amaze anew.
50. Ibid.
51. Küchemann, *Aerodynamic Design of Aircraft*, 12.
52. Vincenti, "Robert T. Jones, One of a Kind," 9.
53. For a detailed review of wind tunnel testing and modeling, see Joseph R. Chambers, *Modeling Flight: The Role of Dynamically Scaled Free-Flight Models in Support of NASA's Aerospace Program*, NASA SP-2009-575 (Washington, DC: NASA, 2009), quote from 2.
54. Polhamus and Thomas, "Research Related to Variable Sweep Aircraft Development," 5.
55. Ibid.
56. John P. Campbell and Hubert M. Drake, "Investigation of Stability and Control Characteristics of an Airplane Model with Skewed Wing in the Langley Free-Flight Laboratory," NACA TN No. 1208 (May 1947), 2.
57. Ibid., 2.
58. Ibid., 12–13.
59. Ibid., 10.
60. Polhamus and Toll, "Research Related to Variable Sweep Aircraft Development," 5.
61. Letter from G.W. Lewis to R.T. Jones, March 14, 1945. NASA Ames History Office.
62. Vincenti, "Robert T. Jones, One of a Kind," 9.
63. Ilan Kroo, "The Aerodynamic Design of Oblique Wing Aircraft," AIAA paper no. 86-2624 (1986), 1.
64. Robert T. Jones, "Thin Oblique Airfoils at Supersonic Speed," NACA TR No. 851 (1946).
65. Robert T. Jones, "Theoretical Determination of the Minimum Drag of Airfoils at Supersonic Speeds," *Journal of the Aeronautical Sciences* 19, no. 12 (December 1952).

66. R.T. Jones, "Possibilities of Efficient High-Speed Transport Airplanes," in *Proceedings of the Conference on High-Speed Aeronautics*, Antonio Ferri, Nicholas J. Hoff, and Paul A. Libby, eds. (New York: Polytechnic Institute of Brooklyn, 1955), 151–153.
67. Ibid.
68. Ibid.
69. Ibid.
70. Robert T. Jones, "Some Recent Developments in the Aerodynamics of Wings for High-Speeds," *Zeitschrift für Flugwissenschaften* 4, no. 8 (August 1956). The conference was sponsored by the *Gesellschaft für angewandte Mathematik und Mechanik* (GAMM), the *Verein Deutscher Ingenieure*, and the *Wissenschaftlichen Gesellschaft für Luftfahrt*.
71. R.T. Jones, "Reduction of Wave Drag by Antisymmetric Arrangement of Wings and Bodies," *AIAA Journal* 10, no. 2 (February 1972): 174.
72. Jones's balsa-wood models are on display at NASA Ames. NASA Ames archivists have published instructions that show the actual size of each glider model part along with instructions on how to make an oblique-wing glider. The glider, which is made of 1⁄16-inch balsa wood, has an oblique wingspan of 6¾ inches with a rounded-up trailing edge. The left end of the wing, which is pointed forward, has a smaller fin perpendicular to the wing, while the right side of the wing has a larger fin. A critical part of the glider is the 2-inch boom consisting of a 3⁄32-inch stick with a nose weight made of clay or wax. The boom is glued at either a 30-degree or 45-degree angle to the wing. A handhold is glued under the wing immediately next to the boom.
73. Jones, "Aerodynamic Design for Supersonic Speeds," 34.
74. Ibid.
75. Ibid.
76. Ibid., 40.
77. Ibid.
78. Ibid.
79. Theodore von Kármán and Lee Edson, *The Wind and Beyond: Theodore von Kármán—Pioneer in Aviation and Pathfinder in Space* (Boston: Little, Brown and Company, 1967), 220–221.

Jones-Gadeburg radio-controlled oblique-wing free-flight model. (NASA)

# CHAPTER 2

# Evolving the Oblique Wing

For aerodynamicists, the Swinging Sixties meant more than a cultural transformation: it was the decade in which practical variable-wing-sweep went mainstream, typified by new aircraft—such as the American F-111, Soviet MiG-23 and Su-24, and French Mirage G—and imaginative concepts for variable-sweep supersonic transports and lifting reentry spacecraft. It was also the decade in which engineers first applied the single-pivot oblique planform to air transport design thanks to British aeronautical engineer G.H. Lee. If imitation is indeed the sincerest form of flattery, R.T. Jones had every reason to feel well-praised.

Lee, then deputy chief designer of Handley Page, Ltd. (Britain's oldest aeronautical firm), had heard Jones's Madrid presentation, during which the American had "demonstrated very convincingly" the oblique-wing concept using his small balsa-wood models.[1] He returned to the United Kingdom determined to undertake his own examination of the concept and as a result, developed a plan for a Mach 2 flying wing transatlantic airliner that he believed could increase "payload by between 50% and 100% if a slewed-wing layout were adopted."[2] Lee argued that when aerodynamicists and aircraft designers considered future high-speed designs,

> [t]he usual solution is to have a highly swept arrow-head type of planform arranged with a joint somewhere on the inner part of the wing so the tips may be moved forward for subsonic parts of the flight where span is required, while they are moved back again to give a highly sweptwing for the supersonic phases…. The main penalty for such a layout is that major shear and bending loads have to be taken through the moving joints, with subsequent severe mechanical and structural problems.[3]

As a solution, Lee proposed a slewed all-wing planform containing the passengers and fuel with a crew cabin at the forward wingtip. Its vertical fin and rudder were at the rearmost wingtip, and four engines in ventral pylon-mounted nacelles were under the central portion of the wing set (like the crew cabin and vertical fin and rudder) to always be parallel to the line of flight, whatever the wing's skew (oblique) angle. Lee noted that with this configuration, unlike a bilaterally symmetrical variable swept wing, only comparatively secondary loads would be taken through moving joints. Longitudinal and lateral control would be provided by elevons (combined ailerons and elevators) and the rudder. Lee noted that,

> [w]ith regard to the performance to be expected from such an aeroplane, the lift/drag ratio in supersonic flight at a Mach No. of, say, 2.0 may be expected to be approximately 10 or 11, which is probably 10% or 20% better than might be obtained with the corresponding slender wing configuration. Subsonically, the slewed wing would have a lift/drag ratio of about 24, which is very much better than could be obtained with the slender wing.[4]

Despite the promise of the oblique wing and its apparent maturity, it would take more than another decade to appear. In retrospect, Lee admitted, the oblique wing, despite its attractiveness, "bristled with magnificent problems,"[5] particularly in stability and control, because with an oblique wing, any deviation in pitch immediately resulted in rolling and yawing as well, thanks to "an inescapable, built-in coupling between all three motions."[6] For his part, Jones left NASA for a period of 7 years to work as a principal research engineer with the Avco-Everett Research Laboratory in areas other than aeronautics, though he continued his own individual research, publishing yet another analysis of thin oblique-wing aerodynamics in 1965.[7] In 1970, Jones returned to NASA's Ames Research Center as a senior staff scientist. By the late summer of 1971, he had formulated a compelling argument for considering oblique wings for future supersonic aircraft, resting on a detailed and provocative examination of wave drag and the comparative performance of bilaterally symmetric V-foremost sweptwings and antisymmetric oblique wings.[8]

## Jones's Progression Toward a Suitable Flight Configuration

Acknowledging that "[o]ne of the unspoken assumptions in aircraft design is that of bilateral or mirror symmetry," Jones argued that there was "no rational discussion"[9] of its merits, and that, indeed,

> once the velocity of sound is exceeded, the laws of aerodynamics change in such a way as to make it seem inadvisable to arrange the components of an airplane side by side or abreast in a supersonic stream unless there are compelling reasons for such an arrangement. Both the transonic area rule and the supersonic small disturbance theory show large adverse interference effects for bodies or wings in mirror-symmetric arrangements.[10]

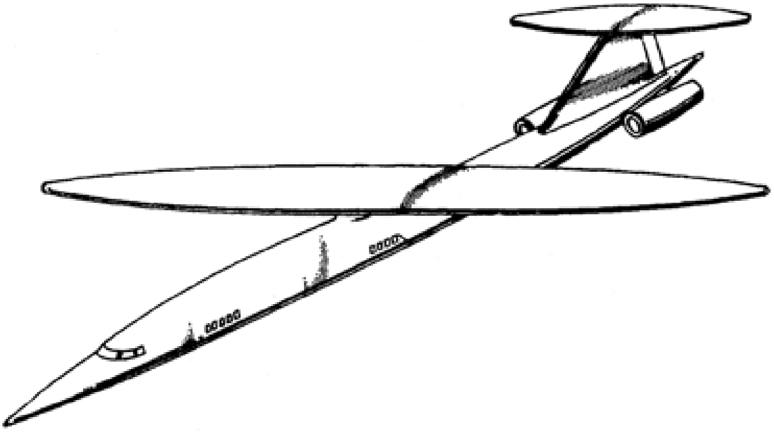
He demonstrated his argument by showing the results of applying supersonic wave-drag theory to two airplanes—in two different formations—flying in close formation at a slightly supersonic Mach number. Alone, one airplane had a measured wave drag of 1. When flying side by side (bilaterally symmetrically) with another airplane of similar type, the two aircraft would produce a combined drag of 4 as the drag of each aircraft would be doubled by interference from the other. But if they flew in a classic military "leader and wingman" formation (with one slightly ahead of the other), producing an oblique, antisymmetrical formation, the total drag of both aircraft was 1. In short, the two airplanes had a wave-drag count equivalent to just a single aircraft.[11] In an obvious critique of contemporary thought, then wedded firmly to the delta or sharply swept bilaterally symmetric arrow wing, Jones pointedly noted that "[t]he arrow shape, which seems intuitively correct for supersonic speed, nevertheless has a predicted wave drag many times larger than the antisymmetric arrangement."[12]

Jones illustrated his paper with compelling plots and graphs and showed two possible supersonic oblique-wing configurations: one with a single fuselage and pivoted wing and horizontal tail and a second with two parallel fuselages joined to a wing and horizontal tail, each with a pivot so that, like a parallel rule, the aircraft could translate one fuselage ahead of the other, forming an aircraft with an oblique wing and an oblique tail. In both of these cases, the tendency in 1960s to 1970s air-transport design of mounting engines aft on the fuselage worked to keep the engines oriented so that their inlets and thrust were always aligned with the line of flight.

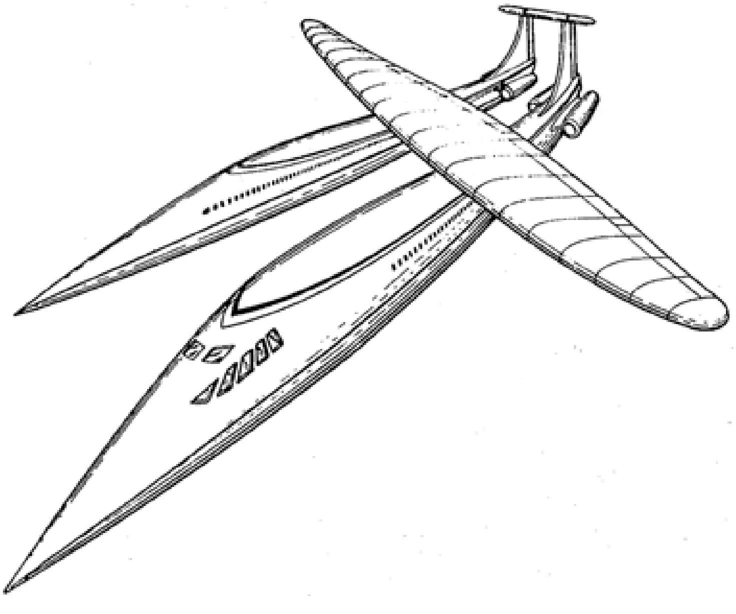
Jones concluded his paper by conceding that

> it is admittedly surprising that aerodynamics and simple mechanics would lead to an antisymmetric form for supersonic flight. The difficulties with such forms may, however, be more conceptual than real and it is hoped that our analysis, though incomplete, will show that such configurations deserve more serious study."[13]

To obtain additional experience in the control and stability of oblique-wing aircraft, Jones (assisted by Burnett L. Gadeburg of NASA Ames, who



Jones's concept for a single-fuselage oblique-wing SST, 1971. (AIAA)



Jones's concept for a twin-fuselage, oblique-wing, "antisymmetric" SST, 1971. (AIAA) served as project pilot) fabricated and tested several radio-controlled models. The radio control system, which was acquired from Kraft Systems of Vista, CA, provided linear, proportional deflection of all surfaces and, in addition to normal control channels, had an extra channel that permitted variation of the wing-skew angle in flight. (The wings were, of course, in a straight position for takeoff and landing). Afterward, Jones noted: "Variations of wing angle up to and beyond 45 deg produced no apparent changes in stability and only slight change in lateral trim—requiring a 1- or 2-deg offset of the ailerons. Elevator and aileron effectiveness remained normal and we observed no change in longitudinal trim."[14] Maneuvers such as loops and rolls were performed without difficulty at angles of 45 degrees. He noted that coupling between longitudinal and lateral motions did not occur in aileron rolls but was apparent in the response to elevator control (pitch), thus indicating aileron deflection had to be employed simultaneously with pitch application.

Jones concluded that varying the sweep of a single wing had several practical advantages over the swing-wing design, including:

1. Turning the wing as a whole keeps the wing structure continuous across the pivot and places the primary load on the pivot tension (separate wing panels pivoted at the root places much greater loads on the pivots);
2. Likewise, turning the wing as a whole does not displace the centroid of area relative to the center of gravity;
3. The optimum fuselage shape for an oblique wing is more nearly cylindrical than the swept wing, which, conforming to the "area rule," requires a somewhat localized and deep indentation in the fuselage;
4. An oblique wing would enable flight at different Mach numbers with greater efficiency, thus enabling overland flights at speeds slow enough to avoid sonic booms (Mach 1.0 to 1.2 with the wings at 45 degrees) and over-water flights at Mach 1.4 with the wing at 60- to 65-degree angles.[15]

Finally, while the oblique-wing aircraft would take off with a straight wing position, the wing's higher aspect ratio would require less takeoff energy than conventional jets.[16]

Over the next several years, Jones continued to proselytize for the oblique-wing configuration while, back at Ames, Lawrence A. Graham and Frederick W. Boltz tested his ideas in the Center's 11-foot Transonic Wind Tunnel (a variable-density, closed-return, continuous-flow tunnel), from Mach 0.60 to Mach 1.40, to determine the aerodynamic characteristics of a high-aspect-ratio oblique wing in combination with a high-fineness-ratio Sears-Haack body.[17] Longitudinal and lateral-directional stability data were obtained at wing yaw angles from 0 degrees to 60 degrees over a test Mach number range from 0.6

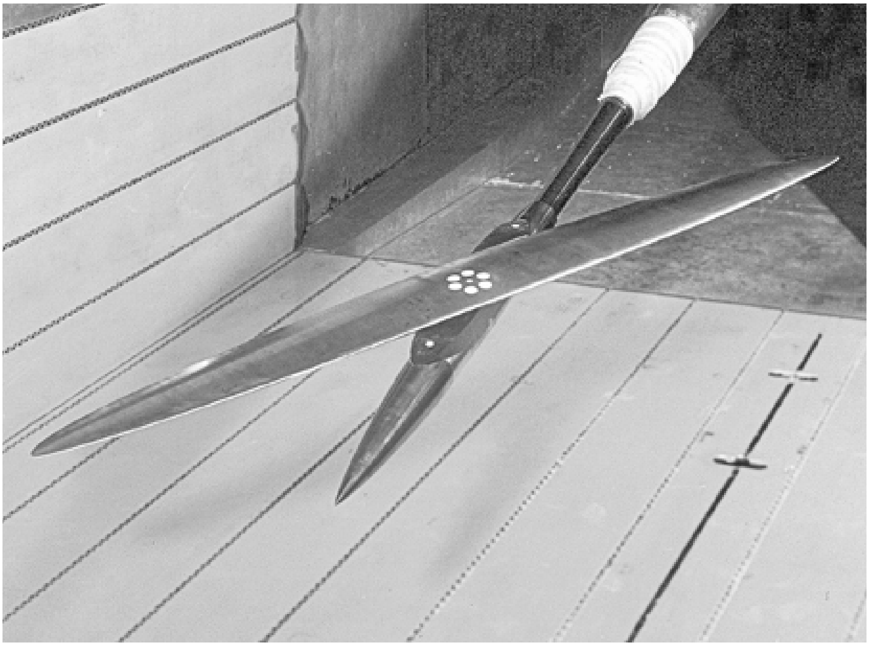
to 1.4 for angles of attack between –6 degrees and +9 degrees. The effects of changes in Reynolds number, dihedral, and trailing-edge angle were studied along with the effects of a roughness strip on the upper and lower surfaces of the wing. In addition, flow-visualization studies were made to determine the nature of the flow on the wing surfaces.

The models consisted of elliptical planform wings mounted on top of a Sears-Haack body. Each wing was pivoted in the horizontal plane about the 0.4 root-chord point in order to obtain oblique angles of 0 degrees, 45 degrees, 50 degrees, 55 degrees, and 60 degrees relative to the body's longitudinal axis. All of the tested wings had elliptical planforms with a straight 25-percent chord line. The basic wing section was an NACA 3610-02,40 perpendicular to the upswept chord line. The experiments indicated that an oblique wing of high aspect ratio can give exceptionally high values of lift-to-drag ratio at all Mach numbers from 0.60 to 1.40 and that these values are significantly higher than those previously obtained with bilaterally symmetric swept or delta wings. Additional findings indicated that the upward curvature of the wing was effective in reducing the changes in trim with changes in yaw angle to very low values within the cruising range and that at higher angles of attack, significant trim changes occur, apparently due to stalling of the downstream tip.[18] The finding relating to upward curvature was very important and was noted in Jones's first patent. Curving the wing upward enabled achieving and maintaining a symmetrical lift distribution even during maneuvering flight. As the load factor (the gravitational, or "g" loading on the aircraft) increased, the upward wing's deflection proportionately increased to furnish the correct effective twist necessary to maintain the symmetrical distribution. It was further elaborated and refined in subsequent wind tunnel testing at Ames and was incorporated on the design of the aeroelastically tailored wing on the AD-1 wind tunnel model at NASA Ames by Ronald C. Smith.

Graham, Jones, and Boltz conducted an additional experimental investigation in the Ames 11-foot Transonic Wind Tunnel in order to determine the aerodynamic characteristics of three different high-aspect-ratio oblique wings in combination with a high-fineness-ratio Sears-Haack body.[19] The shape parameters for the airfoil were selected on the basis of previous wind tunnel tests. All three wings had the same elliptical planform and baseline curvature, but they had different airfoil sections. The first wing had an airfoil section designed to have a lift coefficient of 1.0 at a Mach number of 0.7; the second wing was designed to have a shock-free supersonic flow over the upper surface; and the third wing was designed to have a lift coefficient of 1.3 at a Mach number of 0.6. For the investigation, longitudinal and lateral directional stability data were obtained at wing yaw angles of 0 degrees, 45 degrees, and 60 degrees over a test Mach number range from 0.6 to 1.4 for angles of attack between –7 degrees and +9 degrees. Reynolds numbers for the study were 4 million and 6 million per foot. Flow-visualization studies were made to examine the nature of the flow on the wing surface.

The results of the tests, published in April 1973, found a notable difference in the aerodynamic characteristics of the three wing-body combinations, especially in their lateral directional characteristics. The aerodynamic efficiency of the three wing-body combinations was in most instances approximately the same. Two of the wings generally exhibited slightly higher maximum values. The other wing was slightly more efficient at Mach numbers where supercritical flow existed on the wings. Wing numbers 1 and 3 both had a maximum lift-to-drag ratio of 11 at Mach 1.4 and 60 degrees of sweep. Wing number 2 had a lift-to-drag ratio of 31 at Mach 0.80 and zero wing sweep. Wing number 2, which was designed to operate with shock-free supersonic flow over the upper surface, showed the expected behavior. At a 60-degree sweep, however, the crosswise component of Mach number 1.40 is only 0.70, which is not sufficient to achieve the design condition of the wing. Thus, further refinement of the airfoil selection for oblique wings would depend on the extension of three-dimensional wing theory beyond the linearized formulas now in use and probably also on more detailed wind tunnel studies. The study also identified another noteworthy feature: a remarkably small shift of center of pressure for wing-sweep variations from 0 degrees to 60 degrees. A comparison of the pitching moment of the straight wing at Mach 0.70 with the same wing at a 60-degree angle reflected only moderate changes even though the fore and aft dimension (streamwise chord) of the wing increased nearly tenfold when the wing was swept. Finally, the study noted that with conventional swept-back wings, stalling of tips caused the airplane to pitch up, whereas with an oblique wing, only one tip stalls and thus the airplane may be expected to roll.[20]

NASA Ames conducted several programs involving the analysis, wind tunnel testing, radio-controlled model testing, and, finally, testing of a remotely piloted oblique-wing vehicle. The purpose of these programs was to determine the application potential of the oblique-wing concept for the actual design and fabrication of an oblique-wing airplane. The data obtained during these programs served as the basis for NASA contracts with the Boeing Airplane Company and the Lockheed-Georgia Company for preliminary design studies relating to supersonic transport applications. The contract studies in turn provided practical design data relating to structures, stability and control, and overall performance. The information from these studies was used in the development of a wind tunnel model at NASA Ames and, later, in the actual design and fabrication of a low-speed, low-cost, piloted research airplane—the Ames-Dryden (AD-1) Oblique Wing Research Aircraft. This airplane was to have the general design of one of the configurations developed during the Boeing



Oblique-wing transonic wind tunnel model tested in the 11-foot Ames Research Center Transonic Wind Tunnel at Mach numbers from 0.6 to 1.4 and angles of attack between –7 and +9 degrees at 0-, 45-, and 60-degree sweep angles. (NASA)

studies. After construction of the AD-1, NASA Ames conducted a number of tests, including a wing proof-loads test to compare the static deflection of the wing under a distributed load with design values, a ground vibration test to document the principal structural modes considered necessary for the flutter clearance of the airplane, and a moment-of-inertia test to document the principal moments of inertia and the product inertia about the body axis.[21]

## NASA-Contracted Industry Design and Mission Studies

In addition to the various wind tunnel tests, remotely piloted vehicle flights, and NASA technical reports reviewed above, NASA contracted for a number of industry studies, including four reviewed in this section. The three Boeing studies resulted in conceptual designs for potential development of a transonic oblique-wing transport, and the Lockheed study reviewed the various missions suited for oblique-wing subsonic aircraft.

## Boeing Studies of Transonic Aircraft Design Concepts (1972–1973)

Following Jones's model testing at NASA Ames, the Boeing Commercial Airplane Company was awarded a NASA contract to undertake an initial design study of high-transonic-speed aircraft. This was the first of three contract studies, plus a follow-on report extension, awarded by NASA—two to Boeing, plus one contract extension, and one to Lockheed—for the evaluation of the oblique-wing aircraft concept and for configuration development that led to the recommendation to design and fabricate the AD-1 Oblique Wing Research Airplane. The work on these studies was undertaken between June 1972 and December 1973 for Boeing and from August 1975 until July 31, 1976, for Lockheed. The studies were intended to provide the technical readiness for service introduction in 1985 for an oblique-wing transport airplane.

The objectives of the first Boeing study were to develop five specific configuration types suitable for cruise in the high-transonic regime, make cross-comparisons of each, conduct design tradeoff sensitivity studies, and identify critical research areas pertinent to the development of high-transonic transport aircraft. The Boeing study team selected the following five design concepts for evaluation and comparison: (1) aircraft with a fixed swept wing, (2) aircraft with a variable-sweep wing, (3) aircraft with a delta wing, (4) aircraft with a twin-fuselage oblique wing, and (5) aircraft with a single-fuselage oblique wing.

The study, which was conducted between June 20, 1972, and May 20, 1973, incorporated past programs and earlier studies, including Boeing's work on supersonic transport development and work done under NASA Langley's sponsored contracts for the "Study of the Application of Advance Technologies to Long-Range Transport Aircraft." In addition, the aerodynamic development accomplished by NASA's Ames Research Center on oblique-wing concepts provided essential background data for the Boeing study. The Boeing project study team included Robert M. Kulfan, E.C. Nobel, James L. Stalter, and James K. Murakami (aerodynamics and performance considerations); Mark B. Sussman (propulsion and noise characteristics); John P. McBarron (weight and balance estimates); Alan R. Mulally (flight stability of the unsymmetrical configurations); James W. Nisbet and David W. Gimmestad (structural and aeroelasticity studies); and Frank D. Neumann (general arrangements).

The following design objectives applied to all configurations studied:[22]

Cruise Mach number: Mach 1.2 (to minimize sonic boom)
Range: 3,000 nautical miles (nmi)
Aircraft noise goal: 15 effective perceived noise decibels (EPNdB)

**Below Federal Air Regulation 36**

| | |
|---|---|
| Passenger payload: | 40,000 lbs |
| Cruise altitude: | 39,000 feet |
| Approach speed: | 180 knots (kt) |
| Technology level: | 1985 (subject to pace of technology development) |

The study results indicated that the oblique-wing configuration, due to its superior low-speed aerodynamics, has a big advantage in takeoff and landing performance. Furthermore, the variable-sweep and high-aspect-ratio wing of the oblique-wing configuration provides a 20-percent range improvement for subsonic cruise over its Mach 1.2 design range. The study noted that the stability and control responses of oblique-wing airplanes are unique but that flight control systems could be developed to give swept-wing aircraft handling qualities that are similar to those of more conventional aircraft. All five of the airplane concepts evaluated used a graphite-epoxy honeycomb structure. In this regard, the study noted that the critical structural design conditions for the oblique wings were gust and maneuver loads rather than aeroelastic divergence. Finally, the study noted that the oblique-wing aircraft presented unique design and integration problems and that coordinated theoretical-experimental studies are required to determine whether the predicted performance characteristics are actually achievable.

Due to the promising potential of the single-body oblique-wing concept, the study team recommended that a program be undertaken to verify and further develop the concept's potential. They recommended a three-phase development plan to establish the full potential of the oblique-wing concept.

Phase One called for conducting analytical studies that followed directly from the Boeing study. This phase would include the following tasks:

1. Determine the best structural design speed placard by studying the trade between airframe weight and aerodynamic performance.
2. Develop an alternate configuration that would simplify the engine and landing gear installation while retaining aerodynamic efficiency.
3. Develop a low-transonic-speed yawed-wing configuration to compare directly to the ATT [Advanced Transport Technology] configuration.
4. Match the engine cycle, the amount of noise suppression required, the flap system, and the takeoff and landing procedures to minimize the community noise for the synthesized basic and alternate yawed-wing configurations.
5. Conduct an analysis of the stability and control characteristics of a flexible yawed-wing airplane to identify control system requirements.

6. Conduct a theoretical and experimental wing development study to fully identify the maximum practical wing thickness/chord ratio and the minimum achievable drag due to lift.
7. Analyze operational characteristics of a yawed-wing commercial transport in airline operation and estimate total operating costs. Compare these costs with wide-body and ATT operating costs for similar payload/range categories.[23]

Phase Two called for undertaking the following tasks:

1. Verify the performance of the best Mach 1.2 configuration identified in Phase One through a coordinated theoretical-experimental program covering both the low- and high-speed flight regimes.
2. Conduct a market analysis to determine potential total airline fleet requirements.
3. Based on the results of the Phase One stability and control study and available test data, develop a moving base simulation of the airplane to evaluate flight control systems.
4. Perform an aeroelastic model wind tunnel test to confirm the wing divergence and flutter characteristics.
5. Develop detailed plans, including the design criteria for a yawed-wing flight test vehicle.[24]

For Phase Three of the program, the study team recommended the design, fabrication, and flight testing of an oblique-wing flight-test airplane.

In addition to the work outlined above for the oblique-wing configuration, the study team suggested that the advanced technology programs recommended as part of the Advanced Transport Technology (ATT) Study should be pursued since they apply nearly universally to this concept, especially in regard to structures, flight control, and power systems that require the projected technology advances to achieve the potential identified in the study.

The Boeing study recommendation for further consideration of the single-fuselage oblique-wing concept led to a 5-month contract extension that started on July 1, 1973, and ended on December 1, 1973. This extended contract study had the three following objectives: Task One was to develop an alternate single-fuselage, oblique-wing configuration arrangement with a simplified engine arrangement; Task Two was to determine the structural design speed placard that would allow the engine-airframe match for optimum airplane performance; and Task Three was to conduct an aeroelastic and control analysis of the flexible oblique-wing configuration. The original study evaluated four different engine arrangements—one for four engines, one for three engines, and two configurations involving two engines. The three-engine arrangement of the initial study was used as the design starting point for the extended study. Based on the findings from this followup study, a two-engine arrangement was selected with NASA Ames's concurrence of a more detailed design and evaluation.[25]

These studies all greatly increased confidence in the practicality of the oblique-wing concept and were crucial to its gaining acceptance to the point that the Government and industry were willing to proceed to fabrication and flight testing of a specialized oblique-wing test bed. In 1974, Jones and Boeing's James W. Nisbet noted that while the oblique wing can generate higher lift-to-drag ratios in the transonic range, prior to the above study, it was still not clear that the oblique-wing configuration could be successfully adapted to a real airplane. A question that needed to be answered, for example, was could factors such as increased structural weight and aeroelastic instability nullify a purely aerodynamic advantage? They also noted that the transonic transport study found that the assigned flight mission could be performed by any one of the five concepts evaluated: swept wing (fixed geometry), variable sweep, fixed delta wing, oblique wing with two bodies, and oblique wing with single body. They added, however, that the airplane size and weight for the five different concepts varied widely.[26]

Jones and Nisbet noted the following points regarding the study and earlier test findings:

1. Operation just below sonic ground speed eliminates the sonic boom associated with overland supersonic flight thus enabling flight operations at speeds nearly 50-percent greater than subsonic jets.
2. The oblique-winged aircraft introduced some new problems, and considerable effort was devoted to finding a good general arrangement with major emphasis on the engine and landing gear placement.
3. Structural weight of the oblique wing also received considerable study because of the concern over aeroelastic stability.
4. Reducing the aspect ratio to 10.2 (8:1 ellipse) and increasing the wing-root thickness to 12 percent improved the prior excessive structural weight problem.
5. Selection of the structural materials for all five evaluated wing configurations was based on the Advanced Transport Technology study results. Graphite-epoxy honeycomb was selected for the wing, fuselage, and vertical tail primary structure. Titanium was selected for the wing pivots and pivot-support structure. Using the graphite-epoxy material, as opposed to aluminum, resulted in a weight savings of 35 percent for the oblique wing.
6. The oblique-wing pivot differed significantly from a variable-sweep pivot. A variable-swept-wing pivot transfers wing-bending

> moments through the pivot bearings. This was avoided on the oblique-wing pivot by placing the bearings below the wing and maintaining continuous upper- and lower-wing surfaces to transfer the bending moments. In addition, the pivot diameter was made as large as possible in order to keep the bearing loads low.[27]

Jones and Nisbet concluded their article by noting the following:

> This technically oriented [Boeing] study has yielded, we believe, a realistic performance comparison of the five wing-planform concepts and gives insight into areas unique to the oblique-wing configuration. The oblique-wing offers desirable performance, but further analysis and wind-tunnel work will be needed to develop a rounded picture of its potential. In particular, future work should include an economic evaluation of the consequences of oblique wing's ability to increase today's cruise speeds 50%.[28]

Just months later, in a May 1974 article published in the *Canadian Aeronautics and Space Journal*, Jones made the following additional interesting points regarding transonic transport flight:

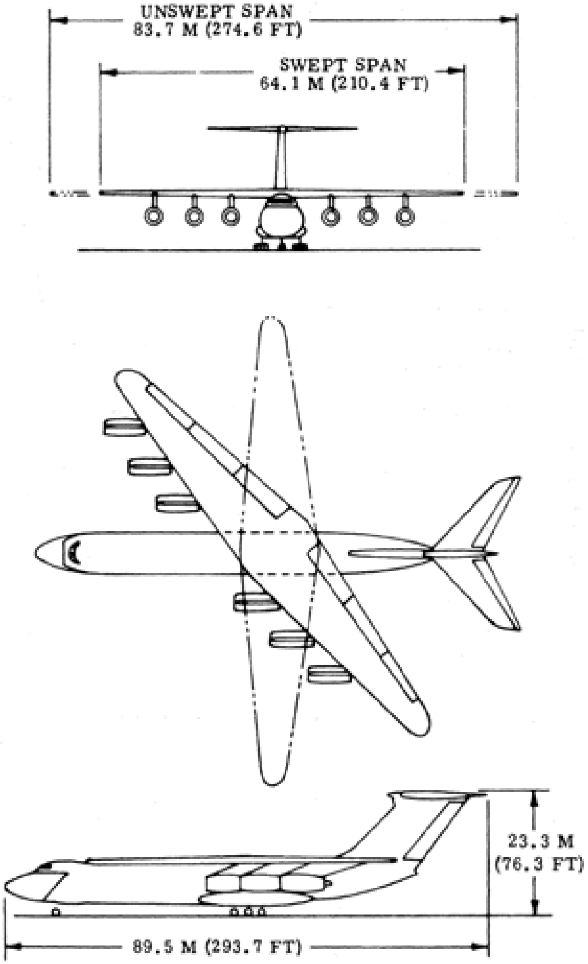
1. An airplane designed for transcontinental flight ideally should be capable of efficient flight at various speeds from subsonic to supersonic, but flight at supersonic speed entails some loss of aerodynamic efficiency. Jones noted, however, that the loss of aerodynamic efficiency at transonic and low supersonic speeds need not be as great as the loss at higher supersonic speeds because it seems possible that the increased utilization of the aircraft and the time saving for the passengers could make up for a moderate increase of energy consumption per mile of flight.[29]
2. Jones added that the loss of lift-to-drag ratio begins at Mach 0.7 or 0.8, and in order to minimize the loss at higher speeds, it is important to consider the shape of the wing. In this regard, Jones noted that "The surprising answer given by aerodynamic theory is that the narrow straight wing of high aspect ratio, ideal for low speed flight, already has the right shape for supersonic speeds provided it can be turned so as to move through the air obliquely."[30]
3. The significant advantage of the oblique wing is the ease that the sweep angle can be varied to suit flight conditions. For example, during takeoff or holding, the wing should be straight and in this configuration the load-to-drag ratio was approximately 30 to 1; that could lead to a very low power requirement and thus minimize power consumption in an airport environment.[31]

## Lockheed Study for a Subsonic Oblique-Wing Transport (1975–1976)

As a followup to the Boeing high-transonic-speed aircraft studies reviewed above, NASA awarded a contract to the Lockheed-Georgia Company for an analytical study involving a subsonic oblique-wing transport concept. Lockheed's approach consisted of a survey of commercial and military missions, the selection of a number of mission possibilities, the application of the oblique-wing concept to these missions, the selection of the best mission-configuration combination, an analysis of the selected configuration, and a technical assessment to define key parameters and technological requirements. The three missions selected by Lockheed were a commercial passenger transport, an executive transport, and a large military cargo transport. The background data used by Lockheed to predict technology availability were obtained from the two Boeing contract studies and from oblique-wing concept development work undertaken by NASA Ames. Lockheed's study started on August 1, 1975, and was completed on July 31, 1976.

The determination of the methodology for assessing aeroelastic effects on wing weight and the selection of the cruise Mach number for all oblique-wing airplane studies were made at an August 1975 conference held at NASA Ames between NASA and Lockheed-Georgia representatives. The methodology for conducting the study consisted of a program plan that divided the study into the following four related elements: mission selection, configuration design and analysis, final analysis, and technical assessment. At a followup December 10, 1975, meeting at NASA Ames, the group conducted a review of the progress and reached an agreement on the selection of the final configuration for the oblique-wing airplane concept. The study was undertaken at the Lockheed-Georgia Company under the direction of Roy H. Lange, Transport Design Department manager. The study manager was Edward S. Bradley, who along with J. Honrath, W.W. Warnock, and P. Shumpert, was assigned responsibility for aerodynamics, structures, propulsion, and design integration. Other contributors were C.M. Jenness (aeroelastic analyses), K. Tomlin (stability and control analyses), and G. Swift (acoustic analyses).

At the beginning of the study, a literature data search was undertaken to identify possible missions applicable to the oblique-wing concept. Approximately 1.7 million Government and private technical abstracts of potential interest to the study team were reviewed using the Lockheed DIALOG computerized data retrieval system. Additional data also was obtained from the Defense Documentation Center, the Advanced Systems Directorate of the National Aeronautics and Space Council (NASC), the Air Force Development Plans and Analysis Group, and the Air Force Systems Command Headquarters Requirements Office. Finally, commercial airplane data were obtained through Lockheed-Georgia Company operations research and commercial



Lockheed-Georgia conceptualization of a six-engine subsonic oblique-wing military airlifter, from CR 137896, 1976. (NASA)

sales organizations and from a Lockheed project titled "Future Wide-Body Dedicated Freighter Aircraft-Payload/Cargo Handling Design Guidelines," or "Project INTACT."

The airplane structural characteristics used by Lockheed relied on the ability to utilize the maximum level of filamentary composite materials primarily consisting of graphite-epoxy and Kevlar 49. Aerodynamic characteristics relied on supercritical airfoil technology, which, due to the oblique-wing concept, depended on a high degree of stability augmentation and a flight control system that would account for cross-coupling effects. Propulsion-system data were based on the Pratt & Whitney STF 433 (bypass ratio 6.5 turbofan), which was the engine design consistent with the airplane technology timeframe for noise and emissions and for thrust-weight and specific fuel consumption improvements. The maximum thrust level achievable for 1985 was estimated to be 65,000 pounds. The wing planform was trapezoidal with a taper ratio of 0.33 and a constant thickness-chord ratio from root to tip. The wing volume between the spars would provide fuel tankage for mission fuel. If necessary, additional fuel volume would be provided in the fuselage. The wing design called for trailing-edge flaps. If necessary, leading-edge devices would be added to augment the maximum lift. The Lockheed report noted, however, that because of the variable geometry feature of the oblique-wing concept, the wing contours must remain unencumbered by any protuberance so that the aerodynamic efficiency of the wing is not impaired. This would require the leading-edge and trailing-edge lift devices to be contained within the wing airfoil contours except at those prescribed conditions of flight requiring deployment of the devices. The empennage configuration was designed to be a tee-tail arrangement with a horizontal stabilizer of conventional configuration articulating in the pitch axis only.

The Lockheed evaluation team concluded that the mission-configuration combination best suited to the oblique-wing concept was the commercial passenger transport due to freedom from design integration problems, freedom from balance and loadability problems, and propulsion systems that were within the technology limitations and close to the base engine characteristics. The passenger-transport mission used for the study involved transporting 200 passengers a distance of 3,000 miles at a Mach 0.95 cruising speed. The team concluded that for this mission, oblique-wing airplanes did not appear to present any insurmountable design integration problems. Lockheed's final configuration called for a "three engine, transcontinental range, high speed, pressured commercial transport with provision for a flight crew of two, pilot and copilot, a cabin crew of 6 attendants and a maximum payload consisting of 200 passengers together with their baggage and 4,536 kg (10,000 lb) of cargo."[32]

The results of the study indicated that the upper-swept aspect-ratio limit was 6.0 in order to ensure divergence-free characteristics for the wing without incurring weight penalties. Additional results indicated that the oblique-wing concept would have 7 percent less takeoff gross weight, 5 percent less direct operating costs, and lower total installed thrust and block fuel, and it would require less takeoff distance than the equivalent conventional configuration. Furthermore, the variable-geometry feature would permit a maximum increase in range at off-design conditions of 10 percent and increased endurance capability up to 44 percent.

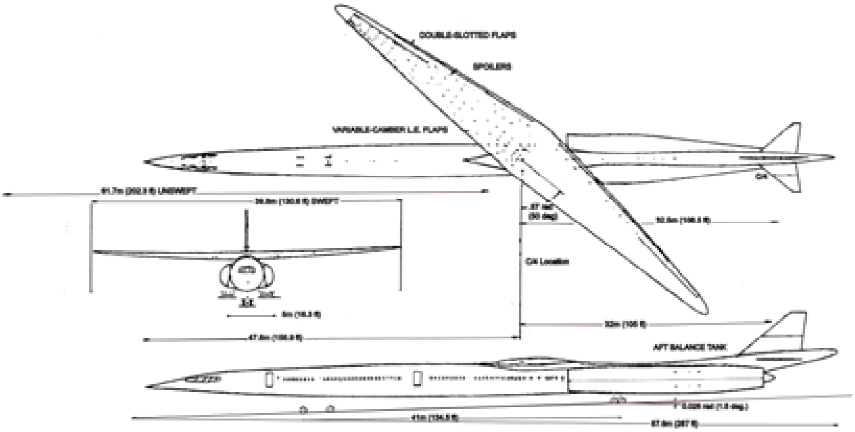
The Lockheed study team noted that the airplane design for commercial passenger transport application is also shown to have military mission capability as either an Air Force tanker or a Navy antisubmarine warfare (ASW) airplane. The Air Force tanker and command post and Navy land-based ASW missions resulted in configurations that were about the same size as the aircraft for the commercial transport mission. The team noted further that the tanker airplane would benefit from the oblique-wing-concept advantages of greater endurance, increased ability to fly mission profiles involving loiter and high-speed segments, and greater capability to match the speed and altitude requirements of receiver aircraft during refueling. The command post application could make use of the higher endurance capability and lower gross weight, while the land-based ASW airplane could benefit from the high-speed cruise and improved on-station loiter capability. The study team, however, concluded that the oblique-wing application was precluded for military cargo transports due to propulsion-system size, wing-flap-system integration problems, center of gravity, and loadability limitations.

The Lockheed team made the following recommendations for followup work on its study: conduct further aeroelastic analyses to determine structural characteristics of wings at aspect ratios greater than 6.0, investigate active flutter suppression systems as a means of achieving higher aspect ratios, continue development of the commercial passenger transport to further improve the design and performance, investigate the short-haul potential of the oblique-wing concept, and further develop the executive transport configuration with emphasis on Navy carrier–borne applications.[33]

## Additional Boeing Oblique-Wing Configuration Development (1976–1977)

The Boeing Commercial Airplane Company was awarded the third study under NASA Ames project-readiness contracts. This study, which involved design and trade studies that were incorporated into the final definition of an oblique-wing transport, investigated wing planform and thickness; pivot design and weight estimation; and climb, descent, and reserve fuel.[34] A tapered, high-aspect-ratio wing planform was selected following aerodynamic, structural, and weight evaluations of several planforms, each of which had a graphite-epoxy primary structure. Ten different pivot-design concepts were evaluated, and a Teflon-coated turntable bearing was selected. Based on the above evaluations and the two previous contract studies, Boeing designers evolved the final Boeing 5-7 configuration.

The Boeing 5-7 design was an elegantly streamlined and extremely large aircraft with an empty weight of 248,070 lb, a payload of 40,000 lb, and a takeoff gross weight of 428,910 lb. It could carry 190 passengers (28 in first class and 162 in tourist class) and had 1,050 cubic feet of cargo space. It cruised at Mach



Boeing 5-7 oblique-wing SST design study, adapted from NASA CR-151928, 1977. (NASA)

1.2 with an approach speed of 140 kt, and it was powered by four afterburning turbofan engines fed by two large inlets, each engine producing a thrust of 35,200 lb. The Boeing 5-7 design had an overall length of 287 feet, and an unswept wingspan of 202.3 feet, which when pivoted to maximum sweep, reduced to 130.6 feet. The wing had an area of 3,040 square feet, double-slotted flaps (a feature of Boeing transport design), spoilers for lateral (roll) control, and variable-camber leading-edge flaps to enhance lift during takeoff and landing. To adjust trim at supersonic speeds, it incorporated an aft fuselage tank to and from which balancing fuel could be transferred. Its supersonic cruise lift-to-drag ratio was 13.4—better than any of the alternative configurations Boeing studied and more than half better than the best traditional tailed bilaterally symmetric delta-wing configuration, the Boeing 3-2a, which had a supersonic cruise L/D of 8.8. It had a wheelbase of 134.5 feet between its forward and main landing gears, could operate from a 7,430-foot runway, and had the best community noise characteristics. Because of all its advantages, the Boeing 5-7 design formed the basis for the aerodynamic configuration of the AD-1 Oblique Wing Research Aircraft.[35]

## Possible Military Applications of the Oblique-Wing Planform

In addition to the civil aviation advantages and missions applications noted in the above industry studies, a number of potential military mission applications were identified in studies conducted by the Advanced Vehicle Concepts Branch at NASA Ames. To assist in identifying these mission applications, NASA Ames engineers used a modularized computerized synthesis program (ACSYNT) that was developed by the Ames Research Center in order to provide rapid conceptual design information at the early stages of vehicle definition. The synthesis program consisted of a control module and technology modules for geometric, aerodynamic, propulsive, mass, and economic information. Additional modules provided automatic design convergence, sensitivity, and optimization calculations in addition to graphical input. As of September 1976, NASA Ames identified the following potential military mission applications of the oblique wing:

1. Land based antisubmarine warfare (ASW) aircraft, which could increase time-on-station (loiter time) for the same total crew time and provide longer ranges for the same crew time;
2. Air-mobile missile launch concept;
3. Carrier-based aircraft, which would provide improved loitering performance and require less storage space (the wing can be aligned with the fuselage while on deck);
4. Remotely piloted vehicles ranging from very small surveillance systems to large military combat vehicles, including an oblique all-wing configuration; and
5. A number of other military concepts, including advanced tactical fighters, cruise missiles, and an airborne battle platform consisting of a very large cargo-type aircraft that carries, launches, and recovers a large number of oblique-wing microfighters.[36]

## Glimmerings of Something Greater: Planning for an Oblique-Wing Test Bed

Even before construction of the AD-1 Oblique Wing Aircraft, Jones was already looking beyond to a genuine transonic and supersonic demonstrator. Several possibilities presented themselves, one being a conversion of an expendable target drone, the Teledyne-Ryan BQM-34F Firebee. The Firebee was a small swept-wing jet-powered target drone that, during the Vietnam War, had been modified to fulfill a variety of intelligence-collection functions.[37] Afterward, Firebees were employed for a variety of experimental purposes, including dropping bombs and firing air-to-surface missiles. NASA looked at the Firebee as the basis for several small, low-cost unpiloted test projects, one of which was a test bed for Jones's oblique wing.

