A Summary Of A Half-Century of Oblique Wing Research

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Oblique wing aircraft hold the promise of combining efficient supersonic and subsonic flight with excellent low speed endurance. For this reason, there has been recent renewed interest in developing oblique wing aircraft. This paper will provide a historical review of oblique wing demonstrator aircraft and other major oblique wing research. A significant amount of early theoretical work was done by R.T. Jones of NASA Ames, beginning in the 1950s. In the past 35 years, a number of small test aircraft were flown to prove the feasibility of oblique wing aircraft flight control. Small gliders, several small remotely piloted aircraft and the manned AD-1 aircraft, were flown by NASA. In the 1990s, Steve Morris of Stanford University built and flew two oblique flying wing aircraft – the first powered oblique flying wings to fly. Numerous conceptual design studies and research papers have addressed oblique wing-body-tail or oblique flying wing designs. A number of wind tunnel tests have been performed on both oblique wing and oblique flying wing designs. This paper provides an overview of the research, testing and flight demonstrations related to oblique wing and oblique flying wing aircraft over the past half-century.

I. Introduction

Oblique wings have long been of interest due to their promise of aerodynamic efficiency for aircraft flying at both transonic and low supersonic speeds. R.T. Jones noted in 1958 that wave drag and drag due to lift could be minimized by a variable sweep oblique wing with an elliptical lift distribution.[1]

At low speeds, the most efficient lifting surface is a high aspect ratio elliptically loaded wing, since drag due to lift is inversely proportional to the aspect ratio. At supersonic speeds, aircraft are dominated by wave drag. A significant advantage of oblique wing arrangements for supersonic flight is that – for equivalent span, sweep and volume – they distribute the lift over about twice the wing length compared to a conventional, symmetrically swept wing (see Figure 1). This reduces lift dependent wave drag by a factor of 4 and volume dependent wave drag by a factor of 16.[*]

A variable sweep design allows an aircraft to vary its aspect ratio (defined as wing span squared divided by wing area) and fineness ratio (defined as length over an equivalent diameter) to optimize the configuration for different flight Mach numbers. Variable sweep wings have been used on

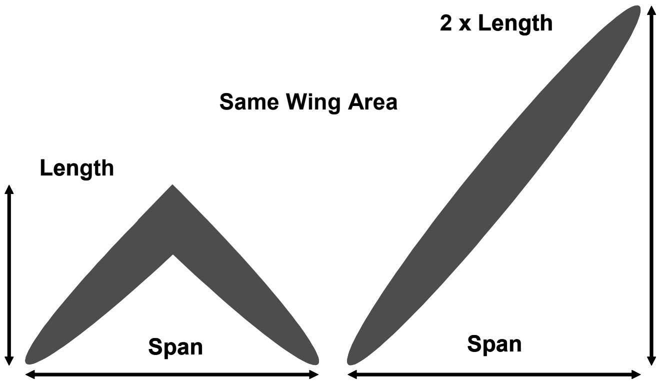

Figure 1. For the same sweep, span and area, an asymmetric wing has about twice the length as a symmetrically swept wing.

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[*] "Oblique Flying Wings: An Introduction and White Paper," Desktop Aeronautics, Inc., http://www.desktopaero.com/obliquewing/library/ofwwhitepaper.pdf, June 2005.

numerous aircraft designs including the F-14, F-111, Mirage G, MiG-23, Su-24 and B-1. These designs, however, must transfer loads from the wings to the aircraft through pivots. These pivots must take bending and torsion loads and thus tend to be heavy, reducing the overall effectiveness of the design.

An oblique wing (see Figure 2) 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 sweep designs.

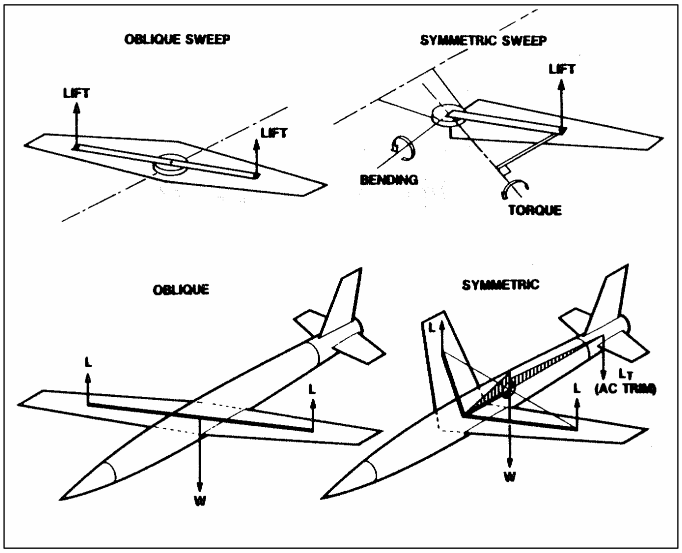

Figure 2. The upper set of drawings show a primary structural advantage of an obliquely swept wing: avoiding the torque and bending loads from wing pivots. The lower drawing shows that fuselage loads can also be avoided. (Graphic by NASA Ames Research Center.) [2]

Numerous aircraft design efforts for oblique wing-body-tail aircraft and oblique flying wing (also called oblique all wing) aircraft have been undertaken over the past several decades. In addition to research by NASA, academia and the military in the United States, studies have been conducted in the United Kingdom, Germany and the Netherlands.[3-6] Most recently, the Defense Advanced Research Projects Agency (DARPA) awarded a contract to Northrop Grumman Corporation in 2006 for preliminary design and risk reduction of a tailless, supersonic, variable sweep oblique flying wing. [7]

Several papers have been published which cover some of the extensive prior research on oblique wings, as well as the unique challenges associated with the concept.[2,8] This paper is an attempt to provide a comprehensive overview of the history of research, design and flight test efforts through the present day.

II. German Designs During World War II

The first known oblique wing design was the Blohm & Voss P 202, proposed by Richard Vogt in 1942. Vogt (1894-1979) was the chief of design at the Blohm & Voss Flugzeugwerke in Hamburg, Germany. He had earned his doctorate in aviation engineering in 1923 and worked at Dornier, prior to moving to Blohm & Voss.[9] There, he and his engineering team completed designs for as many as 33 asymmetric aircraft between 1938 and 1945, including the Bv 141, small numbers of which were built prior to the end of World War 2.

The P 202 was a design for a single engine fighter aircraft with a top mounted wing; the wing rotated in flight to delay Mach divergence, which was beginning to be fairly well understood in Germany at that time. More importantly, the advantages over variable sweep swing wing designs, discussed above, also figured into the conceptual design.

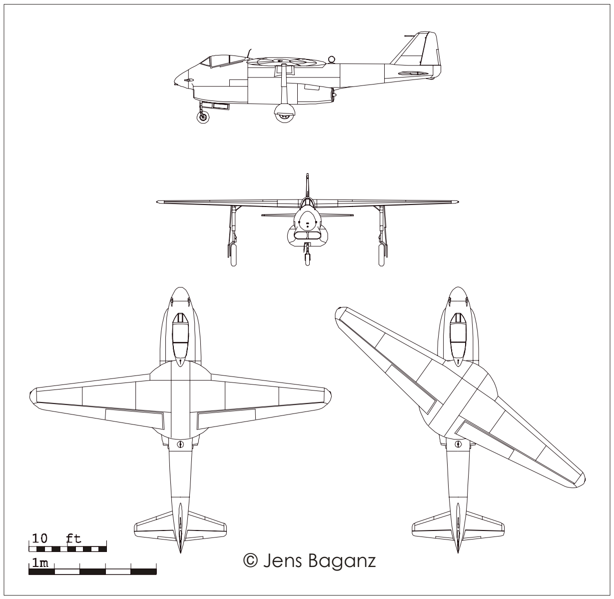

Figure 3. The proposed Blohm & Voss P 202 oblique wing fighter. Note that the left wing tip is swept forward. (Drawing © Jens Baganz, 2006. Used with permission.)

Little information survived about the design, but it was planned to be powered by two BMW 003 axial jet engines mounted in the lower fuselage. The wing was to be capable of pivoting from the normal orientation for low speed flight to 35° left wing tip forward in high speed flight. The wing pivot and the engines occupied the mid-fuselage volume, necessitating very long main landing gear be extended from the wing. Armament was intended to be two 30 mm MK 193 cannon on each side of the fuselage and a single 20 mm MG 151/20 cannon in the nose.

Table 1. P 202 oblique wing fighter characteristics. [10]

Engines	2 x BMW 109-003	
Power	1,760 lb each	800 kg each
Max Wingspan	39.3 ft	11.98 m
Min Wingspan (35°)	33.0 ft	10.06 m
Wing Area	215 ft^2	20 m^2
Overall Length	34.3 ft	10.45 m
Take-Off Weight	11,900 lb	5,400 kg

In July 1944, the Luftwaffe High Command requested aircraft manufacturers to submit proposals for an “emergency fighter program” as a successor to the Messerschmitt Me 262, the world’s first operational jet fighter. The new jet fighter had to be capable of reaching a top speed of 1,000 km/h (540 kt or Mach 0.84) and an altitude of 7,000 m (23,000 ft). The aircraft was to be designed around the 2,700 lb (12 kN) Heinkel-Hirth HeS 011 jet engine that was then in development.[11]

By this time, wind tunnel testing in Germany had clearly shown the benefits of sweeping wings back (or forward) to delay the rapid increase in drag when approaching sonic speeds. At their design bureau in Oberammergau, Messerschmitt studied several different aircraft concepts that could reach these high speeds; the end result was the decision to build the variable sweep P 1101. Although this aircraft was not completed prior to the end of the war, its derivative, the Bell X-5, eventually became the first aircraft to demonstrate swing-wing technology. [11]

Messerschmitt also studied variants of the P 1101 that used oblique wings to vary the aspect ratio. One concept, the P 1101 / XVIII-108 (sometimes referred to as the P 1109),[12] was to use two oblique wings – one on the upper and lower fuselage – that would each sweep up to 60° at high speed; the upper wing would sweep the right wingtip forward while the lower wing would sweep the left wingtip forward (Figure 4). Again, the idea was to provide a high aspect wing at low speed and low aspect wing at high speed. The aircraft used two HeS 011 engines, had a maximum wingspan of 30.8 ft (9.4 m) and an overall length of 39.5 ft (12.05 m).[11]

The conceptual design drawing of the P 1101/XVIII-108 (dated July 11, 1944) also shows a notional monoplane oblique wing aircraft with an oblique sweep of 45°, as shown in Figure 5.[11]

Messerschmitt also explored using a fixed “scissor wing” concept, as shown in Figure 6, on a much larger aircraft, possibly a high speed bomber. No further information about this concept was found.[12]

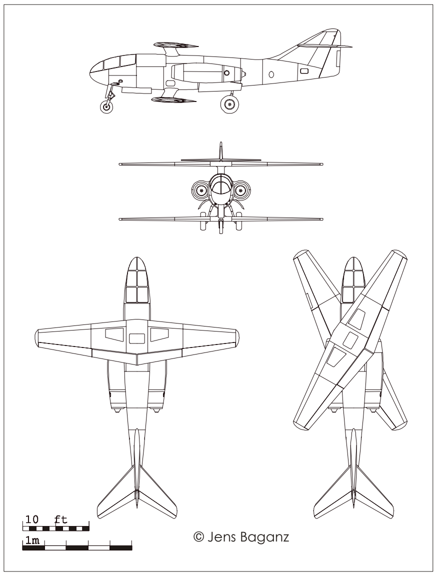

Figure 4. Messerschmitt P 1101 variant with dual oblique wings. (Drawing © Jens Baganz, 2006. Used with permission.)

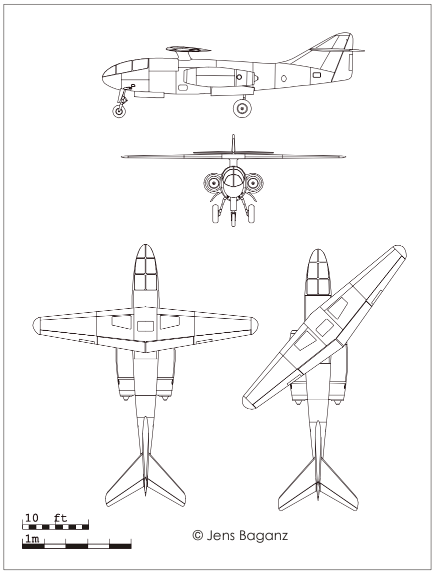

Figure 5. Messerschmitt oblique single wing variant of the P 1101. Note that the right wing tip is swept forward. (Drawing © Jens Baganz, 2006. Used with permission.)

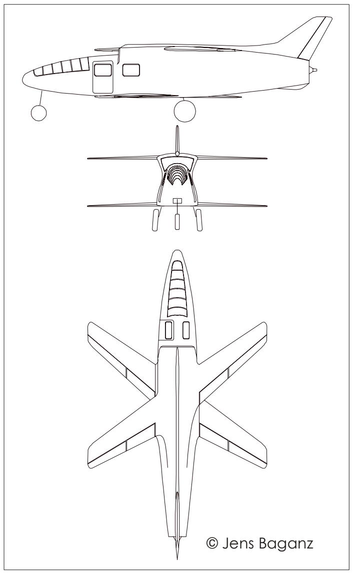

Figure 6. Messerschmitt project with top and bottom fixed oblique wings swept in opposite directions. (Drawing © Jens Baganz, 2006. Used with permission.)

According to Dietrich Küchemann, Erich von Holst – who worked with Küchemann at Göttingen Technical University in Germany during the War – also conducted oblique wing research during this time. In his book (published posthumously in 1978), *The Aerodynamic Design of Aircraft*, Küchemann states:

> …E von Holst (1942, unpublished) suggested the *slewed wing* as the simplest way of achieving variable sweep (on "air bearings", without hinges) and built and flew a number of models to demonstrate their generally satisfactory stability and flying characteristics. These models included not only asymmetrical configurations, without and with a fuselage, but also symmetrical arrangements with scissors-like biplanes. Circumstances prevented the completion of an actual aircraft with a slewed wing. [13]

The reference to the oblique wing aircraft with fuselages and the "scissors-like biplanes" suggest that von Holst's oblique wing models may have been the impetus for or built in support of the Blohm & Voss and Messerschmitt designs discussed above. Von Holst later published numerous papers on flapping and rotating wings, but apparently never published anything on his oblique wing research. Other than the above statement (and another, discussed below) by Küchemann, there does not appear to be any other record of this research.