In November 1974, Teledyne-Ryan submitted a proposal to NASA to undertake an 8-week engineering and design study on modifying a BQM-34F for NASA's oblique-wing aircraft technology programs. The proposal noted that "Teledyne Ryan fully supports NASA's long-range goal of using sub-cost, remotely piloted vehicles to minimize the time span for obtaining flight-proved, low-risk, technology test data applicable to various types of aircraft programs."[38] The proposal outlined four tasks:

- *Task I*—NASA would provide an initial basis for defining a wing size that can be matched to the BQM-34F system;
- *Tasks II and III*—design tasks with support from the technical analyses specialty areas such as stress, loads, aerodynamics stability/control systems; and
- *Task IV*—utilize tasks I, II, and III to ascertain schedules and ROM costs in support of NASA's planning on the oblique wing program.[39]

Teledyne-Ryan would modify the Firebee to have an oblique wing mounted on the top of the fuselage that was capable of being rotated from an unswept position to a sweep angle of 60 degrees. Like the company's other Firebees, it would be air launched from either a Lockheed DC-130 Hercules (the same kind of launch system used in Vietnam with the Firebee reconnaissance drones) or from one of two prototype Northrop YA-9A aircraft that NASA had acquired after it lost out to the rival Fairchild-Republic A-10A for an Air Force attack aircraft contract. Like other Firebees, the oblique-wing test bed would be parachute recovered, snatched in midair by a helicopter, and returned to the ground.[40] After reflection, however, NASA chose not to proceed with the Firebee oblique-wing demonstrator, though it did use Firebees for aeroelastic and flutter control research.

Though the Firebee proposal went nowhere, another attracted far more attention, lasting well over a decade. NASA was fortunate that the 1970s coincided with the U.S. Navy's gradual retirement of the Vought F-8 Crusader fighter from fleet service. The F-8, a highly successful fighter, had a unique high-wing configuration that enabled it to be easily removed and replaced. Already, NASA had modified one F-8 to test Richard Whitcomb's supercritical wing (SCW), a complex airfoil section and wing planform that enabled a dramatic increase in transonic cruising speeds by raising the so-called critical Mach number and, hence, delaying the onset of high drag rise. Another F-8 was being flown as a test bed for electronic flight controls. Jones thought that the F-8 would be an ideal test bed for his oblique wing.

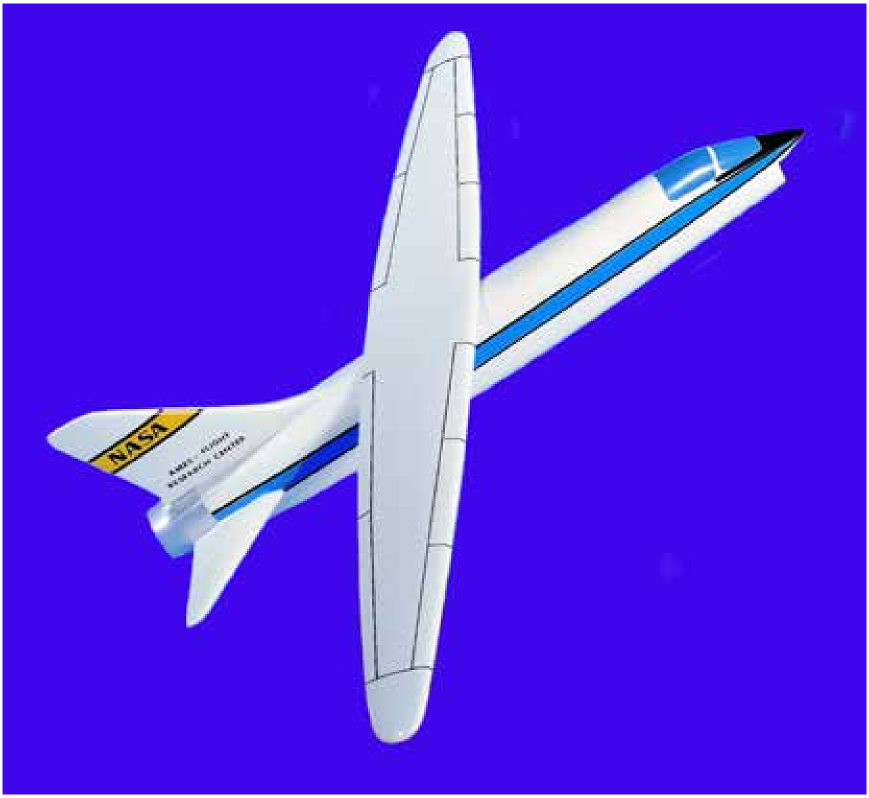
Jones arranged for construction of a 0.087-scale model of an actual F-8 airplane fitted with an oblique wing, and he then tested it in the Ames 11-foot Transonic Wind Tunnel. These tests, which predated the beginnings of a planned AD-1 followup F-8 oblique-wing program (see chapter 5), were conducted because earlier free-flight handling tests on oblique-wing models had indicated a considerable reduction in roll control for wing yaw angles greater than 45 degrees. Also, prior tests were conducted at low speed and low Reynolds numbers that were not necessarily representative of actual flight characteristics. This new series of tests was designed to answer questions regarding the available aileron-control power of oblique-wing aircraft with the wing yawed at angles of 50 degrees to 60 degrees in the Mach number range of 0.6 to 1.4 and at a Reynolds number range from 14.8 to 19.7 x $10^{6/m}$.

Proposed oblique-wing modification to a Teledyne-Ryan BQM-34F Firebee Drone, 1974. (NASA)

The model consisted of an elliptical planform wing mounted on top of the fuselage of a 0.087-scale model of an operational Navy F-8 fighter. The wing was pivoted in the horizontal plane about the 0.4 root-chord point in order to obtain sweep angles of 0 degrees, 45 degrees, and 60 degrees. The wing had a maximum thickness-chord ratio of 12 percent and consisted of an elliptical planform having an elliptic axis ratio of 8:1. It had an unswept aspect ratio of 10.2 and a straight 25-percent chord line. It employed a NACA 3612-02,40 airfoil section at the center, perpendicular to the 25-percent chord line. The wing trailing-edge region was cut out for ailerons that extended from 52 percent to 89 percent of the wing semispan. The ailerons were sealed-gap plain flaps hinged at approximately the 75-percent chord line. The horizontal and vertical tail surfaces retained their original NACA 65A006 airfoil sections. The horizontal tail was all-movable and thus could be set at various angles relative to the body centerline.

As researchers Ronald C. Smith, R.T. Jones, and James L. Summers reported:

> Results of aileron and horizontal tail control power tests of an F-8 model equipped with an 8:1 elliptical-wing indicate no apparent or unpredictable control power deficiencies. Deflection of the ailerons induced significant pitching moments with the wing swept. Because this pitching moment arises from the unbalanced

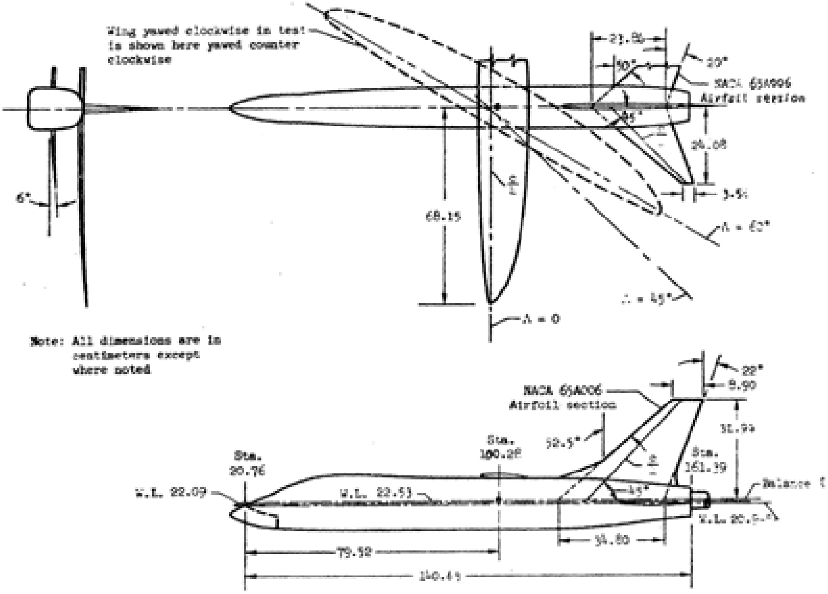


Proposed oblique-wing modification to a Vought F-8 Crusader naval fighter, 1974. (NASA)

> loading about the x axis, it is expected to disappear whenever the spanloading is once again balanced in steady roll motion. Large deflections of the horizontal tail induced some side force and yawing moment, the origin of which is not known.[41]

## Toward the AD-1

Over the mid-1970s, NASA Ames moved steadily toward defining and refining its concept for a small demonstrator oblique-wing test aircraft. In preparation for flights of the demonstrator, which by 1977 had been designated the AD-1, reflecting the shared partnership of the Ames and Dryden



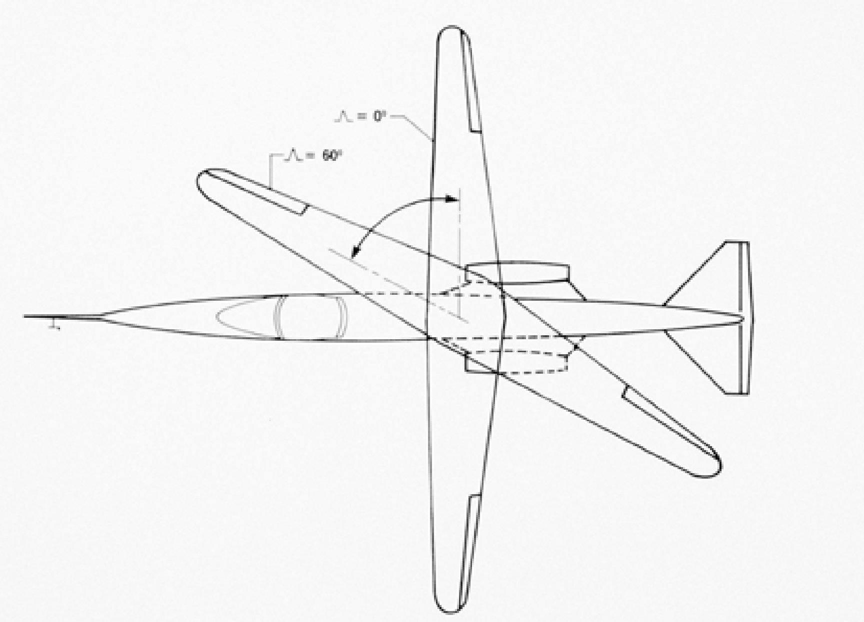
(a) Three-view

Figure 2. - Oblique-wing F-8 model details and photograph.

Configuration of a 0.087-scale model of an F-8 oblique-wing aircraft tested in the 11-foot Ames Transonic Wind Tunnel. (NASA)

research Centers, engineers began a detailed assessment of its anticipated handling qualities and, particularly, its aeroelastic stability, a central concern when considering the flying qualities and behavior of oblique-wing vehicles. The AD-1's development occurred at a time when the growing power of the computer revolution was first being applied to detailed analysis of aircraft behavior and motions. While some early work in this area had been accomplished by the NACA, the Air Force, and industry analysts as early as the mid-1950s (particularly in support of the early X-series research aircraft), the 1970s constituted a period in which computational analysis of structures and aeroelastic response received great attention.

From 1976 to 1977, Ames researchers undertook a pioneering aeroelastic-stability analysis of the AD-1, covering the behavior of the oblique wing alone and the oblique wing with ailerons. The wing with ailerons was included in the tests in order to study their effects on the aeroelastic stability of the AD-1. The tests were performed using the latest version of the MacNeal-Schwendler Corporation's NASTRAN computer code



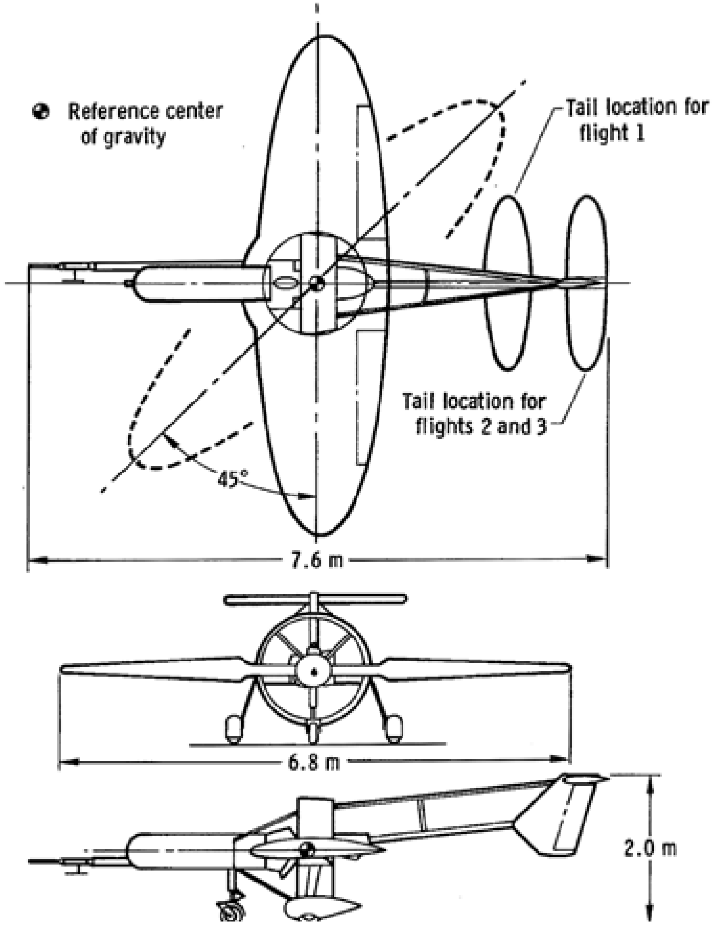
AD-1 configuration showing range of oblique-wing sweep. (NASA)

(MSC-V43) and the Ames programs for PASS and FLUT. The application of the NASTRAN capability to the oblique-wing configuration served to substantiate the results obtained from PASS/FLUT and to evaluate two different flutter analysis methods available in the NASTRAN aeroelastic package (KE-method and PK-method). NASTRAN is a large, general purpose, finite-element computer program for structural analysis. PASS is a structural analysis program and FLUT is a flutter analysis program.[42] The tests run on these computer codes helped to validate the oblique wing's potential for increased aerodynamic efficiency over conventional swept-wing aircraft due to reduced wave drag at transonic and low supersonic speeds. In addition, the tests conducted at NASA Ames, which were also supported by NASA contract studies, demonstrated the mission flexibility of the oblique wing for both civilian and military applications. Finally, the report noted that, if funding became available, a Lockheed F-104 Starfighter aircraft might be fitted with an oblique wing to validate the concept at transonic speeds, though, in fact, researchers were far more interested in using the more easily converted Vought F-8 Crusader than the more challenging (if potentially higher performance) Lockheed design.[43]

## The OWRPRA Flight-Test Program (1976)

Robert Jones had built a small 5½-foot-span radio-controlled oblique-wing model to assess the oblique wing's basic flying qualities, but this small model did not, on its own, suffice to give confidence for progressing with a much larger and more complex vehicle. Instead, what was needed was a larger and much more comprehensively instrumented test bed, and thus, in order to investigate the feasibility of flying an oblique-wing aircraft, NASA Ames and NASA Dryden sponsored construction and flight testing of a small variable-sweep propeller-driven Oblique Wing Remotely Piloted Research Aircraft (OWRPRA). NASA issued a $200,000 development contract to Developmental Sciences, Inc., of City of Industry, CA, and its development took 3 years, from 1972 to the end of 1975. Constructed primarily by hand-laid-up fiberglass and epoxy resin (furnished by the Fiber Resin Corporation of Los Angeles) with steel, aluminum, and magnesium structural components, the resulting vehicle had a 22-foot, 4-inch wing capable of being skewed up to 45 degrees with the left wing foremost, and it was flown in both a short-tail and long-tail configuration. The aircraft was powered by a 90-horsepower four-cylinder air-cooled two-stroke McCullough 4318B reciprocating engine driving a ducted midfuselage three-bladed, 4-foot-diameter propeller with a cruise speed of approximately 3,600 revolutions per minute (rpm). A fixed tricycle landing gear enabled horizontal takeoffs and landings on a dry lakebed.[44]

The remotely piloted model was equipped with an all-movable tail and conventional rudder and aileron surfaces. Artificial stability was furnished via a two-axis, gyro-stabilized autopilot. Telemetry links were used to send pilot control inputs to the vehicle and to return aircraft response data to the ground. Additionally, a television camera was mounted in the vehicle's nose. The augmentation system consisted of pitch-and-roll attitude feedback. All of the standard stability and control variables were instrumented, including static and total pressures, control-surface positions, vehicle attitudes, angular rates, linear accelerations, and angles of attack and sideslip. The moments of inertia for the long-tail configuration were estimated from swing tests of the assembled vehicle after the last flight. Those for the short-tail configuration were estimated by subtracting the predicted differences from the long-tail values. The angle-of-attack and sideslip measurements were taken from standard boom-mounted metal pitch and yaw vanes. The control surface positions were measured by control position transducers on the control surface. The data was acquired at 200 samples per second using an 8-bit pulse-code modulator system and telemetered to the ground for recording.



Basic configuration of the NASA FRC Developmental Sciences Oblique Wing Remotely Piloted Research Aircraft (OWRPRA) test bed, from NASA TP 1336, 1978. (NASA)

Early testing at Bicycle Lake, in the Mohave Desert, CA, was not without problems; a loss of signal during a high-speed taxi run resulted in the craft flipping over, and it was so badly damaged that it required significant rebuilding. Flight testing commenced on August 6, 1976, with an 0615 takeoff from Dryden. The flight constituted the first time that Dryden had flown a remotely piloted vehicle using a pilot located in a remote van. The project manager was Rodney O. Bailey and the Ames test pilot was James "Jim" Martin, who was controlling the OWRPRA. Martin had earlier completed over 30 remote takeoffs and landings with a NASA Piper Twin Comanche (with safety pilot Einar Enevoldson on board) to get a feel for remote vehicle operation. The

The OWRPRA test bed in its original short-tail configuration, on the ramp at NASA DFRF, August 2, 1976. (NASA)

practice proved most fortunate as Martin literally had his hands full with the little OWRPRA once it became airborne. It was so unstable that the horizon continuously oscillated up and down in the television monitors, and afterward, Martin described his piloting experience as "intense;"[45] accordingly, he prudently limited the wing sweep to just 15 degrees, returning the little research vehicle safety to the ground after 24 minutes. Before the vehicle's next flight, technicians increased the size of its tail surfaces and moved them aft, thus creating both a short-tail and long-tail variant. The OWRPRA flew only two more times, on September 16 and October 20, thus limiting its total flight program to three flights of approximately 1 hour each. The remote pilot controller performed 87 maneuvers for stability and control data acquisition during the three flights. Elevator doublets were used for longitudinal maneuvers. Each lateral directional maneuver included a rudder doublet and an aileron doublet. Fortunately, following its early flight-test difficulties, the OWRPRA's last two flights permitted the acquisition of data validating the performance of the oblique wing at 30-degree and 45-degree sweep angles, greatly encouraging developers as they moved toward the larger, faster AD-1.[46]

Predictions of the static derivatives were based on data obtained from full-scale tests conducted in the Ames 40-by-80-foot wind tunnel. The actual

The OWRPRA (in long-tail configuration) in flight with its oblique wing in skewed position, 1976. Note its special bicentennial commemorative markings scheme. (NASA)

flight vehicle in both the short-tail and long-tail configurations was tunnel tested, permitting subsequent comparison of tunnel-test results with flight-test results. However, postflight analysis indicated a large scattering of the data, reflecting limitations in the Ames tunnel's data acquisition system, with predictions in some cases varying "by a factor of 2 or 3 for the same flight condition."[47] Additionally, design of the tail boom to ease tunnel testing of the long-tail variant made it so flexible that "long[-]tail [tunnel] data were judged unusable."[48] (By contrast, the actual flight vehicle had a much more rigid boom). The short-tail variant had less flexibility, but analysts conceded "it still opens the validity of the predictions to question."[49]

Fortunately, testers acquired reliable data during the actual flight-test program. The flight tests and resulting data analysis incorporated an imaginative technique that estimated aircraft aerodynamic derivatives by separating the analysis of longitudinal and lateral directional motion even in the presence of the moderate cross-coupling characteristics of oblique-wing aircraft. Engineers digitally filtered the data acquired during the tests and then used it to estimate the aircraft's stability and control derivatives. This technique was determined to have several advantages over the usual five-degrees-of-freedom approach for some situations. The separation technique was applied to obtain a complete set of stability and control derivative estimates from flight data for a small remotely piloted oblique-wing aircraft. This complete set of flight-determined estimates was presented and compared to predictions. The maximum likelihood estimation method was used to analyze the oblique-wing data. The results of the above analysis demonstrated that this relatively simple approach was adequate for obtaining usable estimates of the aerodynamic derivatives of oblique-wing aircraft. This application represented the first time that aerodynamic derivatives had been estimated from flight data for an oblique-wing aircraft.[50]

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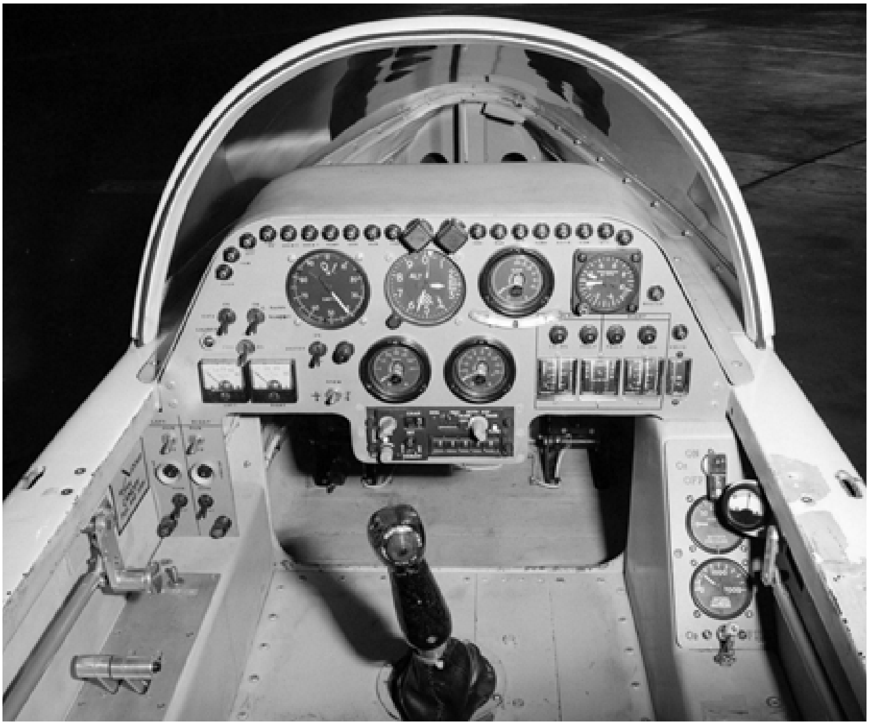

Cockpit and instrument panel of the AD-1 Oblique Wing Research Aircraft. The wing sweep "skew" gauge is center-left on the lower row of panel instruments; the sideslip gauge is center-right on the lower row; the angle-of-attack gauge is center-right on the top row. The dual-engine throttles are on the left side, and the dual-engine instruments are on the lower right side. Note as well the centerline control stick capped by a stabilizer-trim switch. (NASA)

## CHAPTER 3

# Design and Fabrication of the AD-1 Research Aircraft

In his NASA Technical Memorandum titled "Role of Research Aircraft in Technology Development," Kenneth J. Szalai, who was chief of the Dryden Research Engineering Division and later became the director of NASA Dryden, noted the importance of research aircraft to advances in aviation and the resulting technology spinoff into other fields of scientific development. He pointed out that

> [t]he history of research and experimental aircraft in the United States is a rich one.... These aircraft have ranged from exotic forms designed to expand the overall knowledge of aerodynamic configurations, to complex systems aircraft designed to explore improved efficiency or improved mission effectiveness. Some of these aircraft were forerunners of military aircraft; others, such as the Lunar Landing Research vehicle which prepared astronauts for lunar landings, were important trainers.... Flight research has been a vital and continuous part of this nation's aeronautical research program since the inception of the National Advisory Committee on Aeronautics (NACA) in 1915. Flight research with both highly modified service aircraft and new experimental aircraft has contributed to many of the aeronautical advances over the past several decades, drawing on a strong partnership between NACA/NASA, the Department of Defense (DOD), and industry.[1]

## Small Is Beautiful: Undertaking the AD-1's Development

In the early 1970s, the British economist E.F. Schumacher (drawing upon the thinking of his mentor, the Austrian Leopold Kohr) popularized the notion that small is beautiful in a book of essays of the same name. Schumacher's emphasis upon appropriate technology and simplicity as opposed to complexity in approach could have served as a pattern for the development of the AD-1

Oblique Wing Research Aircraft, which stood in marked contrast to the large and complex underpinnings of most experimental aircraft programs. In fact, the AD-1's development fit very well into the traditional model of flight research as practiced by Walter Williams, Paul Bikle, and their successors at the Dryden Flight Research Center, previously known as the NASA Flight Research Center and the NACA High-Speed Flight Station before that. For over three decades, the Center and its personnel, led by Walter Williams, Paul Bikle, Lee Scherer, Dave Scott, and Isaac T. "Ike" Gillam IV, had mastered the art of using models, small specialized test rigs, and aircraft to evaluate larger and, in some cases, highly significant concepts. This included testing reaction controls, developing experimental lifting bodies, and fabricating a jet-and-rocket-powered lunar landing trainer that gave astronauts the requisite skills to land on the Moon. The AD-1 development effort thus constituted a natural extension of the Center's organizational culture and operational philosophy.[2]

Referring to the Ames-Dryden AD-1 Oblique Wing Research Aircraft, Szalai noted: "In the case of oblique-wing technology, wind tunnel tests had shown potential performance benefits transonically and supersonically when an oblique-wing aircraft was compared with an equivalent variable-sweep aircraft."[3] Regarding issues that needed to be resolved by flight testing, Szalai added,

> [a]side from uncertainties regarding the aerodynamic performance, there were those related to the low-speed handing qualities of an oblique-wing aircraft, including the ability of a pilot to land an aircraft with a large wing-skew angle; the stability and control of an oblique-wing aircraft, especially with cross coupling; and finally, dynamics and trim characteristic effects on overall flying qualities.[4]

Szalai noted that NASA's approach to investigating these issues was to build a small, low-cost manned research vehicle that demonstrated that the return on investment could be very high for small and inexpensive flight research vehicles. To accomplish this, NASA contracted with leading designers and builders of small aircraft to build a foam-and-fiberglass piloted aircraft powered by two fan turbine engines. To hold down costs, light airplane avionics and simple mechanical controls were used; instrumentation consisted of a multichannel pulse-code modulator system with structural and dynamic sensor data sent to the NASA ground station. Szalai reviewed the flight research accomplishments, which included obtaining significant high-quality stability, control, and flying-qualities data that helped validate predictions of the characteristics of oblique-wing aircraft; estimating the unique cross-coupling terms of this type of vehicle from flight data; establishing side force and trim requirements; obtaining handling-quality data; and developing pilot techniques and trim sequences for various wing-skew angles. In regard to technology spinoff, Szalai emphasized the refinement of parameter identification techniques for asymmetrical vehicles that would be mandatory for any future asymmetrical vehicle.[5]

While NASA engineers realized that the aerodynamics performance benefits of an oblique-wing configuration occur at transonic speeds, they determined that many of the characteristics associated with asymmetry are not strongly related to compressibility and, therefore, to a limited extent, could be evaluated at low speeds. Accordingly, the purpose of the AD-1 program was to investigate the low-speed characteristics of an oblique-wing configuration. This enabled the AD-1 to be designed and fabricated as a low-speed, low-cost airplane. Low speed allowed the use of a low-technology structure, fixed landing gear, and a mechanical control system that in turn permitted the fabrication of a low-cost aircraft.

The specific technical objectives of the AD-1 program were the assessment of the unique handling and flying qualities of an unaugmented, low-speed, oblique-wing vehicle; general appraisal of the nature and complexity of a flight control system on an oblique-wing configuration; verification of the static aeroelastic design criteria for the wing; and comparison of the flight-determined aerodynamic data with predicted values.[6] But who could build such a craft, and do so quickly, cheaply, and to the highest standards of creativity and technical acumen?

## Enter Burt Rutan and the Rutan Aircraft Factory

The answer was Elbert Leander "Burt" Rutan, a remarkably gifted aerospace engineer who was born in Oregon, raised in California, and educated at California Polytechnic State University at San Luis Obispo. Burt Rutan had served as a flight-test engineer at the Air Force Flight Test Center, had been director of development for Jim Bede's aircraft company (maker of the BD-5, a tiny speedster that attracted a great deal of attention in the early 1970s), and then established his own aircraft company in Mojave, CA, where he produced a string of imaginative aircraft, most having a canard (tail first) configuration. He was unconventional, innovative, open to new ideas, and unbureaucratic—and thus perfect for the job.

Rutan biographer Vera Foster Rollo noted the following:

> One of Burt's important strengths is his "can do" attitude. It didn't matter to him, out there in the Mojave Desert, with no money to speak of, a relatively unknown designer at the time, that he planned to do what aircraft manufacturers spend millions of dollars, with hundreds of engineers and craftsmen, do—design, build

> and land test a new aircraft design with materials not widely used at all in aviation.[7]

While NASA was looking to build an inexpensive basic airplane to test Robert Jones's oblique-wing theory, there apparently was no official contract with Rutan that could be considered a response to a formal Request for Proposals (RFP) to undertake a feasibility study for the preliminary design of the AD-1. Instead, in 1975, with the AD-1 program gestating at both Ames and Dryden (then called the Flight Research Center), two college friends, Charles Van Norman and Richard Fisher, who both had graduated from California Polytechnic State University 1 year ahead of Rutan, approached Rutan with the feasibility study and design idea. According to Rutan, Van Norman, who worked for the Air Force, and Fisher, who worked at NASA Dryden, informed him that NASA was not in a position to put out a formal proposal, but asked him to submit an unsolicited proposal to undertake a feasibility study. They thought Rutan would be the ideal choice due to his having designed and built the VariEze airplane, which used composite materials and was built in 3 months. As a result of this informal process, NASA selected Burt Rutan and his Rutan Aircraft Factory to conduct a feasibility study for the fabrication of a small, low-cost, subsonic, yawed-wing experimental aircraft.[8]

The results of the feasibility study were presented in a December 1975 report by Burt Rutan and George Mead. The study, which Rutan completed in the remarkable time of just 40 work hours, examined the following concepts:

1. Evaluation of the feasibility of building a small piloted research aircraft using the transonic airliner [Boeing design] geometric envelope;
2. Preliminary design of the general structural arrangement and general air-load estimation;
3. Preliminary weight and balance summary;
4. Formulation of the general arrangement of the flight control, landing gear, propulsion, wing yaw, and egress systems;
5. Preliminary estimation of flight performance; and
6. Preliminary estimation of the schedule and cost for detail design and construction of the prototype research aircraft.[9]

The study proposed that the basic configuration should be that of a transonic, single-body, yawed-wing transport of an already defined configuration (this was, of course, the Boeing 5-7 configuration discussed in chapter 2). The aircraft would be a 14-percent-scale size of the above configuration with the forward fuselage upper mold line raised to provide adequate forward visibility and adequate room for the pilot. Also, changes in the geometric shape would be required in order to provide adequate static and dynamic stability since the proposed full-size airliner design used a fly-by-wire control system that could compensate for an otherwise unstable configuration. In the case of the proposed AD-1, sufficient static and dynamic stability would be provided by an increase in tail volume and a forward shift of the wing, achieved by moving the wing yaw pivot forward from its 50-percent chord location.

The oblique-wing configuration would be a composite sandwich glass-on-foam-on-glass semi-elliptical wing with the following dimensions: a mean chord of 34 inches, a span of 35.3 feet, an area of 98.9 square feet, and an aspect ratio of 12.6 (in straight, not oblique, configuration). The control configuration would consist of mechanical ailerons with no high-lift devices. The wing-pivot mechanism would be an electric screw-jack with manual backup permitting a 0-degree (wing straight) to 60-degree (oblique swept) capability. The horizontal stabilizer would have a mean chord of 41 inches, a span of 7.7 feet, and an area of 26.2 square feet. The control mechanism would consist of a mechanical elevator and electric screw-jack stabilizer trim. The vertical stabilizer would have a mean chord of 45 inches, a span of 45 inches, and an area of 14.1 square feet. The control mechanism would be a mechanical bungee-rudder trim. The fuselage would have a length of 426 inches and a maximum diameter of 31 inches. The landing gear would have retraction by electric actuators, differential brake steering, and composite spring energy absorbers. Propulsion would consist of two Microturbo TRS-18 turbojet engines, each producing 220 lbs of thrust. The AD-1 would have an empty weight (including data systems) of 1,015 pounds and an engine-start weight (pilot and 1½ hours of fuel) of 1,565 pounds.

Overall performance was estimated as:

| | |
|---|---|
| Stall speed at take off: | 60 knots |
| Stall speed at landing: | 54 knots |
| Takeoff distance: | 1,400 feet (at 3,000 feet altitude) |
| Rate of climb S/L [sea level]: | 1,400 feet per minute |
| Single engine rate of climb: | 400 feet per minute (at 5,000 feet altitude) |
| Maximum level flight speed: | 260 knots (at 15,000 feet altitude)[10] |

The basic structure would be a composite sandwich airframe utilizing the highly contour-adaptable fiberglass-on-foam-on-fiberglass techniques developed by the Rutan Aircraft Factory. The basic aircraft structure consists of two skins of unidirectional fiberglass separated by a rigid foam core. Rutan noted that the "structural viability of this technique has been proven over a series of three general aviation aircraft designed and fabricated by RAF [Rutan Aircraft Factory]." He added that "the workability of the basic structural materials enables the fabrication of a one-off prototype employing extensive compound curvatures without the expensive molds and form tooling required for other structures."[11]

This technique enabled Rutan to develop the prototype aircraft with an oblique wing and an area-ruled (i.e., complex curve) fuselage at a low cost. He described the process as follows:

> The wing, horizontal, and vertical tail are formed from several straight tapered foam cores, jig assembled, and locally contoured to shape using templates. A tapered glass/graphite box spar is then layered up into the inboard 2/3 of the span (the outer 1/3 being full monocoque) followed by a skin which consists of two spanwise unidirectional glass layers and two layers of bidirectional glass oriented at 45 degrees to provide torsional stiffness.... Structural efficiency is excellent since the tapered spar caps are optimally separated at the contoured wing skin surface and are supported by foam against local buckling. The shear web fibers are oriented at 45 degrees for primary shear and the shear panel is foam supported on both sides. A very conservative design approach is used: instead of reaping the benefits of the improved structural efficiency as a weight savings, the wing is built at about the same weight as an all-aluminum wing, but with extremely large structural safety margins. Surface durability, stiffness and fatigue life are thus greatly increased. Development costs can be greatly reduced since with a design safety factor of three, and a conservative design load (6-g limit)[,] the requirement for proof load testing is obviated.[12]

As for the rest of the aircraft, Rutan noted that the fuselage would be built as a square box of rigid foam slabs, contoured as required inside to clear equipment. The inside of the box would be glassed before assembly. The outside would then be carved to the required contour using templates. The outside skin would be layered up using fiber orientation to provide the desired stiffness and strength. Local stiffness and strength for attachments would be provided by high-density foam and multiple-layer glass layups. Rutan noted further that the resultant structure would be safer than an all-metal structure since multiple redundancy would be provided and cracks could not propagate across layers within the composite. Fuel tanks built into the structure using the glass-on-foam-on-glass sandwich would not flex and fatigue, and thus fuel-tank-leakage problems would be eliminated. The wing would be mounted by attaching the main spar box, which would be stiffened locally by aluminum extrusions in the lower corners, to a flange on an 8-inch length of 7-inch-diameter aluminum tube. The bearing surface would take all asymmetrical bending, torsion, and lift loads from the wing. Wing rotation about the pivot point would be controlled by an electrical screw-jack at the bottom of the large tube. The screw-jack could also be operated manually by the pilot.

In regard to pilot safety, Rutan noted that the design criteria would result in a docile flying aircraft at zero wing-angle of incidence and that the low wing loading and relatively low indicated cruise speed would place the aircraft more in the category of a medium-performance general aviation aircraft than that of a contemporary jet. With the engines out, the rate of sink would be approximately 500 feet per minute at 75 knots, allowing a near sailplane-like lift-to-drag sink-rate condition for glide and landing without power.[13]

The table on the following page shows the preliminary time and charges estimate for development of the AD-1 (RAF 35) aircraft. The feasibility study noted that a more refined cost estimate should be made during the detail-design phase. The final contract cost totaled $261,350 and consisted of a preliminary design study ($560); an initial airplane design ($9,970); a design modification ($4,590); an aircraft fabrication contract ($218,000); a fabrication contract modification ($21,930); and the delivery ($6,300). Although higher than the initial feasibility study estimate, the final total was still remarkably low for a jet research airplane and fulfilled the NASA program objective for a low-cost, low-speed, oblique-wing flight demonstrator.

The final cost of the actual design and fabrication, Rutan recalls, was considered so low that when final approval was given, a number of NASA personnel thought they were approving the construction of a remotely piloted vehicle, not a piloted aircraft.[14]

The estimated time to develop the prototype aircraft was 9 months based on the following schedule:

7. Verification of adequacy of flying qualities of the selected configuration, including NASA-conducted wind tunnel model test program to verify adequate static margins, controllability, and predicted dynamic stability of the modified Boeing 5-2-4 configuration at the Mach and Reynolds numbers expected. Time Duration: Unknown at time of estimate.
8. Detail loads prediction, structural design, and system design. Time Duration: 850 engineering hours over an 11-week period.
9. Prototype construction. Time Duration: 1,800 work hours over a time period of 24 weeks.
10. Final surface contouring and finishing. Time Duration: 90 work hours over a 2-week period.
11. Engine installation, wiring and checkout. Time Duration: 160 work hours over a 2-week period.[15]

Burt Rutan followed up his first phase feasibility study with a second phase consisting of more detailed design plans and drawings that resulted in NASA issuing a formal Request for Proposals to fabricate the AD-1. NASA had expected the Rutan Aircraft Factory to bid on the project, but according to Rutan, his

| **Estimated Cost and Work Hours for AD-1 Fabrication by Task** | | | |
|---|---|---|---|
| **Task** | | **Cost** | **Hours** |
| **Loads Prediction, Structural Design, and System Design** | | **$11,900** | **850** |
| **Components[1]** | | **$42,480** | **--** |
| Two TRS 18 engines: | $38,000 | -- | -- |
| Wheels, tires, brakes, axles: | $780 | -- | -- |
| Control system hardware: | $335 | -- | -- |
| Landing gear struts, mechanism, and actuators: | $525 | -- | -- |
| Fuel system, gauging, fittings, low-level warning: | $310 | -- | -- |
| Wing yaw and pitch trim actuators: | $200 | -- | -- |
| Electrical system components: | $250 | -- | -- |
| Canopy jettison actuators: | $150 | -- | -- |
| VFR instrumentation transponder and com radio: | $1,930 | -- | -- |
| **Structural Materials** | | **$3,670** | **--** |
| Glass and graphite: | $680 | -- | -- |
| Epoxy: | $280 | -- | -- |
| Rigid foam: | $380 | -- | -- |
| Canopy, vendor-formed to RAF mold | $280 | -- | -- |
| Wing pivot machined parts: | $360 | -- | -- |
| Control system machined parts: | $150 | -- | -- |
| Engine mounts and alum nacelles: | $230 | -- | -- |
| Misc. hardware: | $400 | -- | -- |
| Misc. materials: | $550 | -- | -- |
| Finishing/contouring materials: | $360 | -- | -- |
| **Construction Labor—Basic Structure and Systems** | | **$25,200** | **1,800** |
| **Engines Installation, Wiring and Checkout** | | **$2,240** | **160** |
| **Final Surface Contouring and Finishing** | | **$1,260** | **90** |
| **Flight Test Data Instrumentation and Check[2]** | | **--** | **--** |
| **TOTALS** | | **$86,750** | **2,900** |

Burt Rutan, “Feasibility of a Small, Low Cost, Subsonic, Yawed-Wing Experimental Aircraft,” 20-2.

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[1] Acquired via “off-the-shelf” procurement.

[2] To be accomplished by NASA, not the contractor.

company only had two or three employees and could not meet the RFP technical requirement that limited the percentage of new hires that could be made simply to fulfill a NASA contract. To get around this provision, Rutan asked Herb Iverson, who was his partner in the founding of aeronautics company Scaled Composites and who was president of the Ames Industrial Corporation, to respond to the RFP. Rutan thought Ames Industrial could fulfill the contract with Rutan's assistance, especially on the use of composite materials since Ames Industrial's experience was in using aluminum, not composite materials. NASA awarded the contract to the Ames Industrial Corporation of Bohemia, NY. The AD-1, which Rutan designated as RAF 35, was assigned the NASA registration N805NA (800-numbers being reserved by the agency for flight-test aircraft flown at Dryden) and was built on budget and delivered to NASA on March 11, 1979.[16] The actual program schedule called for the completion of the initial design study on February 2, 1976; completion of the actual airplane design from May 28, 1976, until September 8, 1976; and fabrication and manufacture of the airplane from November 18, 1977, to March 11, 1979.

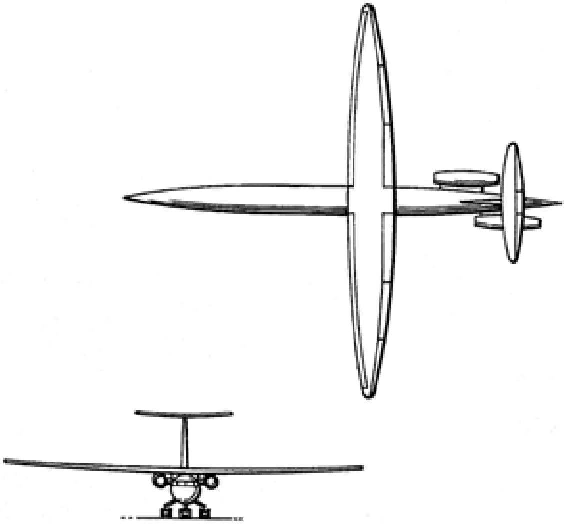
## Jones Secures Patent Recognition for His Oblique Wing

On July 27, 1976, as conceptual work on what would become the AD-1 moved ahead, the U.S. Patent Office granted a patent assigned to the U.S. Government (as represented by NASA) recognizing Robert T. Jones as the inventor of

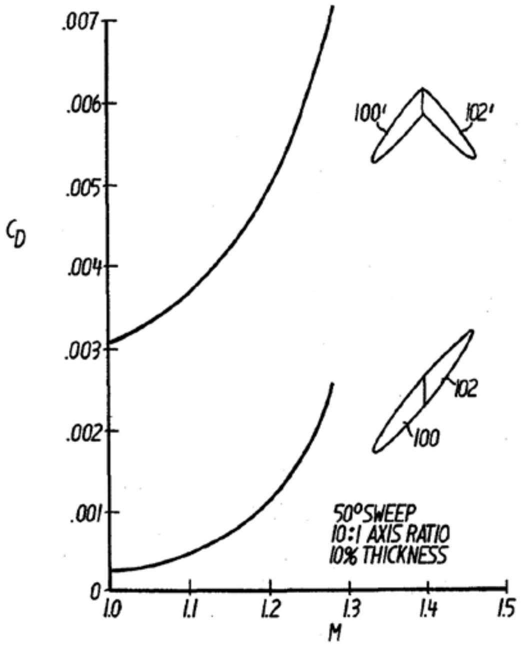
> [a]n aircraft including a single fuselage having a main wing and a horizontal stabilizer airfoil pivotally attached at their centers to the fuselage. The pivotal attachments allow the airfoils to be yawed relative to the fuselage for high speed flight, and to be positioned at right angles with respect to the fuselage during takeoff, landing, and low speed flight. The main wing and the horizontal stabilizer are upwardly curved from their center pivotal connections towards their ends to form curvilinear dihedrals.[17]

Jones had originally filed for the patent on August 12, 1974, and his application claimed the following:

> The instant invention relates to an aircraft having a single continuous wing mounted above a single fuselage and pivoted at the wing center so that it can be rotated from the straight wing perpendicular to the fuselage at take-off to various oblique angles at higher speeds. Half the wing is thus pointed more towards the direction of flight at high speeds and the other half trails. The wing



Jones's 1974 oblique-wing jet transport, showing the wing at 0-degree sweep. Note the "skewed" engine nacelles flanking the tail cone and the subtle curvilinear dihedral of the main wing and horizontal tail. From US Patent 3,971,535 (1976). (NASA)



Jones's 1974 plot of predicted aerodynamic benefits of the single-pivot oblique wing, measuring drag rise vs. an oblique wing. From US Patent 3,737,121 (1973). (NASA)

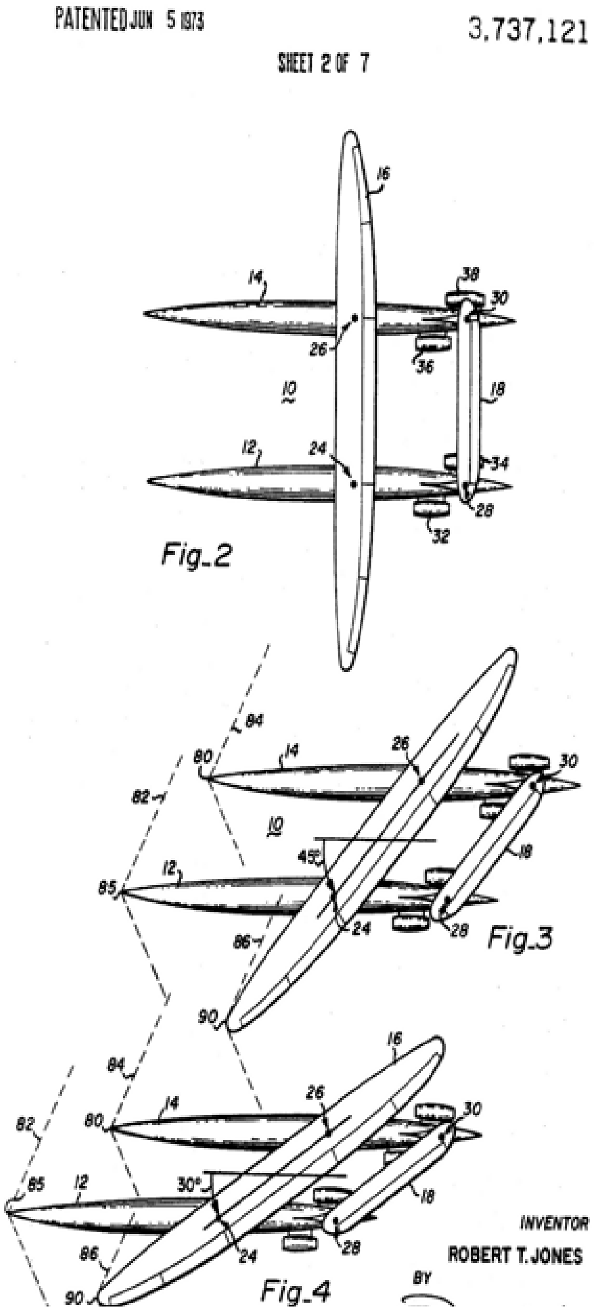
> has a small amount of upward curvature forming a curvilinear dihedral which—when the wing is yawed—is equivalent to twist and affords an increased angle of attack for the forward portion and a decreased angle for the rearward portion.[18]

> Varying the sweep by turning the wing as a whole has several practical advantages over the usual "swing wing" design. In the former case, the wing structure is continuous across the pivot and the primary load on the pivot is tension. With separate wing panels pivoted at the root, however, the loads developed on the pivots are much greater. Also, sweeping the wing panels back for high speed flight displaces the center of lift rearward, compounding the normal rearward center of pressure shift at these speeds. Turning the wing as a whole, however, does not displace the centroid of area relative to the center of gravity. Even with fixed geometry, the structure of the bilaterally symmetric wing is less favorable because of the unbalanced torsion at the wing root. The unbalanced torsion may be equated approximately to increased beam length for the swept wing. Also, conforming to the "area rule," the swept wing requires a rather localized and deep indentation of the fuselage to form a tuck-in or "wasp waist". The optimum fuselage shape for the oblique wing, however, is much more nearly cylindrical. That means more cargo space or passenger space can be provided.[19]

Jones's 1976 patent was preceded by an earlier patent he had applied for on December 9, 1971, and received on June 5, 1973, for a dual-fuselage oblique-wing aircraft, though, for reasons explained subsequently, he soon went back to a single-fuselage concept rather than the twin.

His application described the aircraft as follows:

> Briefly, the present invention includes an airframe in which a parallelogram principle is utilized to achieve an efficient selective angular disposition between a pair of airfoils (a main wing and a horizontal stabilizer) and a pair of fuselages. The main wing and the horizontal stabilizer form one set of parallel sides of the parallelogram while the two fuselages form the other two sides. The two airfoils are pivoted to the spaced fuselages and enable two important in-flight changes in aircraft configuration to be effected: The first is the skewing or yawing of the airfoils relative to the direction of flight for high speed flight; the second is the lateral spreading of the weight distribution



Jones's conceptualization of a dual parallel-fuselage oblique-wing SST, 1971. (NASA)

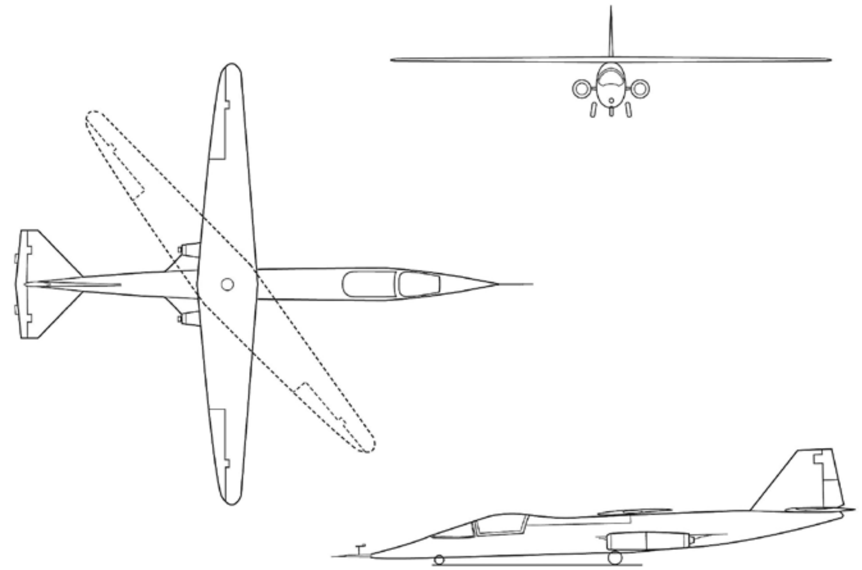
> to minimize the bending stresses of the wing. The increased extension of the aircraft components in the fore and aft direction serves further to reduce the drag at supersonic speed. Another feature of the present invention is the upwardly curved main wing configuration which compensates for any roll tendency caused by the yawed positioning of the wing.[20]

In his February 1972 paper titled "Reduction of Wave Drag by Antisymmetric Arrangement of Wings and Bodies," Jones determined that a single-fuselage oblique wing was more efficient than the dual-fuselage oblique-wing configuration. In this paper, Jones stated the following:

> One of the unspoken assumptions in aircraft design is that of bilateral or mirror symmetry. At slow flight speeds, this assumption seems on rather secure ground, partly because of the indications of aerodynamic theory, but also because it agrees with the observed evolutionary forms of birds. Although it is perhaps natural to extrapolate the forms of birds and animals to the supersonic flight regime, there has been no rational discussion of the merits of bilateral symmetry for supersonic flight. In fact, once the velocity of sound is exceeded, the laws of aerodynamics change in such a way as to make it seem inadvisable to arrange the components of an airplane side by side or abreast in a supersonic stream unless there are compelling reasons for such arrangement. Both the transonic area rule and the supersonic small disturbance theory show large adverse interference effects for bodies or wings in a mirror-symmetric arrangement.[21]

Jones stated further that

> [t]he favorable properties of the oblique wing depend, first of all, on the maintenance of a subsonic type of section flow at supersonic speeds, and this requires that the wing be placed at an angle of yaw such that the component Mach number normal to its long axis be subsonic. If one assumes that the critical "drag divergence" Mach number of the wing sections is 0.7, then the angle of yaw must be such as to reduce the component Mach number to this value.... The advantage of the yawed wing over the swept wing depends on an increased extension of the wing in the flight direction. As is well known, spreading the lift over a greater length diminishes both the sonic-boom intensity and the drag. For a given structural



General arrangement drawing of the AD-1 Oblique Wing Research Aircraft. (NASA)

> slenderness, the single yawed wing panel may have nearly twice the projected length of the corresponding swept wing.[22]

Jones studied three different trims for dual-fuselage oblique-wing configurations as well as the single-body configuration and noted that "[t]he use of two bodies connected across by the wing and horizontal tail in a parallelogram arrangement has certain advantages over the usual arrangements of variable sweep. [For example,] [s]hearing the parallelogram does not displace its center of gravity and only slightly displaces the center of lift."[23] When comparing the dual-body configuration with the single-body configuration, however, Jones concluded that "[s]ince the single fuselage at the center of the wing has almost negligible inertia in roll, one arrives at the surprising conclusion that the one-body arrangement has greater aeroelastic stability than the two-body arrangement."[24] Thus, Jones and NASA proceeded forward with the development of the single-fuselage oblique-wing design.

## The AD-1 Described

The general layout of the AD-1 airplane consists of a high-fineness-ratio fuselage with two French Microturbo TRS-18 engines, each with a sea-level thrust rating of 220 pounds. The engines are mounted on short aft pylons on the side of the fuselage and consume 72 gallons of jet fuel stored in two fuselage tanks installed fore-and-aft of the wing pivot. The AD-1 has conventional horizontal and vertical tails, fixed gear, and a high-aspect-ratio aeroelastic oblique wing. The wing can be pivoted in flight from a 0 degree to 60 degree sweep (with the right wing forward) on a pivot point at the 40-percent root-chord location. The center of gravity while in flight was generally within a few percent of the nominal quarter root-chord position.

Structurally, the airplane consists of a fiberglass-reinforced-plastic sandwich with a core of rigid foam. The thickness varies from 17 plies at the wing root to 4 plies at the tip. Except for the wing pivot, all other components were designed to a 6 g-load limit capacity. The wing pivot was designed to withstand +/–25.0 g-loading. The airplane weighs approximately 2,100 pounds and has potential performance speeds up to 175 knots and flight at altitudes of up to 15,000 feet. The above specifications were considered conservative since the aircraft was not expected to exceed 5 g-loading or 150-knot speed in order to accomplish the program's research goals.

The pilot of the AD-1 sat semireclined in a manner similar to the seating in a high-performance sailplane. The AD-1 has a conventional aileron, elevator, and rudder that were actuated using a mechanical control system. The rudder pedals were mechanically linked to the upper rudder, and yaw trim was provided by the electrically operated lower rudder. Pitch and roll trim were obtained from electrically operated tabs located on the elevator and right aileron. Throttle control was provided through an electronic engine control monitor, and wing sweep was initiated by using a switch on the instrument panel. The wing could be returned to the unswept position by using either the switch or a trigger located on the pilot's center stick. Because it was intended to operate only in visual flight rules (VFR) clear-skies flight-test conditions over the Edwards R-2508 range, the aircraft had a very basic instrument panel containing readings for altitude, airspeed, normal acceleration, angles of attack and sideslip, wing-sweep angle, engine parameters, and rudder trim position. Three separate instruments furnished information on angle of attack ("$\alpha$" or nose pitch), angle of sideslip ("$\beta$" or nose yaw), and wing-sweep angle ("$\Lambda$" or skew angle). All handling-quality maneuvers had to be performed using visual heads-up external references because there were no attitude instruments such as an artificial horizon. The electrical system consisted of an engine-driven generator that powered the battery for engine start, the cockpit gauges, the trim motors, and the onboard data acquisition system.[25] The battery was used to start the engine, and once the engines were started, the generator recharged the battery and provided electrical power for the various electrical components.

The AD-1 was instrumented with a multichannel pulse code modulation (PCM) system with a 32,000-bit-per-second rate with an 8-bit word, 20-word frame length, and a 16-frame data cycle. The data were transmitted to a ground station and recorded on tape. The monitored parameters were related to stability and control, wing-root bending loads, and wing and empennage accelerations. The structural acceleration data were monitored during flight in a spectral analysis facility (SAF) for real-time flutter envelope clearance.[26]

Detailed physical characteristics of the AD-1 are contained in appendix 1, and a detailed description is contained in appendix 2.

## NASA AD-1 Developmental Tunnel Research

Although NASA had already assembled a comprehensive database for the oblique-wing design (in part because of the many industry studies run on the configuration), development of the AD-1, as with any new aircraft, required that the little research airplane have its own wind tunnel development program, complementing analytical and computational studies run on the configuration as well. Accordingly, wind tunnel testing for the AD-1 oblique-wing configuration was conducted in the NASA Ames 12-foot Pressure Wind Tunnel using an aeroelastic one-sixth-scale model of the craft. Two wings were tested: one a stiff, solid aluminum wing, and the other a fiberglass-epoxy composite wing that was designed by Ronald C. Smith to have the necessary flexibility to produce the correct curved dihedral at a 45-degree wing sweep to accommodate a range of structural loadings. This constituted an early example of aeroelastic tailoring of composite wing structures.[27]

Full-scale real-world Reynolds numbers, as well as full-scale wing flexibility, were obtained when operating at 4.5 atmospheres—approximately 66.15 pounds per square inch (psi)—and at a Mach 0.3 (approximately 230 miles per hour [mph]) flow speed. Limited data were obtained at lower Mach numbers or tunnel pressures in order to obtain vehicle characteristics at higher angles of attack or off-nominal wing flexibility. Damping derivatives predictions were obtained using computational methods. A six-degrees-of freedom fixed-base digital simulator was developed using these predictions for safety of flight planning. A spin tunnel test of a one-thirteenth-scale model also was performed at NASA Langley. Most of the wind tunnel data were obtained over an angle-of-attack range from –4 degrees to 11 degrees. The presented predictions were digitized at every 4 degrees of angle-of-attack. The wind tunnel data were obtained at wing-sweep angles of 0 degrees, 25 degrees, 45 degrees, and 60 degrees. The data from these angles were interpolated to obtain predictions at 15 degrees and 30 degrees.

Interference between a wind tunnel model's support system and the model itself has been a frequently encountered problem in tunnel testing, and the AD-1 proved no exception in this regard. The first wind tunnel tests were conducted with a bottom-mounted blade support and a straight midchord

Ronald C. Smith of the NASA Ames Research Center with the AD-1 oblique-wing wind tunnel model. (NASA)

aluminum wing. While these first tests produced a reasonably complete set of wind tunnel data, the results were unrealistic because of apparent losses in elevator control effectiveness accompanied by a 30-percent increase in static margin. As a result, a second set of tests were conducted that, through flow-visualization studies and a model component buildup, revealed that the bottom-mounted blade model support was producing aerodynamic interference in the region of the aft fuselage and horizontal tail. The interference affected pitching moment and, to a lesser degree, rolling moment. The impact on yawing moment was unknown. The problem with pitching and rolling interference was resolved by using a top-mounted blade support system. The top-mounted system interfered with the vertical tail so data from the bottom-mounted support system still had to be used to define yawing moment, sideslip, and rudder characteristics.

The primary tool for estimating damping derivatives was the STBDER computer program. The main application of this program is to compute static and dynamic derivatives for oblique-wing vehicles in the subsonic flight regime.

STBDER uses lifting-line theory for the wing configuration and classical methods for the remaining vehicle components. The MMLE3 computer program was the primary flight-data analysis tool. This computer program uses a maximum likelihood estimation method of analysis. For the AD-1 analysis, the program was modified to include an aerodynamic model that separated the longitudinal and lateral directional equations of the motion while also including the aerodynamic cross-coupling terms. As a result of the investigation, a "best preflight set of predictions was estimated based on both wind tunnel and computational analysis results."[28]

## Dryden's Ike Gillam Defends the Program to Headquarters

Even with the wind tunnel tests, model development, and industry studies well under way, NASA apparently still had concerns regarding the AD-1 program. Over many years, Dryden's enthusiastic pursuit of small "on the cheap" development activities (encouraged by its founding directors who shaped its institutional culture, Walter Williams and his successor Paul Bikle) had occasioned scrutiny from higher headquarters. At the beginning of 1978, the AD-1, like such projects as the Parasev paraglider, the M2-F1 lifting body before it, attracted equivalent headquarters attention. Dryden's director, Isaac T. "Ike" Gillam IV, concerned that the program might fatally stall, responded to Dr. James J. Kramer, then NASA's Associate Administrator running the Office of Aeronautics and Space Technology, vigorously arguing for the program: "We appreciate your concern," Gillam bluntly stated. "We firmly believe that the AD-1 program should be continued as planned."[29] He noted:

1. The program would provide meaningful information on whether or not the oblique-wing concept has potential;
2. Theoretical and wind tunnel studies have demonstrated that the concept has promise;
3. The aeronautical industry has identified potential applications with military and civil aviation through the conduct of preliminary design studies; and
4. Several remotely piloted vehicle programs have further substantiated the feasibility of the concept.[30]

Gillam added that the AD-1 airplane and flight-test program was conceived as an interim step to the final verification of the concept, noting that "the transonic speed regime, where the true advantages of oblique wing technology are realized, cannot be explored with AD-1" and that "the wing structural aeroelastic behavior cannot be assessed."[31] These areas of investigation, according to Gillam, would require a vehicle capable of flying in the Mach number range of 1.4 to 1.6. He concluded, however, that the "AD-1 will provide a means for evaluating the handling qualities and preliminary control system requirements in conjunction with a more systematic assessment of the dynamic aero characteristics than was possible with previously conducted RPV [remotely piloted vehicles] programs."[32]

Gillam allayed Headquarters' concern over program risks by noting that both Ames and Dryden had pursued a risk-reduction strategy that included:

1. Three series of wind tunnel tests had been conducted with the AD-1 model in the Ames 12-foot tunnel to establish the static aerodynamic stability and control characteristics (This information was provided to the designer who, in turn, provided the detailed airplane drawings being used to build the aircraft).
2. NASA Ames completed a flutter analysis of the AD-1 configuration.
3. A six degree of freedom simulation has been mechanized and periodically run at NASA Dryden with the assigned pilot performing the evaluations tasks.
4. The simulation was used to develop the flight plans that will be used to progressively explore the flight envelope of the vehicle for various speed and altitude conditions associated with each of the wing-sweep settings.
5. The simulation will be upgraded with test flight results and then used as a problem-solving tool during the flight envelope expansion period.
6. Considerations are being given to conducting full-scale tests in the Ames 40 x 80 wind tunnel with the flight hardware.
7. Although the AD-1 is considered to be over designed from a structural standpoint, consideration will be given to conducting ground vibration and static loads tests at Dryden.[33]
8. Prior to flight, the Dryden standard center management and technical staff reviews will be performed to establish the flight readiness of the AD-1 and the actual conduct of the program will be initiated with the necessary taxi tests and the subsequent flight envelop buildup through systematic variations of configuration with the speed and altitude.[34]

Based on the above process and the fact that the testing was not driven by a critical time schedule, Gillam stated that "it is felt that the AD-1 program can be conducted in a safe and orderly manner" and it "will provide the next step essential to successfully verify the feasibility of the oblique wing concept."[35] NASA Headquarters obviously concurred as fabrication of the AD-1 proceeded forward, bringing the concept from tunnel to flightline.

## Overseeing Fabrication

A review of the monthly project update reports to NASA Dryden directors from William H. Andrews (from June 1, 1978, through September 9, 1981) and then Weneth D. "Wen" Painter (from October 8, 1981, through September 10, 1982) indicates that program engineers closely and conscientiously monitored the progress of the AD-1. The June 2, 1978, monthly report noted, under the section "New Concepts," that a May 22 visit to Ames Industrial Corporation confirmed that construction of the AD-1 was "essentially on schedule and the airplane is approximately 40 to 45% percent complete."[36] The July 5, 1978, monthly report added that the contractor was still on schedule; that the wing assembly component was completed and was "being worked with cores cut and fiberglass lay in progress"; [37] that the control system, fuel system, and landing gear were being worked; and, finally, that there were no major problems anticipated at the present time. The September 6, 1978, report mentioned that "Bill Andrews and Tom McMurtry [NASA's AD-1 project pilot] of Dryden visited Ames Industrial Corporation (AIC) to observe the status of the manufacturing. The airplane is approximately 80 percent complete."[38] The November 2, 1978, monthly report stated that the "wing-attach plates and pivot bearing have been installed. The wing pivot actuator was delivered to DFRC where the actuator mechanism is to be fabricated and then the entire assembly will be shipped to Ames Industrial Corporation (AIC) for installation....At this time the February delivery schedule still appears firm." The December 4, 1978, report noted that the major effort in November had been "to complete the fabrication of the control system surface and begin the linkage with the cockpit controls, install wiring and fuel system plumbing to the nacelles and complete the engine installation."[39] A wing proof-loads test also was conducted. The report added that "[i]n the month of December the principal effort will be directed towards completion of the systems installations and overall airplane surface finishing."[40]

The January 4, 1979, report noted that fabrication of the airplane was still on schedule but that several minor problems became evident during the engine runs. These problems included an exhaust plume impingement that was enough to cause a noticeable buffet, and with both engines running, there was a tendency for one of the generators to drop off line, which could limit the capacity of the airplane's electrical system. The exhaust plume problem was thought to be caused by the engine's close proximity to the ground in the static runup condition and was scheduled for further evaluation. The tail buffet from the generator problem was to be resolved by a design change to the currently installed simplified relay system. Finally, the report noted that a meeting was held at NASA Ames on December 20 "to review the airplane development status, discuss Dryden fixed-based simulator results, discuss the Ames AD-1 flutter analysis, and firm up plans for a moving base simulation at Ames prior to the first flight of the AD-1."[41]

The February 5, 1979, monthly report noted the following:

> During the week of January 8 the project engineer, airplane crew chief, and inspector spent several days at Ames Industrial Corporation (AIC) to conduct preliminary inspection of the assembled airplane. This resulted in a nine page write-up that identified items that required attention. On January 22 and 23, Bill Andrews and Tom McMurtry visited AIC and at that time a major portion of these items had been corrected....The current schedule shows the airplane being completed and ready for shipment by February 23, 1979.[42]

The March 2, 1979, report added that the "manufacturing of the AD-1 was essentially complete on February 22, with a semi-formal roll-out at Ames Industrial Facility at Bohemia, New York. During the earlier portion of the week Dryden representatives completed a preliminary inspection and acceptance of the airplane that was to be performed before shipment to Dryden.... Upon delivery at Dryden plans are being made to begin preliminary ground testing and installation of the data acquisition systems."[43] Finally, the April 23, 1979, monthly report confirmed that

> [t]he airplane was delivered from the Ames Industrial Corporation facility on Long Island, New York, to Dryden by an Air National Guard C-130 on March 11, 1979. Subsequent to delivery, the wing was installed and an inspection was made for final acceptance. Following the activity, several taxi runs were made to a speed of approximately 25 mph to evaluate the steering capability, using brakes in conjunction with asymmetric power. The responses were satisfactory to the pilot.[44]

The May 16, 1979, update report, which followed acceptance of the aircraft, noted that the ground vibrations tests previously reported were now completed and that all modes "compared favorably with the design analysis except the wing torsional frequency...[which] were somewhat less than predicted and as a consequence, the analysis performed to establish the flutter margins will be recomputed."[45] The report added that the airplane was now being instrumented and prepared for flight test.

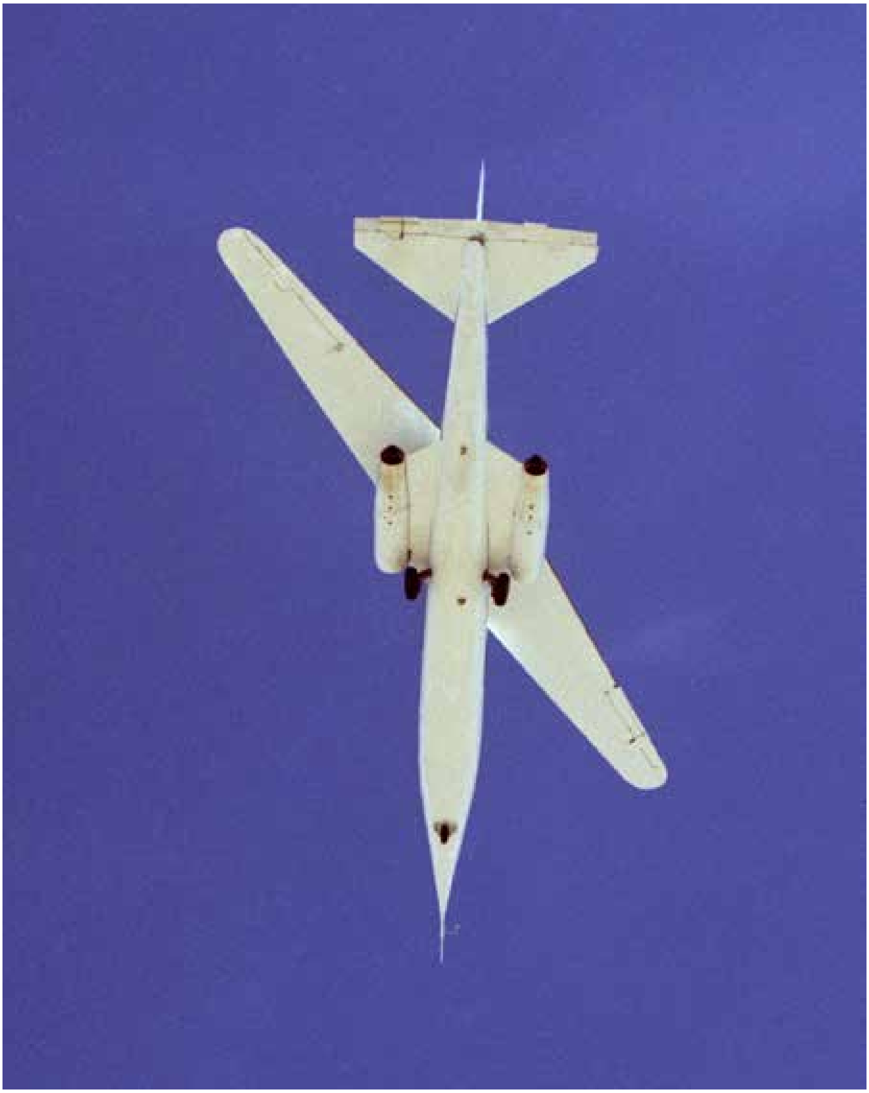
The June 22, 1979, update report added that flight-test instrumentation was still being added and that modifications were made to the landing gear brake assembly plate, the rudder pedals, and control stick and that "all of the control surfaces are being statically balanced as they were not balanced properly on delivery."[46] The report also noted that a moving base simulation was performed at Ames Research Center and that "in general the tests verified the fixed based simulation results obtained at Dryden Flight Research Center."[47] The July 24, 1979, report noted that as a result of a Headquarters briefing on May 14, 1979, coordination was undertaken with Langley regarding the feasibility of conducting a spin tunnel test of the higher sweep-angle configuration. The report covering the month of July 1979 recounted a telephone conference with Dryden, Ames, and Langley scheduled to discuss Langley's William Gilbert's recommendation regarding the stall-spin characteristics. It was generally agreed that Langley would develop a model and conduct spin-recovery tests and that if "the spin tunnel test has not been completed by the time the flight envelope has been expanded to a sweep angle of 45 deg, an assessment will be made before continuing beyond this sweep angle." The September 13, 1979, report informed the director that the flight instrumentation installation was completed and that the cockpit canopy was being reworked to use an aft-mounted hinge arrangement that would enable better pilot egress. The December 12, 1979, report noted concern regarding the strength of the landing gear system due to the increased airplane gross weight over the design. Nine days after this report, however, the AD-1 made its first flight at Edwards AFB. Flight testing of the AD-1 was now under way at NASA Dryden.[48]

## Endnotes

1. Kenneth J. Szalai, "Role of Research Aircraft in Technology Development," NASA TM 85913 (November 1984), 6.
2. See Richard P. Hallion and Michael H. Gorn, *On the Frontier: Experimental Flight at NASA Dryden* (Washington, DC: Smithsonian Books, 2003).
3. Szalai, "Role of Research Aircraft in Technology Development," 7.
4. Ibid.
5. Szalai, "Role of Research Aircraft in Technology Development," 6–8.
6. Alex G. Sim and Robert E. Curry, "Flight Characteristics of the AD-1 Oblique-Wing Research Aircraft," NASA TP 2223 (1985), 1.
7. Vera Foster Rollo, *Burt Rutan: Reinventing the Airplane* (Lanham, MD: Maryland Historical Press, 1991) 35.
8. Interview of Burt Rutan by the writer, July 21, 2011.
9. Burt Rutan and George Mead, "Feasibility of a Small, Low Cost, Subsonic, Yawed-Wing Experimental Aircraft," December 1975, Dryden History Office, folder L1-5-4-8, 2–3.
10. Ibid., 6.
11. Ibid.
12. Ibid., 6–7.
13. Ibid., 1–17.
14. Telephone interview of Burt Rutan by the writer, July 21, 2011.
15. Rutan and Mead, "Feasibility," 19.
16. Telephone interview of Burt Rutan by the writer, July 21, 2011; see also Dan Linehan, *Burt Rutan's Race to Space: The Magician of Mojave and His Flying Innovations* (Minneapolis, MN: Zenith Press, 2011), 58–59, 158–159.
17. Robert T. Jones, Oblique-wing supersonic aircraft, US Patent 3,971,535, filed August 12, 1974, issued July 27, 1976.
18. Ibid. The patent also referenced Vogt's patent that represented an aircraft having a single fuselage with two sets of rotatable mounted integral wings (one for subsonic flight and one for supersonic flight) and the Hubschman patent wherein the wing-to-fuselage angle of separate left and right wings can be independently adjusted by the pilot.
19. Ibid.
20. U.S. Government as represented by NASA, Dual-fuselage aircraft having yawable wing and horizontal stabilizer, US Patent 3,737,121, filed December 9, 1971, issued June 5, 1973.

21. R.T. Jones, "Reduction of Wave Drag by Antisymmetric Arrangement of Wings and Bodies," *AIAA Journal* 10, no. 2 (February 1972): 171.
22. Ibid.
23. Ibid., 174–175.
24. Ibid.
25. Sim and Curry, "Flight Characteristics of the AD-1 Oblique-Wing Research Aircraft," 3; W.H. Andrews et al., "AD-Oblique Wing Aircraft Program," SAE International, TP 801180, 2–3.
26. Andrews et al., "AD-Oblique Wing Aircraft Program," 3. Records give three different communication channel numbers for this—35, 40, and 41.
27. For a comprehensive review of the testing, see Alex G. Sim and Robert E. Curry, "Flight-Determined Aerodynamic Derivatives of the AD-1 Oblique-Wing Research Airplane," NASA TP 2222 (1984), 4–11. The information on the two wing types was furnished to the author by Stephen C. Smith.
28. Ibid., 11.
29. Isaac T. Gillam IV, "NASA Dryden Letter to Dr. James J. Kramer, NASA Headquarters," January 31, 1978, Milton O. Thompson Papers, NASA Dryden History Office, box L1-5-8, folder 16.
30. Ibid.
31. Ibid.
32. Ibid.
33. In a July 21, 2011, telephone interview with the author, Burt Rutan, who did the design work on the AD-1, noted in regard to structural divergence that while the test indicated that the wing was 6-percent too flexible, NASA approved the wing, noting that they had made the requirement 400-percent higher than the amount necessary to avoid structural divergence of the forward swept wing. Rutan stated that this caused the wing to be made much stiffer than necessary, which greatly increased wing weight and resulted in poor flight performance, particularly its single-engine climb rate.
34. Gillam, "NASA Dryden Letter to Dr. James J. Kramer, NASA Headquarters."
35. Ibid.
36. Gene J. Matranga, "Aeronautics Update Memorandum—May 1978," June 2, 1978, Dryden History Office, box L3-4-4B, 4.
37. Ibid.
38. Gene J. Matranga, "Aeronautics Update Memorandum—October 1978," November 2, 1978, Dryden History Office, box L3-4-4B, 4.

39. Gene J. Matranga, "Aeronautics Update Memorandum—November 1978," December 4, 1978, Dryden History Office, box L3-4-4B, 4.
40. Ibid., 5.
41. Gene J. Matranga, "Aeronautics Update Memorandum—December 1978," January 4, 1978, Dryden History Office, box L3-4-4B, 4.
42. Gene J. Matranga, "Aeronautics Update Memorandum-January 1979," February 5, 1979, Dryden History Office, box L3-4-4B, 3–4.
43. Gene J. Matranga, "Projects Update Memorandum—February 1979," March 2, 1979, Dryden History Office, File Box L3-4-4B, 4–5.
44. Gene J. Matranga, "Projects Update Memorandum—April 1979," April 23, 1979, Dryden History Office, box L3-4-4B, 6.
45. Ibid., 5.
46. Gene J. Matranga, "Projects Update Memorandum—May 1979," June 22, 1979, Dryden History Office, box L3-4-4B, 6.
47. Ibid.
48. "Monthly Memorandums to the Director of Dryden Flight Research Center," June 2, 1978, through April 23, 1979, Dryden History Office, box L3-4-4B.



The AD-1 at 60-degree wing sweep, during its 30th flight, on July 1, 1981, for stability and control evaluation, piloted by Tom McMurtry. This is the program's iconic photograph. (NASA)

# CHAPTER 4

# Flight Testing and Evaluation of the AD-1

The flight testing and evaluation phase of the AD-1 program consisted of NASA preflight tasks, flight operations, flight program evaluations, postflight testing, and studies undertaken to compare actual results with predictions. NASA preflight tasks were divided between three NASA Centers. Ames continued its wind tunnel test and structural dynamics predictions; Langley was conducting spin tunnel tests; and Dryden was undertaking instrumentation installation, moment-of-inertia tests, ground vibration tests, component loads tests (excluding wing), and flight simulation.

## Ground Testing the AD-1

Following delivery of the AD-1 to Dryden and prior to flight testing of the AD-1, a proof of loads test was performed on the wing and a ground vibration test was performed on the entire vehicle. The purpose of the wing-loads test was to check wing deflection and to obtain a calibration of the root-bending-moment strain gages for symmetrically and antisymmetrically distributed loads. Shot bags were used to produce loads equivalent to 0.9 g, 1.7 g, and 4.7 g's. Measurements were made at 11 wingspan stations and chord locations of the leading edge, 40 percent of chord, and the trailing edge. These tests indicated that the wing was 10-to-15-percent stiffer in bending than was indicated by the design. Also, a separate torsional rigidity test was conducted on the wing. For this test, three levels of torque were applied to the wing near the tip, and the resulting angle of twist was measured at several spanwise stations inboard of the applied torque. The test results indicated that at lower levels of torque, the wing's torsional rigidity compared very well with the prediction produced from NASTRAN computational structural analysis. At the higher level of torque and near the tip, the wing appeared to have less torsional rigidity (more deflection) than the analysis program predicted.

The AD-1 undergoing a ground vibration test at the Dryden Flight Research Facility, March 15, 1979. (NASA)

After the proof-loads test, a ground vibration test was performed. For this test, the airplane was suspended from an I-beam frame through an airbag system that was connected to a rigid plate attached to the wing pivot. A shaker unit was then attached to the right and left wing sections just inboard of the aileron. Several accelerometers were used to sense the discrete responses of the various components of the aircraft. Wing sweep angles of 0 degrees and 45 degrees were used for the test. Symmetrical and antisymmetrical vibrations were applied to the airplane at frequencies that varied smoothly from 0 hertz to 60 hertz. The response was measured on the wing, fuselage, engine nacelles and pylons, horizontal and vertical tails, and control surfaces. In addition, discrete frequency inputs were made to determine the shapes of the wing modes at a 0-degree wing-sweep angle. The response was pronounced near frequencies of 15 hertz and 43 hertz, indicating that the antisymmetrical responses at these two numbers were related to the second wing-bending and the first wing-torsional modes, respectively.[1]

Finally, during the fabrication of the AD-1, a six-degrees-of-freedom (longitudinal, lateral, and vertical correction at three different rotations) fixed-base simulator was assembled in order to obtain a preliminary assessment of the airplane's flying qualities and to evaluate the vehicle's control system requirements. The simulator's cockpit instrument display was nearly identical to the

| The Cooper-Harper Pilot Rating Scale | | |
|---|---|---|
| **Aircraft Characteristics** | **Demands on the Pilot in Selected Task or Required Operation** | **Rating** |
| **Excellent (highly desirable)** | Pilot compensation not a factor for the desired performance | 1 |
| **Good (negligible deficiencies)** | Pilot compensation not a factor for the desired performance | 2 |
| **Fair (some mildly unpleasant deficiencies)** | Minimal pilot compensation required for desired performance | 3 |
| **Minor but annoying deficiencies** | Moderate pilot compensation required for desired performance | 4 |
| **Moderately objectionable deficiencies** | Considerable pilot compensation required for adequate performance | 5 |
| **Very objectionable but tolerable deficiencies** | Extensive pilot compensation required for adequate performance | 6 |
| **Major deficiencies** | Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question. | 7 |
| **Major deficiencies** | Considerable pilot compensation required for control | 8 |
| **Major deficiencies** | Intense pilot compensation required to retain control | 9 |
| **Major deficiencies** | Control will be lost during some portion of required operation | 10 |

The AD-1 Oblique Wing Research Aircraft on the Dryden Flight Research Center ramp, April 17, 1980. (NASA)

one used in the final airplane design; however, a pitch-and-roll attitude display was included in the simulator in order to give the pilot some outside reference. Also, a moving-base simulation was performed at NASA Ames. This simulation provided a check on the fixed-base simulation and enabled the effects of motion on the various piloting tasks to be evaluated. For the moving-base operation, the attitude display was replaced with a television display. The equations of motion used in both simulators utilized the static aerodynamic derivatives obtained from wind tunnel tests. The data were corrected for the effects of aeroelasticity. The pilot ratings, based on the Cooper-Harper rating scale (see table on previous page), for the above simulations at a 45-degree wing-sweep angle at an altitude of 10,000 feet and indicated airspeeds from 100 knots to 160 knots, generally ranged between 3 and 5. The introduction of motion in the simulator slightly increased the pilot's difficulty in accomplishing the task. At the 60-degree angle, however, the introduction of motion appeared to aid, not hamper, task accomplishment.[2]

With satisfactory completion of the above tests and simulations, the program was ready for actual test flights of the AD-1. Simulations, however, continued during flight testing in order to familiarize additional pilots with the airplane and to assess the need for a more sophisticated control system. Several taxi runs were made at a speed of approximately 25 mph in order to evaluate

NASA research pilot Thomas C. "Tom" McMurtry and the AD-1. (NASA)

the steering capability. These test results were used to validate the input data used in the design flutter analysis. After completion of the vibration test, a torsional loading was applied and the results of the test indicated that the torsional stiffness compared well with predictions. The instrumentation was then installed and the plane readied for flight.[3]

## The Program and its Pilots: An Overview

The primary objectives of the flight-test program that began in December 1979 were to assess the aircraft's unique handling and flying qualities; learn the nature and complexity of oblique-wing flight control; verify the aeroelastic design of the wing; and compare the vehicle's aerodynamic characteristics with predictions. Altogether, the AD-1 completed a total of 79 flights between December 21, 1979, and August 7, 1982. Seventeen pilots flew the AD-1, including the two Dryden program pilots and 15 guest pilots.

NASA's two AD-1 program pilots were Thomas C. McMurtry and Fitzhugh L. "Fitz" Fulton, Jr., both extraordinarily gifted and experienced airmen who had flown a wide variety of experimental and operational aircraft during their careers. Both were enthusiastic airmen who flew privately as well as professionally, and

NASA research pilot Fitzhugh L. "Fitz" Fulton and the AD-1. (NASA)

thus both were ideally qualified to test and assess the radical little AD-1. Forty-nine of the 79 flights were flown by Thomas McMurtry and 15 were flown by Fitzhugh Fulton; the remainder were flown by various guest pilots.

Born in Crawfordsville, IN, on June 4, 1935, McMurtry received his bachelor of science degree in mechanical engineering from the University of Notre Dame in June 1957. Before joining NASA, McMurtry had served as a naval aviator flying the Douglas A-3 Skywarrior and then flew the Lockheed U-2 for Lockheed. McMurtry was a graduate of the U.S. Navy Test Pilot School (TPS) in Patuxent River, MD. While with NASA, McMurtry successively held a number of different positions at NASA Dryden, including chief pilot, director of flight operations, associate director for operations, and acting chief engineer. As director of operations, he supervised the Avionics, Operations Engineering, Flight Crew, Quality Inspection, Aircraft Maintenance and Modification, and Shuttle and Flight Operations support branches. In addition to his role with the AD-1, McMurtry served as project pilot for the F-15 Digital Electronic Engine Control (DEEC) project, the KC-135 Winglets project, and the F-8 Supercritical Wing program, for which he received NASA's Exceptional Service Medal. He also served as coproject pilot on the F-8 Digital Fly-By-Wire (DFBW) program. In 1982, he received the Iven C. Kincheloe Award from the Society of Experimental Test Pilots (SETP), the international

Robert T. Jones meets his creation: Jones inspecting the AD-1 at Ames Research Center, December 1981. In the cockpit is NASA research pilot Tom McMurtry. (NASA)

professional society for test pilots, for his contributions as project pilot on the AD-1 Oblique Wing program. In 1999, McMurtry was awarded the NASA Distinguished Service Medal. McMurtry retired from NASA, following a 32-year career, on June 3, 1999.[4]

Fitz Fulton was born in Blakley, GA, in 1925. A graduate of Golden Gate University and the Air Force Test Pilot School, Fulton had served 23 years as a pilot in the U.S. Air Force before joining NASA as a civilian research pilot at Dryden, where he flew two decades for the Agency from August 1, 1966, until July 3, 1986. While with the Air Force, he received the Distinguished Flying Cross and five Air Medals for flying 55 missions in the Berlin Airlift and then as a B-29 bomber pilot in Korea. He was also awarded three Distinguished Flying Crosses for his test pilot work with the Air Force. Fulton was arguably the world's most experienced multiengine large-aircraft test pilot at the time of his work with the AD-1. He had flown aircraft as diverse as the B-52 launch aircraft for the X-15 and lifting bodies, the Mach 2+ Convair B-58 and the Mach 3+ North American XB-70A Valkyrie, and the exotic Lockheed YF-12A

Blackbird. He was the project pilot on all early tests of the 747 Shuttle carrier aircraft used to air-launch the Space Shuttle Enterprise in the approach and landing tests (ALTs) undertaken at Dryden in 1977. For this program, Fulton received the first of two NASA Exceptional Service Medals, and in 1977, he, like McMurtry, was awarded the SETP's prestigious Iven C. Kincheloe Award as the test pilot of the year. At the time of his retirement from NASA, Fulton had accumulated over 15,000 flying hours in over 200 different types of aircraft—from light sport planes to high-performance fighters, bombers, and experimental test beds.[5]

Tom McMurtry was first to fly the AD-1, making his first two flights on December 21, 1979; the first flight was an unplanned 5-minute excursion occurring during a high-speed taxi test. This was followed on the same day by the first official flight, which took 45 minutes, to check out the aircraft. McMurtry also flew all four of the first oblique-wing translations. The 15-degree wing-sweep test flight was made on April 2, 1980, followed by the 20-degree wing-sweep flight on April 25; the 45-degree flight on May 28; and finally, the 60-degree flight on April 24, 1981. In addition to these flights, McMurtry flew 6 performance test flights (one of these also included handling qualities), 8 stability and control flights, 4 flutter clearance flights, 1 handling-qualities test flight, 2 oil-flow visualization flights, 12 flights to ferry the AD-1 to and from demonstration sites, and 10 demonstration flights. These included a flight to Ames Research Center, where McMurtry completed two demonstration flights and oblique-wing pioneer Robert T. Jones inspected his creation first hand.

The last eight flights of the AD-1 were at the Oshkosh air show in Wisconsin in August 1982. The last Oshkosh air-show flight, which also (according to the flight log summary) was the last flight of the AD-1, was flown on August 7, 1982, thus making McMurtry both the first and last pilot to fly the Ames-Dryden AD-1 Oblique Wing Research Aircraft.

Fitzhugh L. Fulton, Jr., flew 15 of the test flights, making his first flight (pilot checkout and aircraft performance mission) on January 25, 1980. This flight was followed by a second performance checkout flight on February 20; five flutter clearance flights between July 9, 1980, and May 12, 1981; six stability and control test flights between July 1, 1981, and September 3, 1981; and two oil-flow visualization study test flights in June 1982.

NASA Dryden offered various Air Force, Navy, Marine Corps organizations and NASA Centers the opportunity to each have two pilot familiarization flights. These guest pilots, who each flew a single sortie, were

- Einar Enevoldson, NASA Dryden pilot
- John Manke, flight operations director, NASA Dryden
- William Dana, NASA Dryden

- Richard Gray, NASA Dryden[6]
- Don Mallick, NASA Dryden
- Captain John Small, Air Force Flight Test Center
- Major Robert Cabana, U.S. Marine Corps, Naval Air Test Center, Naval Air Station (NAS) Patuxent River
- Commander John Watkins, Naval Air Test Center, NAS Patuxent River
- James Martin, NASA Ames
- G. Warren Hall, NASA Ames
- Captain Denny Mohr, USAF TPS instructor
- Philip Brown; NASA Langley
- Major William Neely, USAF NASA Langley
- Colonel William J. "Pete" Knight, vice commander, Air Force Flight Test Center (AFFTC)
- Steven Ishmael, NASA Dryden[7]

Fittingly, Tom McMurtry flew the last eight flights of the AD-1 at the Experimental Aircraft Association meeting and air show held in Oshkosh between July 31 and August 7, 1982. Wen Painter narrated the flights, which each lasted approximately 10 minutes. R.T. Jones was present for the flight demonstrations, and the air show flights were reported in the August 20, 1982, edition of the Dryden *X-Press* with the following commentary:

> The airplane that proved the concept of oblique winged flight flew its last flights before an audience totaling more than 600,000 in Oshkosh, Wisconsin recently. The unique scissor wing craft flew daily to the delight of attendees at this year's Experimental Aircraft Association meet in the Dairy state.[8]
>
> Amongst the 12,000 aircraft at the gathering, there was no question as to which one was the show-stopper, as NASA Dryden Chief Pilot Tom McMurtry put the AD-1 through its swing-wing paces before impressed and skyward looking crowds. On the ground, the Oblique Wing garnered a continuous circle of the curious and knowledgeable wanting to know more about the plane. On hand to answer the questions were Wen Painter[,] AD-1 Project Manager, Tom McMurtry[,] and Walt Vendolosky, AD-1 Crew Chief.[9]

The flights certainly accomplished their purpose. One young onlooker, Thomas Beutner, was so impressed with the sight of the AD-1 flying confidently through the Wisconsin skies that he determined, at that point, to devote his engineering career to studying oblique wings, subsequently studying with Jones and some of his associates later that decade.[10]

The AD-1 at 20-degree wing sweep, during its 13th flight, on April 25, 1980, for flutter clearance, piloted by Tom McMurtry. (NASA)

After the air show, Walter Vendolosky and Mike Bondy trailered the AD-1 to NASA Langley in Hampton, VA, where the aircraft was scheduled to undergo wind tunnel testing. It is not clear, however, from Langley records and personnel whether the wind tunnel tests were, in fact, ever conducted.[11]

In regard to the AD-1 management team and ground crewmembers, William Andrews served as the first project manager, Weneth D. "Wen" Painter was responsible for flight control and stability augmentation systems and served later as project manager, George Nichols was the instrument technician, and Walter Vendolosky served as aircraft crew chief.