III. Early NACA Research

Much of the early theoretical work on oblique wings was conducted by Robert Thomas "R.T." Jones (1910-1999) at the National Advisory Committee for Aeronautics (NACA). Jones (Figure 7), largely self-taught, was one of the discoverers of wing sweep theory and has been called one of "the premier theoretical aerodynamicists of the twentieth century."[14] Jones' genius was, "in part, to lie in his remarkable ability to extract the essence of a problem and express it in understandable and useful terms. His approach to problems was always of a fundamental character and often yielded results of broad significance." [15]

The first mention of oblique wing research in the U.S. was a NACA report,[17] regarding the test of an oblique wing model (Figure 8) in the Langley free flight tunnel; Jones later commented that "he promoted the tests," [18] although it is not clear if he was the original genesis for the study of oblique wing research. The report, dated July 1946, was published in May 1947. Jones originally worked at the Langley Aeronautical Laboratory in Virginia, but in August 1946, after the completion of the tests, he transferred to the Ames Aeronautical Laboratory in California.[15]

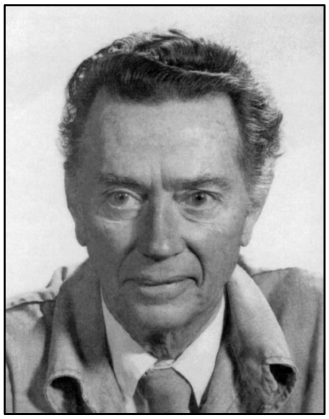

Figure 7. R.T. Jones (1910-1999) was the primary motivation behind most of the NACA/NASA oblique wing research for nearly 50 years.[19]

The Langley tests, as the title of the report states, were an "Investigation of Stability and Control Characteristics of an Airplane Model with Skewed Wing in the Langley Free-Flight Tunnel." Flight tests, force tests and damping-in-roll tests were conducted with the wing set at oblique angles between 0° and 60°.[17] According to the report:

> The results of the investigation indicated that it was possible to skew the wing as a unit to angles as great at 40° without encountering serious stability and control difficulties. At an angle of skew of 60°, however, the aileron control became unsatisfactorily weak. The aileron rolling effectiveness was not reduced by skewing the wing from 0° to 40° because the damping in roll decreased approximately the same amount as the aileron rolling moments. The force tests showed that for a skew angle of 40° the ailerons produced large pitching moments, but in the flight tests 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. The model did not exhibit the undesirably large variation of effective dihedral with lift coefficient that is characteristic of wings with large amounts of sweepback or sweepforward. Skewing the wings as a unit, however, did introduce large changes in lateral trim which varied with lift coefficient and skew angle. [17]

A table of model characteristics is given in Table 2. The center of gravity was varied between 0.20 and 0.35 mean aerodynamic chord of the unswept wing. In the flight tests, control surface deflections of up to ±18° aileron, ±5° rudder and ±5° elevator were used for controlling the model. The model was also tested in the Langley 15 ft free-spinning tunnel to determine the roll damping characteristics.

It was recognized that "to obtain a large increase in the Mach number at which compressibility effects occur, the use of sweep angles of 40° or more is necessary, but these large angles of sweep introduce serious stability and control problems at moderate and high lift coefficients." Although the flight characteristics were considered satisfactory at 50°, they were seriously degraded at 60° sweep. Nonetheless, the tests were acknowledged as being "a preliminary and qualitative indication of whether a design could be flown" and that "Tests of a higher scale of skewed-wing models more representative of high-speed airplane designs will probably be needed before an accurate and detailed analysis can be made of the stability and control characteristics of this type of airplane."[17]

In 1951 and 1952, Jones published theoretical results for minimum drag for an "elliptic wing at an angle of yaw." In the first paper, he used the oblique wing as an example, stating: "For minimum drag…the thickness must be distributed in such a way that the drag per unit volume is constant over the entire wing in the combined flow field." Theoretical pressure distributions in supersonic flight are shown in Figure 9.[19]

In his second paper, he stated that that for an elliptical wing, the drag could be reduced by sweeping it to an oblique angle, and that "the minimum drag occurs when the lift is distributed uniformly over the ellipse." The variation of the coefficient of drag with sweep angle is shown in Figure 10 for elliptical wings with various aspect ratios.[20] Jones also published papers in 1955, 1956, 1957 and 1959, discussing the theoretical characteristics of supersonic wings, including "yawed" elliptical wings.[1,21-23]

Table 2. 1946 NACA oblique wing model characteristics.[17]

Aspect Ratio (0°)	6.0	
Wingspan (0°)	4.00 ft	1.22 m
Wingspan (60°)	2.00 ft	0.61 m
Wing area	2.67 ft^2	0.25 m^2
Weight (variable)	4.73 - 5.03 lb	2.15 - 2.28 kg

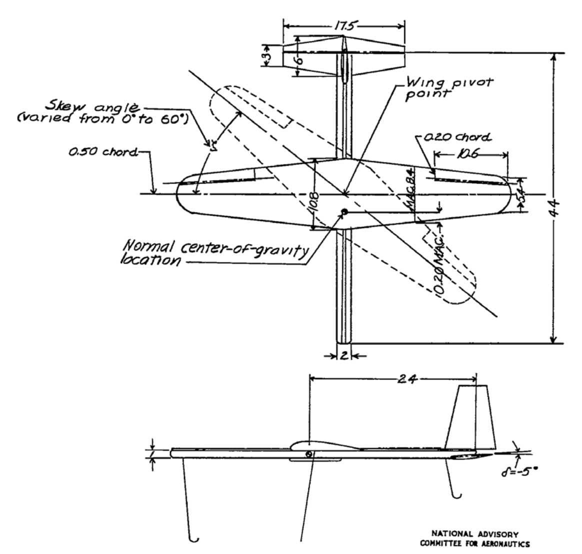

Figure 8. 1946 NACA oblique wing free-flight model. Note the left wing tip is forward. [17]

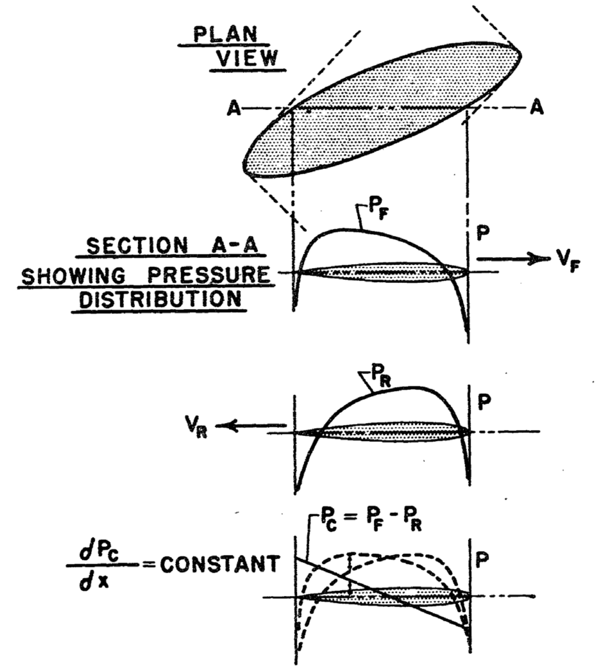

Figure 9. Jones proffered the oblique wing as having the minimum drag in supersonic flow (1951). [19]

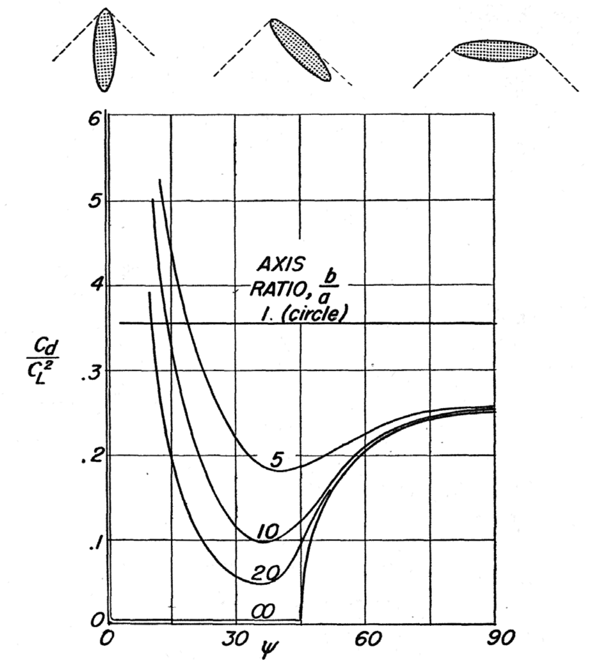

Figure 10. Minimum drag of elliptical wings at sweep angles between 0° and 90° (1952). [20]

The first experimental testing on supersonic oblique wings appears to have been conducted in 1958.[24] These tests, in the NASA Ames 11 ft high speed tunnel, compared the effects of an oblique wing to a conventional sweptback wing, both mounted similarly on the fuselage and both swept at 40°. The results showed that the oblique wing aircraft had much less drag at transonic speeds. [18]

Jones first presented the idea of an oblique *flying* wing (OFW) at the first International Congress in the Aeronautical Sciences (ICAS), in Madrid in 1958.[16] It is interesting to note, however, that his paper, as printed in the proceedings, made little mention of a "yawed" wing, and none whatsoever of flying wings. Comments in the "Discussion" section of the proceeding – by D.W. Holder of the UK's National Physical Laboratory and G.H. Lee of Handley Page (see below) – also do not indicate that he showed something as startling as a supersonic oblique flying wing passenger aircraft. [1]

Other writings, however, discussed below, indicate that Jones did present the idea of the oblique flying wing at the Madrid conference and also conducted demonstration flights of one of his small balsa wood oblique flying wing gliders, which he had apparently first constructed as early as 1945. [25]

IV. Handley Page "Slewed Wing" Transport

As a result of the 1958 ICAS presentation by R.T. Jones on the benefits of the oblique flying wing, Sir Godfrey H. Lee (1913-1998), the deputy chief designer of the British aircraft company Handley Page, Ltd. began a preliminary design of a Mach 2 OFW airliner. Lee discussed his concept in a 1961 article in the popular British magazine *Aeroplane and Astronautics*, in which he concluded:

> I should like to emphasize that the above results are very preliminary and that the opinions expressed are my own and not necessarily those of my firm. I think the results given are sufficiently near the truth to constitute an *a priori* case for giving serious consideration to the slewed-wing concept, the possibilities of which were first brought to my notice by R.T. Jones, of N.A.S.A., during the Madrid Conference in 1958. [26]

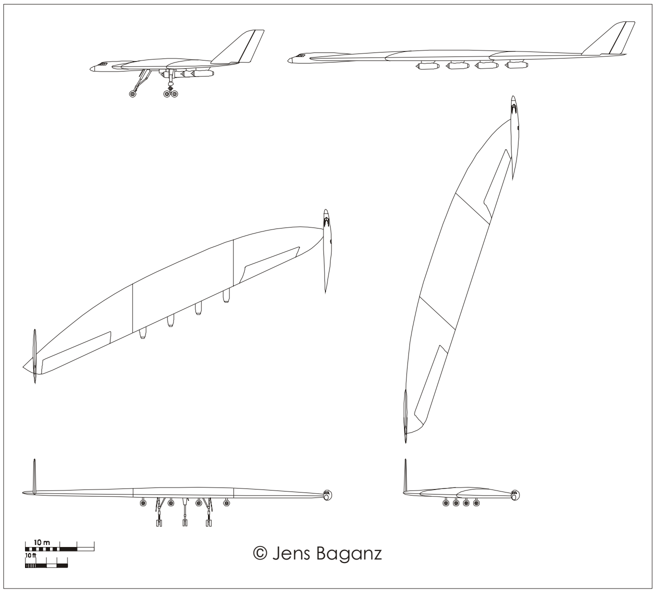

Figure 11. Handley Page "Slewed Wing" design (1961). Note that the right wing tip is swept forward. (Drawing © Jens Baganz, 2006. Used with permission.)

Lee's "slewed wing" design (Figure 11) was a 150 passenger aircraft design intended to provide a 50-100% increase in payload (i.e. passengers) over a delta wing aircraft of the same gross take-off weight, due to the tremendous fuel savings.[26] [Some modern sources refers to this design as the HP "Sycamore" but no contemporary literature could be found to corroborate this name.[*]][27]

This 350,000 lb airliner design housed the crew in a nacelle at the leading (right) wing tip, with a huge fin (approximately 30 ft high) at the other. Four pod-mounted swiveling engines were mounted below the wing, controlling the yaw angle from a minimum of 25° at low speeds to a maximum of 72° at Mach 2.0. Overall span could be varied between approximately 300 ft and 100 ft in flight.[26, 28]

Lift to drag was calculated to be 10 to 11 in supersonic flight and about 24 in the subsonic regime (30° yaw at Mach 0.34).[28] Thickness to chord as drawn was approximately 19%; this seems not only unrealistic but unnecessary as the drawings show cavernous overhead storage area.[26]

Dietrich Küchemann, by now head of supersonics at the Royal Aircraft Establishment (RAE), stated in his presentation at the second ICAS meeting, held in 1962, that the oblique flying wing was "suggested 20 years ago by E. von Holst and taken up again by R.T. Jones at the first Congress…"[28] and asserted that the thick wings required for Jones' flying wing was impractical. [Küchemann, it should be noted, was later

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[*] "Asymmetric Aircraft," http://www.geocities.com/asymmetrics/ow.htm, December 2006.

instrumental in the development of the thin supersonic delta wing in the U.K., and was a major force behind the design of the Concorde supersonic transport (SST).]

J.H.B. Smith, who worked for Küchemann, had conducted an investigation into the effects of thickness on an oblique flying wing configuration. Smith calculated the lift to drag ratios of idealized elliptical oblique wings and found that the lift to drag was essentially the same as that of delta wings. Smith noted that in order to have an adequate volume for passengers the wing would be too thick and have too much drag, or alternatively "the volume distribution which leads to the lowest drag for [the] given volume is not efficient for passenger-carriage." [29]

Küchemann's 1962 talk rebutted Jones' previous ICAS presentation on oblique wings, using Smith's research. Küchemann pointed out the performance penalties of an oblique flying wing that was thick enough for commercial passenger accommodations. At the conclusion of Küchemann's presentation, however, Lee brought up his slewed wing design, and stressed that with a large enough wing (as he had designed), there would be sufficient thickness for a cabin. [28]

In any event, a series of low speed wind tunnel tests were conducted at RAE at sweep angles up to 70°. Eventually, however, Lee determined that although the design was aerodynamically attractive, a number of serious problems were foreseen: the large size of the aircraft, the need to rotate several parts in relation to one another, and stability and control challenges. [8, 28, 30]

As with earlier oblique wing designs, however, the concept was simply ahead of the available technology. And, of course, the operational impacts were also not insignificant. During part of the mission, the passengers would not be facing forwards, and apparently would have any windows. The implications of passenger loading and unloading would also have had to be considered.

It is interesting to note that this Handley Page concept is generally cited as the first oblique flying wing design without reference to R.T. Jones, even though Lee explicitly cites Jones as the impetus for the idea. This may be because Lee's design was published in a popular magazine, as opposed to the proceedings of a specialist's aerodynamics conference, and no description or graphic was published of Jones' original oblique flying wing design.

V. NASA Oblique Wing Studies

Following an absence from the aerospace field during the period 1963-1970, R.T. Jones returned to Ames and, in the early 1970s, sponsored wind tunnel tests and various studies into oblique wing aircraft. Jones co-authored a number of papers regarding oblique wing experiments conducted in the Ames tunnel.[16]

In general, these studies were motivated by a desire for improved commercial transports, capable of lower fuel consumption and reduced environmental impact. Although the U.S. abandoned the pursuit of a supersonic transport in early-1971 due, in part, to their poor economics and a prohibition on imparting sonic booms over land, NASA continued to consider technologies that could allow high speed commercial flights to be flown over land.[31] Wind tunnel tests found that the oblique wing configuration could be designed such that the sonic boom could be delayed or greatly reduced at transonic speeds. As a result, Jones and his fellow researchers began studying numerous applications of the oblique wing.