## NASA Dryden's Monitoring and Oversight During AD-1 Testing

The record of monthly AD-1 progress and situation reports sent to the Dryden Center director offers clear evidence of NASA's close oversight of the AD-1 program as it underwent its flight research phase.[12] These reports also provided valuable additional test-flight and flight-evaluation information. The following extracts and summaries (by report date) are a representative sampling of reports reflecting key contemporary updates as they occurred and were reprinted subsequently.[13]

> *January 14, 1980*: On December 20, a series of taxi runs were made on the Edwards main base runway to evaluate the ground handling qualities up to a nose wheel lift off speed of approximately 65 knots. On December 21, 1979, two flights were performed with the wing locked in the zero sweep position. The first flight was just down the runway at approximately 50 feet to check the wing structural response. The second flight was accomplished with a maximum speed and altitude of 140 knots and 10,000 feet attained respectively. The testing involved flutter clearance, performance evaluation, and stability and control testing. The flight was very successful and the airplane landed with only minor maintenance squawks on the longitudinal trim and rudder controls. These squawks will be corrected and Flight No. 3 is scheduled for January 10, 1980.[14]
>
> *February 1, 1980*: Since the last report six flights have been flown for a total of nine flights to date and about an equal number of flight hours. The first eight flights, which were flown at a 0 deg wing sweep, involved a flight envelope at altitudes of 12,500 and 5,000 feet and over a speed range of up to 178 knots. The ninth flight, which was flown at a wing sweep angle of 15 deg, consisted primarily of establishing a flutter envelope clearance at 12,000 and 7,500 feet altitude for speeds up to 150 knots.[15]
>
> *April 17, 1980*: Three additional flights had been flown. The first flight was to check out another pilot and the next two flights were devoted to completing the evaluation of the 15 deg sweep angle configuration and obtaining data at high angles of attack (12 deg to 14 deg) for 0 deg and 15 deg wing sweep angles. Pilot evaluation from these flights revealed that "From a flutter standpoint, the wing exhibits low damping and caution is being observed as higher sweep angles are explored."[16]
>
> *May 12, 1980*: The latest flight flown was Number 13, which was accomplished on April 25, 1980. The purpose was to open the flight envelope to a sweep angle of 20 deg. The testing was conducted at altitudes of 7,500 and 12,500 feet and airspeeds

The AD-1 at 45-degree wing sweep, during its 14th flight, on May 28, 1980, for flutter clearance, piloted by Tom McMurtry. (NASA)

up to 150 knots indicated. Flutter checks were made at five knot increments. At 7,500 feet the testing was terminated at 125 knots and at 12,500 feet it was terminated at 140 knots. The reason for discontinuing was due to very low damping in wing structural response in the frequency range of 15 to 16 Hertz. The wing had exhibited this behavior at lower sweep angles, but it appeared to be more persistent at 20 deg. Currently, the design flutter analysis and ground vibration test data are being reviewed as well as a more complete analysis of the flight data is in progress. As a result of this experience, the next flight has not been scheduled.[17]

*June 11, 1980*: Flight 14 was flown on May 28, 1980. As in the previous flights, the purpose of the flight was to expand the flight envelope relative to sweep angle and explore the low damped wing structural response noted in earlier flights.[18]

*October 9, 1980*: There was a lower damped left wing structural response on flight 19 as compared with previous flights. This factor was not readily explained. As a result, the wing skin was to be checked for delamination and a series of ground vibration tests were scheduled to be performed.[19]

*December 8, 1980*: A ground vibration test was scheduled in order to define the aileron influence and wing pivot free-play effects on the wing structural responses observed in flight.[20]

*February 6, 1981*: This report identified the suspected source of the structural vibration discussed in the previous report as the lateral control system.[21]

*March 9, 1981*: This report added that, based on recommendations of a Lockheed consultant and the flutter vibration group, a linear snubber is being installed on the aileron in order to remove the effects of slop in the system.[22]

*April 8, 1981*: This report noted that the ground vibration testing analytical model did not show any flutter potential within the region that the AD-1 would be flown. In addition, the installation of the aileron damper noted last month was effective in increasing the stiffness between the aileron and wing responses. This report also advised the director that two additional flights (flights 20 and 21) were flown on March 31. These flights explored the flight envelope at 110 to 120 knots in 5-knot increments and from sweep angles 0 deg to 50.5 deg. The sweep angles between 15 deg and 25 deg still indicated that the low amplitude, low damped 15 Hz responses on the left wing existed but that flying qualities at the higher sweep angles were as good as or slightly better than observed on the fixed base simulator.[23]

*May 8, 1981*: This update reported on flights 22 and 23, both flown on April 24. On these flights the flight envelope was explored between 120 and 150 knots for sweep angles from 15 deg to 25 deg. These flights cleared the AD-1 to fly at speeds of 130 knots and sweep angles up to 55 deg and to perform a preliminary evaluation of the flying qualities at 60 deg to evaluate basic stability, damping and cross-coupling effects. The report noted that "The results appeared to be similar to that observed on the fixed base simulator; however, the real world motion cues naturally enhanced the flying characteristics over those predicted.[24]

*June 9, 1981*: The report noted that three additional flights had been flown bringing the total up to 26 flights. These flights concentrated on obtaining basic stability data in the sweep range from

30 deg to 60 deg in the speed ranges from 130 to 145 knots. This included a series of longitudinal and lateral-directional handling qualities tasks performed out to 60 deg sweep. The overall assessment was that the airplane continued to perform well and the flight operation was to be expanded to one flight per week.[25]

*July 7, 1981*: This update reported on four additional flights that increased the total flight number to 30. The principal testing now centered on performance in the 50 deg to 60 deg sweep range and on obtaining pilot performance ratings for specified tasks.[26]

*August 10, 1981*: This report noted that an additional four flights were performed in the 50 deg to 60 deg sweep range and that successful landings were made at the wing sweep angles of 15 deg, 30 deg, and 45 deg. On the last flight, however, trouble developed in the right-side engine and that the Ames Industrial Corporation had been contacted for a new rental engine.[27]

*September 9, 1981*: This update reported that the new engine had been received and two additional flights flown bringing the total number of flights up to 37. The objective of these flights was to continue the pilot evaluation program especially in the high sweep angle range. Consideration was also being given to checking out additional pilots in order to expand the experience data base. Finally, this report noted that in conjunction with the current handling qualities evaluation, the fixed base six-degree of freedom simulator is being used to evaluate the effect of incorporating stability and damping augmentation.[28]

*October 8, 1981*: Weneth D. Painter reported that the AD-1 flight research program had been completed and that the program team was currently awaiting approval of a "Guest Pilot" program.[29]

*February 10, 1982*: Painter reported on the guest pilot familiarization program noting that Air Force pilots would fly the AD-1 the week of February 1; Navy pilots would fly the week of February 8; and Ames pilots would fly the week of February 15.[30]

*April 9, 1982*: The report noted that 13 guest pilots had flown the AD-1 and that 1 to 3 additional pilots might still get the flight opportunity.[31]

*May 10, 1982*: This report noted that the AD-1 was scheduled to fly to Ames on May 14 for a static display and that 4 more guest pilots were scheduled to fly the airplane on May 19 and 20, at which time the program would be completed.[32]

*June 10, 1982*: This report added that the pilot familiarization was successfully completed and the program team was awaiting approval for 4 additional flights on June 8 and 9 in order to conduct oil flow visualization studies on the oblique wing.[33]

*July 12, 1982*: Guest flights have been completed. NASA will display and fly the AD-1 at the annual Experimental Aircraft Association convention in Oshkosh, Wisconsin later in the month.[34]

*August 9, 1982*: In this update, Kenneth E. Hodge, Chief of Dryden's Aeronautical Project Office, reported that the AD-1 was trucked to Oshkosh for participation in the air show and that "Following the EAA event, it is planned to truck the AD-1 to Langley in response to their request for its use in wing aerodynamics research in the 30-by-60-foot wind tunnel. The loan agreement stipulates that the AD-1 will be returned to Dryden in airworthy condition upon completion of wind-tunnel testing.[35]

*September 10, 1982*: The update reported that the AD-1 was at Langley being prepared for wind tunnel testing and would be returned within the next year.[36]

## First Look: The AD-1 Team's 1981 End-of-Program Evaluation

Less than a month after Weneth Painter had reported the AD-1 research program complete and 3 months before the onset of the guest-pilot evaluation, the AD-1 team offered an initial quick-look assessment of the program at a prestigious international flight-testing conference sponsored by the American Institute of Aeronautics and Astronautics, the Society of Experimental Test Pilots, the Society of Flight Test Engineers, the Society of Automotive Engineers, the International Test and Evaluation Association, and the Institute of Electrical and Electronic Engineers.[37] In evaluating the AD-1 flight program, McMurtry, by now director of flight operations at Dryden, and aerospace

The AD-1 at 60-degree wing sweep, during its 32nd flight, on July 14, 1981, for flow visualization study (note the tufted wing), piloted by Fitz Fulton. (NASA)

engineers Alex Sim and William H. Andrews reminded their audience that the principal purpose of the flight-test program initiated in December 1979 was to demonstrate the flight and handling characteristics of the oblique-wing configuration, especially in the wing-sweep angle range of 45 degrees to 60 degrees.[38] A six-degrees-of-freedom fixed-based simulation of improvements could be realized by incorporating advanced control system technology augmented the flight operations. McMurtry, Sim, and Andrews noted that development of the AD-1 Oblique Wing Aircraft was a good example of the need for complementary advances in technology in other fields in order to implement new engineering principles. In this regard, they noted that,

> [t]heoretically, this configuration, which Robert T. Jones conceived of many years ago, offers aerodynamic, structural and operational efficiency unequalled by conventional designs. The development of a vehicle which would incorporate these new features has been considered impractical, however, because of the structural divergence problems inherent in the forward swept wing sections. However, with recent advances in the state of the art composite structural

> design and the advent of active control systems, the advantages of this concept may be realized in the future.[39]

The NASA Dryden team noted the following aerodynamic characteristics of the AD-1:

1. The lateral-directional trim changes consisted of change in sideforce, rolling moment, and yawing moment as a function of angle of attack and the wing sweep angle.
2. The changes in sideforce flight data and predicted data were due to the difference in construction between the wind tunnel model and the actual airplane. The effect of the sideforce is that either nonzero bank angle or sideslip angle must be maintained to hold a constant heading, thus resulting in an airplane that can be trimmed using many combinations of aileron, rudder, and elevator control.
3. Wing-stiffness problems impacted the plane's dynamics, causing significant effect on vehicle handling qualities and making the AD-1 less stable for large maneuvers involving load factor than for small maneuvers. Also, turbulence tended to amplify the flexibility effects and thus degrade the handling qualities. The handling qualities, however, would be improved by switching the wing construction from fiberglass, which was necessary to use for the AD-1 due to the low technology scope of the program, to carbon-fiber material.
4. Other aerodynamic concerns, including pitching moment due to aileron deflection and sideslip, as well as cross damping, such as pitching moment due to roll rate. These were not shown to have a significant effect on handling qualities, although the aeroelastic response tended to mask any effect they had.[40]

In order to examine the handling qualities associated with an oblique-wing airplane, the following set of tasks were used for the flight tests of the AD-1: trim to constant airspeed, altitude, and heading with zero sideslip; perform windup turns to 1.5 g and change heading 180 degrees while maintaining constant airspeed; descend 500 feet and level off, maintaining constant airspeed and heading; and perform moderate rate rolls to a bank angle of 30 degrees and return to level flight, maintaining constant airspeed and altitude. The above tasks were considered simple since there was no assigned mission for the aircraft. The tasks were evaluated at wing-sweep angles of 0 degrees, 35 degrees, 45 degrees, and 60 degrees. The NASA team noted that the tasks were performed within a range of 11,000 feet and 13,000 feet (the nominal altitude was 12,500 feet) and that this altitude was chosen primarily to allow for pilot egress in case of loss of control. Finally, the Cooper-Harper rating scale, as defined previously, was employed to evaluate the tasks.

Use of the rudder to control roll of the AD-1 when aileron effectiveness was reduced at the higher oblique-wing sweep angles was considered important by the pilots because the static directional stability of the airplane was weak. This characteristic of the AD-1 was noted at all wing-sweep angles, and use of the rudder proved very helpful. Pilots also noted an additional characteristic while performing windup turns. When the wing-sweep angle was 50 degrees or higher, the airplane showed a tendency to increase in bank angle as the maneuver was performed to the left. When the maneuver was performed to the right, the airplane tended to roll out due to pitch coupling. Pilots indicated that the tendency for the AD-1 to roll out of the turn was more desirable than the tendency for the bank angle to increase. When increasing the load factor above 2.0 g's during windup turns, the left roll tendency would exceed the roll authority of the full right aileron unless the pilot used an increasing amount of right rudder.

Pilot ratings were obtained at several different airspeeds. Landings were performed with the wing at 45 degrees of sweep. Pilots noted that the approach and touchdown speed had to be increased slightly. The approach, flare, and touchdown were made with a slight right bank. At touchdown, the airplane generally rocked over until the left main gear touched the runway. The pilots concluded, however, that the approach and landing of the AD-1 were easily completed with the wing at a 45-degree sweep angle. In regard to flight evaluation, pilot ratings indicated that for all maneuvers, the performance of the AD-1 declined as the sweep angle increased. Some of the poorer ratings, however, related to tasks that were performed in light turbulence where the wind gust response of the airplane was typical of a low-wing-loaded aircraft. When gusts were encountered, the roll oscillations were large and roll damping was low.

Pilot ratings were also given to the handling qualities evaluated on a six-degrees-of-freedom simulator. Using the same tasks as used on the actual flight tests, the performance ratings given to the simulation of the basic airplane revealed the same trends as the ratings given to the AD-1 in flight. At 60 degrees of wing sweep, however, the pitch-damper-only configuration had better handling qualities than the basic airplane for all evaluation tasks. Likewise, the roll-damper-only configuration had better handling qualities than the basic airplane. A configuration of a pitch damper and a roll damper resulted in the best handling qualities. A yaw damper, however, appeared to have little, if any, effect. The above results on the simulator tests indicated that a control system using state-of-the-art technology could be tailored to produce a transonic oblique-wing airplane with satisfactory handling. In their concluding evaluation, McMurtry, Sim, and Andrew noted the following:

> The AD-1 flight test program has demonstrated the flight characteristics of an oblique wing configuration to 60° of wing sweep[;]
>
> Pilot evaluations indicated that acceptable handling qualities were experienced at up to 50° of wing sweep[;]
>
> An evaluation of control system augmentation on a fixed based simulator has indicated that significant improvements in flying qualities may be realized on an oblique-wing airplane to wing sweep angles of at least 60°[;] and
>
> The aerodynamic data derived from flight has verified the feasibility of utilizing aeroelastic tailoring to satisfy design cruise criteria.[41]

## Summary Review of the AD-1's Flight Experience

In 1983, Alex Sim and Robert Curry, following up on their TP 2222 (reviewed in chapter 2), reviewed flight operations with the AD-1 aircraft, including basic flight characteristics, both traditional and nontraditional; pilot ratings and comments; envelope-expansion flight results; and control-system augmentation.[42]

### Flight operations

Normally, the AD-1 was taxied using one engine to conserve fuel. Pilot ratings of 5 to 6 were obtained for single-engine taxi while ratings of 3 were obtained when both engines were running. Takeoff consisted of lifting the nosewheel at a speed of approximately 60 knots and holding a pitch attitude of about 3 degrees until takeoff occurred at a speed of about 85 knots. Prior to nosewheel lift-off, a slight forward stick pressure was often used to prevent nosewheel bouncing. Pilot ratings of 2 to 3 were obtained for takeoff. After takeoff, the aircraft would climb to 12,500 feet before research testing started. Since the best rate of climb was performed in the airspeed range between 100 knots and 120 knots, most of the climb was performed at a speed of 110 knots. The rate of climb at 3,000 feet was about 1,000 feet per minute. This rate decreased to about 660 feet per minute at 12,000 feet. Although the initial climbs to the test altitude were performed with a 0-degree wing sweep, the rate of climb remained reasonably constant to about a 35-degree wing sweep. The climb task usually received a pilot rating of 2. Most of the research flying was conducted at an altitude of 12,500 feet and terminated when the airplane dropped below 10,000 feet. Maneuvers were performed to expand the flight envelope for flutter, divergence, and loads; to analyze the aerodynamics; and to evaluate the handling qualities. Structural excitation for flight-flutter testing consisted primarily of stick raps. Maneuvers for the analysis of aerodynamics, flight loads, and handling qualities consisted of doublets, windup turns, slow sideslip variations, 1-g decelerations, pull-up push-overs, descents, and aileron rolls.[43]

Return to base consisted of a descent with the engines at idle and the wing at either a 0-degree or 45-degree sweep. The approach to landing was usually long and flat because of the moderately high lift-to-drag ratio and the high idle thrust. Speedbrakes or spoilers would have improved flying qualities but were not on the AD-1 because they were not considered necessary for either the research or flight operational tasks of the aircraft. An 80-knot touchdown speed was used to provide attitude that allowed for adequate forward visibility and avoided the scraping of the tail that occurred at a pitch attitude of 7.5 degrees. Pilots compared the landing of the AD-1 with that of a low-performance sailplane. Pilot ratings were usually a 3. A chase plane pilot augmented the AD-1's forward visibility and provided all nonresearch-related communications. Control room engineers monitored both the ground track and operational flight limits.

## Traditional characteristics

The maximum lift-to-drag ratio decreased at the higher wing sweeps, causing increased speed stability and decreased maneuver performance. Since verification of oblique-wing aerodynamic performance was not an objective of the AD-1 program, additional precautions were not taken to minimize drag. At initial climbout, the available thrust-to-weight ratio was approximately 0.20, and at test altitude, the thrust-to-weight ratio was approximately 0.16. These numbers indicate that the AD-1's performance was comparable to that of a light general aviation airplane. At airspeeds below 100 knots, the control forces were comparable to a low-performance sailplane. The transient response to a rudder input took about three cycles to damp out and was a result of the low directional stability derivative. As a result, the aircraft tended to wander or search directionally, and this characteristic became greater at high sweep angles and high angles of attack. For operational flying, the directional stability was considered adequate, although for precise maneuvering, the low directional stability often contributed to degraded handling qualities. The transient response to elevator inputs was nearly deadbeat, and the transient response to aileron input increased spiral instability. The spiral instability was primarily the result of the effective dihedral derivative and a strong positive value for the damping in roll due to the yaw-rate derivative.

## Nontraditional characteristics

In addition to traditional flight characteristics, oblique-wing configurations' handling qualities are affected by a number of nontraditional stability and control characteristics. With an increasing angle of attack, the resulting aerodynamic forces on a wing rotate forward and become approximately perpendicular to the wing-sweep angle. With an oblique wing, an increasing angle of attack creates a sideforce that must be neutralized by using either sideslip, bank angle, or a combination of the two in order to maintain a constant heading. In regard to the AD-1 sideforce problem, Sim and Curry noted in their technical paper that

> [m]ost of the apparent side-force and the resulting trim requirements could have been eliminated by tilting the wing pivot axis forward about 5 deg and increasing the unswept wing incidence to maintain the same unswept geometry....This modification would cause the bank angle of the wing to increase as wing sweep increased, thus allowing the fuselage to remain straight and level. This was not realized during the AD-1 design phase.[44]

For a trimmed flight, both the moments and the sideforce must be neutralized. This can be obtained by using a number of combinations of elevator, aileron, and rudder trim. At high wing sweep, the most common technique for obtaining trimmed flight was to use sufficient right (negative) rudder trim in order to allow the center stick to be laterally neutralized. At a 60-degree sweep and 140 knots, this rudder trim procedure brought about a trimmed flight condition with about 1 degree of nose-right (negative) sideslip and 7 degrees of right-wing-down (positive) bank angle.

In comparing the yaw of the AD-1 with the anticipated yaw based on wind tunnel tests of the spin model, Sim and Curry noted that

> [t]he AD-1 spin model had a "yaw into the leading wing" (yaw-right) established spin mode from which recovery was difficult without first unsweeping the wing. Reference 9 [in the report] also indicated that the AD-1 model with the wing highly swept would not sustain a spin into the trailing wing (yaw left). However, experience with the airplane has been that at low speeds, the trailing (left) wing stalled first and caused the airplane to roll and yaw left, away from the potential spin problem. If recovery were not attempted, indications are that the airplane would go into a steep spiral to the left. Rapid pull-ups to stall at high airspeed were not attempted.[45]

The report added that the "negative yawing moment increment due to load factor has an 'adverse yaw' effect for right turns and a 'proverse yaw' effect for left turns. Thus, right rudder was needed to coordinate either left or right turns."[46]

### Pilot ratings and pilot comments

Sim and Curry, as did other NASA engineers and pilots (discussed subsequently), also reviewed the pilot findings and comments from the actual flights of the AD-1. Pilot ratings were obtained from the envelope-expansion flights and from the guest pilot program flights. Ratings from the two pilots who flew the envelope-expansion flights, Thomas McMurtry and Fitzhugh Fulton, were obtained near the end of the flights after each pilot had previously flown in each rated flight condition. Pilots in the guest pilot program only had one flight in which to evaluate and rate the handling qualities of the AD-1, and their flight evaluations were obtained primarily for the trim task. Sim and Curry noted:

> Although the AD-1 geometry was chosen for its similarity to supersonic oblique-wing transport designs, many of the maneuvers performed to evaluate the handling qualities were not transport-aircraft maneuvers. For example, windup turns are often used to evaluate the capability of a maneuvering airplane. Because deficiencies in transport-aircraft handling qualities tend to be amplified in maneuvers like windup turns, these types of maneuvers are excellent for highlighting deficiencies and for ascertaining the need for stability augmentation.[47]

Flight envelope expansion tasks were performed for trim, descent, aileron rolls, windup turns, pull-up push-overs, landings at a 45-degree sweep, and turbulence encounters. For trim below 30 degrees of wing sweep, pilot ratings and comments indicated satisfactory handling qualities. Pilot ratings remained satisfactory at higher angles, but increased pilot compensation was required. Elevator trim authority runs out at airspeeds below 85 knots, requiring the pilot to hold back the stick. At sweep angles of 45 degrees and above, proper trim had to be used or it was possible to run out of aileron trim and even aileron authority. Due to these factors, the AD-1 was trimmed every 5 degrees of sweep for angles above 45 degrees. Pilots noted that at a 60-degree sweep, the aircraft exhibited "a little lateral hunting which required constant watch."[48] Pilot ratings and comments for descent maneuvers indicated that the AD-1 was generally satisfactory below 30 degrees of wing sweep but degraded at higher angles. One pilot noted that at a 60-degree sweep and an airspeed of 84 knots, there was "no problem holding the descent"[49] but that coming out of the descent, the AD-1 developed some pitch and roll "oscillations and cross couples."[50] The pilot added that at below 45 degrees of sweep, the task "required minimal compensation and did not produce significant coupling."[51] For aileron rolls, pilot ratings indicated that there was good command of bank angle with good roll rate and no tendency to overshoot at sweep angles lower than 45 degrees. At 30 degrees of sweep, only slight pitch coupling was noted, and at sweep angles of 45 degrees and higher, the AD-1 resisted rolling to the right and often required rudder action to adequately perform the maneuver. Pilots generally indicated that rolls to the left were slightly easier than rolls to the right, although there was a tendency to overshoot the desired bank angle. A number of pilot comments, however, indicated that the aircraft wandered (primarily directionally), making it difficult to maintain coordinated flight using the rudder.

Windup turns were the most difficult handling task because they required close attention to pitch, roll, and yaw. Below the 45-degree sweep angle, pilot comments indicated that there was no tendency to overshoot the desired g-force and that the maneuver required minimal pilot workload. Above the 45-degree sweep angle, however, the AD-1 exhibited different characteristics when turning right than when turning left. When the pilot increased bank angle to the right, the aircraft "seemed to want to roll out of the turn."[52] At 60 degrees of sweep, if proper rudder trim was not used, it was possible to run out of right aileron control authority before attaining the desired 1.5 g-force. When turning to the left, the aircraft would tend to roll farther into the turn than the pilot had commanded. This situation often required the right aileron to be held in place in order to counter the increased roll tendency. At a 60-degree sweep angle, liberal right rudder was often needed in order to roll back to a straight heading. Primarily during left turns, an oscillation would be superimposed on the maneuver, causing the pilots to refer to the maneuver as "jerky" or "ratchety," and proper rudder coordination could not cause a smooth maneuver.

While pull-up push-over maneuvers were not pilot-rated, pilot comments indicated that at low sweep angles, the AD-1 was able to attain a target g-level "quickly and precisely," but at sweep angles above 45 degrees, the maneuvers were "sloppy since cross controlling of pitch was necessary."[53] Several landings were made with the wing at a 45-degree sweep angle with pilot comments indicating "good control authority in all axes with no adverse ground effects,"[54] but the comments also indicated that forward visibility was poor and that a 3-to-4-degree bank was needed to maintain constant heading. Pilot ratings increased from 3 for 0-degree sweep-wing angle landings to 5 for 45-degree sweep-wing landings. The pilots also noted that throughout the envelope expansion, the presence of light turbulence degraded the handling qualities by two to three pilot ratings, often resulting in overall unacceptable handling qualities. The major cause of the poor turbulence response was the dynamics resulting from the wing aeroelastics.

## Control system augmentation

A stability augmentation system using rate feedback, though not implemented on the AD-1, was incorporated into a pilot simulation. This simulation was mechanized in a fixed-base, six-degrees-of-freedom simulator containing aerodynamic data. Using only one of the program pilots, pilot ratings were obtained from the unaugmented simulation at an air speed of 140 knots. The simulator test results indicated that a control system using only rate feedback was sufficient to yield acceptable handling-qualities ratings at high wing-sweep angles.

Sim and Curry concluded:

> The basic flight characteristics of the AD-1 airplane were discussed, including several stability and control characteristics that have either traditionally affected handling qualities or that are unique to an oblique-wing vehicle. Of particular significance were the low directional stability, the unusual trim requirements, the roll-pitch couplings, the dynamics resulting from the wing aeroelastics, and the stall. Pilot ratings that document many of the vehicle's handling qualities were presented. At or below 30 deg of wing sweep, ratings indicate satisfactory handling qualities. Between 30 deg and 45 deg of sweep, ratings increase, generally indicating the beginning of a degradation in handling qualities caused by wing sweep. The primary degradation in handling qualities occurred between 45 deg and 60 deg of sweep. Light turbulence degraded the handling qualities by up to three pilot ratings. A control system using rate feedback was mechanized on the AD-1 simulator. Simulation studies indicated that only rate feedback was necessary to yield acceptable handling qualities at the high wing sweeps.[55]

In a 1984 follow-on study to their earlier survey of AD-1 flight experience, Sim and Curry compared flight data with preflight predictions in order to provide, along with their two earlier studies, a complete aerodynamic data package for the AD-1 research vehicle.[56] This final paper reviewed wind tunnel data with flight data noted in the earlier reports and made comparisons and formulated their overall conclusions. The two NASA engineers concluded by noting,

> The flight results were compared with predictions based on wind tunnel model data. The correlation was generally good, although it was less favorable for the drag and yaw moment components. The data also indicated significant flow separation and spanwise vortex flow effects which were verified by flow visualization at high angles of attack.

> The static aeroelastically tailored wing design criteria resulted in minimal roll trim requirements at a 60 deg sweep design condition. The bank and sideslip angles required for trim were determined for the flight vehicle. It is suggested that optimal selection of the wing pivot axis angle could eliminate this requirement on future designs.
>
> The moment coefficient characteristics at higher load factors were also determined in flight. Longitudinal static stability was significantly reduced during elevated-g maneuvers. Increased wing stiffness would have improved the flying qualities of the airplane.[57]

As early as 1980, program team members had concluded:

> The oblique wing concept has potential applications, particularly as related to supersonic cruise vehicles. The unconventional aspects of the configuration require that a concentrated effort be made to prove that the potential indicated by theoretical and wind tunnel predictions can be realized in flight. The flight program described in this paper is only a minor step toward establishing the practicality of the configuration. An advanced vehicle should be developed and tests should be performed to extend operational experience and a full-scale data base into the supersonic regime.[58]

Indeed, NASA did proceed forward with a plan to move from the AD-1 program into the supersonic regime through the follow-up F-8 Oblique Wing Research Aircraft (OWRA) program covered in Chapter 5. The OWRA program overlapped NASA's F-8 fly-by-wire program that was a necessary step in the followup oblique-wing program due to the need for computer augmentation for a supersonic or transonic oblique-wing aircraft. NASA engineers, however, were not finished with the planned use of the AD-1 airplane. The engineers thought that the AD-1 aircraft, which actually had very limited flight use, would be an ideal test bed for analyzing the potential for joined-wing aircraft, and so this was the next—and final—direction that the AD-1 program took involving the small, low-cost airplane.

## Last Chance for the AD-1: The Joined-Wing Research Aircraft Effort

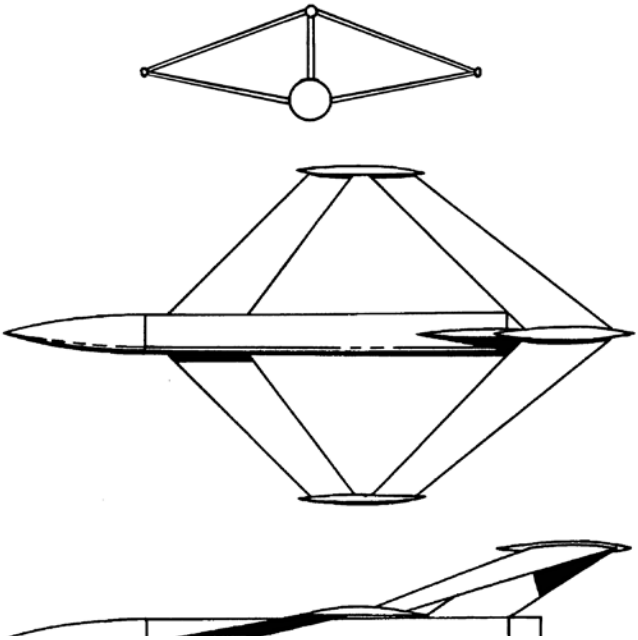
Following the completion of the AD-1's oblique-wing program, NASA Ames planned for the additional use of the AD-1 airplane as a joined-wing flight demonstrator. The oblique wing would be removed from the AD-1 and replaced by a joined wing, and the aircraft would be redesignated as the JW-1 Joined-Wing flight demonstrator or, in NASA shorthand, the JWRA (for Joined-Wing Research Aircraft). Basically, the "new" aircraft would utilize the fuselage, engines, and undercarriage of the existing AD-1. This arrangement was considered a more practical solution to building a separate low-cost proof-of-concept demonstrator. The aerodynamic design of a joined-wing demonstrator was accomplished by NASA Ames in collaboration with ACA Industries, of Torrance, CA, undertaken pursuant to a Small Business Innovation Research (SBIR) program consisting of the two following phases: Phase One was to complete a feasibility study for a joined-wing research airplane during 1984, and Phase Two was a 1986 contract to design and fabricate a joined-wing research aircraft based on the AD-1. The objectives of the joined-wing research program were to demonstrate good handling qualities on a realistic configuration and to validate existing design methods for joined-wing configurations.[59]

## The Joined Wing: An Overview

As defined in 1987 by Stephen C. Smith and Susan Cliff, of NASA Ames's Advanced Vehicle Concepts Branch, and professor Ilan Kroo, of the Aerospace Engineering Department at Stanford University:

> The joined wing is a novel aircraft configuration with a rear wing surface which acts both as a horizontal tail and as a strut brace for the forward wing. This rear wing is attached near the top of the vertical tail, and is joined to the trailing edge of the forward wing, typically somewhere along the outboard half of the span. The projected angle between the two wings created by the vertical separation between the two wing roots, when viewed from the front, allows the rear wing to act as a strut, providing bending-moment relief for the forward wing.[60]

The joined wing, as noted 2 years earlier by Julian Wolkovitch, a pioneer of the joined-wing concept and founder of ACA Industries, Inc., "incorporates tandem wings arranged to form diamond shapes in both plan and front views."[61] The joined wing has a long legacy of interest, with small-scale experimental examples dating to the early interwar period following the First World War. The attractiveness of the joined wing is precisely what Stephen C. Smith and his colleagues noted in the text above—namely, that it offers an ideal tradeoff between aerodynamic performance, weight, and structural efficiency. By combining the aerodynamic functions of a wing and a tail while combining the bracing function necessary to support a high-aspect-ratio wing, the



Configuration drawing of a joined-wing wind tunnel model evaluated by Rockwell, from CR 177543, 1989. (NASA)

joined-wing concept furnishes an opportunity for designers to fulfill a variety of possible civil and military mission applications.[62]

By the mid-1980s, the joined wing, if not necessarily the next big thing in aerodynamic design, offered the potential of a novel concept that, like the oblique wing, could furnish efficient, low-drag flight. A number of research and industry studies (including by Rockwell International, the former North American Aviation concern, the University of Kansas, California Polytechnic State University, Stanford University, and NASA) were under way to examine its possible application for a range of aircraft from agricultural crop dusters to transonic and supersonic aircraft.[63]

NASA's interest in the joined wing began when Wolkovitch approached Joseph Johnson of the Dynamic Stability Branch at Langley Research Center in 1979 to request cooperative testing of a propeller-driven agricultural aircraft concept conceived by the AD-1 designer Burt Rutan. The joined wing seemed particularly valuable for such an aircraft because the exceptionally rugged structure greatly enhanced the structural "crashworthiness" of the design—always a concern for crop-dusting aircraft. Accordingly, Langley tested the design in its 12-foot-low-speed tunnel, and the results encouraged further studies. Simultaneously, Stephen Smith, of NASA Ames, and Ilan Kroo and John Gallman, of Stanford University, were pursuing derivation of a structural and aerodynamic analysis code to ease analysis of joined-wing configurations. Their work eventually resulted in a mission-synthesis model that could be used to undertake vehicle optimization.[64]

As well as assisting in vehicle conceptualization, computational-based analysis played a significant role in refining understanding of the joined wing's aerodynamic performance. Indeed, traditional wind tunnel testing of the joined wing was not without difficulty, and the peculiarities of its design made it more suitable to the newly emerging field of computational fluid dynamics (CFD). In 1985, Wolkovitch explained,

> The structural design of joined-wing wind tunnel models has been a recurring source of difficulty. The wings of wind-tunnel models are typically machined from slabs of uniform (solid) material. Hence they do not have the optimum concentration of structural material… Relative to comparable "solid" cantilever wings, "solid" joined wings contain less volume of structural material, and it is not as well distributed to resist lift loads. The problem is compounded by the standard practice of using simple beam formulas to calculate stresses in wind tunnel models. This is adequate for cantilever wings but is not acceptable for joined wings. Any wind-tunnel program involving joined wings must include adequate stress analyses by finite-element methods, to check model safety and to predict aeroelastic deflections.[65]

In his advocacy of the joined-wing planform, Wolkovitch argued persuasively that

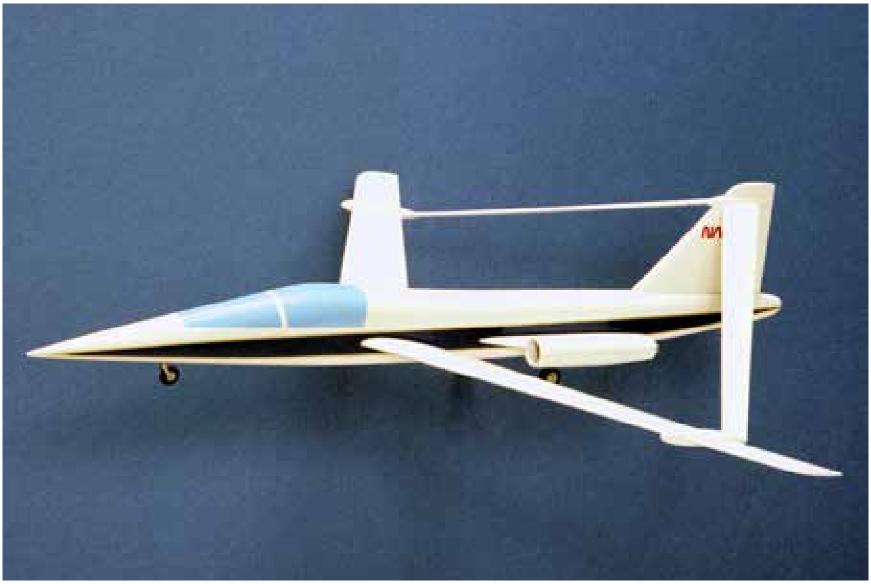
1. The joined wing provides advantages over a conventional wing-plus-tail arrangement, including lighter weight and higher stiffness, less induced drag, reduced transonic and supersonic drag, and built-in direct lift and sideforce capability.[66]
2. Experimental data show that the joined wing has good stability and control in normal flight and at the stall.
3. The joined wing can provide reduction in *parasite* drag through smaller *lifting surface* areas, reduced wing-fuselage interference, and stability for thin airfoils. These beneficial effects offset the effects of lower wing Reynolds Numbers, such that overall savings in parasite drag can be achieved.

4. Although the joined wing is synergistic with new developments such as composite materials, *laminar flow* airfoils, and *control configured* vehicles, it does not depend on new technology. Hence it can provide the above advantages with short development times and low risk.[67]

Initial NASA feasibility studies indicated that one of the most promising applications of the joined wing was a medium-range commercial jet transport. As a result, Agency researchers conducted a transport design study to determine what an optimized joined-wing transport should look like. An additional aspect of the design study was to quantify the potential fuel savings offered by the joined-wing configuration. An existing aircraft analysis and synthesis program, which had been developed to study the effect of tail size and stability requirements on direct operating costs of transport aircraft, was modified to include structural weight and aerodynamic models suitable for the analysis of joined wings. Eleven different design variables were selected for testing with the modified analysis and synthesis program. These included wing area, wing aspect ratio, wing sweep, wing-thickness-to-chord ratio (commonly expressed as "thickness-chord ratio"), wing taper, wing twist, tail area, interwing point location, tail-root height, tail twist, and tail taper. The mission requirement provided for a flight range of 1,500 nautical miles, a flight speed of up to Mach 0.80, and a capacity to carry 155 passengers. A balanced field length and second-segment climb were imposed for each selected aircraft configuration. Each candidate was permitted to operate at its best cruising altitude. Two aft-mounted engines with moderately high bypass ratios were appropriately sized for each design. The aerodynamic analysis used a vortex-lattice model of the nonplaner surfaces to compute the trimmed drag and static margin; an aerodynamic computation was used to determine the loading for structural weight estimation along with a simplified joined-wing structural model that was also used for weight estimation; and the high-angle-of-attack load conditions were examined with various fuel and passenger loadings.

The results of the above tests, which were confirmed by a followup study, were:

1. The optimal joined-wing design would exploit the inherently improved structural efficiency to increase the span so that the structural weight was comparable to a conventional configuration;
2. The optimum cruising altitude was somewhat higher than conventional transport configurations because of the higher aspect ratio and similar wing loading;
3. The wing sweep, wing area, and tail-to-wing area ratio were similar to conventional aircraft, and the optimum interwing joint location was at approximately 60% of the wing semispan; and

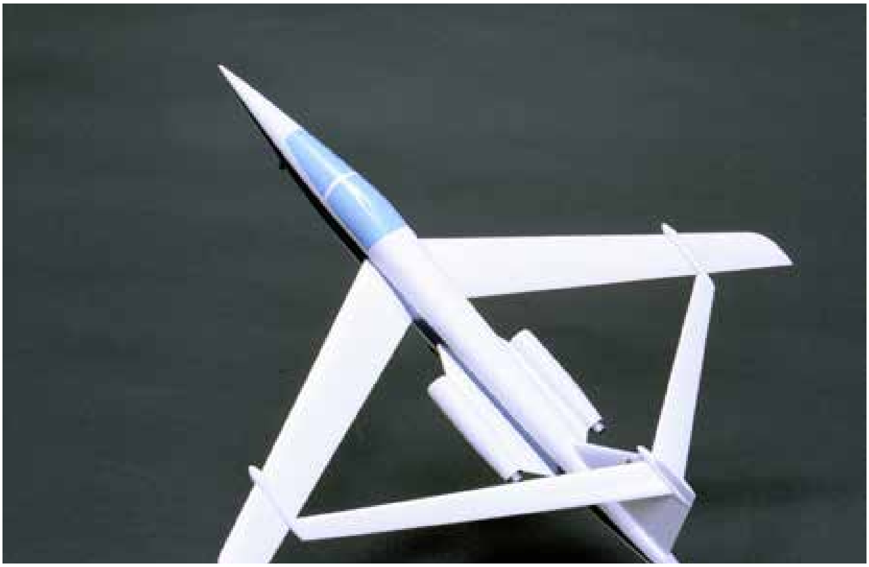


Side perspective of the proposed NASA-ACA JW-1 Joined-Wing Research Aircraft, 1987. (NASA)

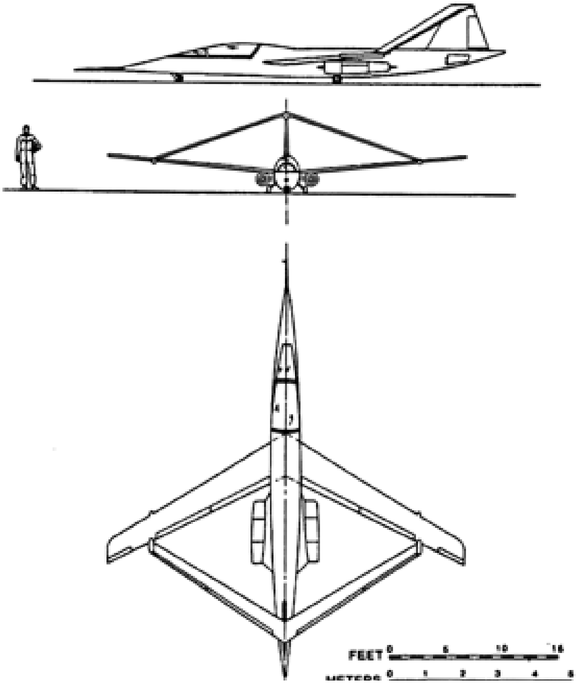
4. The tail aspect ratio was somewhat higher as a consequence of the joint location and tail area.[68]

## Modifying the AD-1 into the Joined-Wing Research Airplane

The goal of the planform design process was to find a joined-wing planform that was both representative of a commercial transport and satisfied the geometric constraints imposed by the AD-1 fuselage. The NASA Ames design study indicated that the basic planform should have the following design values: a wing sweep of 30 degrees; a wing aspect ratio of 14; a tail-to-wing area ratio of 0.30; an interwing joint location at 60 percent of the wing semispan; a static margin of 0.35; and a pair of dihedral angles for the wing and tail of 5 degrees and –20 degrees, respectively. The AD-1 fuselage, however, imposed several constraints on the planform design that would require modification of the aircraft. The existing vertical and horizontal tails of the AD-1 would need to be removed at a convenient fuselage bulkhead, and a new 15-percent-larger vertical tail would need to be installed 2 feet ahead of the original. The wing sweep would need to be increased to 30.5 degrees, and the tail would need to be swept forward 32 degrees so that the planform would fit the fuselage and vertical tail with the desired center-of-gravity location. Depictions of the former AD-1, as modified as the high-aspect-ratio JW-1 variant of the Joined-Wing Research Airplane, together with a three-view drawing of the medium-aspect-ratio JW-2



Top perspective of the proposed NASA-ACA JW-1 Joined-Wing Research Aircraft, 1987. (NASA)



Drawing of the proposed NASA-ACA JW-2 Joined-Wing Research Aircraft, from CR 177543, 1989. (NASA) variant with an interwing joint location at 80 percent of the wing semispan, are shown below.