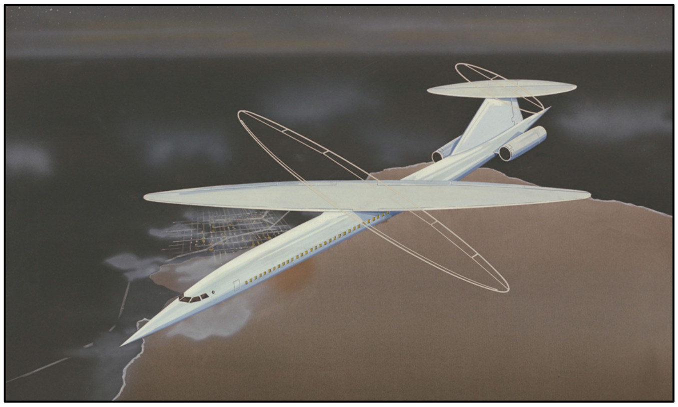

Figure 12. Jones' proposal for an oblique wing supersonic transport. (Photo courtesy of the NASA Ames Research Center.)

Jones studied many different configurations of oblique wing aircraft (e.g. Figure 12). In order to counter the expected wing divergence, Jones studied and patented the concept of a twin-fuselage oblique wing transport, shown in Figure 13. With two fuselages, Jones reasoned that the forward wing would have a shorter moment arm and could be made more resistant to divergence. A radio controlled model may have been built and flown of this concept. [Later theoretical work and wind tunnel research on oblique wing aeroelasticity, discussed below, concluded that wing divergence was not a significant issue.]

Jones' patent abstract describes the concept thus:

> An aircraft including a pair of fuselages disposed in parallel and coupled together by a main wing and a horizontal stabilizer which are pivotally attached to the fuselages. The pivotal attachment allows the airfoils to be yawed relative to the fuselages for high speed flight while at the same time spreading the weight and volume distribution of the aircraft along the direction of flight. The main wing is upwardly curved at the ends to compensate for any roll tendency caused by its yawed positioning. [32]

In April 1971, NASA Langley had sponsored an ongoing "Study of the Application of Advanced Technologies to Long-Range Transport Aircraft," awarding contracts to the Boeing Commercial Airplane Company, General Dynamics (Convair Division), and the Lockheed-Georgia Company. NASA Ames then awarded a "High Transonic Speed Transport Aircraft Study" to Boeing, using the results of the three companies' research; this study was conducted from June 1972 to May 1973. Ames also later awarded Lockheed a contract, as discussed below, for subsonic applications, and General Dynamics conducted wind tunnel tests. The Advanced Vehicle Concepts Development Branch at NASA Ames provided support to all of these oblique wing contracts. [33]

Figure 13. R.T. Jones' twin-fuselage oblique wing transonic transport. With the exception of minor changes to the wing shape, this painting is identical to Jones' patent (filed in 1971).

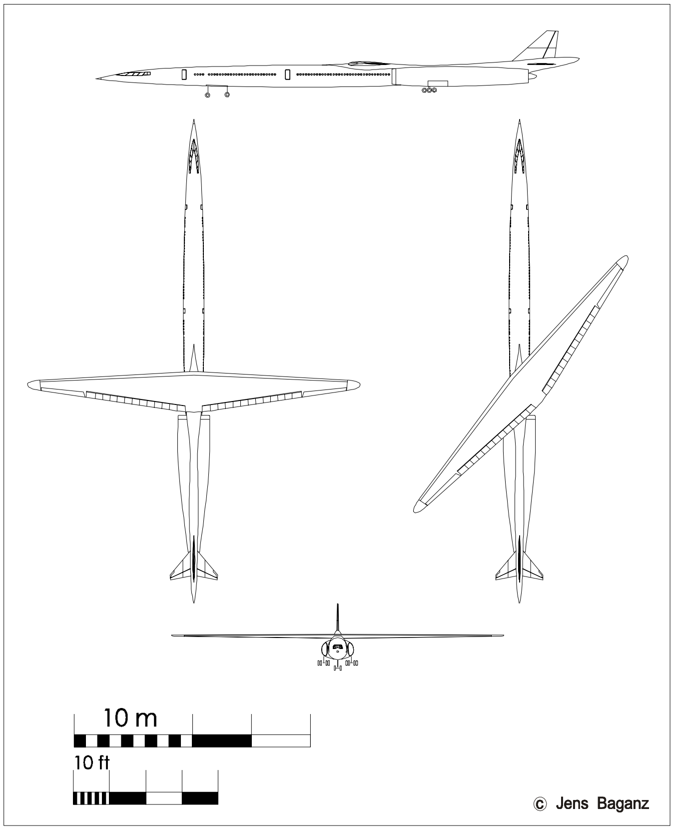

Figure 14. 190 passenger Boeing Model 5-7 oblique wing transonic transport. Note that the right wing tip is swept forward. This design was later used as the point of departure for the AD-1 demonstrator. (Drawing © Jens Baganz, 2006. Used with permission.)

Boeing Transonic Oblique Wing Transport Study

The 1971 studies, also referred to as the Advanced Transport Technology (ATT) study, while not investigating oblique wing concepts, provided important technology data for aircraft designed to operate in the transonic regime, and provided the flight profile and mission rules to ensure consistent comparisons. As an output of the study, graphite/epoxy honeycomb materials were planned for the wing, fuselage and vertical tail primary structure. [8]

Under Boeing's 12 month study (1972-73), five different design concepts were configured and compared. These were (1) aircraft with fixed swept wings, (2) aircraft with variable-sweep wings, (3) aircraft with delta wings, (4) twin-fuselage yawed wing aircraft and (5) single-fuselage yawed-wing aircraft. The study used a cruise speed of up to Mach 1.2 because it was found that atmospheric effects refracted the aircraft shock waves away from the ground, allowing boom-free (and thus, transcontinental) supersonic flight up to this speed.[33]

Boeing found that a single-fuselage oblique-wing configuration with variable sweep had the lowest gross weight for the mission, due to the higher lift-to-drag ratio associated with a 10.2 aspect ratio wing when unswept. The fixed wing and conventional variable sweep concepts were significantly heavier. The double-fuselage concept also had good low-speed performance, but suffered from high fuselage weight associated with the two-fuselage design, and a resulting high gross weight.

As a result, the single fuselage oblique wing transport was selected for further exploration during a follow-on 7 month study. Concurrent efforts in aircraft planform (9 months), pivot design (4 months) and final concept definition (9 months) were completed in December 1976. Aerodynamic, structural, weight, aeroelastic and flight control studies were carried out in sufficient depth to indicate that the oblique wing concept was technically feasible. The research also indicated areas in which further study was required. [8, 34]

Particularly for the NASA goal of flying without a supersonic boom, the variable sweep oblique wing transport was found to be the most efficient configuration – lighter, quieter, and more fuel efficient than a conventional configuration designed for the same mission. With a high aspect ratio wing, take-offs were also expected to generate much less noise, adding to the environmental improvements over a conventional supersonic transport. The selected oblique wing configuration consisted of an 8:1 elliptical wing with four engines (bypass ratio of 1.0) integrated into the rear of the fuselage. [33, 34]

The second study investigated aeroelasticity effects on stability and control for various configurations with two, three and four engines. Four-engine integrated powerplant configurations were found to be the lightest gross weight for the fixed payload of 40,000 lb. [34]

During the third phase, Boeing conducted design and trade studies that resulted in a final conceptual design of an oblique-wing transport aircraft (see Figure 14 and Table 3). These trade studies included wing planform, wing thickness, pivot design/weight, engine cycle and fuel consumption. [34]

Aerodynamic, structural and weight evaluations of several candidate configurations were conducted, with a tapered, high aspect ratio wing – with graphite-epoxy primary structure – finally selected. Ten pivot designs were evaluated, with a Teflon-coated turntable bearing selected. Bypass ratios of 1, 2 and 3 were considered, with a bypass ratio of 2.0 selected for the lowest overall mission fuel consumption, as well as good noise and low-speed characteristics. The wing-sweep schedule and climb trajectory were studied to minimize the reserve, climb and descent fuel requirements. The final selected configuration was found to be superior to conventional swept, variable sweep, delta and twin fuselage oblique wing configurations based on lower gross weight, lower fuel consumption, better low speed performance and noise characteristics. Boeing also noted that the pivoting oblique wing would be more structurally efficient than a conventional dual-pivot variable sweep wing aircraft. [34]

As can be seen in Figure 14, Boeing designed their aircraft with two side-by-side main landing gear (each with twelve wheels) and two tandem single-axle four-wheeled trucks behind the nose. Because of this unique gear design, the aircraft was designed to conduct a take-off without rotation. [34]

Another outcome of the study was that because airport gates are designed to load from the left side, most oblique wing aircraft design studies after this point had wings that swept the right tip forward. It was also found to be desirable to standardize on a convention.[*]

In its conclusion, the report recommended follow-on work to include economic and operational studies, high Mach number designs in combination with variable cycle engines, theoretical and experimental investigation of the aerodynamic design of the wing and integration of the engines, investigations to reduce aerodynamic coupling, and development of stability augmentation system requirements. Boeing also recommended a subscale model of the pivot and flight test of a subscale demonstrator aircraft. Specifically, Boeing stated that it would yield valuable insight in manned flight evaluation of handling and ride qualities, takeoff and landing characteristics of an aircraft with tandem nose gear, and correlation of analytic and wind tunnel results with flight data to provide confidence in aerodynamic prediction techniques for future oblique-wing design programs. [34]

Table 3. 1977 Boeing oblique wing transonic transport Model 5-7 characteristics. [34]

Aspect Ratio (0°)	13.47	
Wingspan (0°)	202.3 ft	61.7 m
Wingspan (60°)	130.5 ft	39.8 m
Wing area	3040 ft^2	282 m^2
Total Fuel	142,800 lb	64,773 kg
Lift/Drag (max)	13.7	
Payload	40,000 lb	18,144 kg
Engine Thrust (sls)	4 x 35,200 lb	4 x 16,000 kg
Cruise Speed	1.2 M	
Body Length	287 ft	87.6 m
Cruise Altitude	42,500 ft	12,954 m
Range	3000 nm	5556 km
Empty Weight	248,070 lb	112,523 lb
Gross Weight	428,910 lb	194,550 kg

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[*] Smith, Steve, NASA Ames, comments to the author, January 2006.

Lockheed Subsonic Oblique Wing Transport Study

Lockheed's studies were somewhat different than the above work. Instead of using an oblique wing for better efficiency at supersonic speeds, Lockheed's studies considered using it for high subsonic speeds up to 0.95 Mach.[35] Due to the "energy crisis" in the mid-1970s, it was reasoned that the subsonic oblique wing could optimize its fuel consumption based on fuel prices and availability. For example, during times of limited fuel supplies, the aircraft could operate at small sweep angles and low speed to minimize fuel consumption; when fuel was plentiful but expensive, wing sweep and speed could be chosen to minimize the airline's direct operating cost (DOC); finally, when fuel was plentiful and inexpensive, the maximum cruise speed could be selected to provide the most benefit to the travelers.[8]

The 12-month Lockheed study (August 1, 1975 to July 31, 1976) built on the fact that Boeing's transonic aircraft study had shown the inherent advantage of an oblique wing concept to attain low induced drag at takeoff, loiter and landing, while maintaining good flight efficiency during cruise. Lockheed found that these same advantages could be applied to subsonic oblique wing aircraft, leading to reduced takeoff weight, improved airport performance and noise characteristics, improved endurance and mission flexibility, and better speed matching.[35]

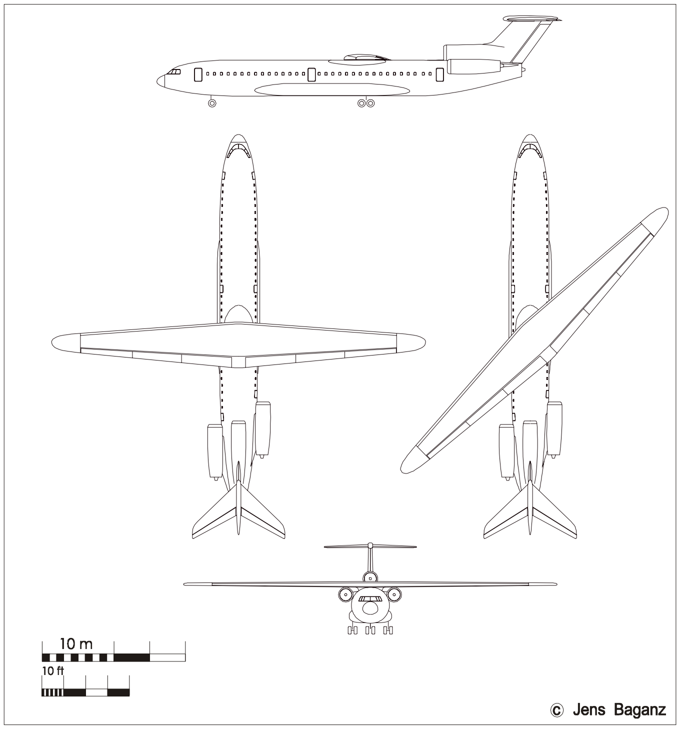

Figure 15. 200 passenger Lockheed subsonic oblique wing transport (1976). Note that the right wing tip is swept forward. (Drawing © Jens Baganz, 2006. Used with permission.)

The specific study objectives were to define a viable high-subsonic oblique-wing transport, identify the key design parameters and the sensitivity of the design to these parameters, assess the impact of advanced technologies on the design, and identify the critical research areas. Missions for a 200 passenger commercial passenger transport, an 18 passenger executive transport, and a large military cargo transport were studied; from these mission analyses, aircraft configurations were selected to satisfy each of the mission requirements. It should be noted that, for consistency, Lockheed complied with the guidelines of the ATT program and other previous studies to allow comparisons of the various concepts. For example, all of the designs used the same percentage of composites. NASA Ames also performed the aeroelastic analysis of the oblique wings.[8, 35]

Although Lockheed developed oblique wing conceptual designs for all three missions, the commercial passenger transport was considered the most viable. The propulsion system size, wing/flap system integration challenges, center of gravity and loading limitations were found too difficult to overcome for a military cargo transport. The executive transport was also found to have problems integrating the propulsion and fuel systems. Nonetheless, the commercial transport was thought to be capable of military applications, such as for an Air Force tanker or a Navy Anti-Submarine Warfare aircraft. [35]

The final configuration of the passenger version (Figure 15) was a three engine design capable of transporting 200 passengers with baggage, plus 10,000 lb (4,536 kg) of cargo. Compared to a conventional swept-wing airliner at the Mach 0.95 design point, the Lockheed oblique wing aircraft was found to be approximately 7% lighter, require 10% less thrust, need 7% less fuel per mission, use 3% less take-off distance and have a 5% lower direct operating cost. Being able to vary the wing sweep during the mission resulted in a 10% range increase and a 44% endurance improvement. The study concluded that the critical area affecting the performance of the oblique wing concept in this application was the aeroelastic stability of the wing. An aspect ratio of 6.0 was seen as the upper limit to avoid a weight penalty. This aspect ratio was contingent on the ability to use composite wing structure as much as possible and take advantage of their improved stiffness-to-density ratio. A table of characteristics is provided in Table 4.[35]

In addition to the reduced fuel consumption inherent in a high aspect ratio wing (i.e., an oblique wing configuration when unswept), there were a number of other environmental factors that favored the oblique wing transport. Noise generation during take-off and landing was expected to be much less, as the high aspect ratio at low speeds would reduce take-off and landing speeds as well as engine thrust required for take-off. The longer wingspan during descent reduced the tip vortex strength, allowing less separation (and therefore higher throughput) at airports. Since the wings could be fully-swept again once on the ground, the aircraft could also be parked much closer and thus reduce the amount of airport real estate required.[8]

Finally, the idea of a short take-off and landing concept was also considered. With the high aspect ratio wing unswept, a small (30 – 150 passenger) aircraft could operate from an airfield with a 3000 – 5000 ft (900 – 1500 m) runway, like a turboprop, but with a much higher cruise speed. These transports were expected to have a range of 500 miles (800 km) or more.[8]

Table 4. 1976 Lockheed oblique wing subsonic transport characteristics. [35]

Aspect Ratio (0°)	6.0	
Wingspan (0°)	171 ft	52.1 m
Wingspan (60°)	122 ft	37.3 m
Wing area	2344 ft^2	217.8 m^2
Total Fuel	95,904 lb	43,501 kg
Lift/Drag (cruise)	16.05	
Payload	52,400 lb	23,786 kg
Engine Thrust (sls)	3 x 30,402 lb	3 x 135 kN
Cruise Speed	Mach 0.95	
Body Length	186 ft	56.7 m
Cruise Altitude	37,000 ft	11,277 m
Range	3000 nm	5560 km
Operating Weight	159,137 lb	72,184 kg
Gross Weight	307,441 lb	139,453 kg

Transonic Transport Wind Tunnel Testing

During the period of 1971 to 1975, NASA Ames conducted tests of high aspect ratio elliptical wings (as shown in Figure 16) in the 11 ft by 11 ft Transonic Wind Tunnel. These wings were mounted on a Sears-Haack body and tested between Mach numbers of 0.6 and 1.4. Tests – including flow visualization studies – were conducted between sweep angles of 0° and 60°.