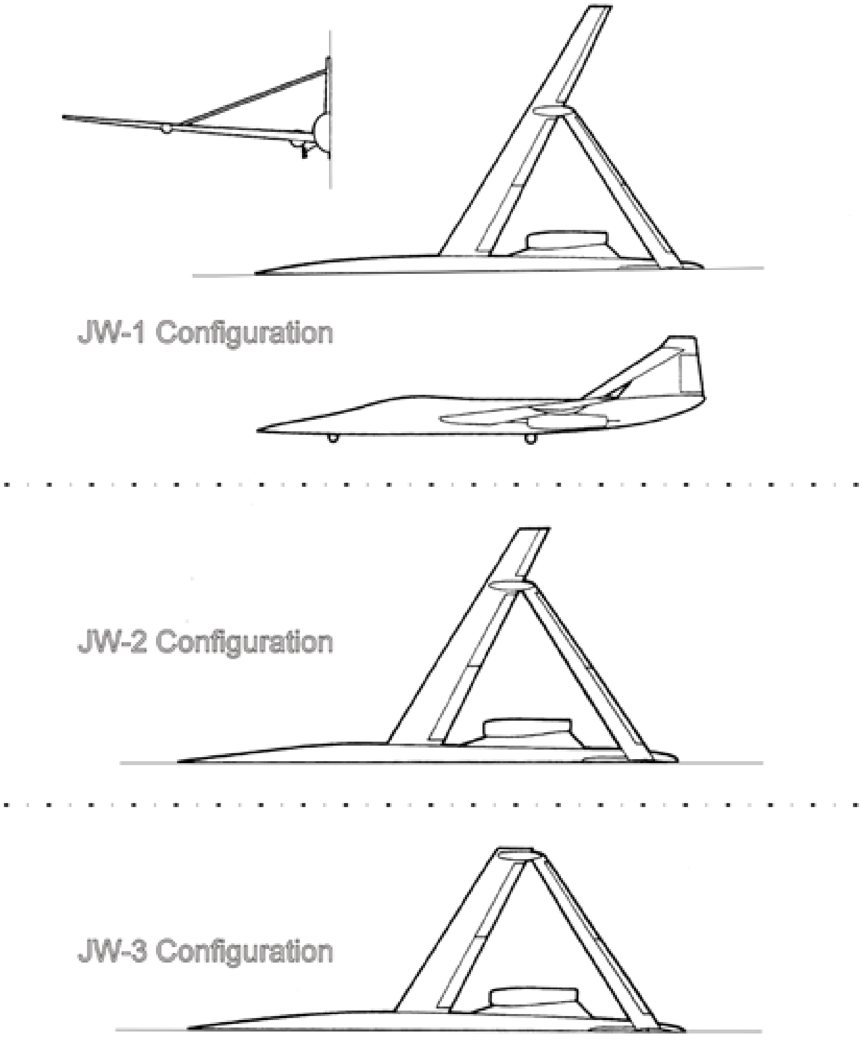
Once the fuselage modifications were determined, the wing and tail incidence distribution had to be addressed. The feasibility study assumed a linear wing twist to reduce computation time and determined the best twist for the cruise design point. A detailed design effort refined the wing incidence distribution to include a climb or maneuver design point, stalling characteristics, and fuselage constraints. Next, the total wing-system incidence was selected so that high lift coefficients for takeoff and landing could be achieved with no fuselage contact with the ground. In this regard, it was noted that the AD-1 landing gear was very short and that the aft area of the fuselage could contact the ground at 7 degrees of fuselage rotation. To start the design process, the completed joined-wing planform was used as an input to the MultOp computer program, which is an inverse, multilifting surface, vortex-lattice method of solving the incidence distribution that produces minimum-trimmed drag at a specified lift coefficient and static margin. As a result, the joined-wing planform was modified using 30 spanwise, full-chord panels for the wing and 18 spanwise, full-chord panels for the tail. Another important wing-design characteristic that needed to be analyzed was the lift-coefficient distribution that occurs near maximum lift. Special airfoil sections were designed for the JW-1 using two-dimensional airfoil design methods. The design goals for these airfoils were to maintain a conservative degree of natural laminar flow at cruise lift coefficients and achieve maximum section lift coefficients of 1.5 for the wing sections and 1.0 for the tail section. The airfoils, which were constrained to be 14-percent thick, were oriented perpendicular to the 25-percent chord line. The airfoils were designed using NACA 6-series airfoils that were modified to satisfy design objectives. Airfoil shapes were modified and smoothed using the PROFILE program, which permits the designer to add various analytical shape functions to alter an airfoil shape subject to a thickness constraint. Candidate airfoils were analyzed at their design-lift coefficient using PROGRAM H to predict forces, moments, pressure distribution, and the extent of laminar flow on the upper and lower surfaces. This program is a two-dimensional airfoil analysis program that uses the full-potential equations and the von Kármán integral boundary-layer solution. The CLMAX vortex-panel code was used to estimate the maximum lift coefficient of each airfoil.[69]

A one-sixth-scale wind tunnel model of the joined-wing aircraft was built at NASA Ames using the fuselage of the existing AD-1 wind tunnel model. This model was tested in the Ames 12-Foot Pressure Wind Tunnel to measure aerodynamic performance, stability, and control characteristics. The model was supported on a swept blade–type strut mounted on a bipod support system. The blade was swept back 50 degrees from the normal axis of the model and was contoured with a 15-percent-thick low-speed airfoil. The model had removable outer wing panels to represent three different joined-wing configurations—designated JW-1, JW-2, and JW-3.

The high-aspect-ratio JW-1 had outer wing panels installed at the interwing joint located at 60 percent of the semispan; the medium-aspect-ratio JW-2 wing had shorter outer panels so that the joint was located at 80 percent of the semispan; and the low-aspect-ratio JW-3 wing configuration had the outer panels removed so that the interwing joint was located at 100 percent of the semispan. The wing geometry was produced by locating each airfoil perpendicular to the 25-percent chord line and lofting straight lines between these defining sections. The joined-wing configurations were fitted with five control surfaces on each side, representing various arrangements of flaps, elevators, and ailerons. The vertical tail was fitted with a conventional rudder. The wings were designed so that small underside leading-edge fences (called vortilons) could be mounted at the three span stations, and the engine pylons were designed so that speedbrakes could be installed between the fuselage and nacelles.[70]

The testing conditions and procedures were done at the following numbers: Mach number of 0.35; a test Reynolds number of approximately $2.2\times10^6$/foot; a chord Reynolds number of approximately $1.0\times10^6$; the angle of attack was varied from –7 degrees to 14 degrees, and the angle of sideslip was varied from –5 degrees to +2.5 degrees. The testing results found that the joined-wing aircraft had acceptable levels of stability and control, especially with the vortilons installed, and that all of the control surfaces maintained sufficient effectiveness to control the joined-wing aircraft well above the stall angle of attack. A small speedbrake arrangement installed on the engine pylons was found to produce a significant amount of drag, which provided a convenient means of glidepath control for landing.[71]

Smith, Cliff, and Kroo noted that considerable attention was given to the stall characteristics during the design of the JW-1 because of its high-aspect-ratio swept wing without any leading-edge high-lift device. Wind tunnel data were used to evaluate stall characteristics by examining the change in pitching moment caused by small changes in angle of attack from a trimmed condition near stall. The tests revealed that the JW-1 model had a minor, unstable pitchup at stall that was addressed in the design phase by installing simple vortilons on the wings. The final conclusion in regard to these tests and the overview of the engineering team's testing of the JW-1 model was that "Good agreement of the test data with the design predictions confirmed that the relatively simple design methods used for the JW-1 *are* suitable for joined-wing configurations."[72]



The three JW-1, -2, and -3 wing planform configurations, from TM 101083, 1989. (NASA)

### "A Sorry State of Affairs": Termination of the AD-1/JW-1 Program

Due primarily to financial concerns relating to ACA Industries running out of SBIR funds to fabricate the JW-1 and to more limited issues involving operational safety and airworthiness concerns regarding the modified AD-1 aircraft, NASA terminated the joined-wing program just prior to the start of the AD-1 aircraft modification phase. In regard to program costs, William Ballhaus, Jr., noted in a June 1987 memorandum to NASA Headquarters that NASA Ames had examined a number of different management approaches to minimize the cost of supporting the program. NASA Ames had originally estimated that costs to support the program would be $7 million, which would include staff time, the cost of additional independent analysis, and various ground tests to ensure that the vehicle was airworthy. He added that a project team of 12 to 15 personnel would be necessary to work with the contractor and conduct or participate in various tests and analysis to establish the airworthiness of the vehicle to NASA standards. Ballhaus added that this total investment would be way out of proportion to the small investment by SBIR to complete the program. He noted further that a second study to reduce the cost and staff decreased the "bare bones" commitment to $1.5 million and fewer than 10 staff members, but even at this level, the approach was unacceptable. The letter contained a proposed solution to permit the program to continue by giving the problem of flight safety responsibility to ACA Industries. Ballhaus noted that "this is the only viable solution to our problem because even if we were provided the necessary funding, we could not properly staff the project without taking personnel from higher priority programs."[73] ACA initially considered assuming this responsibility but later said they were not able to accept the liability. Ballhaus also outlined some of NASA Ames's concerns regarding the use of the AD-1, stating that

> [t]he SBIR proposal of ACA Industries to construct and test a Joined Wing Aircraft by modifying the NASA AD-1 aircraft was approved approximately a year and a half ago. Since that time the contractor has completed a preliminary design and is currently finalizing his design in preparation for modification of the AD-1 to a Joined Wing Aircraft. We at Ames have supported ACA Industries with wind tunnel tests and independent analysis. We have also assumed Project Management responsibilities for NASA's efforts in the program and more notably also assumed flight safety responsibility. We did not take on flight safety responsibility without some soul searching, but we believed that we could not absolve ourselves of that responsibility since NASA was sponsoring the program. The magnitude of the funding and resource problem created by assuming flight safety responsibility is now very apparent and we believe, not acceptable.[74]

In regard to safety and his concerns about being overly cautious, Ballhaus concluded his memo by stating the following:

> [w]hether we care to admit it or not, the current post-*Challenger* environment will not allow NASA to take risks particularly with flight vehicles. NASA cannot survive many more flight accidents. This is really a sad situation for NASA. If you are not taking some risks, you are not taking big enough steps. You are not challenging the technology. If this situation continues, we will have to rely on someone else like ACA [NASA's industry partner in the joined-wing program] or DARPA [Defense Advanced Research Projects Agency] to take the risks and make the breakthroughs. A sorry state of affairs.[75]

In a September 12, 1989, memo from Milton O. Thompson, Dryden's chief engineer, to Theodore G. Ayers, Dryden's deputy director for flight operations and research, Thompson recommended that the AD-1, due to airworthiness concerns, be grounded and used only for display purposes. In his memo, Thompson noted,

> The AD-1 was last flown on Aug 7, 1982, over seven years ago. Since that time, the aircraft has been shipped around the country on numerous occasions, for use as a wind tunnel model and for static display. Although some care has been taken to avoid damaging the aircraft during these movements, we are aware of several incidents in which the vehicle was damaged during shipping… [The AD-1] has served its original purpose. The Government has received a substantial return on its investment and the vehicle should now be retired.[76]

Thus, as NASA's research on joined-wing planforms went forward, the AD-1 did not share in the journey.[77] Originally placed in storage on August 11, 1982, the AD-1 was transferred to Ames, where it remained on display until it was transferred, pursuant to a loan agreement, to the Hiller Aviation Museum in San Carlos, CA. There, it remains as of the date of this writing.

## Endnotes

1. W.H. Andrews et al., "AD-1 Oblique Wing Aircraft Program," SAE International, TP 801180 (1980), 3–4.
2. Ibid., 3–5.
3. Gene J. Matranga, "May 16, 1979, Memorandum to the Director of Dryden Flight Research Center," NASA Dryden History Office, box L3-4-4B.
4. NASA Official Biography, "NASA People: Thomas C. McMurtry," NASA Dryden Flight Research Center Web site, *http://www.nasa.gov/centers/dryden/news/Biographies/Pilots/bd-dfrc-p011.html*, accessed November 28, 2011.
5. NASA Official Biography, "NASA People: Fitzhugh L. Fulton Jr.," NASA Dryden Flight Research Center Web site, *http://www.nasa.gov/centers/dryden/news/Biographies/Pilots/bd-dfrc-p005.html*, accessed November 28, 2011.
6. Richard "Dick" Gray served as an aerospace research pilot at NASA's Johnson Space Center from November 1978 until November 1981, when he transferred to NASA's Ames-Dryden Flight Research Facility. In addition to one flight, as a guest pilot, on the AD-1 Oblique Wing Research Aircraft, Gray was a pilot for the F-8 Digital Fly-By-Wire and Pilot Induced Oscillations investigations. He also had flight experience flying the F-104 and F-15. He was fatally injured when his T-37 jet airplane crashed on November 8, 1982, during a spin-training exercise. Gray was a remarkable airman and one of the Navy's earliest (and finest) F-14 pilots, and his passing was a great tragedy.
7. See "Ames Dryden AD-1 (N805NA) Flight Log," Peter W. Merlin, compiler, December 2002, NASA Dryden History Office, box L1-3-7B, folder 1.
8. "AD-1 Makes Farewell Flight to Oshkosh," Dryden *X-Press*, NASA Dryden Flight Research Center, Edwards AFB, August 20, 1982.
9. Ibid.
10. Thomas J. Beutner and Richard P. Hallion, telephone conversation, December 7, 2011.
11. Joseph Chambers to Tom McMurtry (with copy to author), e-mail message, October 24, 2011.
12. These reports are in the historical archives of the DFRC.
13. The following items were excerpted from monthly "Projects Update" documents located in the NASA Dryden History Office archives, in box L3-4-4B. The citations to follow are identified by title and date.

14. “Projects Update—December 1979,” January 14, 1980, 4–5.
15. “Projects Update—January 1980,” February 1, 1980, 4–5.
16. “Projects Update—March 1980,” April 17, 1980, 6.
17. “Projects Update—April 1980,” May 12, 1980, 3–4.
18. “Projects Update—May 1980,” June 11, 1980, 4–5.
19. “Projects Update—September 1980,” October 9, 1980, 4.
20. “Projects Update—November 1980,” December 8, 1980, 4.
21. “Projects Update—January 1981,” February 6, 1981, 5.
22. “Projects Update—February 1981,” March 9, 1981, 5.
23. “Projects Update—March 1981,” April 8, 1981, 4.
24. “Projects Update—April 1981,” May 8, 1981, 4–5.
25. “Projects Update—May 1981,” June 9, 1981, 3.
26. “Projects Update—June 1981,” July 7, 1981, 3.
27. “Projects Update—July 1981,” August 10, 1981, 4–5.
28. “Projects Update—August 1981,” September 9, 1981, 3.
29. “Projects Update—September 1981,” October 8, 1981, 4.
30. “Projects Update—January 1982,” February 10, 1982, 4.
31. “Projects Update—March 1982,” April 9, 1982, 3.
32. “Projects Update—April 1982,” May 10, 1982, 6.
33. “Projects Update—May 1982,” June 10, 1982, 3.
34. “Projects Update—June 1982,” July 12, 1982, 6.
35. “Projects Update—July 1982,” August 9, 1982, 5.
36. “Projects Update—August 1982,” September 10, 1982. Apparently, Langley did not carry through with the plan to wind tunnel test the AD-1 as Center records reflecting such tests taking place have not been located. The author thanks Joseph Chambers for his tireless efforts to sort out the Langley side of this story.
37. Thomas C. McMurtry, Alex G. Sim, and William H. Andrews, “AD-1 Oblique Wing Aircraft Program,” AIAA paper no. 81-2354, presented at the first AIAA–SETP–SFTE–SAE–ITEA–IEEE Flight Testing Conference, Las Vegas, NV, November 11–13, 1981.
38. As recalled by Richard P. Hallion, who attended the presentation.
39. McMurtry, et al., “AD-1 Oblique Wing Aircraft Program,” 1.
40. Ibid., 2.
41. Ibid., 4.
42. Alex G. Sim and Robert E. Curry, “Flight Characteristics of the AD-1 Oblique-Wing Research Aircraft,” NASA TP 2223 (March 1985). The paper was completed in February 1983, published in March 1985, and held for general release until March 31, 1987.
43. Ibid., 4.

44. Ibid., 6.
45. Ibid., 4–7.
46. Ibid.
47. Ibid., 7.
48. Ibid., 8.
49. Ibid.
50. Ibid.
51. Ibid.
52. Ibid.
53. Ibid., 9.
54. Ibid.
55. Ibid., 9–10.
56. Robert E. Curry and Alex G. Sim, "In-Flight Total Forces, Moments, and Static Aeroelastic Characteristics of an Oblique-Wing Research Airplane," NASA TP 2224 (1984). This represented a final supplement to their earlier AD-1 studies. It was written in June 1983, published in October 1984, and held for general release until October 31, 1985.
57. Ibid., 9.
58. Andrews and Smith, "AD-1 Oblique Wing Aircraft Program," 6–7.
59. In an exchange of e-correspondence with the writer, Stephen C. Smith, a NASA aeronautical research engineer extensively involved in the joined-wing project, noted that in parallel with the NASA joined-wing project, there was substantial conceptual design optimization studies under way with Ilan Kroo and John Gallman, both at Stanford University, and Stephen C. Smith, at NASA. He added that John Gallman later joined NASA and, along with Smith, completed the research studies on the joined wing.
60. S.C. Smith, S.E. Cliff, and I.M. Kroo, "The Design of a Joined-Wing Flight Demonstrator Aircraft," AIAA paper no. 87-2930 (1987), 1.
61. Julian Wolkovitch, "The Joined Wing: An Overview," AIAA paper 85-0274 (1985), 20–21.
62. For a discussion of the joined wing, see Joseph R. Chambers, *Innovation in Flight: Research of the NASA Langley Research Center on Revolutionary Advanced Concepts for Aeronautics,* SP-2005-4539 (Washington, DC: NASA, 2005), 227–244.
63. Wolkovitch, "The Joined Wing: An Overview."
64. Chambers, *Innovation in Flight,* 233–234.
65. Ibid. Wolkovitch added that A. Shyu and H. Miura of NASA Ames performed comprehensive structural analyses of joined wings using

the EAL, SPAR, and NASTRAN computer programs. He noted that buckling was checked using the differential stiffness option of the NASTRAN computer model and NASA Ames was able to obtain usable wind tunnel findings.

66. Direct lift and sideforce control were topics of great interest in the late 1970s and into the 1980s, exemplified by research programs such as the F-16 Control Configured Vehicle (CCV); the Advanced Fighter Technology Integration (AFTI) F-16 (later Advanced Flight Technology Integration); and the NF-15B STOL Maneuvering Technology Demonstrator (the "Agile Eagle").
67. Ibid., 21–22.
68. Smith et al., "The Design of a Joined Wing Flight Demonstrator Aircraft," 2–3.
69. Ibid., 2–6.
70. Stephen C. Smith and Ronald K. Stonum, "Experimental Aerodynamic Characteristics of a Joined-Wing Research Aircraft Configuration," NASA TM 101083 (April 1989), 1–2.
71. Ibid., 9–10.
72. Smith et al., "The Design of a Joined Wing Flight Demonstrator Aircraft," 7.
73. William F. Ballhaus, Jr., memo to NASA Headquarters, June 11, 1987, NASA Dryden History Office, box L1-5-4, folder 8.
74. Ibid.
75. Ibid.
76. Milton O. Thompson memo to Theodore G. Ayers dated September 12, 1989, Milton O. Thompson papers, NASA Dryden History Office, box L1-5-8, folder 16. Unfortunately, Thompson died before he could be interviewed for this project, but Richard P. Hallion, who knew him well, is convinced that he must have been upset that the joined-wing AD-1 did not go forward. Thompson, a former Dryden research pilot of broad experience and great influence, was a strong advocate of such experimental programs and a veteran of several of them, including the Parasev and M2-F1 lifting bodies. He had advocated for many in his career. In his memo, he did acknowledge "a recurring interest" in modifying the AD-1 to a joined-wing configuration, which likely reflected his own wistful hopes.
77. See, for example, John W. Gallman, Stephen C. Smith, and Ilan M. Kroo, "Optimization of Joined-Wing Aircraft," *Journal of Aircraft* 30, no. 6 (November–December 1993): 897–905; John H. McMasters, David J. Paisley, Richard J. Hubert, Ilan Kroo, Kwasi K. Bofah, John P. Sullivan, and Mark Drela, "Advanced Configurations

for Very Large Subsonic Transport Airplanes," NASA CR 198351 (October 1996); and Robert C. Scott, Mark A. Castelluccio, David A. Coulson, and Jennifer Heeg, "Aeroservoelastic Wind-Tunnel Tests of a Free-Flying, Joined-Wing SensorCraft Model for Gust Load Alleviation," NASA Technical Reports Server (NTRS) Doc. ID 20110009997, Report/Patent No. NF 1676L-12256 (2011), *http://ntrs.nasa.gov*, last accessed November 30, 2011. This does not include numerous academic studies on the subject. The previously cited Chambers, *Innovation in Flight*, has a concise summary of NASA work after the AD-1 effort.

Rockwell concept for a Mach 2+ oblique-wing, twin-engine, two-seat, carrier-based, multimission fleet air defense fighter for the U.S. Navy's VFMX study effort, 1985. (NASA)

## CHAPTER 5

# Beyond the AD-1

## The F-8 Oblique Wing Research Aircraft

Coincident with NASA work on the AD-1, various companies had been studying possible application of the oblique wing for commercial and military aircraft. One such firm was Rockwell International. Rockwell was a company with a distinguished lineage, going back to the pre–World War II era and development of North American Aviation's T-6 trainer and the B-25 bomber. Then came the legendary P-51 Mustang, arguably the finest all-around, propeller-driven fighter ever built, and the postwar (and equally legendary) F-86 Sabre, of Korean War fame. Among other accomplishments, the company had produced the F-100, America's first supersonic jet fighter; the hypersonic X-15, its most successful research airplane; the Apollo spacecraft and the Saturn's engines; the OV-10 counterinsurgency airplane; the B-1 strategic bomber; and, of course, the Space Shuttle orbiter, its best-recalled achievement. But in the late 1970s and 1980s, it had its share of disappointments. Rockwell was unsuccessful in entering the stealth field, lost out to Grumman to build what became the X-29, and confronted a full measure of challenges with its B-1 and the Space Shuttle. And then there was the abortive XFV-12A thrust-augmented wing (TAW).

An ambitious attempt to produce a complex, experimental, vectored-thrust-and-augmented-lift Mach 2+ vertical/short takeoff and landing (V/STOL) fighter for the Navy, the XFV-12A used off-the-shelf components (including the nose of an A-4 Skyhawk and the basic wing structure and inlets of the F-4 Phantom II) joined to a complex suction and blowing system involving multiple vanes and flaps—the whole conglomeration powered by a single large jet engine. But when installed in the Impact Dynamics Research Facility (the former lunar landing test rig) at Langley Research Center for testing in 1978, its actual flow-augmented thrust proved insufficient for vertical flight. The sight of the huffing and puffing design, engine thundering away, inspired skeptics of the concept to unkindly dub its much-trumpeted thrust-augmented wing the "thrust-tormented wing."[1] The program died in 1981.

The North American–Rockwell XFV-12A augmented-wing V/STOL test bed at Columbus, OH, with its wing in VTOL configuration, 1978. (USN)

Rockwell hoped to have better luck with Jones's oblique wing, and it launched a study program for a Mach 1.8 Fleet Air Defense fighter (to meet a proposed Navy requirement to succeed the F-14) using either conventional bilaterally symmetric variable-sweep wings or an oblique wing, and it drew heavily on the aerodynamic design of the much larger variable-sweep B-1 bomber. Studies indicated that the oblique wing would be lighter and have greater range than an equivalent symmetrical-sweep design.[2] In retrospect, this large twin-engine, two-seat aircraft (dubbed "VFMX" after the Navy's shorthand for the program effort) was not in congruence with the Navy's plan for its fighter future, a future ultimately based on derivatives of the conventional McDonnell-Douglas F/A-18 Hornet. Nevertheless, for a brief period, the VFMX and Rockwell's design study influenced the course of NASA research on oblique wings.

One result of the Navy-Rockwell studies was a recommendation that NASA and the Navy jointly examine oblique-wing technology, leading to issuance of a joint NASA-Navy Memorandum of Understanding (MOU) executed in May 1984. From this, in November that year, evolved the Oblique Wing Research Aircraft program, which was created to develop and flight-test a supersonic aircraft equipped with an oblique wing. As mentioned in chapter 2, since the early 1970s, NASA already had anticipated the potential need for a supersonic research aircraft and had explored the possibility of using either the NASA Digital Fly-by-Wire F-8 research aircraft modified with an oblique wing or one of Dryden's F-104s. Of the two, the F-8 made greater sense, given the location of its wing and the ease with which it could be modified as well as its electronic (if rudimentary, at that point) fly-by-wire flight control system.

## Rockwell Confirms the F-8's Suitability as a Supersonic OWRA

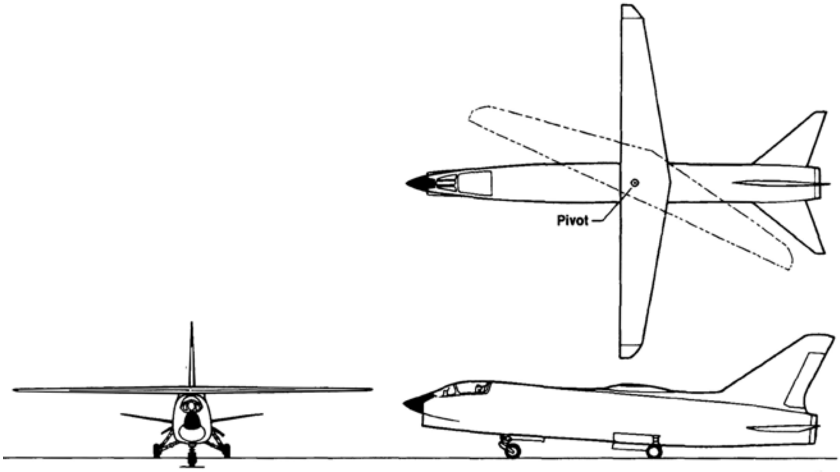
Accordingly, NASA contracted with Rockwell International for a feasibility design study of an F-8 Oblique Wing Demonstrator. Rockwell confirmed that the F-8 provided a unique capability in that its general configuration would easily allow modification for an oblique wing. The purpose of the study was to show the feasibility of modifying NASA's F-8 fly-by-wire aircraft for demonstration of high-speed oblique-wing technology. The study defined the size, shape, arrangement, and modifications of the demonstration aircraft as well as the limitations to adapting the F-8 DFBW aircraft to an oblique-wing demonstrator. It also addressed the design constraints of divergence, flutter, strength, minimum weight, control trim, and roll-pitch coupling. Rockwell noted that this was twice as many design constraints as required for other wing configurations. A subsystem feasibility review was conducted in order to study proposed modifications of flight control and supporting subsystems on the NASA F-8 aircraft. The study used as much of the F-8's existing subsystem hardware as possible within the requirements of still satisfying the goals of the demonstration program. Two finite element models were developed to support the design and analysis effort of the F-8 oblique wing.

Researchers of the F-8 OWRA sought the following goals:

1. The successful design, fabrication, and flight test of a composite, aeroelastically tailored, high-aspect-ratio wing at supersonic, medium-altitude flight conditions.
2. The confirmation of predicted performance benefits through a combination of experimental and analytical results.
3. The achievement of satisfactory handling qualities at combat conditions and improved low-speed characteristics compared to present-generation naval combat aircraft.[3]

The specific aerodynamic design goals of the F-8 OWRA were to eliminate roll trim at the design-point supersonic cruise (M=1.4 at 40,000 feet), minimize sideforce at the design point, minimize roll trim throughout the flight envelope, provide a stable aircraft at all flight conditions, and minimize trim drag throughout the flight envelope.[4]

The wing planform developed for the study differed from the transport wing explored earlier with the AD-1 and first postulated for the F-8 over a decade before. Instead of an elliptical planform, it was a high-aspect-ratio, high-thickness-ratio oblique wing with a straight leading edge and strongly



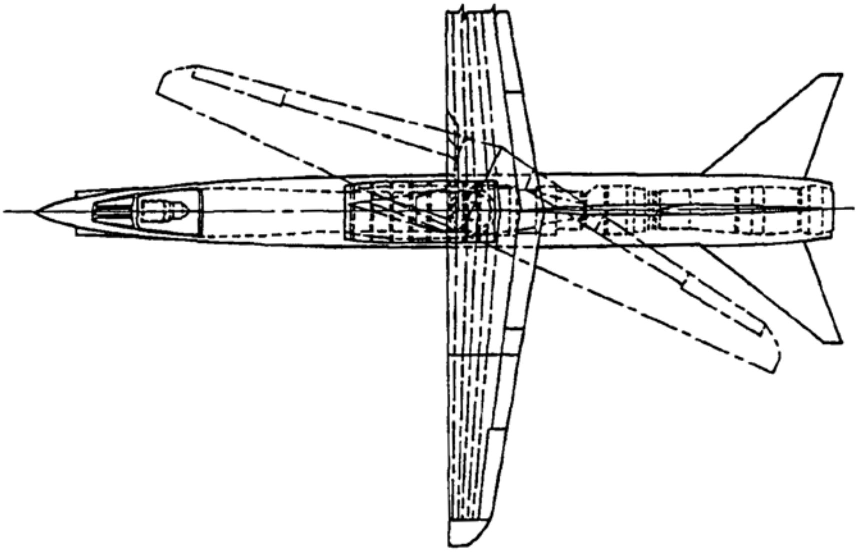
Rockwell Concept for an oblique-wing F-8 test bed, from TP 2874, 1988. Note the differences between this oblique-wing planform (with a straight leading edge and highly tapered trailing edge) and earlier 1970s concepts for an elliptical oblique-wing modification to the F-8. (NASA)

tapered trailing edge designed for two primary wing-angle positions—0 degree (straight) and 65 degrees (swept).

The underlying Navy Fleet Air Defense mission requirements for the airplane were long loiter time, high-speed dash, and carrier suitability. Aerodynamically, these requirements represented low-subsonic vortex drag, low-volume wave drag, and a high lift capability.

Rockwell's February 1, 1984, final report concluded:

1. The F-8 Oblique Wing Demonstrator has been preliminarily analyzed by the k-method for flutter and divergence and by the p-method for rigid body-wing structural mode coupling assuming a flexible wing and pivot, but with a rigid fuselage and empennage.
2. The structural modes have adequate flutter speed margins with respect to the critical flight condition of M=0.95 at sea level for the three skew angles analyzed (Λ=0, 45, and 65 degrees).
3. Adequate divergence speeds were calculated for yaw angles 45 and 65 degrees with respect to M=0.95 at sea level. For 0-degree skew, adequate divergence speeds were calculated with respect to M=0.60 at sea level.
4. Dynamic analyses of the flexible F-8 Oblique Wing Demonstrator with the wings swept 65 degrees with and without SAS [Stability Augmentation System] operating revealed no tendency toward body-wing structural coupling instabilities at the high dynamic pressure M=0.90 flight conditions investigated. Since dynamic pressure is the



Wing geometry at maximum and minimum sweep, and basic structural and internal layout, for a modified F-8 Oblique Wing Research Aircraft, from TM 86808, 1986. (NASA)

key aeroelastic parameter, these M=0.90 results are judged to be representative of the maximum Mach number flight conditions where the same high dynamic pressure exists.

5. More detailed analyses should be performed including flexible fuselage and empennage. The influence of fuselage should be investigated.
6. Although not considered as critical as the M=0.95 condition, analysis should be performed for supersonic mach numbers to determine flutter margins and characteristics.[5]

Rockwell noted that the above demonstrations were "to be achieved in a minimum cost program commensurate with the overall objectives [and that] the output of the program will be the confidence required to incorporate this technology in a future operational weapon system."[6]

## Oblique Wing Pros and Cons in Light of the AD-1 Experience

Developing a supersonic oblique-wing aircraft was eased by the experience of the AD-1 and the growing amount of tunnel and computational fluid dynamics data on oblique-wing performance, but it still involved significant challenges that made it far from a certain thing.

Four years after the AD-1 ceased flying, Ilan Kroo identified the challenges remaining after 30 years of technology development.[7] He noted that the results of the previous 30 years of research and testing illustrated the importance of the interaction between aerodynamics, structures, and controls in the overall design process. Kroo provided a concise assessment of the oblique wing, drawn from its evolution and historical experience, again noting both its advantages and ongoing challenges:

1. The oblique wing has reduced supersonic wave drag as compared with a conventional symmetrically-swept design. Fundamentally, this is due to the increased length of an oblique wing, which is twice as long as a symmetric wing. As the sweep angle increases, however, the differences are smaller so that the oblique wing might be more desirable at lower Mach numbers.
2. "In addition to the drag savings associated with the increased wing length, wing wave drag is also reduced by eliminating the 'kink' at the wing centerline where isobars are unswept and drag may be increased considerably. This difference is less apparent for wing and fuselage combinations, although even in this case the oblique wing system does not require such severe changes to fuselage cross-section to obtain a desirable area distribution."
3. There is also an important practical advantage provided by the utility of a variable geometry arising from the mismatch of configuration optimized for low speed and high speed flight. A variable sweep design permits exceptional performance at low speeds with important implications on reserve fuel requirements. The oblique wing provides a method of achieving a versatile and efficient aircraft over a wide range of operating conditions with smaller aerodynamic and structural penalties than with conventional variable symmetric sweep.[8]

In regard to advantages of oblique-wing variable swept aircraft over conventional variable swept aircraft, Kroo noted the following:

> Only a single pivot structure is required and the pivot is loaded primarily in tension, while each pivot of a conventional design must support the full root bending moment of each semispan. Similarly, the actuator loads are reduced since the aerodynamic forces on each side of the aircraft are balanced.
>
> Additional savings in structural weight and manufacturing simplicity accrue from the absence of a "kink" at the center section of the wing. This enables tip-to-tip composite material layups, straight, unbroken spars, and reduced fuselage carry-through loads.
>
> Furthermore, the centroid of the wing area need not change position as the wing is swept obliquely while symmetric change of sweep produces a rearward shift in center of pressure. This shift is in

> the same direction as the shift associated with supersonic flow and results in the well-known problem of excessive longitudinal stability for the variable sweep wings. The problem has been addressed in several ways, including outboard pivots, glove vanes, translating pivot mechanisms, and others—all of which introduce some mechanical complexity or reduce the effectiveness of the wing sweep.
>
> Finally, the high wing oblique design enables the wing to be "overswept" to angles that are not of use for efficient flight but which provide convenient storage and a low "spotting factor." [The latter is an extremely important requirement for carrier-based aircraft, as even on a so-called "supercarrier," flight deck and hangar deck space is at a premium].[9]

But as well as enumerating the advantages of the oblique wing, Kroo indicated the difficulties in acceptance of the concept, noting that while the oblique wing clearly offered many advantages, it had not won acceptance for an operational design. Kroo believed a combination of factors had worked to delay its introduction into operational service, noting the following:

> First the concept is extremely unconventional. There is a lack of precedent for asymmetrical designs leading to the perception of high risk, and the advantages, although numerous, are of a sort which are seldom properly recognized in a conceptual design study. Several more fundamental technical difficulties do, however, accompany the oblique wing concept and it is these that current research efforts are focused.
>
> The nearly complete decoupling of the longitudinal and lateral motions which arises in the case of symmetric aircraft in normal flight greatly simplifies their control. In the case of oblique wing aircraft, the motions are coupled by aerodynamic and inertial moments, requiring a non-intuitive combination of control inputs to produce desired maneuvers. This situation constituted a major obstacle to oblique wing development thirty years ago, but the development of automatic control systems has reduced the problem to the more tractable challenge of control law design.
>
> Another factor partially responsible for retarding the development of oblique wing aircraft was the concern over undesirable aeroelastic effects.... The phenomenon was investigated analytically and in free-to-roll wind tunnel tests at NASA Ames Research Center in the 1970s, demonstrating stable, controllable properties well above the clamped divergence speed. Thus,

> while aeroelasticity still introduces some complexity in control law design (rolling and pitching moments vary with load factor), and some dynamic instabilities are possible at higher dynamic pressures, the problems are not as severe as was first imagined.[10]

Kroo raised the three following questions in his 1986 paper: Could a control system be devised that would provide good, not just flyable, handling qualities? Are aeroelastic and structural considerations likely to be a problem at supersonic speeds and high dynamic pressures? Can an oblique-wing airplane truly operate efficiently over a wide envelope suggested by the conceptual design studies? He answered these questions by stating: "Sponsored jointly by NASA and the Navy, the Oblique Wing Research Aircraft Program is intended to answer these questions and provide the basic technology necessary to implement this innovative concept."[11]

## The F-8 OWRA Program

Following the numerous theoretical studies, wind tunnel tests, low-speed flight models, and, finally, the low-speed piloted demonstrator—the AD-1—NASA was well prepared to assist the Navy and Rockwell International in developing an oblique-wing supersonic aircraft using an F-8 airplane. A paper outlining the program objectives, the testing and experiments to be conducted, and the program schedule was prepared by Glenn B. Gilyard, NASA Oblique Wing Research Aircraft program chief engineer.[12] The specific objectives of the program were to establish the technology necessary to translate oblique-wing theoretical and experimental results into practical, mission-oriented designs; design, fabricate, and flight test an oblique-wing aircraft throughout a realistic flight envelope; and develop and validate design and analysis tools for asymmetric aircraft configurations. Based on the work of the AD-1 program that had preceded the OWRA program, NASA engineers considered an oblique-wing configuration to be well suited for a Navy Fleet Air Defense mission and for a civilian supersonic transport. Accordingly, the program was directed toward the development and flight testing of a full-scale supersonic oblique-wing demonstrator that would address key technological challenges.[13]

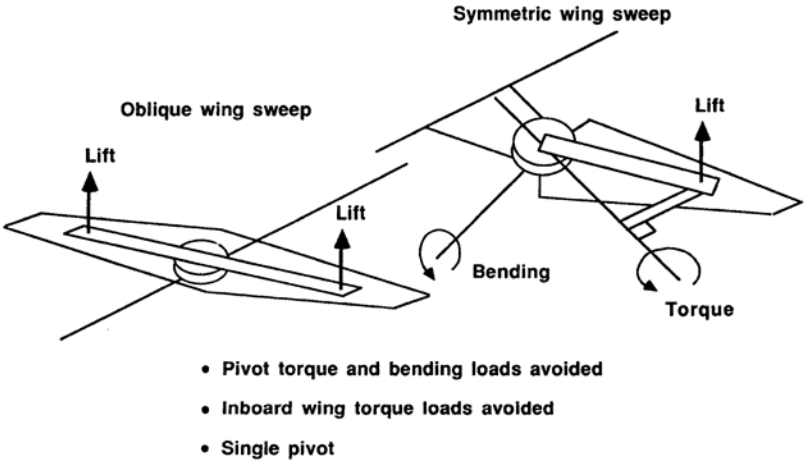
As noted above, theoretical studies had indicated that in supersonic conditions, the oblique wing has a significant advantage over symmetrically swept wings due to less wave drag because the wing volume is distributed over a greater length. In addition, an oblique-wing configuration does not produce the aerodynamic center shift that occurs in a symmetrically swept configuration. Both trim drag and tail loads are reduced, thus resulting in a lighter

F-8 OWRA configuration model depicted in flight, 1985. Note the "mirror image" wing orientation contrasted to F-8 OW studies a decade earlier, as well as its nonelliptical planform. (NASA)

structure and elimination of center-of-gravity control as a function of wing sweep. Also, an oblique-wing configuration has some significant structural advantages over a symmetrically swept-wing configuration. One pivot point, as opposed to two, results in cost and weight reduction and minimizes bending and torque loads transmitted through the pivot.

Preparation for the proposed F-8 OWRA required undertaking a variety of tests and experiments that were to be followed by others once it entered construction and proceeded into flight testing. These tests included the following:

1. Conducting a number of unsteady pressure measurement experiments to follow up on the excellent test results that had been obtained using an F-15 experimental aircraft. The F-15 was also used for unsteady pressure transfer function analysis.
2. Since the unique aerodynamic characteristics of oblique-wing configurations have the potential for producing unusual flutter-type characteristics and other instabilities, a flutter-model wind-tunnel test was planned to provide data for validation of aeroelastic analysis



Load advantages of a single-pivot oblique wing over a dual-pivot, symmetrical variable-sweep wing. (NASA)

codes prior to the first test flight and to support an efficient and rapid envelope-clearing process. There were also tentative plans to obtain limited unsteady pressure measurements for both code validation and correlation with flight results. In this regard, an interdisciplinary analysis code (STARS) capable of performing flutter and aeroservoelastic analysis was developed.

3. It was also noted that as the angle of attack increased, the F-8 OWRA would exhibit nonlinearities in all flight axes—at high wing sweeps the increase in spanwise flow and the formation of a leading-edge vortex can occur at relatively low angles of attack (6 to 8 degrees). Due to the asymmetry of the vehicle, these effects will not be balanced in the lateral directional axis. Furthermore, at higher angles of attack, areas of spanwise flow also form in an asymmetric pattern, generally progressing from the trailing wingtip. It addition to the above characteristics, which impact vehicle flight dynamics, other unusual features, including the interaction of parallel spanwise vortices on the leading wing panel, have been observed in water tunnel studies. Due to the above, program engineers determined that additional water tunnel studies needed to be undertaken. To address the above issues, a computational fluid dynamics analysis was under

way at Ames in Moffett Field, CA, to develop a Reynolds Navier-Stokes solution of the complete vehicle. During the flight-test program, unsteady pressure data would be used to identify vortex and regions of separate flow.

4. NASA project engineers also noted that an accurate determination of the deflected wing shapes in flight was required to validate the wing stiffness and load distribution predictions, which, because of the wing's unconventional attitude, could produce some unpredicted pressure distributions. Accordingly, the objective of these tests was to evaluate the ability of analytical codes to predict structural-loads deflections and pressure distributions. The approach was to measure in-flight deflections to correlate with predictions and define in-flight shape for correlation pressure data with CFD codes.

## Instrumentation for Unsteady Aerodynamics and Aeroelastic Research

The F-8 OWRA would, of course, differ considerably from the basic F-8 airframe. A variable skew wing and pivot assembly would replace the F-8's variable-incidence high wing. The original mechanical flight control system was completely removed. The existing all-moving F-8 horizontal stabilizer, operated symmetrically for pitch control, was to be modified to operate differentially for roll control as well, giving the airplane a so-called rolling tail, like the X-15, for use when the wing was so sharply swept that it could not employ wing ailerons for roll control. The modified flight control system included appropriate sensor sets, triplex control primary and backup digital computers, interface units, and secondary actuators that provided the commanded inputs to the primary actuators.[14]

The F-8 would, like all research airplanes, itself function as a research instrument, using the sky as its laboratory. Accordingly, NASA engineers planned to instrument it carefully to address the issues discussed above and others as well. In particular, fulfilling its role as a test bed for the examination of unsteady aerodynamics, it would have three special instrumentation systems for surveying unsteady pressures, flutter, and deflections.[15]

For measurement of unsteady pressures, researchers planned to install a pressure-sensing system capable of measuring both static and unsteady pressures via electronically scanned pressure modules arrayed in front of the forward-wing spar and aft of the rear-wing spar. They were particularly interested in studying flow effects and interactions when the wing was fully swept to 65 degrees with the left outer wing nearly overlaying the left horizontal stabilizer, and so in addition to the pressure orifices located in the

Flow distribution around a model of the F-8 Oblique Wing Research Aircraft with an experimental Ames wing design having unsymmetrical tip shapes, 1984. (NASA)

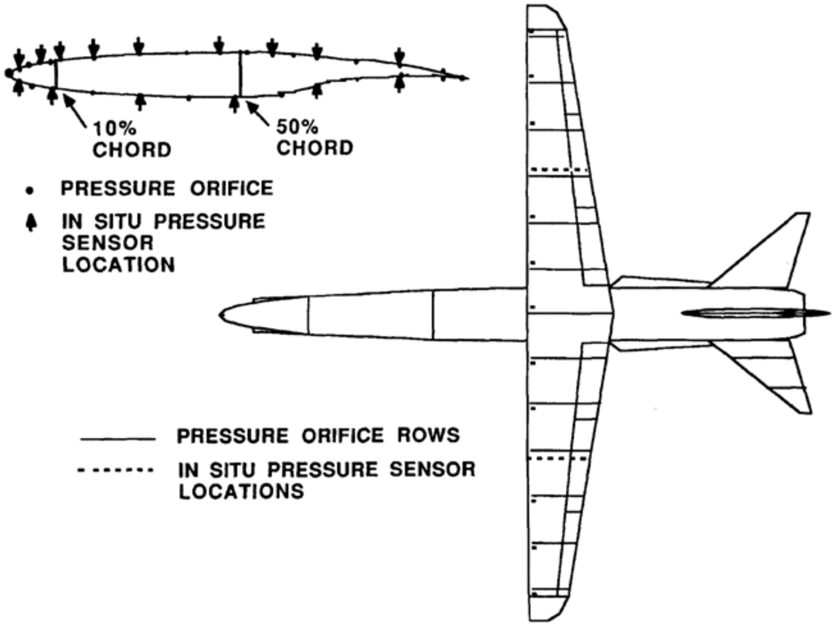
wing, pressures would be measured along two chord locations on the left horizontal tail.

To measure modal response and correlate predicted with actual flight-test results, the F-8 OWRA would have an array of accelerometers installed in the wing, fuselage, and left horizontal stabilizer. These would be employed to identify bending and torsion of the fuselage, leading-edge suction forces, and in-plane wing motions, contributing to understanding the oblique wing's flutter and aeroservoelastic stability characteristics.

The F-8 OWRA would also have an imaginative electro-optical flight-deflection measurement system to evaluate bending and twisting of the wing. Light-emitting targets (16 on each wing) located on the upper surface of the wing above the front and rear spars would be read by a light-sensitive receiver located in a raised, streamlined blister mounted on the top of the wing pivot. This system was designed to be removable, with engineers ensuring that it would not interfere with the complex static and unsteady pressure measurement system installed in the plane's wings.