Initial tests were with elliptical wings of aspect ratio 10.2 and 12.7 and various thickness/chord ratios. Then, a number of airfoil sections for oblique wings were evaluated, all with an aspect ratio of 12.7 and a thickness of 10%. Three different airfoils with a 10% thickness were tested: a standard NACA four-digit airfoil, a supercritical airfoil, and a highly cambered airfoil. The latter airfoil was found to be superior at 60° sweep in the Mach 1.2 to 1.4 range.

Later, various wing planforms with an aspect ratio of 10.2 and a thickness of 12% were investigated; little difference was found in the drag characteristics, but there were large differences in rolling moments characteristics. This indicated that small changes in wing planform could be used to fine tune rolling moments without significantly affecting performance. [8]

Figure 16. High aspect ratio oblique wing model in the NASA Ames wind tunnel at 60° sweep. (Photo courtesy of the NASA Dryden Flight Research Center.)

In parallel, during 1973 to 1976, low aspect ratio elliptical oblique wing tests for fighter aircraft applications were also conducted. These were run in the Ames 6 ft by 6 ft Wind Tunnel between Mach 0.6 and 1.4, and wing sweeps between 0° and 60°. Initial tests used a 10% thick oblique wing with an aspect ratio of 6.0 at 0° and 3.7 at 45°. For comparison, a conventional 45° swept back wing was used with an aspect ratio of 3.2. Again, the wings were mounted on a Sears-Haack body. The wings were tested with different upward bend distributions along the span of the wing. The results showed that at all Mach numbers, the variable sweep oblique wing had higher lift/drag ratios. Later, the effects of leading and trailing edge control surfaces on the stability and control of the low aspect ratio wing were explored.

In February 1975, the Convair Division of General Dynamics conducted tests of three oblique wing transport configurations in the NASA Ames 11 ft Transonic Wind Tunnel at Mach numbers between 0.6 and 1.4, and at sweep angles between 0° and 60°. The three configurations had a common forward fuselage, wing and test support system, but featured different aft fuselage sections to model various propulsion system installations. Convair documented the wing aeroelastic deflection and performance data in their NASA test report. [35]

The model had an aspect ratio of 13.5 and represented a 2.2% scale of the Boeing configuration. Differing amounts of spanwise pre-bend was built into the left and right wings. The aerodynamic twist and deflection were analyzed using stereo-photography and compared with the force measurements. The propulsion concepts modeled on the aft fuselage were an integrated (internally ducted) system, shown in Figure 17, a pod-pylon arrangement, and a clean configuration to use as a reference. All three configurations had the same area distribution at Mach 1.2 and 55° sweep. [35]

Figure 17. R.T. Jones with the oblique wing model used for the Convair wind tunnel testing. This photo shows the integrated propulsion system, as well as where the model mounted on the blade support. (Photo courtesy of the NASA Ames Research Center.)

Other Wind Tunnel Tests

In early 1973, the idea of adding an oblique wing to an F-8 was studied, in anticipation of eventually developing a manned oblique wing demonstrator. Several wings were tested in the Ames 11 Ft Transonic Wind Tunnel on an 8.7% scale model between Mach 0.6 and 1.2. The first wing had a 12.7 aspect ratio (at 0° sweep) wing with 10% thickness, but studies indicated that this aspect ratio would lead to a wing that was heavy, while a thicker wing would have better overall performance. The second wing had an aspect ratio of 10.2 and a thickness of 14%; a third wing had the same aspect ratio, but a thickness of 12%. In comparison to fixed swept wings, the oblique wing again demonstrated a significant performance advantage (as shown in Figure 18). [8, 36, 37, 38]

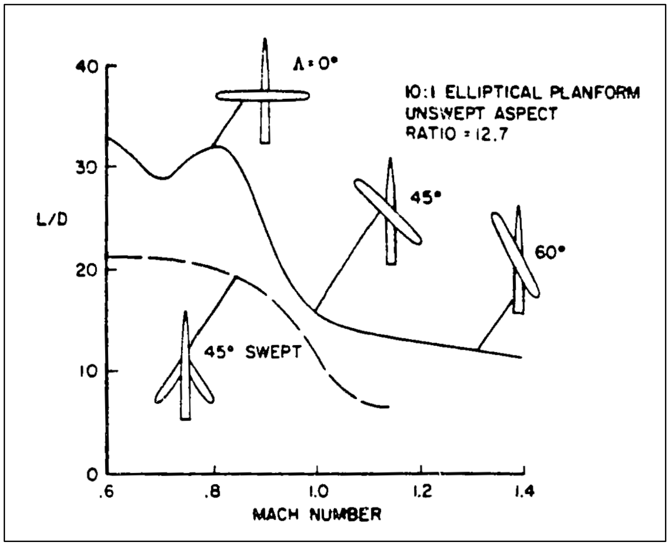

Figure 18. Comparison of maximum lift-to-drag ratios for a variable-sweep oblique wing and a conventional swept wing. [42]

In late 1974, in order to verify the theoretically predicted aeroelastic behavior of an oblique wing, Jones and his fellow researchers conducted a wind tunnel test of an aeroelastic model. As discussed above, it was believed that oblique wings, like forward swept wings, were subject to aeroelastic divergence. Wind tunnel testing in the Ames 7 ft by 10 ft subsonic wind tunnel, however, indicated that the oblique wing aircraft had a favorable affect on divergence characteristics. An upward bending of the forward wing tip will cause loads that induce a roll, which then reduces the effective angle of attack on the forward wing and the wing deflection. The Ames testing was conducted with a model that was free to roll and compared to results when the model was clamped, as shown in Figure 19. Radio controls were used to remotely actuate ailerons for trim and roll control. Slack wires attached to the top of the wooden wing were used to limit the amplitude of the unstable aeroelastic oscillations to prevent damage to the wing. These tests found that allowing the

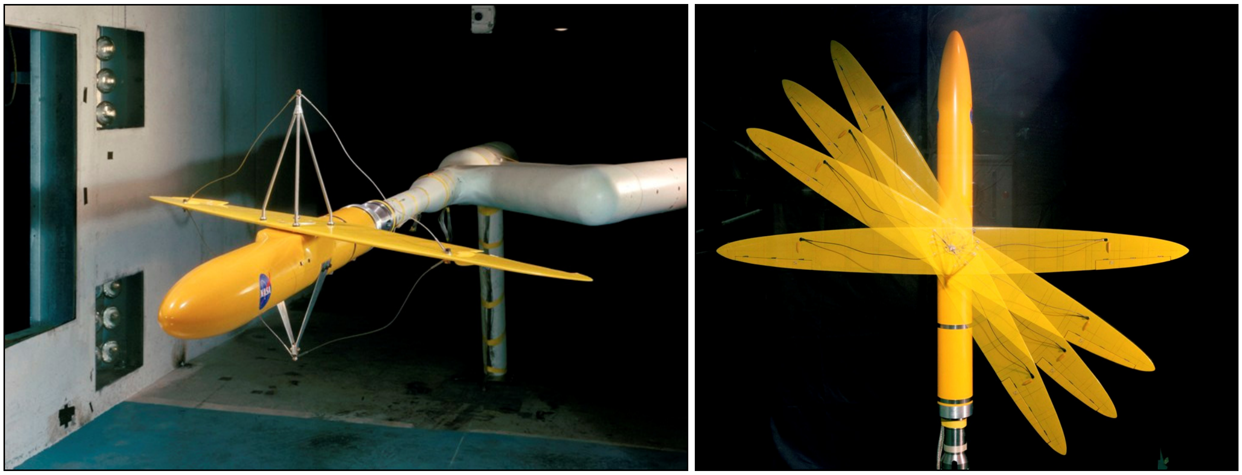

Figure 19. Jones' aeroelastic model in the Ames subsonic wind tunnel. Note the left wing is forward. [40]

model to roll delayed the onset of the instability until the dynamic pressure increased beyond that for the clamped model tests by 50%. The twin-fuselage oblique wing transport that Jones designed in 1971 was, in effect, clamping the wing. [8, 38, 39]

Later, in May 1991, a 14% thick wing was tested in the Ames 9 ft by 7 ft Supersonic Wind Tunnel at angles of 60° and 72° sweep, with Mach numbers of 1.6, 1.8 and 2.0. This test was the first use in the U.S. of pressure-sensitive paint on a large scale supersonic wind tunnel model. The luminescent paint (which was correlated with the model's existing pressure taps) was found to quickly and inexpensively measure the mean surface pressure, and provided hundreds of thousands of data points, compared to the conventional point measurements of pressure taps or transducers. [41]

NASA Military Aircraft Studies

In parallel with the civil oblique wing studies, the Ames Advanced Vehicle Concepts Branch also performed in-house studies of military oblique wing aircraft applications, including a land-based ASW aircraft, an ICBM air-launch platform, a Navy fleet defense aircraft, a highly maneuverable Remotely Piloted Vehicle (RPV), and other concepts, as described below. The Ames-developed Aircraft Synthesis (ACSYNT) computer program was used to provide rapid conceptual design data at the early stages of aircraft definition. [8]

The land-based anti-submarine warfare (ASW) oblique wing aircraft was explored in mid-to-late 1972. This study was conducted to gain a preliminary assessment of the potential benefits that the efficiency across a wide speed range that an oblique wing aircraft would have in this mission. The results were generally similar to those obtained by the later Lockheed study, discussed above. For a 12 hour ASW mission, an oblique wing aircraft flying at Mach 0.95 to 1.25 had 25 to 45% more time on station than the contemporary P-3C Orion.[8]

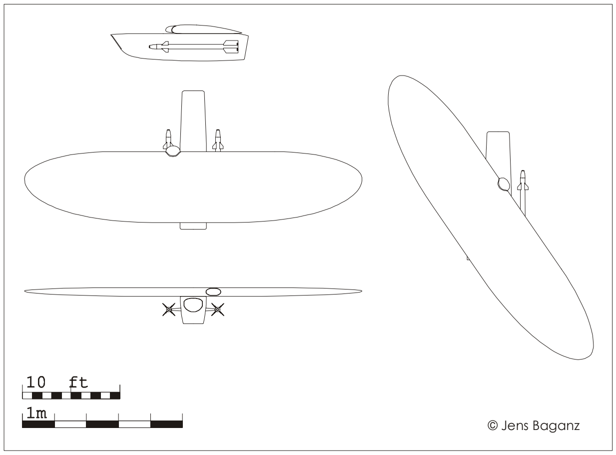

Figure 20. The Highly Maneuverable Oblique Wing RPV would have been a supersonic tailless oblique flying wing. Note the left wing is forward. (Drawing © Jens Baganz, 2006. Used with permission.)

During a study of highly maneuverable air-to-air combat remotely piloted vehicles (RPVs) that lasted from mid-1972 to late 1973, the most promising approach was found to be an oblique wing design. The aircraft was air-launched and recovered, with the design mission including speeds up to Mach 1.6 at 30,000 ft with two AIM-9 air-to-air missiles. The fuel and 500 lb of avionics were located in the wing, which could pivot above the afterburning turbojet engine. An electro-optical system was located on the leading edge, and was positioned so that it would be approximately at centerline when the wing was fully swept. The engine thrust pointed down slightly, resulting in a thrust axis through the center of gravity. [42]

The wing sweep was set to pivot with increasing Mach number to maximize its aerodynamic efficiency. The aircraft, shown in Figure 20, was designed for 11g loads and could outmaneuver existing fighters as well as competing RPV designs at Mach 0.9, due to its low wing loading. Predicted characteristics are shown in Table 5. [8]

From mid-1974 to mid-1975, Ames studied a "dash-on-warning" air mobile Intercontinental Ballistic Missile (ICBM) launch platform. This study, conducted for the Air Force Space and Missile Systems Organization (SAMSO), evaluated aircraft designs that could dash supersonically to a perimeter area and then loiter for six hours at a time – ready to air launch two internally housed ICBMs – each weighing 100,000 lb (90,700 kg). A total of eight configurations were explored, including two concepts that were called "two position oblique wing designs." These two concepts (one of which is shown in Figure 21) used a rocket-boosted take-off to reach supersonic speeds with the wing completely rotated to 90°. It would then rotate to 0° for long term loiter. While not flying steady state with the wing at an oblique angle, it would still have transitioned between the two positions. No research appears to have been conducted into this transient wing movement, however. [43]

Another Ames study, conducted from early 1975 to early 1976 with the Naval Postgraduate School, developed a conceptual design of a "two-position oblique wing" carrier aircraft that was "armed with a special weapon system." The wing was again rotated to the 90° position, this time for stowage on deck. [8]

Several other designs for military missions were explored using ACSYNT during the early 1970s. These included an oblique wing Advanced Tactical Fighter (ATF – the predecessor program to today's F-22 Raptor) that needed to have good maneuver performance at both subsonic and supersonic speeds, as well as be capable of cruising supersonically. Figure 21 shows a "typical oblique-wing ATF configuration." It closely resembles the later Rockwell oblique wing Navy fighter (Figure 34).[8]

Table 5. Highly Maneuverable Oblique Wing RPV. [8]

Aspect Ratio (0°)	6.19	
Wingspan (0°)	35.8 ft	10.91 m
Wing area	207 ft^2	19.25 m^2
Total Fuel	1,745 lb	791 kg
Payload	320 lb	145 kg
Engine Thrust (sls)	5,370 lb	2,400 kg
Cruise Speed	Mach 1.6	
Body Length	14.40 ft	4.59 m
Cruise Altitude	30,000 ft	9,800 m
Radius	200 nm	370 km
Gross Weight	4,795 lb	2,175 kg