## Preparing the Way Forward

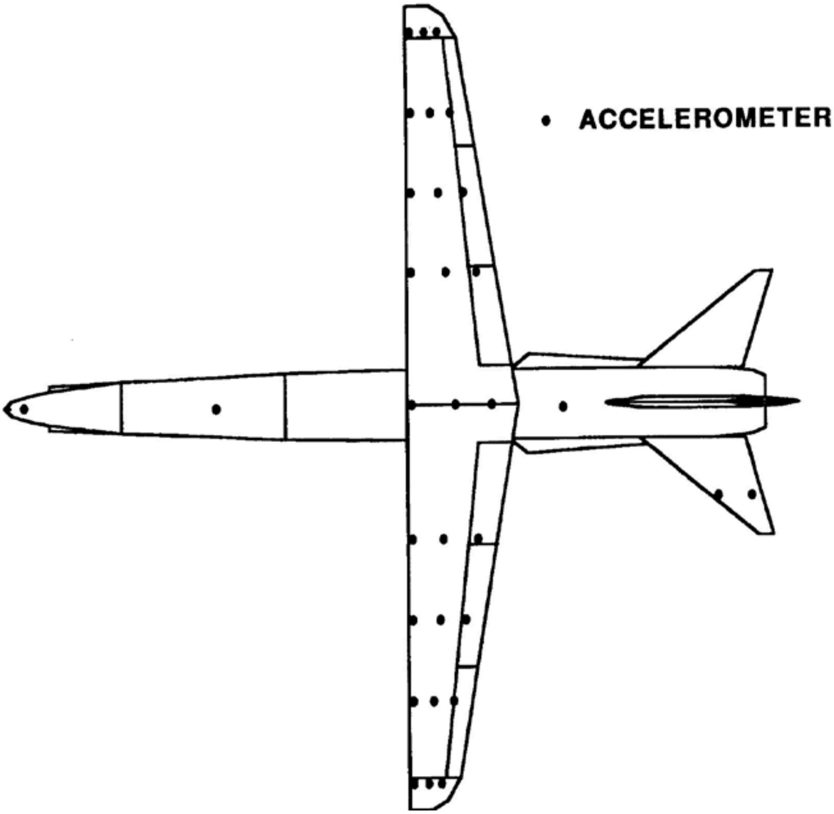
In a July 18, 1985, presentation to a subcommittee of the Congressional Advisory Committee on Aeronautics, NASA Ames presented a timeline and a proposed budget and funding program for the planned F-8 OWRA effort. This timeline stressed that the F-8 OWRA program was a planned supersonic



F-8 Oblique Wing Research Aircraft planned sensor distribution for measuring static and unsteady pressures. (NASA)

airplane followup to the earlier subsonic AD-1 Oblique Wing Research Aircraft program—effectively, an assurance to Congress that this did not represent some big new and ill-defined effort but rather that it constituted a logical extension of decades of previous work. The history portion of the presentation emphasized this earlier work, particularly the various design studies from 1972 and earlier through 1976, the wind tunnel tests from 1972 through 1976, the simulations from 1974 through 1976, the Remotely Piloted Vehicle flight program from 1976 through 1977, the AD-1 flight program from 1978 through 1983, and the proprietary studies from 1980 through 1984.[16] The planned OWRA project schedule provided for wing construction from July 1987 to July 1990 (the preliminary design phase was already completed); systems checkout from July 1990 to April 1991; and finally, a planned first flight in May 1991.[17]

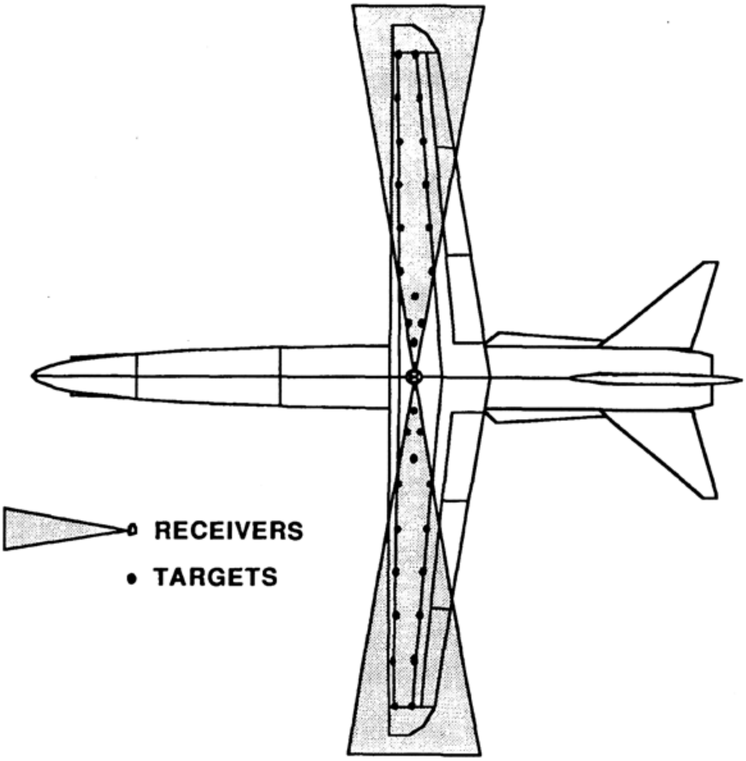
As noted in previous chapters, this historical background timeline, while a close approximation, was not the exact timeline actually followed by the AD-1 program. The F-8 portion of the timeline provided for the following: (a) feasibility and design work from 1983 through 1986 to modify NASA Dryden's TF-8C Digital Fly-By-Wire test bed aircraft to an oblique-wing aircraft, (b) modifications and flight testing of the TF-8C from 1986 through 1989, and (c) technologically ready-for-flight-test status by the end of 1989.[18]



F-8 Oblique Wing Research Aircraft planned accelerometer array to measure modal response. (NASA)

In regard to the budget and division of responsibilities between NASA and the Navy, under the terms of the NASA-Navy Memorandum of Understanding, a $36 million budget for fiscal year (FY) 1985 through FY 1989 was to be divided 50-50. The NASA responsibilities (via the Ames-Dryden Flight Research Center[19]) were program management and development and flight testing. The Navy responsibilities (executed via Naval Air Systems Command) included technology assessment for Navy applications and support development and flight testing.

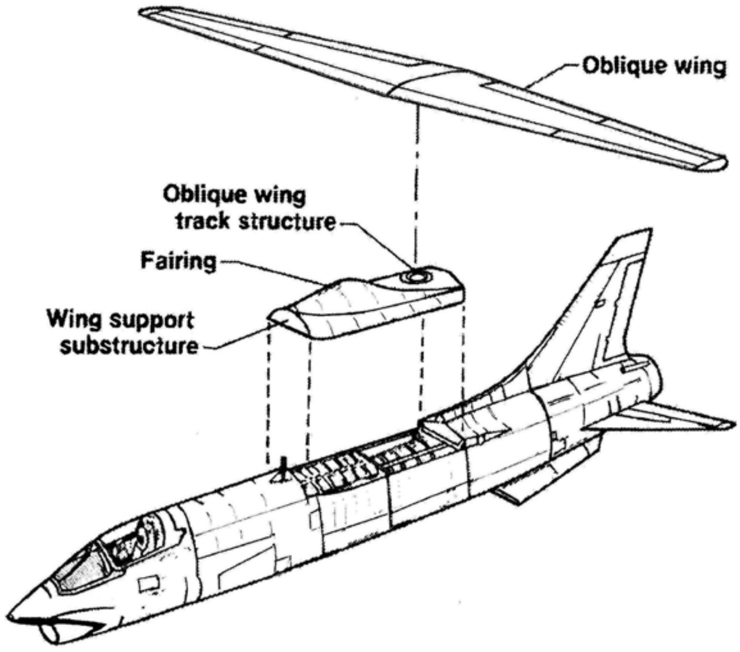
Rockwell's F-8 oblique-wing program manager was C.D. Wiler and the project engineer was S.N. White. Ron Murphy and Robert Traskos served as the Navy's program managers, and Erwin Roeser and Henry Lystad served as Navy project managers. For their part, NASA's flight research professionals looked forward to the chance to apply the oblique wing to the F-8, and



F-8 Oblique Wing Research Aircraft planned wing deflection measurement system. (NASA)

in announcing the initial staffing of the F-8 Oblique Wing program to the Dryden staff, Kenneth J. Szalai stated that

> I am personally extremely excited about this program. It has all the elements of an outstanding flight research program including the challenges in three aeronautical disciplines as well as an opportunity to further advance the state of the art in design of highly interactive systems. Tom Gregory has been working oblique wing technology for a decade at Ames North, and I share with him the expectation that Ames can and will play a significant role in developing this technology, which has a tremendous potential for strongly impacting future aircraft design.[20]



Component breakdown of F-8 Oblique Wing Research Aircraft. (NASA)

To run the program, one of Dryden's most experienced flight testers, Cal Jarvis, was appointed acting project manager, with Tom Gregory his deputy project manager. A core research engineering group was formed under Mike DeAngelis. The engineering group was "chartered to lead the Dryden technical effort in planning the experiment, participating in the joint North-South vehicle syntheses activity, and in preparing the statement of work."[21] Additional research engineering staff would be "matrixed to the project in the normal manner."[22] The initially designated team members were John Bresina (simulation), Harry Chiles (instrumentation), Robert Curry (aerodynamics), Glenn Gilyard (structural dynamics), Dale Mackall (flight systems), and Joe Pahle (flight controls). All of these people were experts in their field, their expertise honed by having worked other programs with shared interactions and responsibilities.[23]

## Challenges: Cross-Coupling, Flutter, Controls, and Simulation

As the F-8 effort went forward, engineers and researchers confronted a series of explicit technical challenges, including the inherent longitudinal-lateral (pitch-roll) cross-coupling encountered with any oblique-wing vehicle, the unique flutter characteristics of oblique wings, the development of flight control technology and software for the OWRA, and the process of undertaking simulation.

### Cross-Coupling

NASA engineers Robert W. Kempel and Joseph W. Pahle, together with Gurbux S. Alag, an associate professor of electrical engineering at Western Michigan University, studied the problem of cross-coupling related to asymmetrical oblique-wing aircraft. While recognizing the "substantial aerodynamic performance advantages"[24] offered by oblique wing aircraft, they also noted (as earlier engineers likewise had recognized) that the oblique wing "has significant aerodynamic and inertial cross-coupling between the aircraft longitudinal and lateral axes."[25] As a result of their studies, they developed a technique for synthesizing a decoupling controller while providing the desired stability augmentation. They noted that then-current typical design procedures synthesized aircraft controllers based on 2-degrees- or, at most, 3-degrees-of-freedom solutions but that the NASA-Navy OWRA program had to address at least 5 degrees of freedom simultaneously.

This study team recognized that a significant component of the OWRA program would be the synthesis of a control system that would provide acceptable stabilization and decoupling across the F-8's "Mach [number, M], angle-of-attack [AoA, $\alpha$,] and wing-skew [sweep angle, $\Lambda$] envelope"[26] and that NASA's F-8 DFBW aircraft offered the opportunity to apply modern control theory techniques for solving problems associated with oblique-wing aircraft. They added that model-following has been a popular method for the design of multivariable control systems and that "[i]n this method, the desired behavior of the plant is provided by an ideal model, and that the problem is one of designing a suitable controller for the plant so that its response follows that of the model."[27] The three engineers proposed to integrate two previously developed techniques—the Yore model and the eigenstructure assignment. In the Yore model, the synthesis procedure consisted of constructing an ideal model, designing feedback gains by quadratic optimization, and designing feed-forward gains. The noted disadvantage of this procedure, however, was that the method of selecting the feedback gain is an "iterative and time-consuming process"[28] and the determination of the gain becomes a more complex problem when all states are not available, thus causing output feedback to be used. The eigenstructure assignment technique involves interpreting the performance specifications in terms of the eigenvalues and eigenvectors or the closed-loop system.[29] The study added that J.R. Broussard and P.W. Berry used the equivalent of this technique to the design model-following systems.

Alag, Kempel, and Pahle defined the model-following problem as follows:

> The concept of model-following is useful when an ideal set of plant equations of motion can be specified. The ideal objective of model-following flight control is to force the aircraft to respond as the model would to a given pilot command. It is often desirable to simulate the model dynamics in the flight computer and to generate the aircraft control signal using the aircraft outputs, the pilot input commands, and the model states. This situation is sometimes referred to as the pilot flying the computer, while the computer is flying the aircraft....There are two configurations of model-following, one is implicit model-following, and the other is real model-following (RMF). In implicit model following, the model is part of the system. In RMF, however, the model is part of the system as control law requires the states of the model. The technique of RMF has been shown to be amenable to the solution of many aircraft control problems.[30]

The study team, while noting that the conditions for perfect model-following are not attainable, pointed out that Y.T. Chan derived an asymptotic RMF control law for the class of plants and models whose output vectors are identical to their state vectors. Chan, therefore, showed that, even if the conditions for perfect model-following are not satisfied, the use of perfect model-following gains can yield a control capable of keeping the error between the model and plant to a small region of state. Next, the team noted two widely used synthesis techniques of modern control theory—linear quadratic regulator design and the modal control theory involving pole placement or eigenvalue assignment. The team pointed out that the difficulty in incorporating specifications such as damping, natural frequency, and decoupling within the quadratic performance index makes the eigensystem synthesis procedure a "promising design alternative"[31] and that other engineers have successfully demonstrated the use of the eigenstructure assignment procedure for aircraft control system design.

As a result of their investigation, Alag, Kempel, and Pahle concluded,

> A method is presented to obtain a decoupled control for a highly coupled asymmetric aircraft. The method utilizes a real model-following control law in which gains for perfect model-following

> are used even when the conditions for perfect model-following are not satisfied. The feedback gain, using output feedback, is computed by using eigenstructure assignment. The results indicate that the method does obtain the decoupling incorporated in the ideal model for the flight condition considered.
>
> Future investigations will be conducted to evaluate the control algorithm under nonlinear 6-degree-of-freedom flight conditions. These investigations will consider such factors as nonlinear aerodynamic data, control system surface rate and position constraints, and system hysteresis.[32]

## Addressing the Challenge of Flutter

Flutter has been an insidious problem in aeronautics since the earliest airplanes. The advent of the monoplane highlighted the dangers of control surface and tail and wing flutter. Flutter can take many forms, and it persists through the hypersonic regime, even affecting extremely robust flight structures. With this legacy of danger, it is understandable that NASA's aeroelastic and structural researchers took the risk of flutter with the proposed F-8 OWRA very seriously.

John J. Burken and Glenn B. Gilyard, NASA Ames aerospace engineers, and professor Gurbux S. Alag (who also worked on the cross-coupling problem reviewed above) addressed the challenge of oblique-wing flutter, examining a mode that develops under flight conditions of Mach 0.70 and altitudes of 3,048 meters (10,000 feet).[33] The three engineers identified the following problem to be solved:

> The unsymmetric configuration and forward sweep of one semispan result in aeroelastic behavior distinctly different than that of straight, swept-back, or swept-forward wings. It should be noted that in addition to unsymmetric modeling characteristics, unsymmetric configurations will typically have significantly larger plant formulations since all degrees of freedom must be adequately represented. Separation of an unsymmetric model into two smaller models (as is possible for symmetric and antisymmetric modes of a symmetric aircraft) is not possible, because the response motion is coupled and not separated.[34]

In order to evaluate the analytical tools required for the analysis of an oblique-wing configuration, the researchers developed a generic skewed-wing model of the aeropanels and node points with a wing-skew angle of 45 degrees operating at M=0.70 and 10,000 feet. The objective of the testing was to

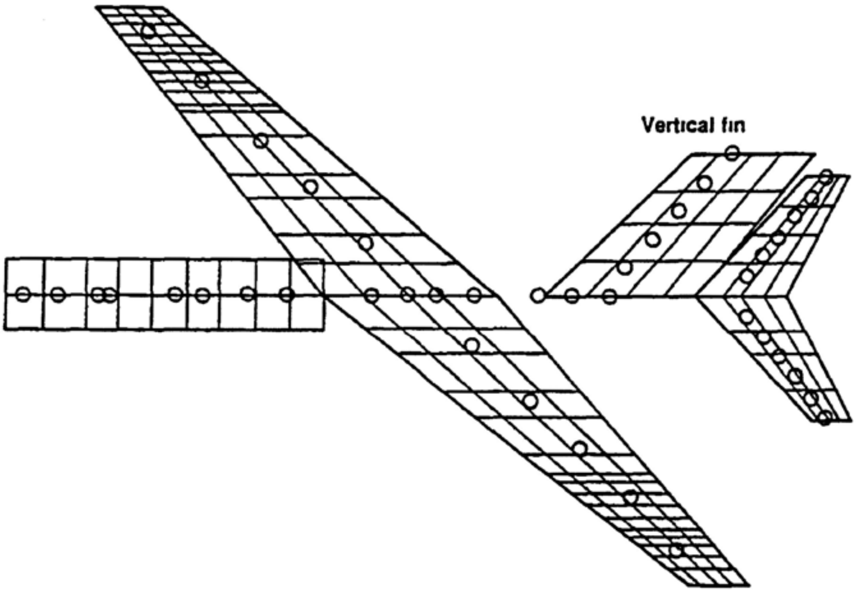


Fig. 2 Generic model (aero panels and node points). Vertical fin shown in X-Y plane.

Generic 45-degree skewed-wing model using simple beam representation of the F-8 Oblique Wing Research Aircraft wing and fuselage, from TM 86808, 1986. (NASA)

demonstrate the control synthesis design process required to develop a practical control law for stabilization of the oblique wing's flutter mode. The process involved the formulation of the state-space model, including the independent wing actuators, a Dryden gust model,[35] and the S-plane approximations of unsteady aerodynamics; optimal full-scale-control-law determination; robust output-feedback control-law determination; reduced-order (practical) control-law formulation; and critical evaluation of the practical control law.[36]

The model used in the system synthesis process was a simple beam representation of the fuselage and wing. The aircraft aeroelastic characteristics were modeled using the now-common NASTRAN computational analytical tool. At the assumed flight conditions, the unaugmented aircraft had a flutter mode characterized primarily by wing bending but with some torsion. The formulation of the complete, integrated (structures, aerodynamics, and controls) state-space model for use in the analysis and design process followed the Peele and Adams process. Left- and right-wing actuators were modeled independently because the synthesis process determined unique control laws for each surface. The active control synthesis was based on LOG theory modified to accommodate the high-order model of the aircraft. The design process involved the following steps: state-space-model generators, full-state-feedback design, estimation of states from available measurements, and development of the reduced-order controller.

The engineering team's conclusions were:

> An implementation flutter controller for the 45°-skew oblique-wing aircraft mathematical model was designed using the LOG design methodology. Kalman estimators produced low stability margins, however, the Doyle-Stein procedure for robust estimator design can be used to improve these margins to acceptable values without excessive surface activity. A modal residualization technique was used to obtain a reduced-order controller that satisfied the performance requirements and can be implemented.[37]

The bottom line was simply this: the team had evaluated a potentially serious danger-to-flight flutter mode, creatively explored how to address it, and, using complex mathematical analysis, developed a flight control law that could be implemented by the F-8 OWRA to suppress the flutter before it reached potentially dangerous divergent levels.[38]

## Ensuring Adequate Flight Control for the F-8 OWRA

In 1986, Dale F. Enns and Daniel J. Bugajski, of the Honeywell Systems and Research Center, and Martin J. Klepl, of Rockwell North American Aircraft Operations, reviewed the development of multivariable control laws for the F-8 Oblique Wing Research Aircraft. They noted that the aircraft control laws were scheduled for piloted moving-base simulations at NASA Ames for early 1987 (subsequently discussed). It was crucially important that the control laws decouple the longitudinal from the lateral directional motions of the F-8 aircraft. If not, all motions of the highly skewed oblique-wing aircraft would be highly coupled, seriously degrading its performance and preventing satisfying conventional handling-qualities specifications. Other objectives for control of the aircraft were gust attenuation, desensitization, good command tracking (a measure of precise flight control), stability augmentation, good handling qualities, and stability robustness with respect to model uncertainty.[39]

The control laws were developed using a loop-shaping methodology involving three loops—roll, pitch, and yaw. There are five control-surface actuator commands—left elevator, right elevator, rudder, left aileron, and right aileron. There are seven sensor outputs—roll rate, pitch rate, yaw rate, lateral acceleration, normal acceleration, roll angle, and pitch angle. A matrix transfer function combines the seven sensor outputs into three regulated variables that represent the basic flight control objectives for the three axes. The pilot commands the roll variable with the lateral stick, the yaw variable with the rudder pedals, and the pitch variable with the longitudinal stick. A number of different models, which were all obtained through Rockwell, were used for the control-law development. The simplest model was a standard eight linearized model of the rigid-body dynamics. The most complex model used was a simulation of the aircraft dynamics, including nonlinear kinematics and aerodynamics as well as actuator dynamics. This simulation model was used for assessing the performance of the control laws in the presence of nonlinearities. The pilot objectives were identified as maintaining wing level, heading hold, altitude hold, and velocity hold. Care was taken to maintain bandwidths within the limits of what a human pilot could perform. Bandwidths were selected at 1 radian per second for heading and bank angle, 0.5 radian per second for velocity, and 0.3 radian per second for altitude.

Enns, Bugajski, and Klepl summarized their investigation by noting,

> The loop shaping procedure for designing the control laws was presented. The performance and stability robustness objectives for the control laws were presented in terms of singular values and structured singular values of specific frequency responses. The handling qualities of the closed-loop system were analyzed with the equivalent systems technique. Time histories of the closed-loop response to pilot inputs were examined. The analyses using highest fidelity models available showed that the design goals were achieved.[40]

## Simulations of Decoupling Control Laws and OWRA Motions

Simulation has always played a significant role in flight testing and flight research, both for its own sake and as a tool for research into how a new aircraft will behave. Thus, it is not surprising that NASA Ames undertook an extensive simulation of the proposed F-8 Oblique Wing Research Airplane, using the Center's large Vertical Motion Simulator, to evaluate the decoupled handling qualities of the proposed flight control system. When combined with expert opinion from test pilots "flying" the simulator, the Vertical Motion Simulator provided a valuable means of realistically evaluating the preliminary handling qualities of the oblique-wing research airplane. The Vertical Motion Simulator, in conjunction with realistic large-motion and visual-simulation systems, provided a unique capability to investigate the OWRA's anticipated dynamic characteristics early in the control system design phase.

The goals of the simulation tests were to obtain preliminary pilot evaluations of a prototype flight control system designed to provide decoupled handling qualities, identify important response variables in the evaluation of the oblique-wing configuration, and develop criteria and requirements for use in future control laws for highly coupled airplanes. Accordingly, five discrete flight conditions were evaluated, ranging from low-altitude subsonic Mach numbers up to moderate-altitude supersonic Mach numbers.[41]

Six pilots participated in the evaluation with each required to perform a variety of maneuvers and tasks and to provide pilot ratings for each maneuver. The control law was a prototype system based on the loop-shaping approach with the objectives of decoupling the longitudinal and lateral directional motions of the aircraft as well as satisfying the conventional flight control objectives, including gust attenuation, stability augmentation, good command tracking, good handling qualities, and stability robustness. All simulation flights were flown at a fixed wing skew and were limited to relatively small variations in Mach number, altitude, and angle of attack. The study team noted the following:

1. The results of the evaluation should be considered preliminary and not necessarily characteristic of a final OWRA configuration or typical of an operational oblique-wing configuration;
2. The preliminary aerodynamic data base used was for a wing area that was only 67% of the most recent OWRA wing design and that since cross-coupling is largely dependent on angle-of-attack change required for maneuvering, the increased wing area would be expected to result in reduced coupling; and
3. The five flight conditions selected for evaluation were at moderate to high dynamic pressures that would tend to aggravate unusual dynamic characteristics.[42]

The weight of the NASA DFBW F-8 ranged from a loaded weight of 23,500 pounds to an empty weight of 18,800 pounds, and the simulation study used a weight of 21,116 pounds, which represented 50-percent fuel loading. The airplane's aerodynamic controls consisted of the following movable surfaces: wing ailerons for roll control,[43] symmetric and differential stabilizer for pitch and roll control, rudder for yaw control, and flaps.

Based on the simulation testing and analysis of the data, the study team reached the following conclusions:

1. Participating pilots were unanimous that the high levels of sideforce or lateral acceleration in pitch maneuvers were unsatisfactory.
2. Pilots were more critical of left turns than they were of right turns. At the higher dynamic pressure conditions, the difference was as much as 2 pilot ratings. Pilots indicated that the airplane rolled into

the bank angle in left turns and rolled out of the bank angle in right turns.

3. Pilot comments and ratings deteriorated with both increasing wing skew and dynamic pressure. The most favorable comments were received for the lowest dynamic pressure and wing skew condition, and the most unfavorable comments were received for the highest dynamic pressure and wing skew condition.
4. Roll-to-pitch coupling was not a significant problem.
5. Pitch-to-roll coupling in the open loop configuration was substantial and was a major concern in the control law design. This coupling caused only minor handling qualities problems in the closed loop airplane.
6. The flight control system provided satisfactory pitch-to-roll decoupling at all flight conditions, but did not provide acceptable pitch-to-sideforce decoupling.
7. The use of a motion-based simulation with visual cues provided handling qualities conclusions for this vehicle that were not obvious using a fixed-base simulation with no visual cues.[44]

The overall finding was that "the flight control system was effective in generally decoupling the airplane."[45] Clearly, however, refining the flight control of the F-8 OWRA to address sideforce and lateral acceleration issues during pitch maneuvers would have required considerable work.[46]

## Investigating the Aerodynamic Characteristics of an Oblique Wing for the F-8 OWRA

In addition to the 300-square-foot Rockwell oblique-wing proposal, a number of other oblique-wing designs for the F-8 model were tested at NASA Ames, including two smaller 250-square-foot wings and an additional wing with an 8-to-1 elliptical planform. A number of these designs, however, were not directly comparable with each other due to differences in inlet fairing, tail incidence angle, presence of ventral fins, and method of wing attachment.[47] In addition, NASA Ames undertook in own oblique-wing design and tested and compared this NASA design with the Rockwell design. Indeed, the testing indicated that the NASA wing performed better than the Rockwell wing. "Had the F-8 OWRA project continued," NASA engineer Stephen C. Smith noted afterwards, "it is most certain that this wing would have been the wing selected for the airplane, over Rockwell's mild objection that it was slightly more expensive to manufacture."[48]

During June and July 1987, NASA Ames engineers conducted an experimental study of the aerodynamic performance and the stability and control characteristics of a 0.087-scale model of an F-8 airplane fitted with a NASA Ames–designed tapered (10.47 aspect ratio) wing that used specially designed supercritical airfoils with a 14-percent-thickness-chord ratio at the root and a 12-percent-thickness-chord ratio at the 85-percent span location. The tests, which were conducted in the NASA Ames 11-foot Transonic Wind Tunnel, were part of the OWRA program undertaken in conjunction with Rockwell International. The Ames-designed wing was tested at two different mounting heights above the fuselage. The performance of this wing was compared with the performance of the oblique wing designed by Rockwell International and tested by NASA Ames as part of same development program. The test objectives were to examine the performance and stability characteristics of the Ames-designed wing, provide timely information on the effects of the wing height and pivot axis inclination angle proposed by Rockwell, examine the benefits of varying the wing camber with wing sweep for efficient roll trim, measure the effectiveness of deflected tips as an alternative to ailerons for roll control at high sweep angles, and test a simple fuselage-mounted vortex generator.[49]

In designing the wind tunnel model, the fuselage, empennage, and ventral fins were based on the Ames-Dryden F-8C Digital-Fly-by-Wire test bed vehicle. The model engine inlet was faired over and the wing was mounted above the fuselage on a pivot shaft instead of being submerged within the fuselage. The horizontal and vertical tail surfaces had NACA 65A006 airfoil sections and a 45-degree sweep as measured at each surface's quarter-chord line. The horizontal tail was mounted at a 0.0-degree incidence relative to the fuselage centerline. The oblique-wing airfoils were modern, thick, supercritical sections. Lofting of the wing surface was linear from the root to the planform break at 85-percent semispan and the wing leading edge was then sheared forward 4 degrees. There were 2 degrees of washout between the reference axes of the defining airfoil sections. The wing was lofted with a small amount of dihedral so that the upper surface was flat along the 40-percent chord line. The wing pivot axis was inclined so that the wing banked as it swept (right tip forward and down). The pivot axis inclination of 7.894-degrees forward and 5-degrees right was chosen by Rockwell International in order to counteract a sweep-dependent sideforce observed in previous wind tunnel tests. High and low mounting posts were used to simulate the two selected wing heights.

The wing had flaps, ailerons, and deflectable tips that consisted of detachable segments machined at fixed angles. The tips were hinged along a chord line at a 85-percent semispan, and the trailing-edge devices were hinged at a 70-degree chord. The ailerons extended laterally from a 58-percent to 85-percent semispan. The flaps were built in two segments in order to permit evaluation of the effectiveness of inboard versus outboard location and for testing their effect on cruise drag. The outboard flap segments covered a 34-percent to 58-percent semispan and the inboard flaps ran from 9 percent to 34 percent. The left inboard flap could not be deployed in a positive (downward) sense when the wing was swept. The left-hand and right-hand side-control surfaces had the same chordwise and spanwise dimensions.

The study team, consisting of Robert A. Kennelly, Jr., Ralph L. Carmichael, Stephen C. Smith, and James M. Strong from NASA Ames and Ilan M. Kroo from Stanford University, concluded the following:

1. As in the case of the previously reported Rockwell wing, the high pivot caused excessive drag with little reduction in wing/fuselage interference and was less stable in pitch for high angles of attack.
2. Simple models of lift and drag based on airfoil characteristics and simple sweep theory, with extensions for separated flow, provide a useful characterization of oblique wing performance.
3. The overall F-8 OWRA drag is rather high, but most of this is caused by the large, blunt fuselage with abruptly faired-over engine inlet.
4. Side force and the three moments are complex functions of sweep, Mach number, and lift. The underlying flow mechanisms are similar to those observed on conventional, symmetrically swept wings, but they manifest themselves differently because of the asymmetric wing and its interactions with the fuselage.
5. The directional stability of the F-8 OWRA with the wing swept is only slightly degraded in comparison to the zero-sweep configuration.
6. The performance benefits of variable geometry were confirmed for sweep angles up to 60-degrees at Mach 1.40; higher speed testing will be required to check whether higher sweeps are desirable.
7. The thick, high-lift, supercritical airfoils designed for the Ames 300 sq ft wing appear to have achieved their design objectives. Both the wing drag-rise characteristics and performance envelope at the various sweep angles are in agreement with expectations based on simple sweep theory. No off-design penalty attributable to the use of supercritical sections was observed.
8. Cruise and loiter flaps were found to be ineffective in reducing drag for the limited set of flap deflections tested. Asymmetrical deflection of cruise flaps can be useful for roll trim with negligible drag penalty.
9. (High lift performance with segmented plain flaps was measured. Although maximum lift was somewhat improved by flap deflection, the largest effects were an increase in drag and a shift of $\alpha$ for maximum lift to lower values. The maximum lift coefficient was strongly affected by Mach number.

10. Deflected [wingtips] were found useful for roll control and are superior to ailerons at high sweep angles. Both deflected tips and ailerons have side effects on pitching and yawing moments.
11. A pitch-up was observed for intermediate sweep angles at transonic Mach numbers. The pitch-up is associated with the increase in lift loading on the rear wing panel as angle of attack is increased, leading to buffet and/or stall of the rear wing panel. This pitch-up is typical of conventional swept wings except for the coupled nonlinearities in rolling and yawing moment due to the asymmetric configuration.
12. A fuselage-mounted vortex generator positioned ahead of the center of the wing did not significantly affect the nonlinear characteristics of the oblique wing as various portions of the wing stalled.
13. With the exception of drag, the forces and moments were not significantly affected by variation in Reynolds number. The decrease of drag with increasing Reynolds number was typical of models tested at these Reynolds numbers.[50]

## Program Monitoring and Project Termination

Review of the monthly update reports indicates that NASA Dryden monitored very closely the progress of the OWRA program and indicated that project funding became a critical problem that eventually led to the cancellation of the project that was well along the road to being completed. After the Navy withdrew funding, NASA approached the Air Force and DARPA for help in continuing the program. When these efforts failed, NASA was forced to terminate the program.

A sampling of monthly reports offers insight into the program's progression, its challenges, and its accomplishments:

- The June 12, 1984, monthly report reflected the program startup, noting that an overview briefing of the F-8 Oblique Wing Program was presented to management and disciplinary personnel at both Ames-Dryden and Ames North; task teams that would comprise the project office were currently being established at both sites; and the program Memorandum of Understanding was formally approved and signed by both NASA and Navy management, thus establishing funding and schedule commitments by both agencies. The report also noted that wind tunnel testing of a scale F-8 Oblique Wing model was scheduled to begin in the Ames 11-foot wind tunnel on June 11, 1984, and a statement of work had been completed for the development of the initial F-8 Oblique Wing Aero Model and for support in establishing an

F-8/OWRA operational "Iron Bird" (a ground simulator for piloted controls evaluation).[51]

- The September 12, 1984, update added that an August 30 meeting with the Charles Stark Draper Lab (CSDL) was held in order to discuss required hardware and software modifications to the F-8 primary digital flight control system and that a meeting was held with Sperry Flight Systems to discuss required modifications to the F-8 backup flight control systems. Contractor wind tunnel tests were completed in the Ames 11-foot Transonic Wind Tunnel, and the results were presented at Ames. Flow-visualization tests were planned for September using the Ames-Dryden water tunnel. Planning continued in order to define the approach and requirements for in-house research and testing development in support of the OWRA program. A visit was made to the Ling-Temco-Vought Corporation by NASA Ames and Navy representatives in order to acquire baseline loads data on the F-8, and the Phase B (preliminary design) procurement activity was on schedule.[52]
- The February 22, 1985, report added that the final aeromodel was received from Rockwell for the Oblique Wing fuselage configuration and that a presentation was given to the Ad Hoc Congressional Review Committee regarding program objectives and technology development items in support of the study.[53]
- The March 7, 1985, update reported that a "correct and complete" aerodynamic model for the F-8 oblique-wing program had been received and was in the process of being implemented into simulations at Ames and Dryden.[54]
- The June 10, 1985, report noted that the only final actions remaining to implement the oblique-wing preliminary design contract were project plan approval, project funding release, and contract award. Also, the "batch simulation" of Rockwell's aerodynamic model was now operational at Dryden, and five check cases had already been evaluated with satisfactory results.[55]
- The July 8, 1985, update reported that Dr. Gupta, of the Ames-Dryden Aerostructures Branch staff, had completed an aeroelastic modeling of the 250-square-foot oblique wing and noted that the results of the investigation with the analytical approach "appear realistic."[56]
- The August 12, 1985, monthly report reviewed the following program progress: a piloted simulation, which can be flown at all wing-skew angles, of the F-8 OWRA was activated at Dryden, and it was anticipated that "controls augmentation" would be added to the simulator in August; Rockwell had completed a wind tunnel test of its wing model incorporating the 4-degrees of leading-edge sweep as recommended

from the NASA in-house wing design; and a smaller scale model of the in-house wing was being fabricated for Dryden Flow Visualization Facility (water tunnel) testing.[57]

- The September 12, 1985, update identified the three following additional work items: a real-time, six-degrees-of-freedom simulation was now operational, and computational pressure data that agreed with water tunnel test results had been generated; the final award of the oblique-wing preliminary design activity was awaiting release of FY 1985 funds; and the project plan document was being reviewed for final approval by the Navy.[58]
- The December 12, 1985, update added that the preliminary design contract for the oblique wing was awarded to Rockwell and that a water tunnel model of the in-house oblique-wing design had been constructed and was ready for testing at Dryden.[59]
- The January 10, 1986, monthly update reported on a review meeting attended by Rockwell, NASA, and Navy representatives held at Ames on December 18, 1985, in order to review Rockwell's progress and to compare Rockwell's proposed design with NASA's in-house design. The report added that Rockwell was now leaning toward a larger wing that would be canted on the fuselage to minimize the out-of-trim moments resulting from the wing skew.[60]
- The February 10, 1986, report noted that NASA Dryden, Rockwell, and Honeywell had been independently studying different control-law methodologies, and while no particular methodology had been selected, it appeared that the loop shaping and model-following would be the prime contenders. Also, the report indicated that acceptable OWRA control characteristics were achievable without major difficulties.[61]
- The March 7, 1986, update reported that the release of Navy funding appeared imminent.[62]
- The April 10, 1986, report indicated that the Navy funding had been released to the NAVAIR program and was in the process of being transferred to NASA.[63]
- The August 11, 1986, monthly update reported that the NASA project team was continuing its in-house development in order "to assure that the Rockwell selections are appropriate or if necessary to redirect them."[64]
- The September 15, 1986, report reflected how far along the program was. The synopsis for the oblique-wing final design and fabrication was released, a vertical motion simulation was planned to be accomplished early in October, and the project team had finished assimilating the results of the wind tunnel tests of the in-house wing. The in-house

wind tunnel tests indicated that the oblique wing was "somewhat more efficient at the loiter cruise condition than the wing design previously tested."[65]

- The October 8, 1986, update noted that a 3-year contract for the control system modifications to accommodate the flying wing was awarded to the Charles Stark Draper Laboratory. The proposed flight control computer system was a "quadraplex computer with strapped triplex sensors and actuators." The October report also added that NASA Ames was designing two simple force-and-moment wind tunnel models for testing in January 1987 and that these tests would enable a direct comparison of the performance of the NASA technology developed for the oblique wing with the contractor's (Rockwell International) oblique wing as well as identifying any problems that the contractor's wing might encounter.[66]
- The November 12, 1986, monthly report, however, revealed the first major problem that threatened to end the F-8 OWRA program. The Navy's funding of the program, while included in the Congressional authorization bill, was omitted from the appropriations bill.[67]
- The March 13, 1987, report added that the Navy had withdrawn from the F-8 OWRA program. The Navy indicated that it still supported the technology that the program would develop but that overall budgetary constraints precluded the funding of their portion of the program.[68]
- The May 11, 1987, report noted that a Memorandum of Agreement for the conduct of a joint DARPA-NASA Oblique Wing Research Aircraft program was in circulation for review.[69]
- The June 12, 1987, monthly update report noted that Rockwell had initiated a contract with Honeywell for control-law development and that approximately 160 hours of wind tunnel testing were planned on the NASA-designed 300-square-foot oblique wing. The report added that negotiations were still under way to secure DARPA funding for the project.[70]
- The July 8, 1987, monthly update stated that the Ames wind tunnel tests of the 300-square-foot NASA-designed oblique wing were completed and that the test revealed some difficulties with the aerodynamics of the pivot design that supported the wing above the fuselage. Preliminary analysis of the problems indicates that the Rockwell-proposed design would need to be modified to eliminate the pivot extension. The report added that negotiations were still under way to find a funding partner and that the Air Force

had expressed interest in the program as it would pertain to the Conventional Defense Initiative.[71]

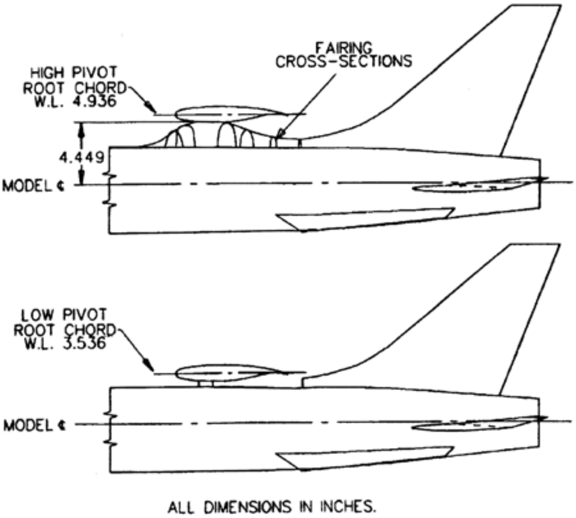
- The August 12, 1987, monthly update status report noted, in regard to the F-8 OWRA program, that a Critical Design Review for the flight control computers, which were being procured from the Charles Stark Draper Laboratory, was held at Dryden in August and concluded that the CSDL work was now technically ready to start fabrication. The report added that discussions were still under way with the Air Force to secure a funding partner for the project.[72]
- The October 13, 1987, update report noted that the wind tunnel tests planned for September had been deferred until October and that these tests were designed to enable a comparison of the aerodynamics of Rockwell and in-house wing designs, although it was noted further that even these tests would not be of sufficient scope to enable the development of a complete aerodynamic model for the simulation scheduled to be developed in Phase C of the project (which was recently canceled). Finally, the report informed the Dryden Director that the Honeywell control laws, which were generated using a 200-square-foot-wing-area database, should be delivered in October.[73]

But by now, the program had already collapsed; a month earlier, Dryden's September 9, 1987, update report had signaled the end of the program with the following directive:

> Direction from NASA Headquarters to cease further cost obligations on the Oblique Wing Research Aircraft project was received on August 27, 1987. We have been informed that a request for a Termination Plan to terminate the project in an orderly manner will be forthcoming from Code RX at Headquarters. The acceptance of this plan will enable limited expenditures for those items that are desirable to complete.[74]

The report added that the wind tunnel tests of the Rockwell designed wing would be completed in September.

Termination of Navy funding and the subsequent withdrawal of DARPA and Air Force interest ended NASA's F-8 OWRA program, which was poised to enter its next to final phase, thus ending a very promising effort to realize NASA's plan to have a supersonic oblique-wing airplane to follow the Agency's earlier subsonic AD-1. In retrospect, the cancellation was an unfortunate one because the F-8, despite what challenges may have existed as it made its way



Comparison of a high vs. low pivot location for the proposed F-8 Oblique Wing Research Aircraft, from TM 102230, 1988. (NASA)

toward flight, would most likely have demonstrated the benefits of a supersonic oblique-wing aircraft. The cancellation stemmed in part from cost overruns that the Navy experienced on another program for an experimental "X-Wing" stopped-rotor research aircraft, which itself failed to go forward.[75]

Even without flying the F-8 demonstrator, the program added measurably to the oblique-wing technology base, particularly by identifying and projecting solutions for most of the previously identified stability and control problems. For a while, F-8 inspired research played out within the Agency. For example, in July 1988, almost a year after cancellation, Ames researchers tested a 0.087-scale model of an F-8 fitted with an oblique wing designed by Rockwell in the Center's 11-foot Transonic Wind Tunnel (as hinted at in the October 1987 progress report). Unlike the earlier Jones-style elliptical transport wing, this wing had a straight taper (as discussed previously), with an aspect ratio of 10.3 and a thickness-chord ratio (t/c) of 14 percent. The wing was evaluated over a Mach range of 0.25 to 1.40 at Reynolds numbers ranging from 3.2 to $6.6 \times 10^6$/feet; at 0-, 30-, 45-, 60-, and 65-degree sweep angles; and at a range of angles of attack from –5 degrees to +18 degrees. Most flights were at a 0-degree sideslip, "but a few runs were made at sideslip angles of ±5 deg."[76] On the basis of these tests, the research team found that wing location was crucially important to the aircraft's aerodynamic performance. The wing, which employed a Langley-derived SC (2)-0714 airfoil section, was designed to produce a lift coefficient of 0.70 at Mach=0.735. It was tested in two mounted positions—one low to the top of the fuselage and one higher.

Surprisingly, the higher location proved to have greater interference and a smaller lift-to-drag value than the lower location. Overall, the straight leading-edge, forward-swept trailing-edge Rockwell wing proved inferior to the earlier Ames-modified elliptical configuration, which "offers higher L/D ratios at most conditions, higher CL (max) [maximum coefficient of lift], and more moderate force and moment breaks than the present [Rockwell] design does."[77] The team concluded that the tests raised issues meriting further investigation. In this, they were both prescient and fortunate, as interest in the oblique-wing concept certainly did not end within the Agency, as illustrated by the followup studies, proposals, and designs reviewed in the next chapter.

## Endnotes

1. Including rival British Aerospace V/STOL Sea Harrier designer John Fozard, who informed Richard P. Hallion of this after the British designer had visited Langley and observed the XFV-12A in action. (Hallion recollection to the author). See "XFV-12A: V/STOL in Need of a Lift," *Flight International* (January 20, 1979): 171.
2. See the previously cited Michael J. Hirschberg, David M. Hart, and Thomas J. Beutner, "A Summary of a Half-Century of Oblique Wing Research," a paper presented at the 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 8–11, 2007, AIAA paper no. 2007-150 (2007), 21–22.
3. Rockwell International (S.N. White, project engineer). "Feasibility Design Study of an F-8 Oblique Wing Demonstrator," NASA Contract NAS-11409 (February 1984).
4. Ibid.
5. Ibid., 5–58.
6. Ibid., 1-1.
7. Ilan Kroo, "The Aerodynamic Design of Oblique Wing Aircraft," a paper presented at the AIAA-American Helicopter Society- (AHS)American Society for Engineering Education (ASEE) Aircraft Systems Design and Technology Meeting, Dayton, OH, October 20–22, 1986, AIAA Paper 86-2624, 1 (internal references in quotation omitted). Ilan Kroo is an individual who has featured prominently in this work. He worked at NASA Ames during much of the time period that involved the F-8 Oblique Wing Research Aircraft program, and later, as a professor at Stanford University, he continued his association with the program. He gave special acknowledgment in his paper to the work undertaken at Ames and the previous studies "by many government, industry, and university researchers" noted in the references to his paper. For this paper, he gave particular acknowledgment to Robert Kennelly (Sterling Software) and Ralph Carmichael (NASA Ames) and stated that "frequent discussions with R.T. Jones were always enlightening."
8. Ibid., 1–2.
9. Ibid.
10. Ibid., 2–3.

11. Ibid., 1–3. Kroo added that a large number of engineers at three NASA Centers, Navy installations, universities, and contractor sites were already involved in the effort.
12. Glenn B. Gilyard, "The Oblique-Wing Research Aircraft: A Test Bed for Unsteady Aerodynamic and Aeroelastic Research," NASA N89-19253.
13. Ibid., 396.
14. The proposed flight control system for the actual F-8 oblique-wing aircraft called for replacing the triplex primary and triplex backup computers with a quadruplex fault-tolerant computer architecture, including a software backup system. The existing sensor sets, interface units, and secondary and primary actuators were planned to be used but were to be modified as required. The control law would be an entirely new design that would make use of the differential horizontal stabilizer for roll control at high skew angles and trim to all surfaces. This was not a normal F-8 aircraft function. See Robert W. Kempel, Walter E. McNeill, Glenn B. Gilyard, and Trindel A. Maine, "A Piloted Evaluation of an Oblique-Wing Research Aircraft Motion Simulation with Decoupling Control Laws," NASA TP 2874 (November 1988), 5.
15. Ibid., 401–402, 410.
16. NASA Ames Presentation to Congressional Advisory Committee on Aeronautics.
17. Gilyard, "The Oblique-Wing Research Aircraft," 413.
18. NASA Ames Presentation to Congressional Advisory Committee on Aeronautics.
19. From 1981 to 1991, Ames Research Center and Dryden Flight Research Center were merged into a single bureaucratic and organizational entity, with Dryden referred to officially as the Dryden Flight Research Facility (DFRF). However much sense this seemed to make to decision makers at the time, in retrospect, it made very little sense, as the two Centers, beside being 288 miles apart (as the crow flies) shared little in common. After a decade, Dryden was again restored to independent status.
20. Kenneth J. Szalai, "Memo for Distribution, Subject: F-8 Oblique Wing Staffing," June 20, 1984, Dryden History Office.
21. Ibid.
22. Ibid.
23. Ibid., 1.

24. Gurbux S. Alag, Robert W. Kempel, and Joseph W. Pahle, "Decoupling Control Synthesis for an Oblique-Wing Aircraft," NASA TM 86801 (June 1986), 1.
25. Ibid.
26. Ibid., 2.
27. Ibid.
28. Ibid., 2.
29. In linear algebra, an *eigenstructure* is a set of eigenvalues presented in a matrix. An *eigenvalue* is the changed magnitude of a vector that does not change direction under a linear transformation. An *eigenvector* is a vector that is not rotated while undergoing a linear transformation.
30. Alag, Kempel, and Pahle, "Decoupling Control Synthesis for an Oblique-Wing Aircraft."
31. See T.B. Cunningham, "Eigenspace Selection Procedures for Close Loop Response Shaping with Modal Control," *Proceedings of the IEEE Conference on Decision and Control*, December 1980, 178–186; A.N. Andry, E.Y. Shapiro, and J.C. Chung, "On Eigenstructure Assignment for Linear Systems," *IEEE Transactions Aerospace and Electronic Systems*, September 1983, 711–729.
32. Ibid.
33. Ibid. For a period in the 1970s to 1980s, NASA adopted metric measurements for its technical reports and publications before returning to a more traditional and accessible approach subsequently.
34. John J. Burken, Gurbux S. Alag, and Glenn B. Gilyard, "Aeroelastic Control of Oblique-Wing Aircraft," NASA TM 86808 (June 1986), 2.
35. See John C. Houbolt, Roy Steiner, and Kermit G. Pratt, "Dynamic Response of Airplanes to Atmospheric Turbulence Including Flight Data on Input and Response," NASA TR R-199, 1964.
36. Burken et al., "Aeroelastic Control of Oblique-Wing Aircraft," 2.
37. Ibid., 5. Burken et al., "Aeroelastic Control of Oblique-Wing Aircraft," 5.
38. See also Gurbux S. Alag, John J. Burken, and Glenn B. Gilyard, "Eigensystem Synthesis for Active Flutter Suppression on an Oblique-Wing Aircraft," NASA TM 88275 (1986).
39. Dale F. Enns, Daniel J. Bugajski, and Martin J. Klepl, "Flight Control for the F-8 Oblique Wing Research Aircraft," a paper presented at the 1987 American Control Conference, Minneapolis, MN, June 1987, 1112.

40. Enns et al., “Flight Control for the F-8 Oblique Wing Research Aircraft,” pp. 1113–1116, quotation from 1116.
41. Kempel et al., “A Piloted Evaluation,” 1.
42. Ibid., 2–15.
43. For the record, use of wing ailerons was not evaluated in the simulation study.
44. Kempel et al., “A Piloted Evaluation,” 14–15.
45. Ibid.
46. Indeed, in a Ph.D. dissertation on developing integrated flight control for oblique-wing vehicles, Stephen Morris of Stanford University bluntly noted, “In the case of the NASA-Rockwell Oblique Wing Research Aircraft, attempts to improve the handling qualities by implementing a stability augmentation system have produced unsatisfactory results *because of an inherent lack of controllability in the proposed design*.” (Emphasis added.) See Stephen James Morris, “Integrated Aerodynamic and Control System Design of Oblique Wing Aircraft,” NASA CR 192614 (January 1990), abstract.
47. Robert A. Kennelly, Jr., Ralph L. Carmichael, Stephen C. Smith, James M. Strong, and Ilan M. Kroo, “Experimental Aerodynamic Characteristics of an Oblique Wing for the F-8 OWRA,” NASA TM 1999-209579 (September 1999), 1.
48. Stephen C. Smith, recollection to the author, January 2012.
49. Kennelly, et al., “Experimental Aerodynamic Characteristics,” 1–2.
50. Ibid., 11–12.
51. Kenneth E. Hodge, “Project Update—May,” June 12, 1984, Dryden History Office, box L3-4-4B, p. 2. Note: The following “Project Update” documents are located in the aforementioned Dryden History Office box. The documents will be identified by title and date.
52. “Projects Update—August 1984,” September 12, 1984, 7.
53. Ibid.
54. “Projects Update—February 1985,” March 7, 1985, 5.
55. “Projects Update—May 1985,” June 10, 1985, 5.
56. “Projects Update—June 1985,” July 8, 1985, 5.
57. “Projects Update—July 1985,” August 12, 1985, 5.
58. “Projects Update—August 1985,” September 12, 1985, 5.
59. “Projects Update—November 1985,” December 12, 1985, 4.
60. “Projects Update—December 1985,” January 10, 1986, 5.
61. “Projects Update—January 1986,” February 10, 1986, 3.
62. “Projects Update—February 1986,” March 7, 1986, 3.
63. “Projects Update—March 1986,” April 10, 1986, 6.

64. “Projects Update—July 1986,” August 11, 1986, 5–6.
65. “Projects Update—August 1986,” September 15, 1986, 6.
66. “Projects Update—September 1986,” October 8, 1986, 5.
67. “Projects Update—October 1986,” November 12, 1986, 5.
68. “Projects Update—February 1987,” March 13, 1987, 5.
69. “Projects Update—April 1987,” May 11, 1987, 5.
70. “Projects Update—May 1987,” June 12, 1987, 4.
71. “Projects Update—June 1987,” July 8, 1987, 4.
72. “Projects Update—July 1987,” August 12, 1987, 4.
73. “Projects Update—September 1987,” October 13, 1987, 4.
74. Dryden monthly projects update report, September 9, 1987, 2.
75. Hirschberg, Hart, and Beutner, “A Summary of a Half-Century of Oblique Wing Research,” 24.
76. Robert Kennelly, Jr., Ilan M. Kroo, James M. Strong, and Ralph L. Carmichael, “Transonic Wind Tunnel Test of a 14% Thick Oblique Wing,” NASA TM 102230 (August 1990), 1.
77. Ibid.

First takeoff of the Northrop B-2A Spirit, July 17, 1989, Palmdale, CA. (R.P. Hallion)

## CHAPTER 6

# Subsequent Oblique-Wing Plans and Proposals

The previous chapters reviewed the theoretical studies and concept development of the oblique-wing idea; the wind tunnel models and testing that demonstrated that the oblique-wing idea was feasible, thus laying the groundwork for further study and development; the computer modeling that was used to augment the wind tunnel testing and to compare test data with predictions; the development of remotely piloted oblique-wing models that demonstrated the feasibility of flying larger-scale piloted aircraft; the development and use of flight simulators to prepare pilots for flying an actual oblique-wing aircraft; and finally, the building and flying of a piloted proof-of-concept oblique-wing research aircraft—the Ames-Dryden AD-1. The NACA and its successor, NASA, played the leading role in this effort, starting with the remarkable concept developmental work of Robert T. Jones and the first wind tunnel testing of the concept by John P. Campbell and Hubert M. Drake that eventually led to the building and flying of the AD-1.

The engineering advantages of the oblique-wing concept that resulted in NASA's building and flying the AD-1 were summarized concisely in the following historical survey of oblique-wing research undertaken by Michael Hirschberg, David Hart, and Thomas Beutner:

> An oblique wing…can vary the wing sweep with a single pivot that is primarily loaded in tension, trading aspect ratio for fineness ratio by sweeping one wing tip forward and the other wing tip back. This design allows a greater reduction in the wave drag, automatically accounts for area ruling, and reduces pivot torque and bending loads as well as fuselage loads. In addition, asymmetric sweep can increase the fineness ratio of the wing more significantly than symmetric designs.[1]

It is thus both somewhat ironic and intriguing that, even given the engineering advantages outlined above and all of the work done the previous 40-plus years (including, most notably, building and flying the AD-1), the potential for supersonic and transonic oblique-wing aircraft has not yet been fulfilled. It reflects an oft-encountered situation within aeronautics and, indeed, virtually all scientific and technological fields, though perhaps to a greater and more surprising extent because fewer ideas have so clearly demonstrated their value. In retrospect, AD-1 team members Tom McMurtry, Alex Sim, and William Andrews appear prescient in light of remarks they made in addressing this issue in 1981:

> There is often a delay between the discovery and the application of new engineering principles. Usually such principles must be widely known and accepted before designs begin to reflect them. Furthermore, complementary advances in technology in other fields are often necessary before new discoveries can be applied. In the field of aerodynamics, the oblique swept wing aircraft design concept serves as a good example. Theoretically, this configuration, which Robert T. Jones conceived of many years ago, offers aerodynamic, structural and operational efficiency unequaled by conventional designs.[2]

While the potential outlined above has not yet been realized, work has continued on a number of proposed designs and projects, including a variety of examples outlined below, starting, once again, with R.T. Jones.

## Jones's Inspired Ames-Stanford Oblique-Flying-Wing SST Concepts

One of the most enduring dreams in aeronautics has been the idea of a pure flying wing, dating to the conceptualizations of the German engineer and thermodynamicist Hugo Junkers prior to the First World War. The flying wing, a pure lifting surface, constitutes the most efficient form of flight vehicles. Junkers, Britain's John Dunne and Barnes Wallis, Germany's Alexander Lippisch and Reimar and Walter Horten (the Horten brothers), and America's Vincent Burnelli and Jack Northrop all envisioned large propeller- (and later turbojet-) powered military and civilian flying wings. Jones was likewise entranced with the purity of the all-wing concept, having advocated such a design in passing at an international aerospace congress held in Spain in 1958. "Oblique flying wings were where he always was going," recalled oblique-flying-wing advocate Thomas J. Beutner, who heard Jones extol their virtues during a graduate seminar at Stanford.[3] The advent of computer-controlled flight and fly-by-wire flight control made the flying wing (which previously always had a tendency toward persistent pitching and annoying Dutch roll lateral directional coupling) a practicality, evidenced by the first flight of the Northrop B-2A flying-wing stealth bomber, on the morning of July 17, 1989, at Air Force Plant 42 in Palmdale, CA.

In 1990, R.T. Jones, 45 years after his initial conceptualization of the swept wing (and at the mature age of 80), returned to the idea. Over the previous decade he had reinvigorated his own research on oblique wings, particularly an oblique-flying-wing supersonic transport. In an article on a flying-wing supersonic transport, published in 1991 by the prestigious Royal Aeronautical Society, Jones noted that the flying wing was "simply a straight wing of high aspect ratio and of sufficient size to contain passengers comfortably. Such a wing can be steered to different sweep angles and thus adaptable to efficient flight over a range of Mach numbers."[4] Jones added that G.H. Lee, of Handley Page, Ltd., had reviewed the advantages of this configuration at a subsequent meeting, acknowledging his intellectual debts to Jones, beginning with the latter's demonstration of a small balsa glider oblique wing at the Madrid meeting. Jones stated,

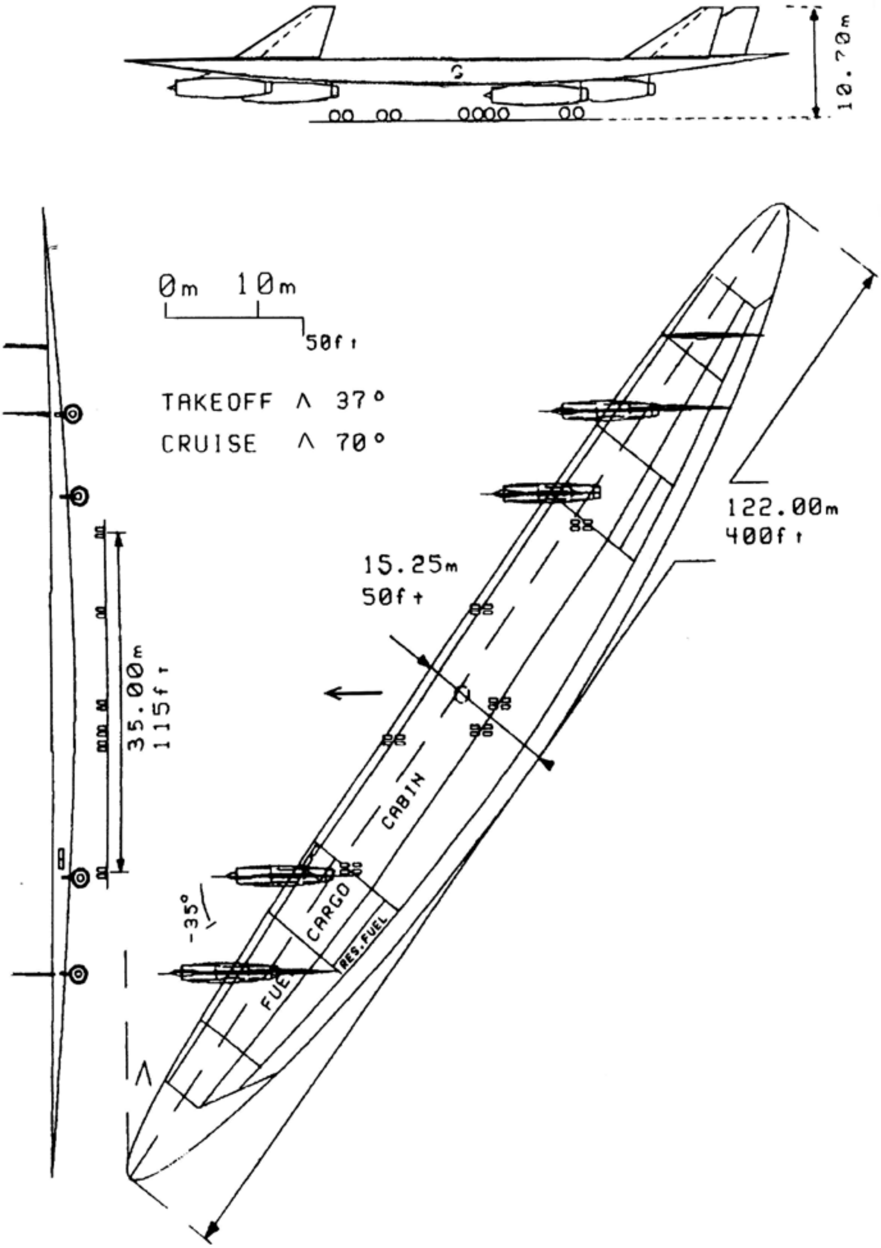
> Artifacts created by humans show a nearly irresistible tendency for bilateral symmetry. Thus we envision the supersonic transport as having the symmetric shape of an arrow, traveling naturally point foremost.
>
> Aerodynamic theory however discloses no preference for such symmetry, but shows instead a distinct preference for fore and aft symmetry. Thus the theorems of Kármán and Hayes indicate that the drag of a thin body having given lift and volume ought to be the same if the direction of flow is reversed. Surprisingly, even though the Mach waves at supersonic speed show a definite direction and trail backward from the nose of a body, all known shapes satisfying the requirements of minimum wave drag show fore and aft symmetry, that is they present the same aspect flying in either direction....
>
> According to theory if a lifting surface is to achieve the minimum drag[,] every loading projected along oblique characteristic lines should be elliptical....[And that] *calculation shows that an arrow elliptic wing turned with its long axis inside the Mach cone has less drag than other distribution of lift or volume within a wide constraint area.*[5] [Emphasis added.]

Jones then compared his oblique-flying-wing concept with the Concorde SST, a slender ogee delta planform then in airline service with British Airways and Air France. He noted that the Concorde, due to its fixed short-span, low-aspect ratio planform, was inherently inefficient at low speeds, requiring afterburning for takeoff, and wasted fully 40 percent of its fuel for low-speed operations. The oblique flying wing, however, could minimize its drag over a wide range of speeds, subsonic or supersonic, by simply skewing to different angles. He added that subsequent to G.H. Lee's paper, studies at NASA Ames and Stanford University had greatly improved the understanding of the aerodynamic properties of the oblique flying wing, testing models that had elliptical wings of a 10-to-1 axis ratio with subsonic airfoil sections in Ames's 11-foot Transonic Wind Tunnel. The wings, which were mounted on a small body, could be set at various angles of yaw. Three different airfoil sections were used for the tests. Jones noted that the propulsion system would need to be adapted to a wide range of conditions necessitating the need for variable cycle or variable bypass engines for the supersonic transport. Jones added, however, that at high Mach numbers, such as between 2 and 3, the narrowing Mach cone limits the volume of air that can be influenced by the wing and lifting efficiency declines, but at slower speeds, around Mach 1.5, "it seems possible that fuel economy approaching that of subsonic transports could be achieved."[6]

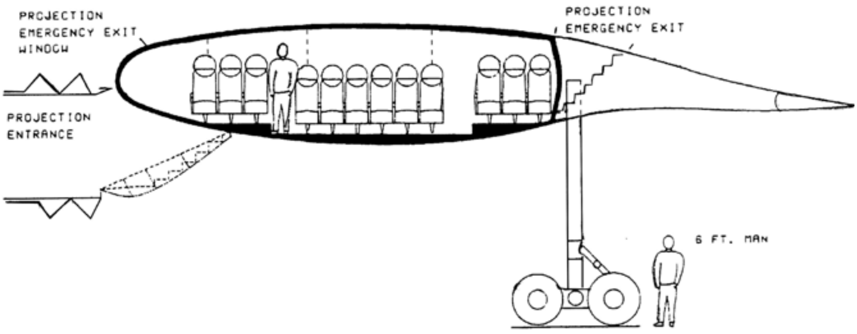
In 1989, NASA awarded a contract to Alexander J.M. Van der Velden, of the University of California at Berkeley, to undertake a performance and economics analysis of a Mach 2 oblique-flying-wing transport aircraft suitable for replacing the already venerable Boeing B747 passenger airliner. In undertaking the contract, Van der Velden rightly credited Jones with proposing the concept of an oblique flying wing in 1957, adding that in connection with his study, Van der Velden met with Jones in Los Altos in 1987, discussing its reintroduction in view of the emerging technology of artificial stabilization and fly-by-wire flight control. The oblique supersonic flying wing synthesizes three challenging concepts—the oblique wing, the flying wing, and the supersonic passenger aircraft. The oblique-wing concept provides high lift-to-drag ratios at all speeds and therefore greatly increases the low-speed performance for aircraft designed for maximum efficiency at high speeds. The flying wing has higher cruise lift-to-drag ratios and lower empty weights due to the reduced wing-bending moment. The supersonic passenger aircraft, such as the Concorde, presented economic problems that, as Van der Velden noted, "led to the abandonment of the idea of commercial supersonic flight, even though everyone recognizes the importance of reducing the current long-haul flight time."[7]

The baseline configuration for Van der Velden's conceptual design accommodated 462 passengers and 16 cabin crewmembers who could be seated at a 35-inch pitch, 12 abreast. Windows were located in the nose and emergency exits, reached by access ramps leading up to the top of the wing, positioned in the nose and trailing-edge side of the passenger cabin. Two entrance doors were in the wing nose. The study concluded that it did not make sense to design a protruding cockpit structure. Instead, the cockpit space, housing both pilots, was located on the left end of the cabin, affording the pilot good visibility during approach and climb, his field of vision encompassing from 70 degrees left to 70 degrees right. If additional cabin space was desired, sections could be added at the area of maximum thickness, which actually worked to increase the configuration's lift-to-drag ratio. The wing had an elliptical planform with a near-elliptical spanwise thickness-to-chord distribution, resulting in minimum wave drag for a given volume. The wing had some upward curvature to maintain uniform distribution of lifting pressures. In order to achieve the necessary lift coefficient with minimal drag and a low floor incidence, the center of lift during cruise had to be as far back as the artificial stability and control system would permit. Like other supersonic aircraft, center-of-gravity location would be maintained from subsonic through transonic and into the supersonic regime by shifting fuel.

The proposed oblique flying wing had a conventional monocoque and honeycomb structure, using the same aluminum alloy employed on the Concorde. The airframe life, however, would be significantly longer than the Concorde's. This would be accomplished by reducing the maximum speed to Mach 2, which would reduce the equilibrium skin temperature and hence the progressive "aging" of the structure. The ceiling to floor connectors were placed every 10 feet in order to enable the structure to carry the loads of pressurization while maintaining a near-unobstructed wide-body-cabin appearance. In order to increase one-engine-out yaw control and to minimize the wave drag and wind stress, the engines would be podded in four nacelles. The nacelles, distributed optimally along the span, could be pivoted over a 35-degree range. The engines could either be a refanned Rolls Royce Olympus (the same type used in the Concorde) or a double- scale GE F101/110 engine (the basic engine of the B-1 bomber). The undercarriage would have six legs with four 40-by-14-inch tires each. The legs could be redesigned so the oblique flying wing could operate from the same runways as the Boeing 757, which would increase the number of potential flight destinations. Stability and control around the $x$ and $y$ axis would be provided by a 10-percent multi-segmented edge flap similar to one proposal earlier by NASA for another transport. The flying-wing configuration had three "all-flying" vertical fins mounted on the engine pivots. In order to ensure static stability around the $z$ axis, the flying wing would have two rear vertical tailplanes. The vortilons could be used to control the boundary layer at the high angle of attack that might be produced during heavy wind gust conditions. The proposed flying planform and center cabin section are illustrated in the following drawings.



Van der Velden conceptual design for a supersonic oblique flying wing, from CR 177529, 1989. (NASA)



Cabin cross section with OFW16 airfoil.

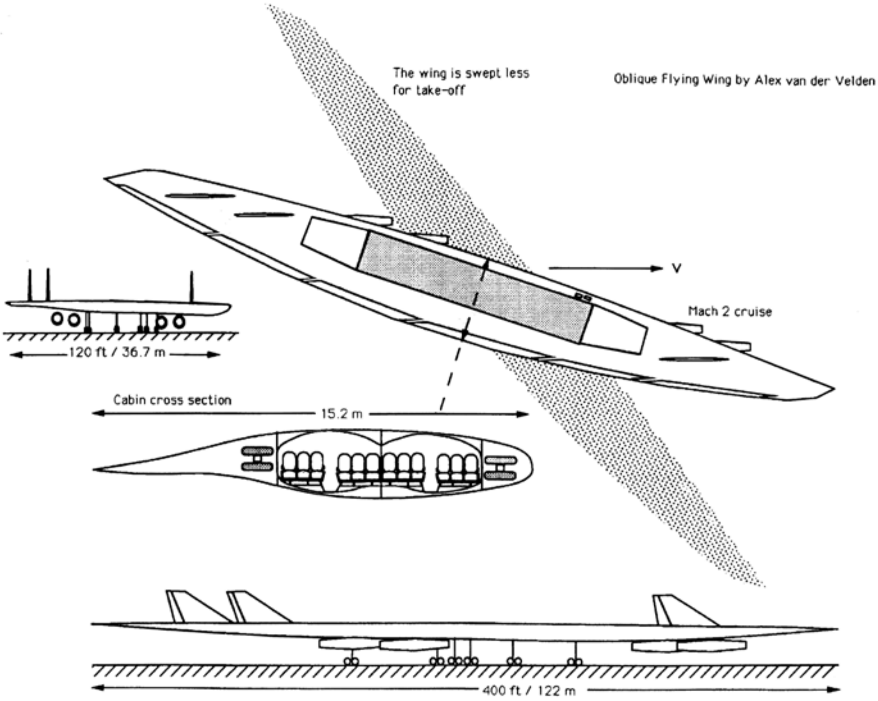
Internal cabin arrangement of the Van der Velden supersonic oblique flying wing, from CR 177529, 1989. (NASA)

Van der Velden concluded by noting the following:

1. As compared to contemporary subsonic aircraft of the same size its operational characteristics are superior. The Aircraft can fly at the same holding speeds as today's subsonic transports, and requires only half the takeoff field length.
2. The total cost of development of the aircraft is going to be higher than any other aircraft so far (around 10 billion ('86) USD), but due to the high blockspeed the direct operating costs of the aircraft are going to be comparable to the Boeing 747's.
3. It is therefore proposed that further research is done to validate the results presented in this study and to expand the database on oblique flying wing configurations.[8]

Van der Velden extended his work in association with Ilan Kroo with a follow-on study prepared for Ames Research Center that was issued in 1990, featuring a more-refined wing than previously examined. This later study explicitly presented the advantages of the oblique flying wing versus conventional bisymmetrical configurations as employed by the high-subsonic Boeing B747 (conventional swept wing with podded engines), and the High-Speed Civil Transport (HSCT), with a highly tailored arrow wing.

Aerodynamically, it had a higher L/D ratio over its entire operating envelope, from Mach 0.2 to Mach 2.0. Structurally, it had less weight than any conventional configuration because the cabin was enclosed within the lifting surface, avoiding the penalties of the classic "tube and wing" airliner. In the



Van der Velden and Kroo supersonic oblique flying wing, from CR 177552, 1990. (NASA)

all-important area of passenger load and runway accessibility, it could carry almost twice as many passengers (462 versus 247) yet use a runway almost half that of the HSCT design (2,000 meters [6,500 feet] versus 3,600 meters [12,000 feet]). Additionally, its payload fraction (percentage of maximum takeoff weight) at Mach 2 was as high—14 percent—as that of the Boeing B747 at Mach 0.86 and almost twice as high as the bisymmetric HSCT.[9]

Following on NASA Ames's preliminary studies of an oblique all-wing transport, at cruise Mach numbers between 1.6 and 2.0, a group of NASA,industry, and academic investigators from Ames, the Eloret Institute, Stanford, Santa Clara University, and Sterling Software undertook a detailed assessment of Ames's work on the oblique-flying-wing concept, examining all aspects of its design and conceptualization, including the wing planform, cabin and cargo bay layout, airfoil cross section, cockpit design, engine placement, landing gear configuration and location, and vertical tail placement. The baseline geometry of the vehicle was as follows[10]:

| | |
|---|---|
| **Aspect Ratio** | 10 |
| **Wing Maximum Thickness/Chord Ratio** | 0.16 |
| **Passenger Cabin Span** | 149 ft |
| **Taper Ratio** | 0.4 |
| **Leading Edge Ratio** | 0.32 |
| **Tip Ratio** | 0.50 |
| **Total Wingspan** | 406.8 ft |
| **Chord in Payload Section** | 51.4 ft |
| **Chord at Tip** | 20.6 ft |
| **Maximum Wing Thickness** | 8.22 ft |
| **Total Planform Area** | 16,542 sq. ft |
| **Vertical Tail Plan Area/Wing Planform Area** | .059 |
| **Leading Edge Sweep Angle** | 4.75° |
| **Trailing Edge Sweep Angle** | 10.02° |

*Wing Planform*—The study team noted that the most important thing to recognize in an oblique all-wing configuration is that once the wing-thickness-chord ratio and aspect ratio have been selected, the major dimensions of the wing, including wingspan and planform, are determined by the need for the passengers to be able to stand inside the aircraft. Therefore, the ratio of aircraft takeoff weight to planform area becomes a necessary parameter in any analysis. The engineering team selected a rectangular plan for the passenger cabin with straight taper sections outboard to the wingtips. The tips are completed with a short dual-ellipse shape. Cargo and fuel are stored in the tapered sections. The wing geometry is defined by specifying the absolute values of the maximum wing thickness and the length of the payload cabin, the thickness-to-chord ratio of the section, the aspect ratio and taper ratio of the planform, the tip ratio, and the ratio that sets the leading-edge and trailing-edge-wing-sweep angles for the taper section. Finally, the engineering team noted that with a low taper ratio, the chord length near the tip would become very short. Furthermore, the spanwise lift distribution is assumed to be elliptical, and thus the section lift coefficient must be increased near the tip to achieve the necessary lift, which might require unacceptable wing twist and camber variations. For this study, the wing-taper ratio was limited to a minimum of 0.4.

*Cabin Arrangement*—The proposed cabin arrangement constitutes a second rectangle within the rectangular center section of the wing. Seats and cross aisles would be arranged in chordwise bays. Entry doors would open to four of the bays, and each bay would be divided into a fore cabin by a single main spanwise aisle. A lavatory would be located within each bay, and emergency exits would be located at the end of each aft cabin bay. Seat and aisle dimensions would define the bay plan size, and the bays would be arranged side by side to build up the total cabin space.

*Cargo Bay Section*—Cargo containers, which would be arranged in chordwise rows, would be stored outboard of the cabin in the taper section of the wing. Loading of containers would be done through the wing leading edge or through the wing lower surface.

*Fuel Tanks*—The inboard edge of the fuel tank would be just outboard of the cargo section. This would provide the best distribution of weight for the structural design. The engineering team noted that since the fuel volume required for a typical long-range mission is considerably less than the available space, there is a lot of freedom in locating the fuel tanks.

*Wing Cross Section*—The maximum thickness-to-chord ratio for the proposed airfoil section is nominally 16 percent. A thinner section would result in a longer chord and thus a longer span for a given aspect ratio, and a thicker section might result in an adverse chordwise shift of the center of gravity aft. This shift, however, can be avoided if the number of rows in the cabin is reduced. Control of the chordwise shift of the center of gravity is a critical design requirement. For stability reasons, the study team estimated that the center of gravity should never be farther aft than 32 percent of the chord. Also, the wing-section leading edge must be as blunt as aerodynamic considerations will allow so that the passenger cabin can be integrated into the wing as close to the leading edge as possible. In addition, the forward landing gear must be stowed in the wing leading edge. The entry door height and location would establish the maximum thickness of the wing for a given wing section. The proposed aircraft's entry door would be cut on a diagonal so that the required 72-inch opening could be located farther aft on the chord. The door would cut the structure at the floor at 10 percent of the chord and cut the ceiling of the cabin at 15 percent of the chord. The proposed internal heights in the cabin are 63 inches ahead of the first row of seats, 72 inches at the top of the entry door, 80 inches at the maximum point in the fore and aft cabins, and 77 inches at the intersection of the two structural lobes.

*Access/Egress*—The proposed aircraft would have four Type A exits (floor level, width of 42 inches, height of 72 inches, direct access from main isle, and a 32-inch-wide passage from the opening to the main aisle). These exits would also serve as main entry doors. In addition, the aircraft would have a Type I exit at the rear of each aft cabin (floor level, width of 24 inches, and height of 48 inches). For emergencies, there would be stairs to the top of the wing and access to an escape slide from each cabin bay.

*Cockpit*—The engineering team pointed out that with the oblique all-wing aircraft swept on takeoff and landing, the pilot would experience unconventional motion and visual cues and that the best location for the cockpit is not clear. They added that a convenient location would be at the wing leading edge adjacent to any one of the four entry doors. In addition, the study team thought it desirable to locate the cockpit at or near the aircraft's centerline in order to minimize potential problems for landing. The plan that the team developed has the cockpit oriented at 40 degrees to the wing's leading edge. This swept angle was dictated by the spanwise position of the landing gear. The cockpit location, however, would displace a number of passenger seats, and the pilot's visibility from the cockpit would be considerably reduced from the visibility that currently exists for subsonic transport aircraft. Recognizing these disadvantages, the engineers noted that there might be better locations for the cockpit, including on top of the aircraft with access through a spiral staircase at the intersection of the center cross aisle and the main span aisle.

*Engine Placement*—The proposed aircraft would have four engines located symmetrically on the planform. The engines would be pivoted 68 degrees for cruise flight. The inboard engines would be mounted just beyond the passenger cabin and the outboard engines would be located approximately 24 feet farther outboard on the span. This spacing is dictated by engine separation on the trailing wing in cruise. The engines would be mounted on pivots that are at 9 percent of the chord and tied directly to the primary structure. The precise location of the engines raised several questions. At the 9-percent chord position, the engines would create a yawing moment if they were located symmetrically on the span. The engines could be located at the 32-percent chord line, but this location would cut into cargo or fuel volume, and the engine inlets would have to be longer to reach beyond the wing leading edge at cruise speed. The yawing moment could be counteracted by pivoting all the engines to toe in, but approximately 7 to 9 degrees would be required, which would increase the required engine thrust by about 1 percent, and the profile drag of the nacelles also would likely increase. The engineering team's proposed solution to the above problems was to vector the gross thrust of the exhaust nozzles. They explained that this solution would have a much more powerful effect because gross thrust rather than net thrust is acting, and typically only 3 degrees of thrust vectoring would also be a positive factor in vertical tail sizing for the engine-out case at takeoff. Another issue raised by the engineers was that the vertical position of the nacelle below the wing was thought to have been an important parameter that would have a strong influence on the interference drag. They added, however, that there was no available data to either support or refute this concern. The team concluded that it would be desirable to tuck the engines as close to the wing as possible to reduce the length of the pivot and the length of the landing gear. In regard to the positioning of the engines, the study team added:

> The correct positioning of the engines both on the planform and vertically with respect to the bottom of the wing is a major unknown in the OAW [oblique all-wing] aircraft configuration definition. There is no reason to necessarily locate the engines symmetrically on the wing. Factors that must be considered are the interference with wing, interference between nacelles, effect on the center of gravity both spanwise and chordwise, and the potential yawing moment produced by the engines without thrust vectoring.[11]

*Landing Gear Number and Placement*—The engineering team noted that the landing gear for an oblique all-wing aircraft would require more consideration than for a conventional aircraft configuration. There must be a minimum of four struts with steerable trucks. The gear for the proposed aircraft design are just fore and aft of the passenger cabin, and the forward and aft gear share the load of the aircraft weight nearly equally. Due to this load on the struts, a forward gear is not possible. Furthermore, when runway pavement loading constraints are considered, eight struts (four ahead of the cabin and four behind the cabin), each with four tires, likely would be required. In order to locate the gear farther out on the span, this study planned to sweep the wing to 40 degrees for takeoff.

*Vertical Tail Sizing and Placement*—In this study, the vertical tail is sized assuming that the tail must create a restoring moment with a lift coefficient of 1.0 to balance the loss of one outboard engine at takeoff. The added drag of the unpowered engine is included in the study team's analysis. The two tails would be mounted on pivoting supports located nominally 90 percent of the semispan from the aircraft centerline. The vertical tails are assumed to have an aspect ratio of nominally 1.0 and the leading- and trailing-edge sweep angles are assumed to be 45 degrees and 30 degrees, respectively.

The engineering team concluded its study by noting the following:

> It must be emphasized that this paper represents a first step in defining the configuration details of an OAW aircraft, and thus it is premature to draw any definitive conclusions about the viability of the concept or even a "best" design. One fact is clear—the aircraft is large, and it should be designed for a large payload.
>
> The basic performance of the OAW aircraft is considered to be excellent. For a flight Mach number of 1.6, the lift-drag ratio at cruise is high—nominally 11.5, and the wing unit weight is reasonably low compared to conventional wings—nominally 6.5 pounds per square foot of surface area. Verifying these performance estimates is the primary focus for the continuing research at NASA Ames. Aerodynamic efficiency would be improved at a reduced cruise Mach number; and included in the plan for continued study is a detailed economic evaluation of the OAW aircraft at different Mach numbers. Finally, the research is to be expanded to include a detailed evaluation of low and high speed stability and control requirements.[12]

Altogether, the early 1990s were a particularly fruitful time for oblique-wing studies, both for conventional "tube and wing" and pure flying-wing designs. A 1995 survey tracing the past history of oblique-flying-wing proposals, the work accomplished in the NASA Oblique All-Wing program, and future planned activity (including Stephen J. Morris's then-ongoing radio-controlled (RC) model work), enumerated the many NASA and industry activities undertaken between 1991 and the end of 1994 (and it is worth remembering that, even prior to NASA's direct involvement in Jones's oblique flying wing, important predecessor work was carried on at Stanford University from 1988 to 1990, with grants from NASA Ames). See the following table.[13]

## Samples and Examples: Extrapolating Beyond Jones's Inspired Work

Van der Velden and Kroo's work, joined with that of others in NASA, academia, and industry, encouraged subsequent work by Ames, defining a range of possible transonic and supersonic oblique flying wings for various civil air transport missions, carrying up to 500 passengers, and spawning a series of industry studies, including those by McDonnell-Douglas and Boeing.[14] The

| *Activity* | **Completed** |
|---|---|
| **Systems Analysis Study at NASA Ames** | July 1991 |
| **Conceptual Design by Frank Neumann of Boeing** | December 1991 |
| **AIAA Papers—Structural/Aero and Economics by NASA Ames** | August 1992 |
| **Configuration and Airport Interface Study by Boeing** | June 1993 |
| **Design Study by the University of Kansas** | June 1993 |
| **Wind Tunnel Test Design Team established at NASA Ames** | July 1993 |
| **Aerodynamics and Stability-Control Study by McDonnell-Douglas** | October 1993 |
| **20-Foot Ground and Flight Test by Stanford University** | May 1994 |
| **Supersonic Wind Tunnel Test at NASA Ames** | August 1994 |
| **Mission Analysis Study by McDonnell-Douglas** | December 1994 |

following indicate the sweep of research inspired by Jones's oblique-flying-wing work and his oblique-wing research in general.

### General Electric Mach 2 Oblique-Flying-Wing High-Speed Civil Transport

In 1991, three General Electric Aircraft Engines company engineers—D.W. Elliot, R.D. Hoskins, and R.F. Miller—outlined their findings regarding oblique-wing aircraft. They noted that NASA's goals for the High-Speed Civil Transport Study were to identify a cruise Mach number, a certification date, and the relevant technologies required to support an HSCT aircraft. The primary contracted participants were airplane builders Boeing and McDonnell-Douglas and aircraft engine manufacturers General Electric (GE) Aircraft Engines and Pratt & Whitney. The specific identified goals were a 2005 certification date, a 5,000-nautical-mile range, and a 300-passenger capacity. As background, the GE engineers noted that environmental constraints (takeoff noise, emissions, and sonic boom) were playing a significant role in sizing the airframe and engine combination. They added that even though the HSCT appeared to be a point-design system with over three quarters of the fuel burned in a single condition (Mach 2.4), neither the cycle nor the engine size was optimized for cruise in a fixed-wing configuration. To meet the environmental challenges and HSCT performance goals, the engine companies headed by GE and Pratt & Whitney joined forces in 1990 to provide the airframers with an acceptable engine. This effort included working nozzle-suppressor schemes and exotic variable cycles to meet the noise standards, designing combustors that would reduce emissions indexes by 10 times the current subsonic designs, and circumventing the sonic boom with lower fuel consumption for efficient subsonic operation over populated areas.[15]

The GE engineers also noted that the airframe companies, working independently, both had fixed-wing baseline configurations reminiscent of the 1970s Aeronautical and Space Technology (AST) configurations. In this regard, the GE team posed the question, "Is the level of aerodynamic and propulsion efficiency sufficient to produce a viable HSCT and meet the environmental constraints of 2005?"[16] At this point, the GE engineers noted that "[g]ranting the need for variable geometry, the oblique wing concept envisioned by R.T. Jones in the late 1950s offers even more advantages by eliminating some of the major drawbacks of the conventional variable sweep designs exemplified by the F-14, F-111, and B-1."[17] In response to their own question, the GE team noted several advantages of using an oblique-wing configuration. For one, they noted that area ruling of the fuselage was not necessary, thus allowing a constant section and ease in extending the fuselage ("plugging") for future growth. By contrast, an area-ruled fuselage, necessary on fixed-wing configurations, required varying frames and compound surface contours that are difficult to plug economically. Also, the landing gear is expected to be shorter by mounting the engines Caravelle style (e.g., off the sides of the aft fuselage, in the fashion of the French Caravelle, an early twin-jet airliner), since the nozzle of the wing-mounted engines were currently setting the tail down line. The GE team added, "The safety benefit related to the variable geometry is the fact that an oblique wing malfunction in the swept cruise position would not compromise the landing (but necessitate a higher speed) since the gear is independent of the wing sweep."[18]

A unique feature of the oblique-wing configuration reviewed in the paper was the location of the oblique wing under the pressurized passenger compartment and above the landing gear bay. The GE team noted that this configuration solved the most aggravating problem in utilizing the oblique wing, which was fairing the wing to the fuselage. The engineers noted that this problem was so severe that a past Navy high-wing design had considered raising the wing for low speed and lowering the wing to set in a fixed fairing for supersonic flight. The configuration reviewed had a lazy Susan bearing above and below the wing, thus eliminating the loads associated with canter levering the wing on a post above or below the bearing set. Also, the midwing location on a constant section fuselage makes the fairing a very simple hinged and/or sliding-door-type closeout. In regard to weight, the team noted that the major weight savings of an oblique-wing configuration was due to the approximately 15-percent-less-fuel requirement over a fixed wing. The takeoff advantages of an oblique wing were due to the high aspect ratio available in the unswept position and the need for only a simple single-slotted flap (whereas a fixed wing requires both leading and compound trailing edge devices to make up for the high sweep and low aspect ratio). An oblique wing's takeoff speed could be as much as 30 knots slower and at a 3-degree-smaller angle of attack than that of a conventional bisymmetric wing.

The GE team concluded,

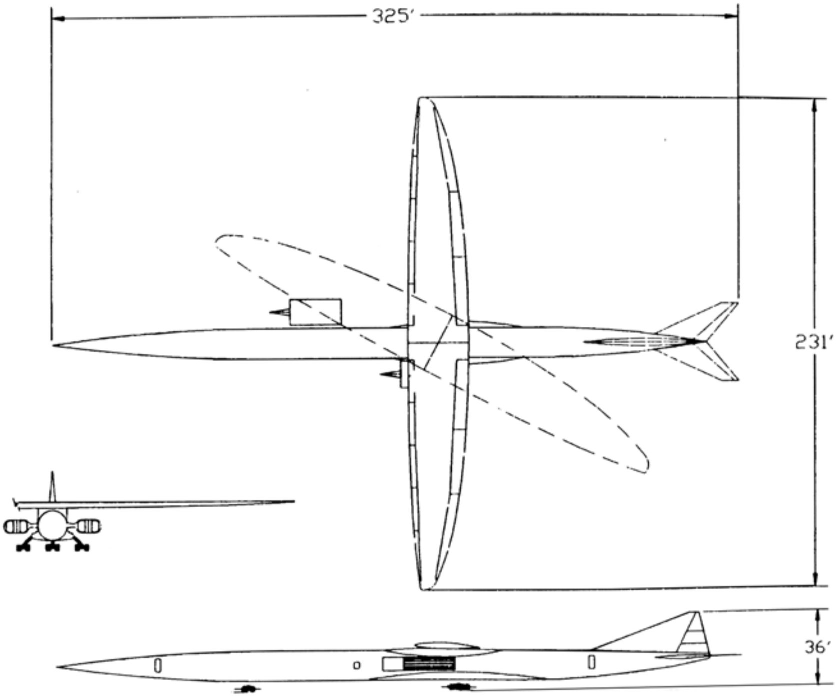
> The estimated improvements throughout the total flight regime, allied with the reduction in potential problem areas demand a serious and timely assessment of an oblique wing HSCT. The positive attributes far outweigh the negative aspect of this concept. The liabilities have been identified and many studies have addressed both the aerodynamic characteristic and flying qualities peculiar to oblique wings; there should be no surprises. In this industry where percents in single digit are eagerly pursued, the double digit gains to be realized with the oblique wing concept must be pursued.[19]

## California Polytechnic State University HSCT Project

California Polytechnic State University at San Luis Obispo has always had a robust reputation in aeronautics, enhanced by the number of distinguished graduates and alumni—Burt Rutan being one such—who have graced its halls and laboratories. In 1992, six aeronautical engineering seniors at California Polytechnic State University, as a required senior project, responded to a NASA Request for Proposals for a preliminary design of a 300-passenger, Mach 1.6, 5,000-nautical-mile-range high-speed transport. The six aeronautical engineering students designated their High-Speed Civil Transport design, which included a variable-geometry oblique wing, the RTJ-303. The overall length of the proposed aircraft was 325 feet with an unswept wingspan length of 231 feet. If the wing was swept during all ground operations other than takeoff, the aircraft was much more slender than conventional winged aircraft. The projected wing area was 5,235 square feet. The determining factor for the wing-area choice was the thrust-to-weight ratio that was limited to 0.30 in order to use reasonably sized engines. The study noted that while no supersonic flight-test data had been obtained to date, supersonic wind tunnel data had been obtained by NASA for Mach numbers up to 1.4 with wing-sweep angles up to 60 degrees. Also noted were the subsonic flight tests conducted by NASA using remotely piloted aircraft and the low-cost piloted AD-1 Oblique Wing Research airplane. The aeronautical engineering students added that the payload of 300 passengers was a compromise between length restrictions on the aircraft and the desire to remain competitive in the market with the maximum number of passengers carried for each flight. The 5,000-nautical-mile range was based on a flight model of 4,700 nautical miles from Los Angeles to Tokyo plus a 300-nautical-mile reserve to reach an alternate airport. This range requirement necessitated a fuel volume that must be carried mostly in the wing. The students concluded that "this aircraft could be built with today's technology and does not rely on vague and uncertain assumptions of technology advances."[20]

The proposed aircraft configuration for the RTJ-303 resulted from a combination of a series of industry oblique-wing studies. Altogether, it was a much more traditional oblique-wing design than the pure flying-wing conceptions popular at the time, with a tube-and-wing approach strongly reflecting the early work of Jones and his initial conceptualizations. But appearances could be deceiving, and the RTJ-303 had a number of interesting features. Two of the attractive features identified for the configuration were the constant cross-section fuselage and the variable-wing geometry. The fuselage did not have the area-ruled bottleneck appearance characteristic of many conventional airplane designs, thus allowing a fuselage of constant cross-section to be utilized, which simplifies the fabrication processes and enables the fuselage to be easily lengthened. The design featured an elliptical variable-geometry oblique wing with a high aspect ratio (10 to 1) with conventional tail-aft control surfaces. The maximum sweep angle of 62 degrees was selected because beyond this angle, a dramatic loss of aileron control effectiveness exists, as does the occurrence of aeroelastic divergence problems on the forward swept wing. At the 62-degree angle, the wing leading-edge normal Mach number was just below drag divergence for the airfoil section of the wing. The fuselage nose and tail cones consisted of modified paraboloids joined by a cylindrical center section. The proposed RTJ-303 would have four mixed-flow turbofan engines grouped into two separate pods staggered and mounted on either side of the fuselage. The vertical and horizontal tail surfaces were swept at 65 degrees in order to facilitate the use of rounded leading edges on conventional NACA airfoil sections. A retractable tricycle-design landing gear would be used on the RTJ-303.

The study included a cost analysis based on 1992 U.S. dollars. The estimated price for each airplane was $183 million ($295 million in 2011), which included the costs from the initial research and development through the production of the aircraft. The price estimate was based on a production run of 300



RTJ-303 student design project for an oblique-wing SST, California Polytechnic State University, from CR 192054, 1992. (NASA)

aircraft. The estimated per airplane life cycle cost (LCC) was $2.6 billion ($4.2 billion in 2011). This number included research, development, testing and evaluation; manufacturing and acquisition; operation cost; and disposal cost.