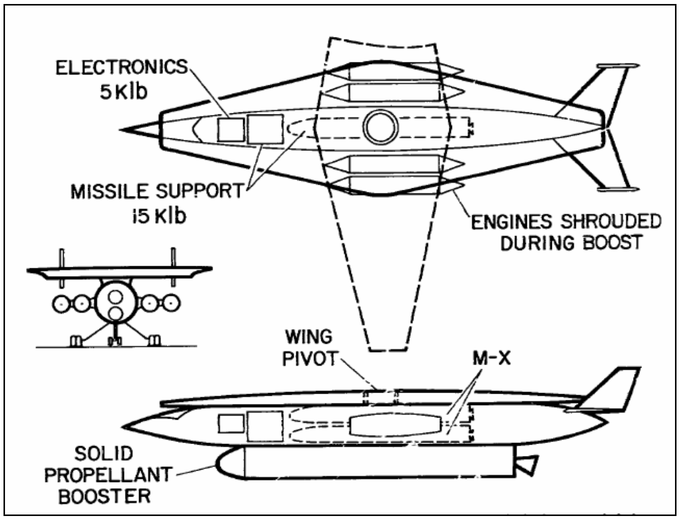

Figure 21. "Two-position oblique wing" aircraft capable of carrying two ICBM missiles. The vehicle was estimated to weigh approximately one million pounds (450,000 kg). [43]

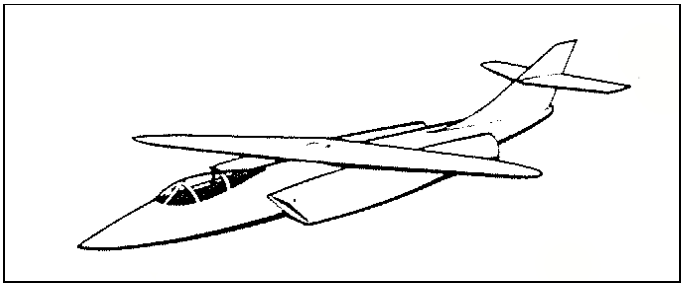

Figure 22. Oblique wing advanced tactical fighter concept.[8]

Another study for the Air Force investigated the use of an oblique wing for a cruise missile that had size and shape constraints, but needed an efficient wing for long range. An oblique wing that aligned itself with the body of the missile (similar to the "two-position" wings described above) during storage could then sweep to the optimal angle during cruise. A similar concept that Ames studied was for small manned (or smaller unmanned) oblique wing fighters to be launched and recovered from a mothership.[8]

It should be noted that other studies considered using oblique wings on other types of vehicles, included glide bombs,[*] missiles,[44] space launch vehicles,[45] and an oblique wing for the Space Shuttle solid rocket booster. This

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[*] "Guided Munitions, HOPE/HOSBO", Diehl BGT Defence, http://www.diehl-bgt-defence.de, December 2006.

latter concept, shown in Figure 23, was evaluated as a way of avoiding the expense and effort required to recover the boosters after splashdown. Adding an oblique wing that could be mounted flush with the body of the rocket, then deploy after separation from the orbiter, allowed the boosters to glide back to a runway. The variable sweep oblique wing would have provided a high lift-to-drag ratio of the range of Mach numbers; deployment at 68° was expected as high as Mach 2.5. The added weight for the wing, tail and landing gear was estimated to be approximately 30,000 lb, which would have been 2.3% of the gross weight of the booster and 15.6% of the empty weight.[46]

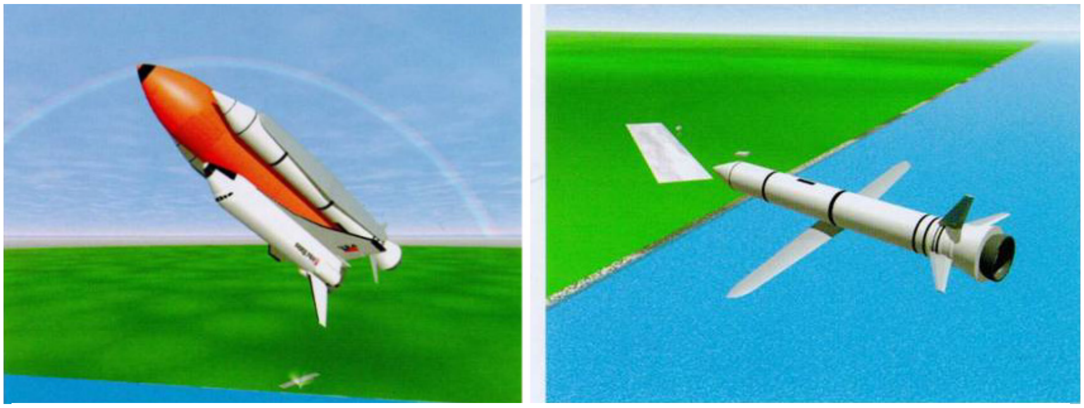

Figure 23. 1999 study of an oblique wing fly-back capability for the space shuttle booster. [46]

VI. NASA Unmanned Flight Research

In addition to the theoretical and aerodynamic research on oblique wings that R.T. Jones initiated after his return to Ames in 1970, he also began sponsoring a great deal of experimental work that resulted in several demonstrator aircraft being built and successfully flight tested.

Oblique Wing R/C Model

Soon after returning to Ames, Jones built a radio controlled model (shown in Figures 24 and 25) with a 5.5 ft (unswept) wing span.[8] With Burnett L. Gadberg, who was also the pilot, Jones conducted flight test experiments with the model, with in-flight control of sweep angle, ailerons, rudder and elevators. The wing and tail were both swept as shown in. The aircraft performed loops and rolls at a 45° wing sweep and flew with sweep angles beyond 45° during less aggressive maneuvers. According to Jones, "Yaw angles greater than 45º were not attempted because of the speed of the model (50 to 100 mph) and the difficulty of visual orientation. The aircraft was designed with the left wing tip forward in order to use propeller torque to help cancel (rather than aggravate) the untrimmed rolling moment.[47]

Figure 24. R.T. Jones with the NASA Ames oblique wing radio controlled model (circa 1970). (Photo courtesy of the NASA Dryden Flight Research Center.)

Flight tests demonstrated that the aircraft remained stable at high sweep angles and could be controlled with decoupled control surfaces. Lateral trim at high sweep angles could be corrected with small aileron inputs of one or two degrees. Aileron control remained decoupled, creating pure roll moments. Longitudinal trim was found to be constant while elevator and ailerons remained effective across the full range of sweep angles. Jones noted that: "The model nosed down and gained speed to compensate for the loss of lift due to yaw." [47]

Coupled motion in pitch and roll was observed with elevator inputs. Attempts at performing loops at high sweep angles resulted in a helical motion. Jones studied the motion and found the angle of the helix corresponded to the sweep angle; indicating that the motion generated by the elevators tended to align with the long axis of the wing. This effect was also seen for banking turns in which the elevators were employed. A left tip forward aircraft in a left turn would see a steeper bank angle with the use of the elevators. [8]

The flight tests proved that an oblique wing aircraft was stable and could be flown with simple decoupled controls, clearing the way for further research on larger-scale vehicles.

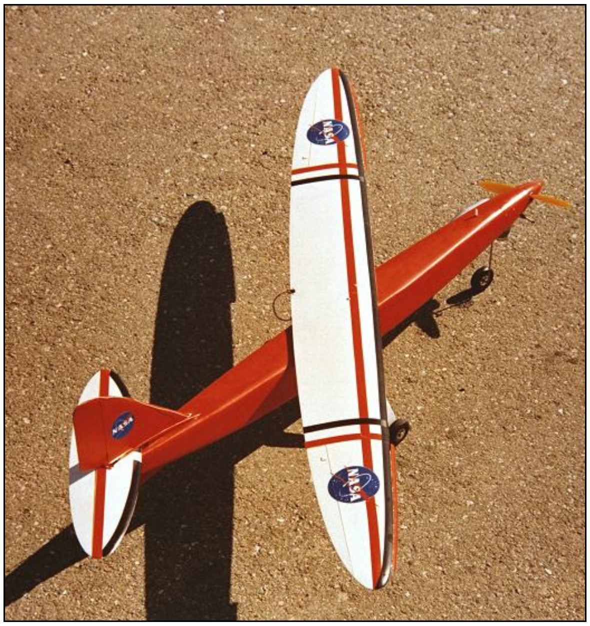

Figure 25. The oblique wing radio controlled model flew with sweep angles beyond 45 deg. (Photo courtesy of the NASA Dryden Flight Research Center.)

Oblique Wing RPV

The Oblique Wing Remotely Piloted Vehicle (RPV) was a small research craft designed and flight tested to investigate the aerodynamic characteristics of an oblique wing and the control laws necessary to achieve acceptable handling qualities. NASA Dryden Flight Research Center and the NASA Ames Research Center conducted research with this aircraft in the mid-1970s to investigate the feasibility of flying a larger oblique wing aircraft. [48, 49 *]

This effort was led by Rod Bailey of NASA Ames, who had previously been involved with the ACSYNT-developed oblique flying wing RPV. Bailey's branch chief, Tom Gregory, believed that RPVs were an important emerging field in which NASA should become more involved, and asked Bailey to put together a plan to fly an oblique wing RPV. Bailey had seen Jones' radio controlled model fly and was able to pull together sufficient funding to initiate the project.[†]

The first step in the design process was the construction of a small unpowered all wing model aircraft as shown in Figure 26. The model had an aspect ratio of 8 and a wing area of 3 ft^2 (0.28m^2); it weighed 2 lb (0.91kg). The aircraft performed glide tests at wing yaw angles of up to 60°. Trailing edge elevons were capable of trimming the aircraft at all wing sweep angles, though static stability was not confirmed at 60° wing sweep. The wing tip rudders employed to maintain the desired flight orientation lost effectiveness at high sweep angles. The model was found to de-yaw at 60° wing sweep and then roll due to differential elevon trim. The trends noted in these tests were confirmed in later wind tunnel tests.[49]

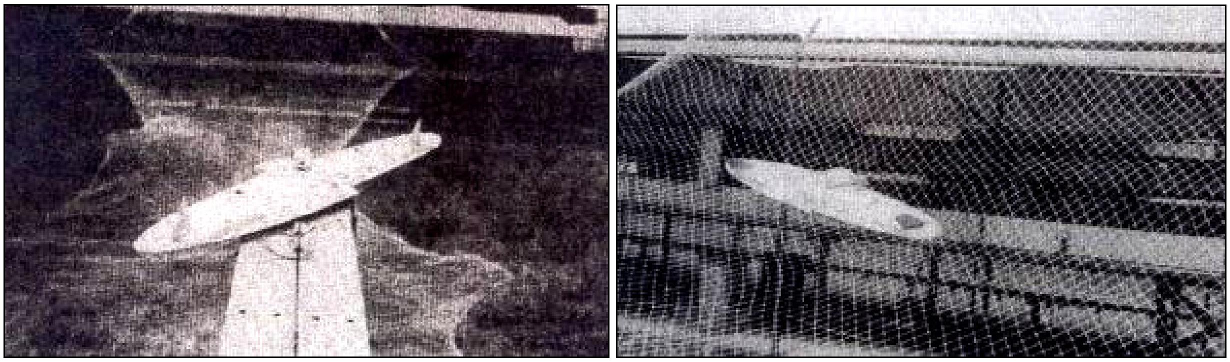

Figure 26. NASA Ames oblique wing unpowered model: on launch rail (left) and during net recovery (right). Note wingtip rudders set for 50° wing yaw. Right wing tip is forward.[49]

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[*] NASA Dryden Oblique Wing Research Aircraft (OWRA) web site, http://www1.dfrc.nasa.gov/Gallery/Photo/OWRA/index.html.

[†] Bailey, Rodney O., comments provided to the authors, December 2006.

The RPV was originally envisioned as an oblique flying wing, but this layout was compromised early on by the addition of a horizontal tail, required to offset the movement of the aerodynamic center as the wing yawed. Unlike the previous radio controlled model, the yaw angle of the elevator on the RPV remained fixed relative to the fuselage.

Characteristics of the aircraft are given in Table 6. The aircraft's wing was capable of being swept up to 45° left wing forward. A trailing wing vertical stabilizer was also present on early versions of the RPV (as shown in Figure 27) which would have rotated relative to the wing to maintain alignment with the fuselage. The plan was to remove the conventional tail and fly the RPV as a flying wing with the trailing stabilizer; this was ultimately abandoned, however, due to the stability and control issues discussed below and the complicated mechanical linkage that would have been required to actuate the surface.[50]

Table 6. Initial Oblique Wing RPV characteristics. [49]

Wingspan (0°)	22.3 ft	6.8 m
Wing Area	99.8 ft^2	9.27 m^2
Engine Power	90 hp	67 kW
Overall Length	13.3 ft	4.06 m
Empty Weight	847 lb	384 kg
Gross Weight	1060 lb	481 kg

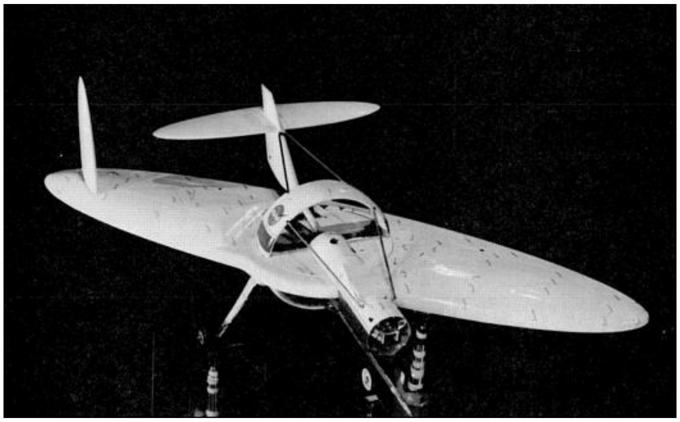

Figure 27. NASA Ames oblique wing remotely piloted vehicle. This photo clearly shows the wingtip vertical stabilizer. The left wing tip is forward. [50]

Power was provided by a single McCullough 90 hp, four cylinder, air-cooled, reciprocating engine mounted at the center of the wing. The engine drove a pusher propeller shrouded in a 50 inch duct designed specifically to minimize damage in the event of a crash. The aircraft was designed for a top speed of 146 kt but even with a custom adjustable pitch propeller, the RPV was still found to be badly underpowered.[49] *

In keeping with the goal of survivability and reparability, the airframe and key structural components were composed of fiberglass and epoxy laid up by hand. The aircraft was constructed by Developmental Sciences, Inc. of City of Industry, California. The total effort cost approximately $200,000.[49]

Figure 28. The Oblique Wing RPV in the NASA Ames 40 ft by 80 ft wind tunnel. (Photo courtesy of the NASA Ames Research Center.)

To facilitate the remote piloting task, a television camera was mounted in the nose of the vehicle to provide forward looking views. Additionally, a two axis gyro-controlled autopilot provided stabilization for pitch and roll along with altitude hold. The vacuum tube-based sensors resulted in a significant weight penalty to the final vehicle.[49]

Two rounds of wind tunnel tests were conducted. Preliminary testing in the 7 ft by 10 ft tunnel was used to develop the basic layout of the aircraft and confirmed trends noted in the unpowered model. Based on these data, the vehicle was designed and built and then ground tested at Bicycle Lake Army Air Field, northeast of Edwards Air Force Base. Taxi tests, using a low cost model aircraft transmitter, showed that the aircraft was underpowered. These tests ended when the aircraft momentarily lost communication and flipped over on the ground.