The study team concluded their report with the following observations and recommendations:

> Having such a long list of benefits, one should wonder why supersonic oblique wings are not flying today. The answer to this question would most likely be the fact that industry is reluctant to make large investments in a configuration which has not proven itself yet. Furthermore, real concerns have been brought up in the past regarding the aerodynamic problems and controllability of such an asymmetric design. However, problems previously thought to be insurmountable are believed to be solvable with today's technology. The highly cross-coupled nature of the plane can be easily solved with current fly-by-wire technology. The

> pilot need never know that he is flying an oblique wing aircraft. An aeroelastically tailored composite wing using unidirectional carbon fibers drastically reduces the problem of aeroelastic twisting and divergence.
>
> Recommendations for the HSCT design program are that supersonic flight tests be performed and performance characteristics be studied, research into synthetic vision be carried out, and composite wing tailoring be tested for effectiveness of reducing aerodynamic twisting and divergence. Further studies should be made as to the economics of variable sweep HSCT that carries fewer passengers in order to reduce the overall length and weight of the plane.[21]

## Oblique Options: Pros and Cons of "Tube and Wing" or "All Wing"

As the Stanford and California Polytechnic State University (Cal Poly) studies showed, considerable divergence of thought existed as to the likely future of oblique technology as applied to air transport design. That conundrum—which road to choose—led Thomas Galloway, Paul Gelhausen, and Mark Moore, of NASA Ames, and Mark Waters, of the Eloret Institute, to examine the respective technical and economic characteristics of two supersonic transport concepts—one an oblique wing-body configuration that carries the passengers in a traditional cylindrical-cross-section "tube" fuselage and the other an oblique all-wing configuration that accommodated the passengers within the wing structure à la Jones, Van der Velden, and Kroo. They compared these oblique-wing-on-fuselage and oblique-all-wing configurations with Boeing's 300-passenger 767 and 777 and the 400-plus-passenger 747. The study parameters included passenger capacities from 300 to 500, a design range of 5,000 nautical miles, a standard international fuel-reserve requirement, design Mach numbers of 1.6 and 2.0, a production quantity of 500 aircraft, a development period of 5 years, and a 15-year delivery schedule.[22]

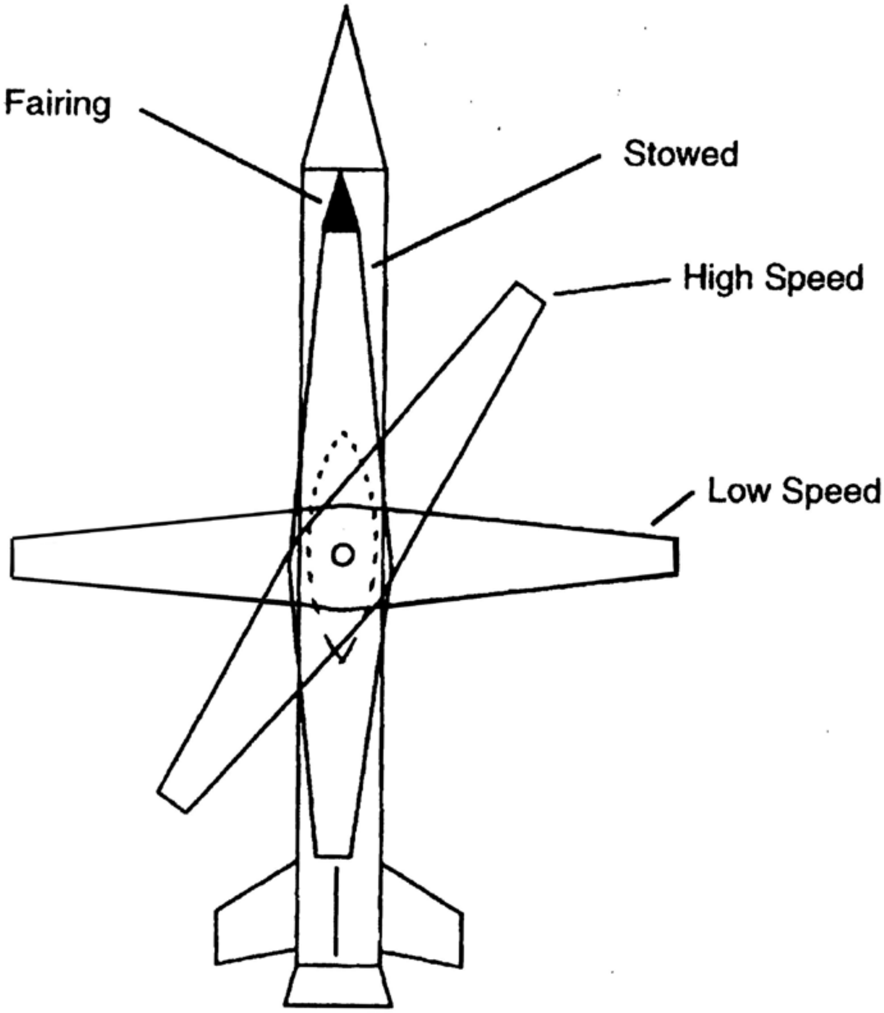
Although designed for a maximum range of 5,000 nautical miles, the concepts were evaluated for economic analysis based upon an average trip distance of 3,800 nautical miles. The computer model used was the ACSYNT design synthesis program, which estimated the aircraft performance and sized the aircraft to meet the specified mission requirements reviewed above. The cost modules in ACSYNT estimated the aircraft price, operating costs for the mission, and the overall return on investment to the airline and aircraft manufacturer. The economic viability was assessed based on the average passenger revenue (cents-per-revenue passenger-mile) required for the airline to make a 12-percent return on investment when the aircraft is priced so that the manufacturer also makes a 12-percent return on investment.[23]

The study's conclusions were summarized as follows:

> The study focused on identifying the economic potential of supersonic OWB [oblique wing-body] and OAW [oblique all-wing] designs compared to equivalent passenger size subsonic concepts. At the smallest passenger size studied (300), the Mach 2.0 OWB required the least increase in revenue above the subsonic baseline. As the passenger sizes increased to the largest size studied (544) the Mach 1.60 OAW required revenue only 9 percent above the subsonic concept. The variable sweep capability of the oblique wing designs offers the flexibility to cruise subsonically, if required because of sonic boom constraints, and suffer no penalty in the aircraft's range capability. Since the oblique wing designs can meet takeoff field length requirements with significantly throttled engines, current Stage 3 noise levels can be met without major noise suppression devices. At the supersonic speeds of the study current aluminum airframe can be used to keep manufacturing costs low. In summary, the oblique wing concepts offer supersonic flight with trip times one-half the subsonic aircraft, needs only a modest increase in revenue, and have operational features that allow efficient subsonic operation and minimize noise around the airport.[24]

## Stephen Morris and Small-Scale Radio-Controlled Oblique-Flying-Wing Flight Test

In his advocacy of the oblique-flying-wing concept, R.T. Jones cited the encouragement and assistance that he had received from Stephen Morris, then a doctoral student at Stanford, where, among others, he worked with Ilan Kroo. It would be Morris who would undertake a notable step forward in oblique-flying-wing studies by actually constructing and flying two radio-controlled flying wings, a significant first in aviation history arguably equivalent in significance to Alphonse Pénaud's first flight of a powered model airplane in 1871. In the late 1980s, Morris and Kroo had studied aircraft design optimization, looking at interactions between weight, aerodynamic performance, and handling qualities using various design examples, including the proposed F-8 OWRA and the challenge of dynamic mode decoupling. At the time, Morris was completing a doctoral dissertation on integrated aerodynamic and control system design for an oblique wing, looking at the challenge of ensuring adequate stability, control, and handling qualities at sweep angles above 30



Ames study for an oblique-wing "Turn and Glide-Back" space launch booster recovery system, 1999. (NASA)

degrees, where the highly asymmetric nature of a swept oblique wing induced aerodynamic and inertial couplings that degraded both stability and handling qualities. Eventually, as part of his research, Morris built a 10-foot-span, radio-controlled, statically stable oblique flying wing powered by a small two-stroke engine. Though initial flight trials were disappointing, Morris persisted until he had refined a stable configuration whose wing could be swept between 25 degrees and 65 degrees. He followed this in 1994 with a more complex, statically unstable, twin-ducted-fan, radio-controlled model with a three-axis rate gyro. Though it completed only a single flight before NASA funding shortfalls ended the program, it did demonstrate satisfactory handling qualities up to a 50-degree sweep, a notable accomplishment.[25]

## Beyond Civil Air Transport: Oblique Wings for Other Mission Areas

The advent of the oblique wing, coming as it did coincident with the revolutions in electronic flight control; lightweight, resilient, and strong composite materials; advances in command, control and sensor architectures; the onset of the Unmanned Aerial Vehicle (UAV), formerly, the Remotely Piloted Vehicle (RPV), and subsequently, the Remotely Piloted Aircraft (RPA); the era of space transportation and routine access to space; and the precision-weapon and cruise-missile eras, ensured that the planform would soon be evaluated for far more than simply its suitability to civil air transports.

One area of appeal involved something far afield from conventional air transport: using an oblique wing to enable recovery of the Space Shuttle's booster system. NASA already recovered the burned-out solid-rocket boosters (SRBs) after each launch via a parachute-and-floatation-bag system, but it was complex, entailed search and recovery costs, and then extensive refurbishing and processing costs as well, since they were thoroughly soaked in the Atlantic Ocean. The appeal of recoverable first stages was long-standing within the astronautics community because recovering and then reusing a first stage could considerably reduce the operational costs associated with space launch and routine access to space. Fly-back boosters and recoverable booster concepts featured prominently in early Shuttle concepts, but the complexity of such systems and the penalty they imposed upon vehicle configuration, weight, and, hence, performance, dissuaded the designers from using them. But nearly two decades after the first orbital flight of the Shuttle, the technical situation, and rising concern over the cost of space launch (particularly the Shuttle), led to a resurgence of interest in fly-back boosters. The oblique wing, a much more suitable wing configuration than some sort of fixed delta wing, lifting body, or variable-geometry approaches, had decided appeal.

Accordingly, in 1999, Stephen C. Smith, Robert A. Kennelly, Jr., and James Reuther of the NASA Ames Research Center Aeronautics Directorate studied the feasibility of a "Turn and Glide-Back" system using an oblique wing to make the Shuttle's solid-rocket boosters, and other spacecraft first-stage boosters, more easily recoverable, including running a series of tunnel tests on a suitable configuration. Unlike conventional bisymmetric swept wings, which posed daunting structural, storage, and deployment challenges, the oblique wing stowed lengthwise on a booster with minimum impact on its ascent configuration. When deployed, the oblique wing could operate efficiently from a highly swept low-aspect-ratio profile at high supersonic speeds (L/D=3.5 to 4.0) down to a subsonic high-aspect-ratio, high-lift profile (L/D=10 to 15), thus furnishing adequate L/D across a wide Mach number range from M=0.35 to 2.35.[26] The oblique wing remains an intriguing possible approach to reduce the cost and increase the flexibility of space access.

Another area constituting a natural field for oblique-wing utilization has been the steadily emerging field of remotely piloted aircraft. In 2000, R.K. Nangia, a consulting engineer with Nangia Aero Research Associates, and D.I. Greenwell, then principal scientist with the United Kingdom's Defense Evaluation Research Agency (DERA), addressed potential military applications of oblique-wing combat UAVs and piloted aircraft.[27] Their paper focused on design for transonic cruise at low altitudes, noting that "for oblique wing aircraft, the intuitive feeling is that the main problems are more likely to do with ensuring adequate control rather than drag reduction,"[28] and concluding:

> The Oblique Wing (OW) concept remains a proposition for meeting rigorous aerodynamic performance goals for Mach numbers to about 1.7 over a wide flight envelope up to 40,000 ft. With appropriate wing sweep, high efficiencies can be obtained at low speed. The handling, stability and control issues remain a strong design challenge to ensure adequate stability in pitch, yaw and roll. This has led to a work programme with the objective of assessing the suitability of such concepts for manned and UAV combat aircraft applications.[29]

In this vein, in August 2005 (following upon an encouraging earlier study on the prospects of supersonic oblique flying wings undertaken for the Defense Advanced Research Projects Agency by the Massachusetts Institute of Technology and Desktop Aeronautics), DARPA issued a Request for Proposals for an Oblique Flying Wing experimental aircraft (OFW X-Plane) that meets the following "non-tradable" design requirements:

- reusable conventional takeoff and landing (CTOL) using a retractable landing gear,
- conventional air-breathing propulsion,
- max Mach greater than or equal to 1.20,
- tailless configuration,
- variable-oblique-wing sweep from 30 degrees to greater than or equal to 60 degrees,

- aspect ratio greater than or equal to 7 at minimum sweep, and
- wingspan greater than or equal to 40 feet at minimum sweep.[30]

On March 16, 2006, this resulted in the agency awarding a $10.3 million, 20-month contract to Northrop Grumman for risk reduction, testing, and preliminary design of an OFW X-Plane demonstrator aircraft. (Subsequently, funding was increased to 14.5 million, and Northrop Grumman contributed $7 million of its own.)

Though not directly tied to the Air Force's contemporary interest in precision long-range strike, the DARPA effort noted the oblique wing's promised range of flight efficiency from subsonic through supersonic velocities, guaranteeing a favorable combination of speed, range, and endurance that would be desirable in any long-range strike system. The result of this study was an 18,334-lb gross weight, twin-engine subscale oblique-flying-wing design powered by two afterburning GE J85-21 turbojet engines (the same kind used in the Northrop F-5E/F Tiger II lightweight fighter) mounted in swiveling pods with an unswept span of 56 feet 4 inches. Its aspect ratio (AR) varied from 7.2 at minimum sweep to 1.33 at maximum (65 degrees) sweep. Over the length of the study effort, more than 1,000 wind tunnel test runs were performed on the configuration. Unfortunately, though the program satisfactorily completed its preliminary design phase, DARPA canceled it in May 2008, before it was actually fabricated and flown, a decision that appears unfortunate given the value such a flight demonstration could have had.[31]

The oblique wing has also received consideration for use on basic weapons such as projectiles and missiles. Because (as with space launch, discussed earlier) the oblique wing can easily be rotated to a fully streamlined position where the span of the wing is aligned parallel to the longitudinal axis of a projectile and missile, it offers an attractive means of giving a ballistic or near-ballistic weapon a high lift-to-drag ratio, thus greatly extending its engagement range and affording standoff to the launching system from enemy defenses.

In 2005, ZONA Technology, Inc., proposed that the U.S. Navy extend the range of its standard 5-inch, 54-caliber naval cannon (typically used on destroyers and cruisers) by modifying its shell with a "body-conformal oblique wing/tail with smart-structure (actuator) control."[32] The Navy was working on an Extended Range Guided Munition (ERGM) 5-inch precision round, the EX-171, scheduled to reach initial operational capacity. The Navy was considering achieving the extended range through a combination of rocket assistance and gliding flight. The rocket motor, however, would have a negative impact on payload, cost, safety, and reliability, so the Navy design strategy under their Naval Surface Fire Support (NSFS) program was to eliminate the rocket motor while at the same time trying to satisfy most of the extended-range requirement. ZONA's work was sponsored by a Navy contract (N00178-00-C-1051) awarded under a Small Business Innovation Research (SBIR) phase II program. NASA Langley and NASA Ames assisted one of the ZONA engineers in setting up and using PEGUS overset grid data. ZONA Technology noted that their innovative oblique-wing projectile "would maintain the maximum lift-to-drag ratio (L / D) throughout its gliding phase and achieve an extended range which exceeds the maximum range required for the rocket-assisted ERGM [Extended Range Guided Munition]."[33] The study pointed out that

> [t]he oblique wing has superior aerodynamic characteristics because it can maintain a subsonic leading edge throughout the supersonic/transonic ranges and significantly reduce the wave drag. In fact, it can achieve a much higher lift-to-drag ratio at all Mach numbers than virtually any other wing. For supersonic-flight deployment of the wing near the apogee, maintaining the maximum lift-to-drag ratio of the projectile throughout the whole gliding phase requires the oblique wing to move in a continuously [*sic*] manner at each optimal sweepback position with a simple, light-weight mechanism.[34]

In conducting their study, the ZONA engineering team made extensive Navier-Stokes computations to search for the best sweepback positions of the oblique wing for the given pairs of Mach numbers and the angles of attack in the supersonic and transonic gliding phases. The engineers used the NASA CFL3D v6 computer code, which was developed and supported by NASA Langley. The CFL3D code is a three-dimensional, thin-layered, Reynolds-averaged Navier-Stokes code that uses an implicit approximately factored, finite-volume, upwind, and multigrid algorithm. Through the use of this code, after generating all component grids at one wing angle, it was only necessary to rotate the wing and wing-cap grids for different wing positions. The study results, reported at the 23rd AIAA Applied Aerodynamics Conference in Toronto, Canada, in June 2005, concluded the following:

> Extensive Navier-Stokes computations have been performed to determine the optimal scheduling of the oblique-wing for a projectile during the supersonic and transonic gliding phases. It is found that using the oblique-wing technique, a guided projectile can achieve the maximum lift-to-drag ratio throughout its gliding phase and therefore extend its range beyond the target 100 nm without rocket gliding assistance.[35]

In January 2008, two Air Force Institute of Technology researchers presented study results of wind tunnel tests of an oblique-wing-missile model. In undertaking their study, Captain Matthew J. Dillsaver and Milton E. Franke found that

> [e]ver since Chuck Yeager broke the sound barrier in 1947, aerial vehicle designers have been looking for wing designs that perform well at both subsonic and supersonic speeds. One way to accomplish this goal is through wing morphing of some kind providing variable wing geometry. One purpose of wing morphing is to provide a high aspect ratio for low-speed flight and loitering and a low aspect ratio for high-speed flight.
>
> A variable geometry concept currently garnering more research is the oblique wing design. In 1952, Jones proved that for any flight Mach number the minimum drag for a given lift could be achieved by an oblique swept wing with an elliptic planform. Other wind tunnel tests have shown that oblique wings are very effective at reducing wave drag at supersonic speeds. In 1958 Jones noted that wave drag and induced drag could be minimized by a variable sweep oblique wing with an elliptical lift distribution. At supersonic speeds drag on an aircraft is dominated by wave drag. One major advantage of oblique wings for supersonic flight is that for equivalent span, sweep, and volume the wings distribute the lift over twice the length of a more conventional sweep wing planform. This reduces lift dependent wave drag by a factor of four and volume dependent wave drag by a factor of 16. Jones also showed that the induced drag of an oblique wing at optimal sweep is half of that for a delta wing of the same span.[36]

Dillsaver and Franke noted that from 1979 to 1982, NASA successfully flew the full-scale demonstrator, the AD-1, for a total of 79 hours. They also noted that NASA's F-8 oblique-wing program confirmed that controllability was a major issue to be addressed when dealing with oblique wings. In a comment on tunnel testing and test-result fidelity, the two engineers recognized the limitations of using a ground plane in a wind tunnel because the boundary layer buildup on the plane's top surface can distort flow, compromising accurate data acquisition. As a possible solution, they recommended incorporation of a boundary layer removal system.

Dillsaver and Franke undertook their wind tunnel testing in the Air Force Institute of Technology (AFIT) 3-by-3-foot low-speed wind tunnel at Wright-Patterson AFB, OH, employing an aluminum missile model. The model had a length of 28.44 inches with a projected diameter of 2 inches. The missile model, which had previously been used for joined-wing testing, had four identical tailfins, two horizontal and two vertical, employing a symmetric airfoil. The oblique wing had a span of 17.5 inches, with no twist or dihedral; its chord was 2 inches; and it had a blunt leading edge. The wing section had a positive camber. The oblique wing was installed on the missile with the pivot point near the model's center of gravity. The wing-sweep angle was measured from 0 degrees to 90 degrees. (Zero degrees was defined as when the wing was perpendicular to the missile body—i.e., fully spread—and 90 degrees was defined as the wing being aligned parallel to the longitudinal axis of the missile body.) A ground plane, consisting of two steel plates supported by eight cylindrical steel legs, was installed in the tunnel to simulate the missile separating from an aircraft. The missile and wing were tested in two different flight conditions. Simulated launch effects from an aircraft were performed by inverting the missile above the ground plane to determine the forces caused by the simulated inground effects.

Based on the wind tunnel test results, Dillsaver and Franke concluded that

> [t]he oblique wing model presents an alternative to missile range extension and may allow a way to provide range extension. The tests herein, however, are preliminary tests as additional information is required at higher speeds to take possible advantage of the oblique wing both in release and in flight. Also, to get an understanding of the separation and stall, additional testing will need to be accomplished using pressure transducers and some flow visualization.[37]

## Afterword: Robert T. Jones, the Oblique Wing, and His Legacy

Conceptualizing and refining the oblique wing constituted the culminating achievement of Robert T. Jones, an individual whose place in the pantheon of American aerospace pioneers is secure, together with colleagues such as Max Munk (airfoil theory and the variable-density tunnel), John Stack (supersonic research aircraft), and Richard T. Whitcomb (area rule).

Ironically, while he achieved great success with the bisymmetrical swept and delta planform, the same has not been true of the oblique wing, despite its obvious advantages. This has not been lost on his admirers, either before Jones's death or after.

In his Introduction to the *Collected Works of Robert T. Jones*, written before Jones's passing, William R. Sears (commenting on why no transonic oblique-wing transports had yet been built) noted the following:

> The aeroelastic properties of the oblique wing have frightened a number of engineers, for the upstream panel surely wants to deflect aeroelastically upward and the downstream panel downward. To Bob it seems obvious that these effects simply do not occur in flight. A study of the equilibrium of rolling moments will confirm that he is right. The details are left to the reader; it must be said that the conclusion is not quite "obvious," even to most aeronautical engineers![38]

In his 2005 biographical review of R.T. Jones, written as a memorial tribute, the engineer-historian Walter G. Vincenti (himself a notable NACA-NASA pioneer), in reviewing the legacy left by Jones in regard to the oblique-wing concept, noted the following:

> Thanks to R.T.'s impetus and vision, there now exists a large body of knowledge of possible oblique-wing airplanes in both the pivoted and flying-wing versions. In the course of this work, the stability-and-control and aeroelastic problems that accompany the oblique wing have been solved. Sears writing in 1976 with regard to the pivoted wing said "I, for one, fully expect to see future transport airplanes with Jones oblique wings." Though aircraft companies have studied the possibilities, what Sears expected has not, for a complex of reasons, come to the pass with either version.[39]

It is pleasant to record that Jones did more than theoretically conceptualize the oblique wing. Through his advocacy and persistence, he ensured that it actually did appear in flight, most notably, of course, with the AD-1 but, significantly as well, with subscale radio-controlled models and as a conceptualization that attracted the attention of major design firms and national agencies. It is even more pleasant to note that he was an observer to, and a participant in, such accomplishment, having witnessed the flights of oblique-wing test beds, particularly, again, his AD-1.

In their assessments, both Sears and Vincenti identified some points worth pondering and exploring. Sears noted the tendency toward design conservatism. Just as the comfortable traditionalism of the tube-and-wing airliner has persisted long after the era of electronic flight control has made the flying wing a practicality, so too has the seductive mirror image of bisymmetric sweep inhibited the creativity of many who should look to the barrier-breaking oblique wing with greater enthusiasm than they do. Vincenti, in acknowledging what has come to pass, rather than what might have been, has illuminated a future that has not, to date, been realized—but a future that will because the advantages of the oblique wing are simply too great to ignore. For any flight vehicle operating in the high transonic-supersonic regime, for any conventional space launch system boosting into space or returning from it, for any projectile or weapon that has to fly a distance at supersonic speeds, the oblique wing offers a simplicity of concept and fabrication that makes it more acceptable than other forms of variable sweep.

Reviewing the history of the oblique wing, its application to the AD-1, and its subsequent history since that milestone aircraft, one can see that the actual flight demonstration—in an inhabited aircraft, and not simply a model or rudimentary remotely piloted aircraft—was an important moment in NASA research. Jones had conceived the oblique wing, and his reputation ensured it would be taken seriously. But nothing was more convincing than the sight of the AD-1—an SST configuration, if flying at only a quarter of the speed—coursing through the air, its wing sharply swept, a veritable flying scissors.

The legacy of Robert Jones—and those he inspired, influenced, and mentored—is this: While the transonic or supersonic oblique-wing transport, either as a pivoted wing on a fuselage or as a flying wing, has not yet been built, the promise of the oblique-wing configuration, as evidenced by the many design proposals and projects this work has enumerated, remains attractive to many in the aerospace community for a number of applications, ranging from advanced airliners and remotely piloted aircraft to missiles, rockets, and shells. That oblique-wing vehicles will fly is not in doubt. The only question is when.

## Endnotes

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39. Walter G. Vincenti, “Robert T. Jones, One of a Kind,” *Annual Review of Fluid Dynamics* 37 (January 2005): 11.

## APPENDIX 1

# Physical Characteristics of the Ames-Dryden AD-1 OWRA[1]

| Description | Specification |
|---|---|
| **Total height** | 6.75 feet (ft) |
| **Total length** | 38.80 ft |
| **Wing reference and actual planform area** | 93 square (sq) ft |
| **Wing reference and unswept span** | 32.30 ft |
| **Wing reference and unswept chord (root)** | 4.28 ft |
| **Wing aspect ratio** | 11.2 |
| **Wing airfoil** | NACA 3612-02, 40 (constant) |
| **Wing dihedral angle** | 0° |
| **Wing twist** | –2° |
| **Wing root incident angle** | 2° |
| **Wing quarter chord sweep angle** | 0° |
| **Wing leading edge sweep angle** | 2° |
| **Wing average chord** | 2.90 ft |
| **Wing sweep (yaw) angle range** | 0° to 60° |
| **Horizontal tail planform area** | 26 sq ft |
| **Horizontal tail span** | 8 ft |
| **Horizontal tail average chord** | 3.30 ft |
| **Horizontal tail root chord** | 5.40 ft |
| **Horizontal dihedral angle** | 0° |
| **Horizontal incidence angle** | 0° |
| **Horizontal tail leading-edge sweep angle** | 45° |
| **Vertical tail area (exposed)** | 14.4 sq ft |
| **Vertical tail span (exposed)** | 3.70 ft |
| **Vertical tail average chord** | 3.90 ft |

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[1] "AD-1 Owner's Manual," 1-4 and 1-5 (December 11, 1979).

| | |
|---|---|
| **Vertical tail root chord** | 5.80 ft |
| **Vertical tail leading-edge sweep angle** | 43° |
| **Aileron hinge line** | 0.75 chord |
| **Aileron total span** | 12 ft |
| **Aileron area** | 23 sq ft |
| **Aileron root station** | 0.62 |
| **Aileron root chord** | 0.65 ft |
| **Aileron range (each)** | +/–25° |
| **Elevator hinge-line sweep angle** | 0° |
| **Elevator area** | 5 sq ft |
| **Elevator average chord** | 0.62 ft |
| **Elevator root chord** | 0.75 ft |
| **Elevator range** | 25° up to 15° down |
| **Rudder hinge-line sweep angle** | 0° |
| **Rudder area** | 31.2 sq ft |
| **Rudder average chord** | 0.71 ft |
| **Rudder root chord** | 0.92 ft |
| **Rudder range** | +/–25° |
| **Empty mass** | 1,122 lb |
| **Useful load** | 600 lb |
| **Fuel load** | 400 lb |
| **Gross weight** | 1,722 lb |
| **Engines** | Two TRS-18-046 |
| **Engine sea level static thrust (each)** | 220 lb |

## APPENDIX 2

# Detailed Description of the Ames-Dryden AD-1 OWRA[2]

| | |
|---|---|
| **The Airplane** | The AD-1 is a very small, low-subsonic aircraft whose purpose is to explore the aerodynamic and aeroelastic response characteristics of an oblique-wing design. The principal distinguishing feature of this craft is a top-mounted, high-aspect-ratio wing, which pivots on the fuselage from a conventional straight-wing position to a skew angle of 60 degrees. |
| **The Engines** | Two 220-pound-thrust TRS-18-046 centrifugal-flow turbojet engines power the AD-1. Engines are pod-mounted to each side of the fuselage in a midships position. Pilot control of the engines consists of starting, thrust selection, and stopping. Engine functional parameters are displayed on the instrument panel. An onboard battery provides self-contained ground and inflight starting capability for both engines. |
| **Electronic Engine Controls** | The electronic control unit for each engine automatically modulates fuel flow to maintain operation within prescribed limits. The cockpit-mounted thrust lever positions a potentiometer for throttle control. This is, in effect, a fly-by-wire throttle. No backup control for the electronic control unit is provided. The operator must maintain supervisory vigilance of the engine functional parameters and shut the engine down in the event of unsatisfactory operation. |
| **Engine-Oil System** | Each engine-oil system consists of an internal sump reservoir, pressure pump, and distribution network. The oil pump is actuated by compressor bleed air. Usable oil capacity is one pint. Oil pressure for each engine is displayed on the instrument panel. Additionally, a low-pressure-warning light for each engine is provided. Since the pump is driven by compressor bleed air, oil pressure will vary with engine revolutions per minute (RPM) and density altitude. |

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[2] "AD-1 Owner's Manual," 1-10 and 1-19 (December 11, 1979).

| | |
|---|---|
| **Fuel System** | All fuel for the AD-1 is carried internally in two integral, tandem cells. The capacity of the forward cell is 40 gallons. Aft-cell capacity is 32 gallons. The left engine normally feeds from the forward cell while the right engine feeds from the aft cell. For single-engine operation, a solenoid-operated equalizing valve may be opened to allow fuel to gravity flow from one tank to the other. The equalizing valve is normally left closed in flight to prevent fuel from draining to one tank because of fuselage attitude. Fuel gravity flows from each tank to a nacelle-mounted electric fuel pump and thence to the engine. Excess fuel is bypassed by the fuel control and routed back into the fuselage cells. Fuel flow back is at a rate of approximately 25 gallons per hour. |
| **Electric Power Supply System** | Electric power for the onboard aircraft and data systems is supplied by a single 6.5-amp-hour, 24-volt Ni-Cad battery. The battery is maintained in a fully charged state by an engine-driven starter generator on each engine. Each starter generator feeds a single, common electrical power distribution subsystem (BUS) without regard to the status of its mate. The starter generators are each capable of delivering 20 amps, 28 volts at maximum engine RPM. |
| **Flight Control System** | The AD-1 Flight Control System is an all-mechanical, nonboosted system. Stick and rudder pedals control ailerons, elevator, and rudder in a conventional fashion. Three-axis electric trim is provided through tabs on the aileron and elevator and through a separate surface rudder. Pitch and roll trim controls are conventionally located on the top of the control-stick grip. Yaw trim is controlled by means of a spring centering toggle switch mounted just forward of the throttles on the left console. All trim controls are of the “beep” style. There are no cockpit trim indicators, so in order to set the trims for takeoff, the pilot must (1) physically look at tab positions; or (2) take direction from the crew chief, who is looking at the tabs; or (3) take direction from NASA 1, which is looking at tab positions on telemetry. The Roll Control System linkage is designed so that the stick-to-surface relationship does not change with wing-skew angle. |

| | |
|---|---|
| **Wing Skew System** | The AD-1 wing pivots on a single, 14-inch-diameter roller bearing. The pivot assembly is designed so that the wing will remain attached to the fuselage if a catastrophic bearing failure occurs. Actuation of wing skew is by a dual electric-motor-gearbox assembly that is built into the pivot. Pilot operation of the wing skew is by a spring toggle switch. In order to skew the wing, the operator must hold the switch to the right. Full skew will be achieved in approximately 20 seconds. Wing motion will stop as soon as the switch is released. Actuation of the wing back to its conventional position is accomplished by moving the skew switch to the left of center. The skew switch will remain in the left (unskew) position with no further pilot action. Emergency unskew can be commanded by depressing the trigger switch on the stick grip. Electrical limit switches at the wing pivot limit wing movement at 0 degrees and +60 degrees. Hard mechanical stops are placed at –2 degrees and –62 degrees on the pivot to prevent overtravel in case of a runaway actuator. |
| **Landing Gear** | The AD-1 employs fixed, tricycle landing gear. Main gear consists of an epoxy-fiberglass strut protruding from each side of the fuselage. A single 5.00-by-5 wheel and 4-ply tire are mounted to each strut. Landing-shock absorption is accomplished by the flexing of the composite struts and by tire deflection. The nose landing gear is a simple epoxy-fiberglass-composite strut that is internal to the fuselage. A single, steerable wheel is mounted to the nose strut. The nosewheel is capable of steering 20 degrees left or right by conventional rudder. The calculated maximum-landing sink rate is 5 feet per second. Landings at sink rates in excess of 5 feet per second may result in the blowout of the main tires, damage to the wheel rims, and in severe cases, abrasion of the fuselage bottom. |
| **Wheel Brake System** | The AD-1 employs individually toe-operated main-wheel disc brakes. Hydraulic brake lines are routed from the brake pedals, back through the fuselage, and down the composite main landing gear struts. No boost is provided. |
| **Instruments** | All flight instruments for day VFR flight and research flight tests are located on the main instrument panel. Angle-of-attack, sideslip, and wing-skew indicators are driven by the Data System. |

| | |
|---|---|
| **Data System** | A research flight test Data System is installed in the aircraft. Except for remote sensors and the cockpit displays, the Data System is located on a single pallet in the upper third of the fuselage between F.S. 240 and F.S. 275. All flight data are transmitted to a ground receiving-and-recording station. No onboard data recording is provided. The Data System is turned on by means of a single switch on the instrument panel. It is possible to run the onboard Data System without transmitting data. Circuit breakers for this purpose are on the Data System pallet. |
| **Pilot Seating and Restraint** | Seating in the AD-1 is semisupine. The seat-back angle is 45 degrees. Conventional seat belt, shoulder harness, and crotch-strap restraints are employed. The seat is designed to be used in conjunction with the Security Model 250-EPA parachute. No survival kit is provided. Adjustment for pilot size is by means of seat cushions. |
| **Canopy** | The AD-1 is fitted with aft-hinged, manually operated canopy. Entry and exit is from the left side of the aircraft. The canopy latch is a two-point restraining device that may be operated either from inside the cockpit or from the outside. From inside the cockpit, the canopy is locked by moving fully forward until a spring-loaded detent is engaged. Locking of the handle may be checked by attempting to move the handle aft. To unlock the canopy, pull the handle inboard and move fully aft. An external canopy handle is mounted on the left-fuselage side just below the canopy sill. To open from the outside, push the button and rotate handle counterclockwise. Partial opening of the canopy for ventilation during taxi may be accomplished by lifting the canopy, slightly engaging the canopy lock handle, and lowering the canopy onto the closed hooks. Taxiing with the canopy partially open should be done with considerable care as there is nothing to prevent the canopy from fully opening due to wind or aircraft motion. The pilot should not unlock the canopy in flight except for purposes of canopy jettison. While no flight demonstration has been made, it is expected that the canopy will depart the aircraft immediately if it is unlocked in flight. |

## APPENDIX 3

# Flight Log Summary for the Ames-Dryden AD-1 OWRA[3]

| Flight Number | Date | Pilot | Organization | Time Duration | Remarks |
|---|---|---|---|---|---|
| **1** | Dec. 21, 1979 | Thomas C. McMurtry | NASA DFRC | 0:05 | Resulted from high-speed taxi test |
| **2** | Dec. 21, 1979 | Thomas C. McMurtry | NASA DFRC | 0:45 | First official flight; aircraft checkout |
| **3** | Jan. 11, 1980 | Thomas C. McMurtry | NASA DFRC | 0:45 | Performance; handling qualities |
| **4** | Jan. 21, 1980 | Thomas C. McMurtry | NASA DFRC | 0:50 | Performance |
| **5** | Jan. 21, 1980 | Thomas C. McMurtry | NASA DFRC | 0:50 | Performance |
| **6** | Jan. 23, 1980 | Thomas C. McMurtry | NASA DFRC | 0:20 | Performance |

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3. The information in items 48–79 was taken from: Peter Merlin, "Ames Dryden AD-1 (N805NA) Flight Log" (Dec. 2002), Box L1-3-7B, Folder 1, NASA Dryden History Office.

| | | | | | |
|---|---|---|---|---|---|
| **7** | Jan. 23, 1980 | Thomas C. McMurtry | NASA DFRC | 0:55 | Stability and control |
| **8** | Jan. 25, 1980 | Fitzhugh L. Fulton | NASA DFRC | 1:00 | Pilot checkout; performance |
| **9** | Feb. 1, 1980 | Thomas C. McMurtry | NASA DFRC | 1:15 | Performance |
| **10** | Feb. 20, 1980 | Fitzhugh L. Fulton | NASA DFRC | 0:55 | Performance |
| **11** | Mar. 7, 1980 | Thomas C. McMurtry | NASA DFRC | 0:40 | Performance |
| **12** | Apr. 2, 1980 | Thomas C. McMurtry | NASA DFRC | 1:05 | First 15-degree-wing-sweep flight; evaluate stability at high angle of attack |
| **13** | Apr. 25, 1980 | Thomas C. McMurtry | NASA DFRC | 0:50 | First 20-degree-wing-sweep flight; flutter clearance |
| **14** | May 28, 1980 | Thomas C. McMurtry | NASA DFRC | 1:30 | First 45-degree-wing-sweep flight; flutter clearance |
| **15** | July 9, 1980 | Fitzhugh L. Fulton | NASA DFRC | 1:15 | Flutter clearance |
| **16** | July 9, 1980 | Thomas C. McMurtry | NASA DFRC | 1:15 | Flutter clearance |

| | | | | | |
|---|---|---|---|---|---|
| **17** | July 17, 1980 | Fitzhugh L. Fulton | NASA DFRC | 1:15 | Flutter clearance |
| **18** | July 17, 1980 | Thomas C. McMurtry | NASA DFRC | 1:15 | Flutter clearance |
| **19** | Aug. 12, 1980 | Thomas C. McMurtry | NASA DFRC | 0:40 | Flutter clearance |
| **20** | Mar. 31, 1981 | Fitzhugh L. Fulton | NASA DFRC | 1:15 | Flutter clearance |
| **21** | Mar. 31, 1981 | Thomas C. McMurtry | NASA DFRC | 1:20 | Flutter clearance |
| **22** | Apr. 24, 1981 | Fitzhugh L. Fulton | NASA DFRC | 1:10 | Flutter clearance |
| **23** | Apr. 24, 1981 | Thomas C. McMurtry | NASA DFRC | 1:30 | First 60-degree-wing-sweep flight; flutter clearance |
| **24** | May 12, 1981 | Fitzhugh L. Fulton | NASA DFRC | 1:10 | Flutter clearance |
| **25** | May 12, 1981 | Thomas C. McMurtry | NASA DFRC | 1:05 | Flutter clearance |
| **26** | May 28, 1981 | Thomas C. McMurtry | NASA DFRC | 1:00 | Handling qualities |

| | | | | | |
|---|---|---|---|---|---|
| **27** | June 11, 1981 | Thomas C. McMurtry | NASA DFRC | 1:10 | Stability and control |
| **28** | June 16, 1981 | Thomas C. McMurtry | NASA DFRC | 1:10 | Stability and control |
| **29** | July 1, 1981 | Fitzhugh L. Fulton | NASA DFRC | 1:15 | Stability and control |
| **30** | July 1, 1981 | Thomas C. McMurtry | NASA DFRC | 1:20 | Stability and control |
| **31** | July 7, 1981 | Fitzhugh L. Fulton | NASA DFRC | 1:10 | Stability and control |
| **32** | July 14, 1981 | Fitzhugh L. Fulton | NASA DFRC | 1:15 | Stability and control |
| **33** | July 28, 1981 | Thomas C. McMurtry | NASA DFRC | 1:20 | Stability and control |
| **34** | July 30, 1981 | Fitzhugh L. Fulton | NASA DFRC | 1:10 | Stability and control |
| **35** | Aug. 18, 1981 | Thomas C. McMurtry | NASA DFRC | 1:10 | Stability and control |
| **36** | Aug. 20, 1981 | Fitzhugh L. Fulton | NASA DFRC | 1:20 | Stability and control |

| | | | | | |
|---|---|---|---|---|---|
| **37** | Aug. 31, 1981 | Thomas C. McMurtry | NASA DFRC | 1:05 | Stability and control |
| **38** | Sept. 3, 1981 | Fitzhugh L. Fulton | NASA DFRC | 1:15 | Stability and control |
| **39** | Oct. 9, 1981 | Thomas C. McMurtry | NASA DFRC | 0:30 | Ferry flight from Edwards AFB to Lancaster, CA (Fox Field), for air-show static display |
| **40** | Oct. 13, 1981 | Thomas C. McMurtry | NASA DFRC | 0:30 | Ferry flight from Lancaster, CA, to Edwards AFB |
| **41** | Nov. 8, 1981 | Thomas C. McMurtry | NASA DFRC | 0:30 | Ferry flight from Edwards AFB to Norton AFB, CA, for air-show static display |
| **42** | Nov. 8, 1981 | Thomas C. McMurtry | NASA DFRC | 0:35 | Ferry flight from Norton AFB to Edwards AFB |
| **43** | Dec. 4, 1981 | Einar K. Enevoldson | NASA DFRC | 0:50 | Pilot familiarization; guest pilot |
| **44** | Dec. 4, 1981 | John A. Manke | NASA DFRC | 1:00 | Pilot familiarization; guest pilot |
| **45** | Dec. 8, 1981 | Thomas C. McMurtry | NASA DFRC | 1:10 | Ferry flight from Edwards AFB to Paso Robles, CA (refueling stop) |

| | | | | | |
|---|---|---|---|---|---|
| **46** | Dec. 8, 1981 | Thomas C. McMurtry | NASA DFRC | 0:50 | Ferry flight from Paso Robles to NASA Ames Research Center (Moffett Field) |
| **47** | Dec. 9, 1981 | Thomas C. McMurtry | NASA DFRC | 0:20 | Demonstration flight at NASA Ames |
| **48** | Dec. 10, 1981 | Thomas C. McMurtry | NASA DFRC | 0:20 | Demonstration flight NASA Ames |
| **49** | Dec. 10, 1981 | Thomas C. McMurtry | NASA DFRC | 1:05 | Ferry flight from NASA Ames to Paso Robles (refueling stop) |
| **50** | Dec. 10, 1981 | Thomas C. McMurtry | NASA DFRC | 1:00 | Ferry flight from Paso Robles to Edwards AFB |
| **51** | Jan. 5, 1982 | William H. Dana | NASA DFRC | 1:00 | Pilot familiarization; guest pilot |
| **52** | Jan. 22, 1982 | Richard Gray | NASA DFRC | 1:05 | Pilot familiarization; guest pilot |
| **53** | Jan. 22, 1982 | Donald L. Mallick | NASA DFRC | 1:00 | Pilot familiarization; guest pilot |
| **54** | Feb. 5, 1982 | Capt. John Small | USAF AFFTC | 1:05 | Pilot familiarization; guest pilot |
| **55** | Feb. 11, 1982 | Maj. Robert Cabana | USMC NATC | 1:15 | Pilot familiarization; guest pilot |

| | | | | | |
|---|---|---|---|---|---|
| **56** | Feb. 11, 1982 | Cmdr. John Watkins | USN NATC | 1:15 | Pilot familiarization; guest pilot |
| **57** | Feb. 24, 1982 | James Martin | NASA ARC | 1:10 | Pilot familiarization; guest pilot |
| **58** | Feb. 24, 1982 | Warren Hall | NASA ARC | 1:10 | Pilot familiarization; guest pilot |
| **59** | Mar. 5, 1982 | Capt. Denny Mohr | USAF TPS | 1:10 | Pilot familiarization; guest pilot |
| **60** | May 14, 1982 | Thomas C. McMurtry | NASA DFRC | 1:20 | Ferry flight from Edwards AFB to Paso Robles (refueling stop) |
| **61** | May 14, 1982 | Thomas C. McMurtry | NASA DFRC | 1:10 | Ferry flight from Paso Robles to NASA Ames (Moffett Field) |
| **62** | May 17, 1982 | Thomas C. McMurtry | NASA DFRC | 1:00 | Ferry flight from NASA Ames to Paso Robles (refueling stop) |
| **63** | May 17, 1982 | Thomas C. McMurtry | NASA DFRC | 1:00 | Ferry flight from Paso Robles to Edwards AFB |
| **64** | May 19, 1982 | Phil Brown | NASA LARC | 1:00 | Pilot familiarization; guest pilot |
| **65** | May 19, 1982 | Maj. William Neely | USAF/NASA LARC | 1:00 | Pilot familiarization; guest pilot |

| | | | | | |
|---|---|---|---|---|---|
| **66** | May 20, 1982 | Col. William J. Knight | USAF AFFTC | 1:05 | Pilot familiarization; guest pilot |
| **67** | May 20, 1982 | Steven P. Ishmael | NASA DFRC | 1:00 | Pilot familiarization; guest pilot |
| **68** | June 8, 1982 | Fitzhugh L. Fulton | NASA DFRC | 1:05 | Oil-flow visualization study |
| **69** | June 8, 1982 | Thomas C. McMurtry | NASA DFRC | 1:05 | Oil-flow visualization study |
| **70** | June 11, 1982 | Fitzhugh L. Fulton | NASA DFRC | 1:00 | Oil-flow visualization study |
| **71** | June 11, 1982 | Thomas C. McMurtry | NASA DFRC | 1:05 | Oil-flow visualization study |
| **72** | July 31, 1982 | Thomas C. McMurtry | NASA DFRC | 0:10 | Oshkosh air show demonstration flight |
| **73** | Aug. 1, 1982 | Thomas C. McMurtry | NASA DFRC | 0:10 | Oshkosh air show demonstration flight |
| **74** | Aug. 2, 1982 | Thomas C. McMurtry | NASA DFRC | 0:10 | Oshkosh air show demonstration flight |
| **75** | Aug. 3, 1982 | Thomas C. McMurtry | NASA DFRC | 0:10 | Oshkosh air show demonstration flight |

| | | | | | |
|---|---|---|---|---|---|
| **76** | Aug. 4, 1982 | Thomas C. McMurtry | NASA DFRC | 0:10 | Oshkosh air show demonstration flight |
| **77** | Aug. 5, 1982 | Thomas C. McMurtry | NASA DFRC | 0:35 | Oshkosh air show demonstration flight |
| **78** | Aug. 6, 1982 | Thomas C. McMurtry | NASA DFRC | 0:10 | Oshkosh air show demonstration flight |
| **79** | Aug. 7, 1982 | Thomas C. McMurtry | NASA DFRC | 0:10 | Oshkosh air show demonstration flight; Final flight of AD-1 |

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# About the Author

**Bruce I. Larrimer** holds B.A. and M.A. degrees in history from The Ohio State University. Mr. Larrimer served on active duty as a U.S. Army officer assigned to the Intelligence Staff, U.S. Army Pacific (USARPAC), and later served in various positions with a Federal regulatory commission. He currently lives in Columbus, OH, where he has his consulting practice. Mr. Larrimer's previous writings include the history of NASA's participation in the Federal Wind Energy Program and NASA's development and testing of high-altitude, long-endurance (HALE), solar-powered remotely piloted aerial vehicles.

The AD-1 cruising over the Mojave in 1980 with its oblique wing set at a 60-degree sweep. (ASA)

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