Over the course of approximately a year, the

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* Bailey, Rodney O., comments provided to the authors, December 2006.

aircraft was rebuilt and full scale wind tunnel tests in the NASA Ames 40 ft by 80 ft tunnel were conducted (see Figure 28). Three tail configurations, varying only in length, were tested; the short tail was initially selected for flight tests. The tests also determined the static aerodynamic characteristics of the aircraft at varying wing sweep angles and provided the fundamentals required for ground simulation development. The simulation effort, also conducted at NASA Ames, attempted to determine the pilot information requirements as well as tune the control system, and was ultimately used to train the RPV pilot, Jim Martin. [49]

The aircraft made its first flight on August 6, 1976, and flew for 24 minutes, sweeping its wing in flight from 0° to 15° at speeds of 70 to 90 kt.[51] The initial flight indicated insufficient longitudinal stability due to the center of gravity being too far aft, so the medium length tail position – approximately 3 ft (1 m) longer – was implemented after it had been modified by the Rutan Aircraft Factory, Mojave, CA (the predecessor of Scaled Composites, Inc.) to reduce the weight. The flight program was limited to two more flights over the next four months, logging about 20 minutes on each flight.[52] These flight tests took place at Edwards AFB on the dry lake bed. The aircraft performed a variety of flight maneuvers to collect as much dynamic flight information as possible. The second flight swept the wing to 30° and the third flight to 45°. Air-to-air photography was employed on the final flight, as shown in Figure 29.

Figure 29. NASA Ames oblique wing remotely piloted vehicle (first flight 1976). Maneuvers were performed at wing angles of 0 to 45°. The long tail is noteworthy.(Photo courtesy of the NASA Dryden Flight Research Center.)

The RPV was the first oblique wing that was instrumented and provided data for stability and control derivatives. The predicted behavior was based on simple lifting line theory, but the flight experiments showed that the predictions of the dynamic derivatives were within 15% of the measured values. The oblique wing RPV flight tests provided credence to the oblique wing concept and helped bolster the movement toward the next step, which became the AD-1 manned oblique wing demonstrator program.[53]

Oblique Wing Firebee II RPV

Meanwhile, in 1972, Teledyne Ryan began studying the feasibility of modifying a supersonic BQM-34F Firebee II remotely piloted research vehicle to be used in support of NASA's oblique wing transport aircraft technology programs. The Firebee would have been air-launched by a C-130 or other aircraft and recovered by a Mid-Air Retrieval System (MARS). The Firebee II was capable of supersonic flight approaching Mach 2.0. Based on the NASA studies, the oblique wing BQM-34F would have targeted Mach 1.4 as the primary test point of interest. A display model is shown in Figure 30.

Teledyne continued studying the concept through at least 1974. Although some work was apparently funded toward this effort, the aircraft was never built. [48,50] Little data on this oblique wing aircraft demonstrator program is available. Typical Firebee II characteristics, which would have been very similar to the proposed Oblique Wing Firebee II, are provided in Table 7.

Figure 30. Model of the Oblique Wing Firebee II RPV. (Photo courtesy of the NASA Dryden Flight Research Center.)

Table 7. Typical BQM-34F Firebee II characteristics.

Wingspan	8.9 ft	2.7 m
Engine Thrust (sls)	1920 lb	8.5 kN
Max Design Speed	Mach 1.8	
Overall Length	28.25 ft	8.6 m
Empty Weight	1,446 lb	656 kg
Gross Weight	2,100 lb	951 kg

VII. AD-1 Oblique Wing Demonstrator

The Ames-Dryden-1 (AD-1) aircraft was designed to take the next step in investigating the concept of a pivoting oblique wing, taking advantage of advances in the state of the art of composite structural design, with an aeroelastically-tailored wing bend designed to maintain roll trim over a range of g-loading.

The AD-1 was intended to be low cost, low technology and fly at relatively low speeds, with a general shape based on the final Boeing configuration, Model 5-7. Although the benefits of a highly swept oblique wing were found at transonic and higher speeds, it was recognized that compressibility was not a major influence on many of the problems that arise from asymmetry, so the concept could still be investigated at low speeds.

A 1/6 scale model, shown in Figure 31, was tested in the NASA Ames 12 ft pressure tunnel, developing the essential flight characteristics. Full-scale Reynolds numbers were achieved during the tests, in which aeroelastic damping derivatives for wing bending were computed. A six degree-of-freedom, fixed-base digital simulator was developed at NASA Dryden based on these predictions, and used for safety of flight and flight training, as well as to develop the control system requirements for the flight test aircraft. NASA Ames also tested a moving-base simulation, which was used to cross-check the fixed-base and to evaluate the effects of motion on piloting tasks. A 1/13th scale model was also tested later in the NASA Langley spin tunnel.[54, 55]


Figure 31. AD-1 one-sixth scale model in the NASA Ames pressure tunnel. (Photo courtesy of the NASA Ames Research Center.)

The preceding wind tunnel data, simulator results, and contractor studies were used to support the detailed design and loads analysis for the vehicle, which was conducted by the Rutan Aircraft Factory. NASA Dryden then released a request for proposals (RFP) for companies to bid on the construction.

The Ames Industrial Co. of Bohemia, NY was awarded a $240,000 fixed-price contract on 20 February 1978. Ames Industrial Co. (no connection to NASA Ames) was the U.S. name of the French Microturbo company, whose engines were used on the aircraft. To minimize the cost, the aircraft systems were kept as simple as possible and the structure was conservatively designed. For instance, the aircraft was designed for +8g and -4g, and the pivot for ±25g, but the flights were limited to +4g and -2g. The aircraft had a fixed landing gear, no hydraulics, a simple electrical system and no ejection seat.[54, 55]

The engines were two Microturbo TRS-18-045 engines, rated at 200 lb of thrust. The AD-1, as built, weighed about 10% more than originally expected (largely due to a slightly heavier wing than expected). As a result, Ames Industrial uprated the engines by 10% to 220 lb, by small changes to the design. The lift-to-drag of the AD-1 and the idle thrust of the engines (about 50 lb) were such that one engine had to be shut down in order to descend and land. During the program, both engines suffered from turbine rub failures, so the company leased three replacement engines. It was speculated that the in-flight starts and stops contributed to the turbine rub.[*]

The high fineness ratio of the aircraft led some within NASA Ames to advocate for upgrades to the aircraft that would allow it to actually reach transonic speeds. This would have required a retractable gear (which would have been difficult to integrate into the slender fuselage), a stronger canopy and a pressurized canopy (or pilot's oxygen supply), and an all-moving tail to decouple the aeroelastic effects (this was expected to require a hydraulic system due to stick forces and the danger of cable stretching). The engines would also obviously have had to be upgraded, but the nacelles were oversized for the Microturbo engines: they were in fact originally designed for much larger Williams turbojet engines. Nevertheless, it was recognized that the AD-1 program was specifically designed to be low-cost and low risk; modifications for supersonic flight would have run counter to this. The AD-1 demonstrated the ease of flying an asymmetric configuration without an autopilot.[†]

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[*] Smith, Stephen C., comments to the authors, December 2006.

[†] Smith, Ronald C., comments to the authors, December 2006.

The aircraft was constructed of reinforced fiberglass sandwich skin separated by a rigid foam core. A wing proof test was conducted in order to compare the measured and predicted static deflection of the wing under a distributed load. In order to prepare for the future flutter clearance, a ground vibration test was conducted to determine the principal structural modes and compared with the design predictions. The moments of inertia were also measured.[48] Basic aircraft characteristics are provided in Table 8.

Table 8. AD-1 demonstrator characteristics. [57]

Aspect Ratio (0°)	11.2	
Wingspan (0°)	32.3 ft	9.8 m
Wing area	93 ft^2	8.6 m^2
Engine Thrust (sls)	2 x 220 lb	2 x 100 kg
Max Flight Speed	150 kt	278 km/hr
Overall Length	38.8 ft	11.8 m
Empty Weight	1,450 lb	658 kg
Gross Weight	2,100 lb	950 kg

The aircraft was delivered to the Dryden Flight Research Center, Edwards, CA, in February 1979. Throughout the rest of the year, initial check out tests – including high speed taxi tests – were conducted and mission profiles were explored in the simulator.[48]

NASA Dryden research pilot Thomas C. McMurtry conducted the first flight, a short 5 minute hop on December 21, 1979. The second flight later in the day, considered the first "official" flight, lasted 45 minutes, reaching 10,000 ft and 140 kt. McMurtry found that oscillations that had been felt during the taxi tests were not a problem in flight. Fitzhugh Fulton was the second NASA Dryden project pilot.[48]

The first wing sweep flight – to 15° – was conducted on April 2, 1980 during flight number 12. This was expanded to 45° two flights later on May 28, 1980. McMurtry noticed that low damped oscillations on the aft-swept wing occurred at a sweep angle of 20°, but no significant vibrations were found until the aircraft reached 140 kt and 42.5° sweep. While flying at 130 kt, the wing was finally swept to 60° on April 24, 1981, during flight 23. Flights up to 150 kt were eventually achieved, but structural resonances with very low damping were experienced, and the aircraft was limited to this maximum speed. [48] The aircraft is shown in flight in Figure 32.

Figure 32. Ames-Dryden AD-1 oblique wing demonstrator (first flight 1979). It flew with the wing at angles from 0° up to 60° and speeds up to 150 kt. (Photo courtesy of the NASA Dryden Flight Research Center.)

McMurtry found the handling qualities were very close to the simulator, but that the aircraft's asymmetry resulted in unusual trim requirements, asymmetric stall and inertial coupling.[48] For instance, the AD-1 required about 10° of bank in order to trim the aircraft with no sideslip at 60° wing sweep.[2]

In addition to McMurtry and Fulton, 15 NASA and military guest pilots flew the aircraft over the next six months, providing handling quality evaluations at various speeds and wing sweep angles. The guest pilots were given a one-day ground school and then asked to conduct fairly simple tasks during a one-hour mission that included a sweep to 60°.[48] Pilot ratings degraded by 2 to 3 points on the Cooper-Harper scale when changing wing sweep angles from 30° to 60°. Several landing tests were also conducted with the wing swept up to 45°. [58, 59]

The aircraft was also demonstrated at the nearby Fairfield Air Show, NASA Ames, Norton Air Force Base (near San Bernardino), the Edwards AFB Open House and the Experimental Aircraft Association's (EAA's) annual airshow in Oshkosh, WI, with its last flight on August 7, 1982. The aircraft was trucked from there to NASA Langley for wind tunnel tests, and finally returned to storage at Dryden a year later. A total of 79 flights were conducted, accumulating 73 hours and 40 minutes in the air. Various arrangements of tufts were attached to the upper wing surface, fuselage and tail in early 1980 and oil flow tests were conducted in June 1982 for flow visualization.[48]

As hoped, the low-cost, low-speed, low-technology AD-1 successfully demonstrated the concept of a manned oblique wing aircraft, sweeping the wing to a maximum of 60°. The aircraft experienced cross coupling between pitching moment and aileron deflection. This pitch-roll coupling and the aeroelastic effects contributed to unpleasant handling qualities at sweep angles above 45°. The fiberglass material that was used limited the wing stiffness; more advanced materials, such as carbon fiber composites, could have reduced the aeroelasticity effects. A more sophisticated flight control system could also have improved the handling qualities.[48] In a concurrent study using the simulator, it was found that a simple rate feedback control augmentation system would significantly improve the flight characteristics up to the full 60° of sweep.[55]

As a result of the AD-1 program, NASA's parameter identification techniques were referenced for asymmetrical vehicles. This effort had been started as part of the Oblique Wing RPV flight test program, but the AD-1 provided significantly more data across a much broader flight regime. The flight test program also introduced the fairly radical asymmetrical planform to a large number of pilots, engineers and test personnel, as well as the general public.[58]

Pilot evaluation reports suggested that the oblique wing design be looked at closely for a carrier-based anti-submarine role because of its predicted loiter capability, low approach and landing speed, and its expected supersonic dash capability. Studies also indicated that the oblique wing concept has great potential in a fighter aircraft role, again because of predicted loiter and supersonic dash capabilities.[59, 60]

VIII. F-8 Oblique Wing Research Aircraft

After completion of the AD-1 project, there was still a need for a transonic oblique-wing research aircraft to assess the effects of compressibility, evaluate a more representative structure, and analyze flight performance at transonic speeds. NASA had originally planned to follow up the AD-1 research effort with a supersonic demonstrator based on the Vought F-8 Crusader fighter.[61, 62]

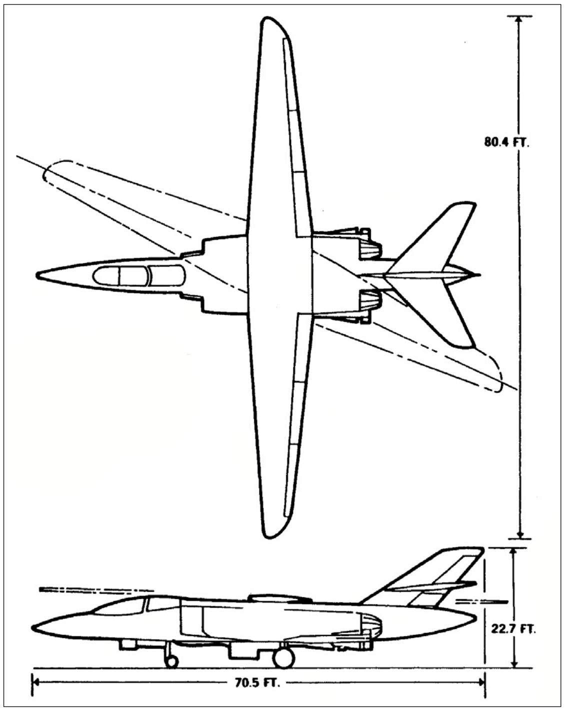

Figure 33. Rockwell oblique wing fighter designed for the Navy VFMX fleet defense mission. [63]

As mentioned above, the possibility of an oblique wing F-8 was studied in 1973. At that time, a two-seat TF-8 oblique wing aircraft was planned to follow the AD-1. Vought (known as LTV at the time) completed a study on the feasibility of converting a NASA F-8 to an oblique wing research aircraft. The study formulated the preliminary structural arrangements, the pivot design, aeroelastic shape, flutter margins and weight and balance estimates.[8]

During the period 1984-1990, the F-8 Oblique Wing Research Aircraft (OWRA) program planned to take the concept to the next step and build a high speed demonstrator based on the NASA F-8C Digital Fly-By-Wire (DFBW) testbed aircraft. The effort, however, was cancelled due to funding constraints prior to modification of the aircraft, although extensive analysis and design research – including significant wind tunnel testing – was completed. The OWRA was a joint program between NASA Ames, NASA Dryden and the U.S. Navy to explore the potential for a supersonic aircraft that could benefit from high speed and a long loiter time; in addition, the Navy was interested in its compact footprint with the wing fully swept, which would result in a smaller spotting factor on an aircraft carrier, obviating the normal requirement for a wing fold. The F-8 OWRA was seen as a demonstrator for an operational concept that could provide stand-off perimeter defense for Navy aircraft carrier groups (see Figures 33 and 34 and Table 9).

Table 9. Rockwell VFMX oblique wing fighter characteristics. [63]

Aspect Ratio (0°)	10.2	
Wingspan (0°)	80.3 ft	24.5 m
Wing Area	583 ft^2	54.1 m^2
Gross Weight	81,000 lb	36,700 kg
Empty Weight	36,600 lb	16,600 kg
Overall Length	70.5 ft	21.5 m
Engines	2 x GE F110 (aka F101 DFE)	

Studies by Rockwell on a potential fleet air defense mission (designated VFMX), which would have to be able to loiter for long periods of time and dash supersonically, compared an oblique wing to a variable geometry swept wing design. Both aircraft had a common fuselage capable of carrying 10

AIM-120A AMRAAM missiles or six AIM-54C Phoenix missiles. Maximum design speed was Mach 1.8.[64]

Both aircraft had wings that could be swept to 65° for supersonic flight and unswept to 0° with an aspect ratio of 10.2 for long endurance, but the oblique wing had a minimum aspect ratio (at maximum sweep) of 1.82 vs 2.74 for the conventional swing wing fighter. Rockwell found that the oblique wing produced less drag and had a greater useful load at a lower empty weight. Specifically, the oblique wing fighter would have a 17% improvement in takeoff weight or a 29% mission radius increase at the same gross weight.[64]

Tom Gregory at NASA Ames was a key individual in getting the Navy and Rockwell International to participate, with a memorandum of agreement was signed between NASA and the Navy in May 1984. The OWRA program was formally initiated with an RFP that November. The goal of the program was to address the remaining uncertainties regarding oblique wing aircraft and to demonstrate the feasibility of a versatile and efficient supersonic aircraft. NASA and Rockwell developed the wing design, as well as the computational tools that would be applicable to the F-8 and other future oblique wing designs.[2] Development was initiated using state-of-the-art analytical methods, previous wind tunnel test data, and water tunnel tests for flow visualization in the NASA Dryden Water Tunnel (a example of which is provided in Figure 35).

By 1988, Rockwell had completed the preliminary design of the OWRA aircraft.[65] An aspect ratio of 10.2 (at 0° sweep) was selected due to the extensive NASA wind tunnel database of that configuration, discussed above, and because it was compatible with their Navy Fleet Air Defense design.[64] The design of the supersonic demonstrator was extremely challenging, as it involved "an unusually important integration of aerodynamics, structures and controls because of the strong aerodynamic and aeroelastic coupling of the dynamic modes."[2]

The F-8C DFBW was considered a near ideal testbed platform since it had an adaptable flight control system and was originally designed for flight up to Mach 1.8. Planned modifications to the NASA F-8C DFBW, graphically depicted in Figure 36, included a composite wing with a pivot assembly for wing sweep up to 65°; flight control computers and interfaces; and a differential horizontal stabilizer.[65] The DFBW system was expected to decouple the dynamic modes so that the handling qualities were similar to a conventional aircraft. Since the AD-1 flights showed a reduction in handling qualities with sweep angle, the F-8 DFBW control system was being designed to provide acceptable handling qualities across a large flight envelope.[2]

Figure 34. Rockwell concept for a Navy oblique wing aircraft, based on their VFMX fleet air defense studies. (Graphic courtesy of the NASA Dryden Flight Research Center.)

Figure 35. 1984 water tunnel test of the F-8 OWRA. (Graphic courtesy of the NASA Dryden Flight Research Center.)

The proposed wing pivot was also to be canted so that at 0° sweep, the wing was canted to 0°, but at 65° sweep it would be canted to 10°. The wing incidence would also have been increased (a standard feature of the F-8) with higher sweep angles. These features were expected to reduce aerodynamic cross-coupling, such as the necessity to bank the whole aircraft to trim sideslip, as found in the AD-1 flight testing.[61] The OWRA was designed to demonstrate low speed loiter, long range subsonic cruise, 4 g maneuvers at high and low speed, and supersonic dash up to Mach 1.6.[2]

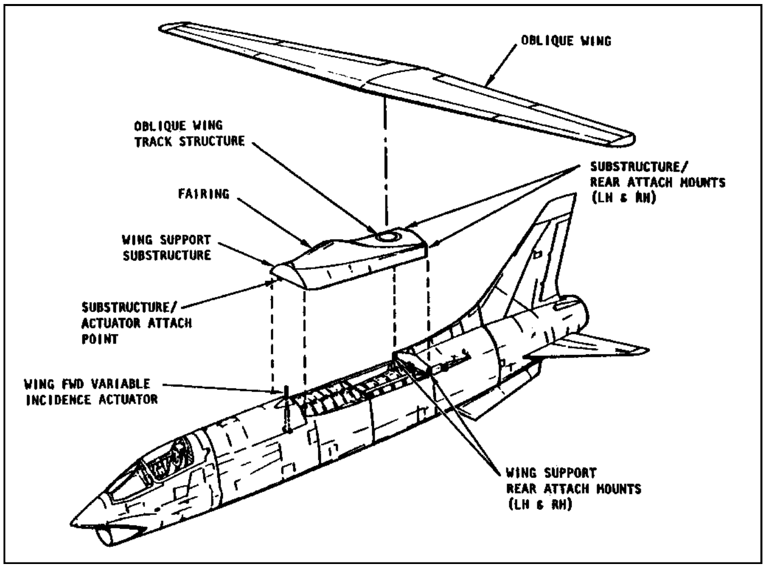

Figure 36. Conceptual diagram of the F-8 DFBW aircraft modifications into the OWRA demonstrator.[58]

It should be noted that although the use of the F-8 DFBW testbed reduced the development effort and cost of a new aircraft, it nonetheless introduced its own design complications, as the aircraft had never been designed to take such asymmetric loads. The F-8 was also hampered by a landing gear design that prohibited landing at high angles of attack (see Figure 37) and an in-flight angle of attack limit of only 12-14° before lateral instability would have become problematic.[2] In January 1987, four NASA test pilots and two Navy pilots evaluated the proposed OWRA flight control system in the Ames large vertical motion simulator (VMS), which provided ± 17 ft of lateral motion and up to ± 25 ft of vertical motion. The flight control system was designed to provide decoupled handling qualities and was evaluated at five discrete flight conditions from low altitude subsonic to moderate altitude supersonic speeds. In addition to the preliminary pilot evaluations of the prototype control system, the investigation was also intended identify important response variables and to develop criteria and requirements for use in future control laws for highly coupled aircraft.[65, 61]

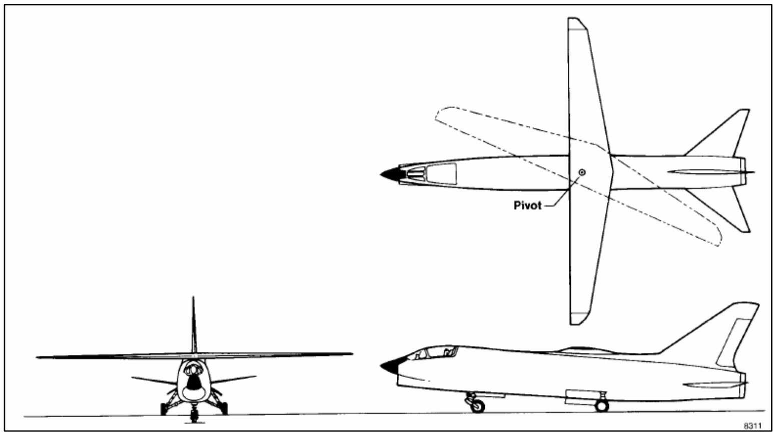

Figure 37. F-8 OWRA layout. The short landing gear would have prohibited high angle of attack landings.

In general, the flight control system successfully decoupled the aircraft controls, but all of the pilots indicated that lateral acceleration during pitch maneuvers – due to the asymmetric sideforce as a function of angle of attack – was unacceptable. Left turns were less decoupled in roll than right turns due to the tendency to roll into the left turns (the direction with the trailing wing tip) and roll out of right turns, caused by variations of roll and yaw moments as a function of angle of attack. The OWRA wing area as modeled in the VMS was 200 ft^2, only two-thirds the size of the later design; the larger wing may have alleviated these shortcomings somewhat. [For reference, the standard F-8 has a 350 ft^2 wing area and an aspect ratio of 3.6; the wings are swept back at 42°.] [61, 65] The primary characteristics of the F-8 OWRA is provided in Table 10 and a graphic of the proposed demonstrator is shown in Figure 38.

Table 10. F-8 OWRA characteristics (1986).[61]

Aspect Ratio (0°)	10.2	
Wingspan (0°)	45.17 ft	9.8 m
Wing area	200 ft^2	18.6 m^2
Overall Length	52.8 ft	16.1 m
Empty Weight	18,800 lb	8,525 kg
Gross Weight	23,500 lb	10,650 kg
Maximum Speed	Mach 1.6	

NASA conducted testing in June-July 1987 in the Ames 11 Ft Transonic Wind Tunnel on the 8.7% scale model. The wing was designed by Ames, with an aspect ratio of 10.47 and a wing area of 300 ft^2, and used specially-designed supercritical airfoils with 14% thickness (measured at the root). The model was tested from Mach 0.3 to 1.4, with the wing swept at 0°, 30°, 45°, 60° and 65°. Flap deflections during cruise were studied to determine the effects on roll trim and to tailor wing camber for different flight conditions. Roll authority of the flaps and ailerons was studied, as well as a unique deflected wingtip for roll control at high sweep. The wind tunnel tests demonstrated good performance over a wide speed range, with the specially-designed airfoils meeting their design goals with respect to drag rise and maximum lift-to-drag curves.[61]

Figure 38. Proposed supersonic F-8 Oblique Wing Research Aircraft. (Graphic Courtesy of the NASA Ames Research Center.)

These NASA tests were compared against those with an OWRA wing designed by Rockwell in July 1988. The Rockwell wing had an aspect ratio of 10.3, a (full-scale) wing area of 300 ft^2, and a wing thickness of 14%. The same sweep angles from 0° to 65° were tested, and Mach Numbers from 0.25 to 1.4. The wing was tested at two different heights above the fuselage; it was found – counter to expectations – the higher position was not beneficial and actually had reduced performance: it caused more drag, with little reduction in the wing/fuselage interference and was less stable in pitch at certain transonic conditions. Low speed characteristics were measured for both the clean wing and with the flaps deflected, as well as aileron settings across the full speed and sweep range. Testing also indicated that the maximum lift coefficient expected by Rockwell would not be realized by the flight test aircraft with this wing design. The NASA Ames-designed wing discussed above, although slightly more complex, indicated that improved performance and handling qualities were possible.[61]

Joint funding was budgeted (50/50 cost share with the Navy) for the F-8 OWRA program, but cost overruns on another joint effort with the Navy – the X-Wing stopped rotor program – caused the OWRA program to be canceled. The wing design was essentially complete, but fabrication had not yet begun. At that point, the Navy had also developed interest in other combat aircraft, such as the General Dynamics/McDonnell Douglas A-12, then under development.[67]

IX. NASA / Stanford OAW and OFW Studies

R.T. Jones – the driving force behind NASA's oblique wing research for more than a quarter century – retired from Ames in 1981, but served as a consulting professor at Stanford University until 1997. He acted as an advisor at Ames and Stanford, assisting several doctoral candidates with oblique wing research, as discussed below.[16] Jones and Ilan Kroo directed research on oblique wings for the next decade at Stanford University in collaboration with NASA Ames.

In the late 1980s and early 1990s, Jones focused on the potential for a supersonic oblique flying wing transport. His interest in the concept spawned a new generation of oblique flying wing (OFW) research. Jones appeared to be particularly encouraged by variable bypass engine technology research that would allow better speed matching and efficiency for an aircraft with high aerodynamic efficiency at a wide range of speeds, and the realization that the Concorde was nearing the end of its service life, opening the door for a replacement. Jones felt that a long-range OFW would be ideal for flights across the Pacific Ocean. A sketch of Jones' OFW concept is provided in Figure 39. A painting was commissioned by NASA Ames in 1989 of a later design, as shown in Figure 40. The later illustration includes differences in the vertical tail configuration and the inclusion of engine pods. [25]

Jones envisioned an OFW with a wingspan of 400 ft and a 14% thick wing, which would have given the same internal volume as a Boeing 747, at one-third the wing loading, thus alleviating the need for high lift devices. Jones saw the OFW transporting 500 passengers from San Francisco in half the time as a conventional subsonic transport, with only a small increase in relative fuel consumption.[25] It would be difficult to design a supersonic passenger-carrying OFW that was much smaller, since thicker wings would create more drag, and a wing thickness of much less than 7 ft would provide insufficient head room. With an aspect ratio of about 10 for good low speed performance, a wing span of 500 ft would be about optimal from a performance perspective and still allow passengers to stand fully upright in the cabin.

Alexander Van der Velden, then at Stanford, conducted a conceptual design of a Mach 2 OFW for NASA Ames' Fluid Dynamics Division. His design, which he had begun in Spring 1987, could sweep between 37.5° and 72°, with four large turbofan engines capable of pivoting between those two angles. The aircraft was designed to fly 500 passengers at Mach 2.0 over water and Mach 1.2 over land to avoid the sonic boom. Three large tails provided directional stability.[69] Characteristics of the design and an illustration are provided in Table 11 and Figure 41, respectively.

In 1990, Van der Velden continued his research on his OAW for NASA. He noted that recent research indicated that thick oblique wings at very high sweep angles could be efficient at supersonic speeds if transonic normal Mach numbers were permitted on the upper surface of the wing. He used a two-dimensional Navier-Stokes computational fluid dynamics (CFD) solver to design airfoils as thick as 16%.[70]

In July 1991, NASA Ames' Systems Analysis Branch completed a preliminary design of an OFW transport. [During this time, NASA used the moniker of "oblique all wing (OAW)" and "oblique wing body (OWB)" to refer to these oblique wing aircraft.] The aircraft was intended to transport 484 passengers 5500 nm at a cruise speed of Mach 1.6 at 68° sweep. For low speed, the minimum sweep angle was 37.5°. Speeds of up to Mach 2.0 were originally envisioned.[71]

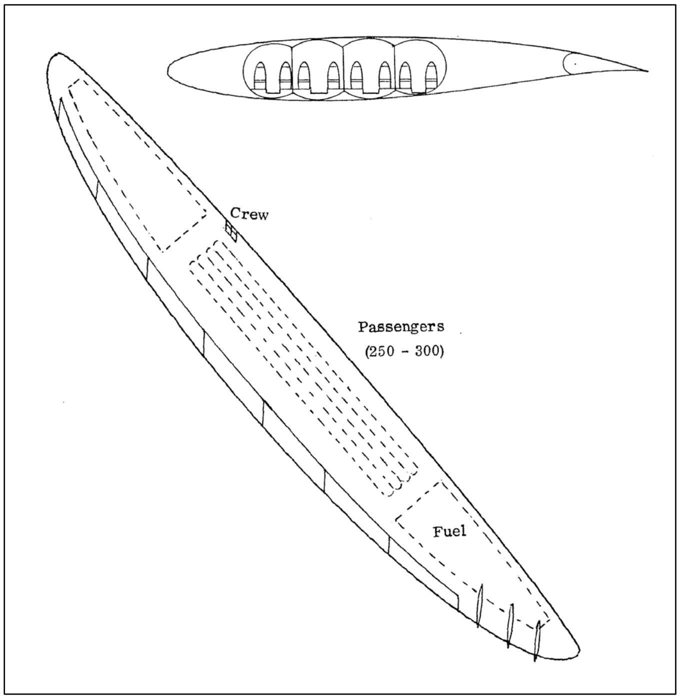

Figure 39. NASA Ames notional sketch of Jones' Trans-Pacific OFW (circa 1986). Left wing tip is forward.[68]

Figure 40. Artwork of Jones' OFW concept (1989). Right wing tip is forward. (Graphic courtesy of the NASA Ames Research Center.)

Studies continued to refine a 400 passenger supersonic transport with a 16% thick wing, the maximum practical speed was most likely around Mach 1.8. With a constant normal Mach number of 0.6, the sweep angle was 70.5° at this speed; aerodynamic performance at higher sweep angles was thought to be problematic. Similar to the original 1989 OFW painting (Figure 40), two wing tip fins were used at the 90% span locations, as shown in Figure 42, although this concept was also drawn (and circulated to the media) without any vertical surfaces (see Figure 43). The aircraft had a wingspan of 406.8 ft, an aspect ratio of 10, an operational empty weight of 416,679 lb and a gross weight of 865,000 lb. A reduced-size OAW for 324 passengers (with the same wing geometry) had a wingspan of 391.1 ft and a range of 5600 nm.[71]

It was noted that the wide wheel track needed for stability during taxi and take-off would greatly exceed the taxiway width. A quad-gear with steerable trucks was found to be necessary, with a significant sweep angle required to navigate standard airport taxiways. Integration of the four large gears into the fuselage was also seen as challenging, due to the need for a contiguous passenger compartment.[71]

Studies continued refinement, leading to a 400 passenger supersonic transport with a 400 ft wingspan that would vary the wing sweep from 35° for take-off to 68° for cruise at Mach 1.6. NASA's goal was to develop a supersonic transport (SST) that could fly from Los Angeles to Tokyo at Mach 1.6, but at the same ticket price as a Boeing 747. Static instability was selected to increase airfoil efficiency and to best package the passengers within the airfoil volume.[71]

Following these initial studies, NASA Ames conducted a technical and economic comparison of OAW and OWB designs versus conventional swept-wing subsonic transports using ACSYNT. The three conventional designs were capable of flying at Mach 0.85 with 300, 400 and 500 passengers, respectively. Three OWB aircraft were designed: one capable of transporting 300 passengers at Mach 1.6; one with 300 passengers at Mach 2.0; and one with 400 passengers at Mach 2.0. Three OAW aircraft (each with an aspect ratio of 10.0) were designed for 291, 440 and 544 passengers, respectively, at Mach 1.6. Each aircraft was designed for a 6000 nm range.[72]

The comparison determined that for aircraft designs above 350 passengers, the OAW would have a lower gross weight than the OWB. Both supersonic aircraft types were significantly heavier than the conventional subsonic swept-wing designs; but the empty operating weight fraction for the conventional designs was around 50%, while the OAW and OWB configurations were between 41% and 46%. The economic analysis showed that the OAW had a rapid decrease in cost per passenger seat mile with the size increase, while the OWB showed a slight increase in cost with size; in fact, the OAW cost actually approached the subsonic seat mile cost with increasing size. This is significant, since the supersonic flight time would be roughly half that of conventional trips, and the OAW would be capable of efficient subsonic operations and meet future noise requirements (since the oblique wing aircraft would have a higher aspect ratio for take-off and landing and the engines could be run at part power for take-off).[72]

Table 11. Van der Velden OFW design (1989). [69]

Aspect Ratio (0°)	10.16	
Aspect Ratio (72.5°)	1.06	
Wingspan (0°)	400 ft	122 m
Wing area	15726 ft^2	1461 m^2
Engine Thrust (sls)	4 x 56,200 lb	4 x 250 kN
Max Speed	2.0M	
Cruise Speed	1.2M	
Max Payload	540 pax + 32,000 lb cargo	
Max Op Wt Empty	289,000 lb	130,200 kg
Gross Weight	676,000 lb	304,200 kg

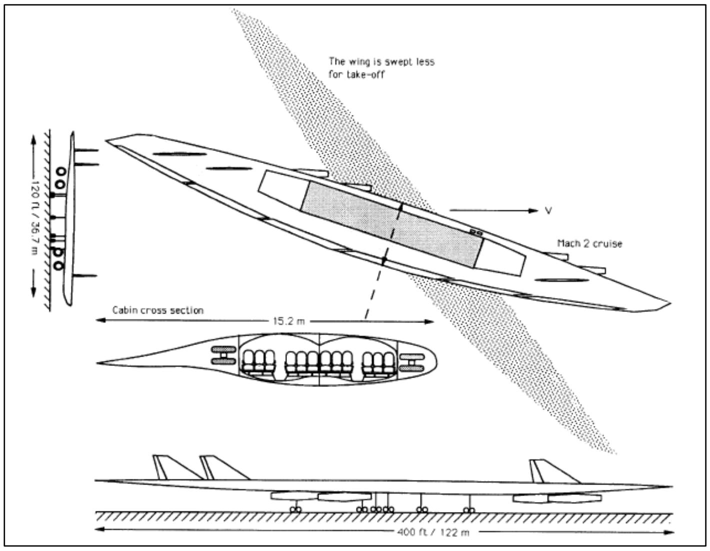

Figure 41. Van der Velden OFW design (1990). [70]

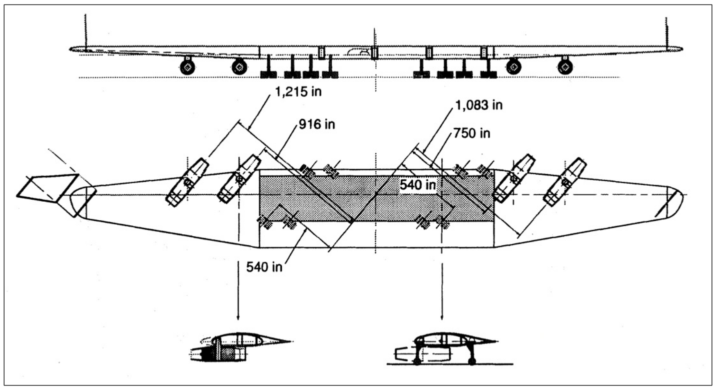

Figure 42. NASA Ames 500 passenger OAW design (1991) with two vertical fins.[71]

Also beginning in August 1992, a study group comprised of Boeing, McDonnell Douglas Aircraft Company, NASA Ames, and researchers at Stanford University collaborated to investigate the feasibility of a commercial OAW. Industry was invited to participate in the OAW studies in order to ensure that real-world design constraints were included, as well as to gain access to industry design expertise. The study considered aerodynamic performance, stability, structures, landing gear, aircraft exit procedures, and airport regulations.

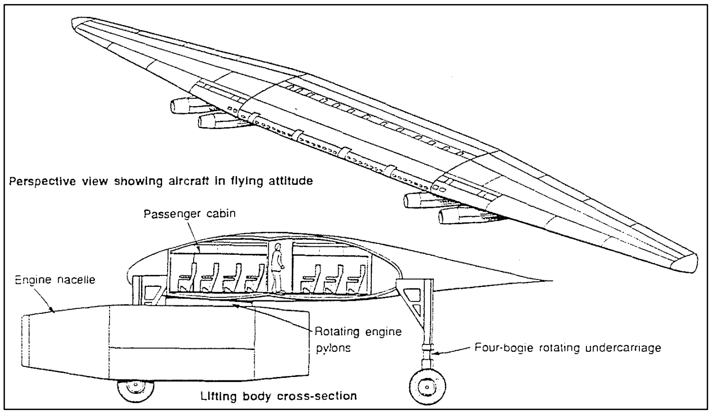

Figure 43. 1991 NASA Ames design for a supersonic oblique all wing transport without vertical fins. [71]

The Ames team began with the above aerodynamic design, designated OAW-0 and – through the use of CFD – analyzed and designed the airfoil shape and deflection of the wing to optimize the design. Modifications were made to minimize wave drag within the geometric constraints, including Boeing's suggestions on revising the cabin layout. High fidelity computational analysis was then used to optimize engine nacelle shape and location, vertical tail size and orientation (a fin above and below the trailing wing surface), and wing bend. The final OAW-3 wing represented a highly optimized design based on the configuration constraints and performance metrics (e.g. fuel burn for a given mission). It had a constant chord center section to house the passenger compartment, with smoothly lofted transitions to the linearly tapered wing tips.[*] [†]

Boeing completed a conceptual design of their 865,000 lb, OAW configuration (see Figure 44) with 450 passengers, which included folding wing tips for maneuvering on airport ramps, while McDonnell Douglas progressed to a more mature design of their DAC-1 wing. This was a classical elliptical planform, optimizing the airfoils for the best pressure distributions at the cruise point. The elliptical planform, however, had more wetted area, so that even though the drag coefficients were lower, the actual drag was higher than the OAW-3 wing because the reference area was larger.[*]

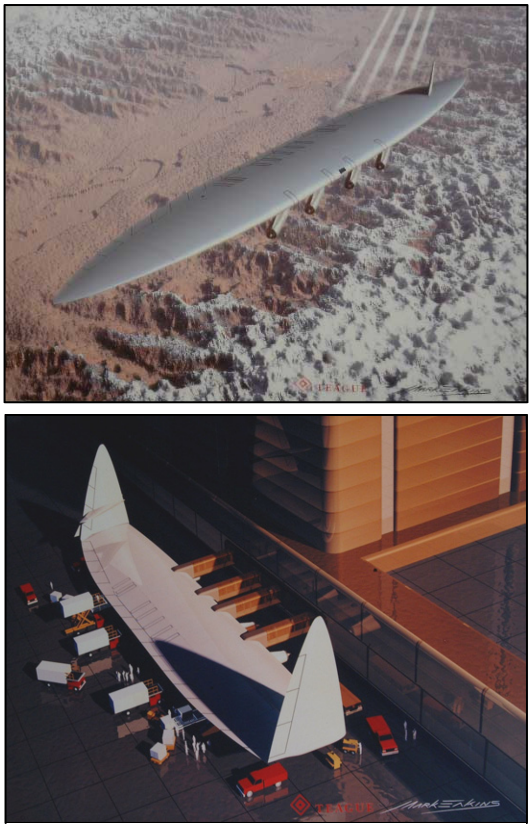

Figure 44. Boeing design for a large OAW passenger aircraft.

Both the OAW-3 and DAC-1 wings were tested in the Ames 9 ft by 7 ft supersonic wind tunnel in June-July 1994. The 1.8%-scale blade-mounted model of the Ames OAW-3 design, however, also included the engines and all of the control surfaces, as shown in Figure 45. The model was tested between Mach 1.56 and 1.80, and at a single sweep angle of 68°: a significant challenge of testing a supersonic OAW configuration is incorporating an internal strain gage force balance into the model without distorting the outer mold lines. A special flat balance was developed for the OAW program; unfortunately, it could only be used at one sweep angle. Pressure sensitive paint was also used and compared to Navier-Stokes analysis. The wind tunnel data for the OAW-3 tests were recently published.[†] [73]

In addition to the highly constrained OAW design described above, McDonnell Douglas was also funded to continue work with OAW design exploration using fewer constraints. A wide range of OAW designs were

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[*] "Oblique Flying Wings: An Introduction and White Paper," Desktop Aeronautics, Inc., http://www.desktopaero.com/obliquewing/library/ofwwhitepaper.pdf, June 2005.

[†] Smith, Stephen C., "Oblique All-Wing OAW-3 Wind Tunnel Test," http://www.desktopaero.com/obliquewing/library/NASA_WT_Data/OAW_test_report.pdf, April 20, 2005.

investigated, including concepts carrying between 0 to 1,600 passengers, and cruising at Mach numbers of 0.85, 0.95 or 1.30. Aspect ratios between 6 and 12 were considered, with the wing shape (apparently DAC-1) kept constant for all trade studies. The wing had a maximum thickness of 17.0% at the centerline and the airfoils were designed to maintain a constant normal Mach number of 0.60; this resulted in a sweep angle of approximately 45° at Mach 0.85 and 62.5° at Mach 1.30.[74]

A technology level for a 2020 service entry was assumed, with "rubber" engines designed for the specific cruise Mach number. For the subsonic cases, a range of 7,000 nm with reserves was set; for the supersonic design, a range of 5,146 nm was fixed (5,000 nm plus allowance for headwinds). Parametric curves were generated for variation of altitude, wing area, weight, lift-to-drag, thrust required, and direct operating cost (DOC) with passenger count and aspect ratio, etc. Final configurations for a subsonic and a supersonic design were selected. For Mach 0.85, the 800 passenger OAW with an aspect ratio of 6.0 (shown in Figure 46) was the clear winner based on gross weight, DOC and size. With allowance for adequate passenger cabin height, seating density and luggage, after the conceptual design was complete, the expected number of passengers was 708.[74]

A tail was used for additional controllability. Cargo was stored outboard of the passenger cabin. The fuel was contained in the wing tips, which would have caused taxi bump and flight load problems; McDonnell Douglas recognized that this would have to be addressed with further design iterations.[74]

At Mach 1.30, the 800 passenger OAW with an aspect ratio of 10 was selected. This design, shown in Figure 47, had a wingspan of 455 ft. A 1200 passenger OAW (aspect ratio 11) was found to have a slightly lower DOC, but the wingspan was nearly 100 ft greater and felt to be untenable. The conceptual design allowed for 733 passengers plus luggage.[74]

Figure 45. OAW-3 model (with impressionistic background materials). (Photo courtesy of the NASA Ames Research Center.)

Table 12. McDonnell Douglas Mach 0.85 OAW (1994).

Aspect Ratio (0°)	6.0	
Wingspan (0°)	317.0 ft	96.6 m
Wingspan (45.1°)	229.8 ft	70.0 m
Overall Length (0°)	138.8 ft	42.3 m
Wing Area	~16,747 ft^2	~1,555.8 m^2
Engine Thrust (sls)	4 x 45,000 lb	200 kN
Max Speed	Mach 0.85	
Max Payload	708 passengers	
Max Op Wt Empty	480,000 lb	217,724 kg
Gross Weight	~ 975,000 lb	~442,252 kg

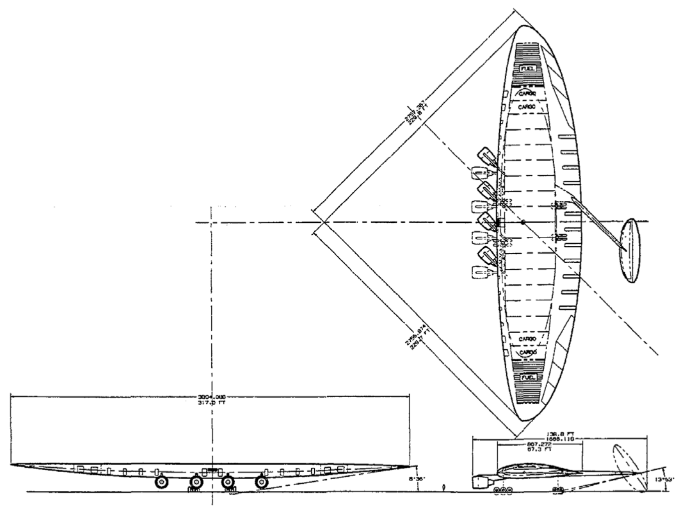

Figure 46. 1994 McDonnell Douglas Mach 0.85 OAW.[74]

Based on the parametric studies and the conceptual design refinements, McDonnell Douglas reached some interesting conclusions. The need for adequate wing thickness to accommodate the passengers creates "a fundamental conflict in OAW airplanes between the improved packaging efficiency provided by lower aspect ratio wings and their reduced aerodynamic efficiency. The low aspect ratio shapes have the least wetted area per passenger, and they do this at practical airliner capacities, but they also have lower efficiency due to their relatively small wing spans." The study also stated that a "windowless cabin with a relatively low ceiling may require enhancements to be acceptable for the very long flights of which the OAW is capable" and indeed is one of the few compelling cases for the OAW airliner.[74]

Table 13. McDonnell Douglas Mach 1.3 OAW (1994). [74]

Aspect Ratio (0°)	10	
Wingspan (0°)	455 ft	138.7 m
Wingspan (62.52°)	217.8 ft	66.4 m
Wing Area	~20,788 ft^2	1931 m^2
Overall Length (0°)	87.4 ft	26.6 m
Max Speed	Mach 1.30	
Max Payload	733 passengers	

Other passenger inconveniences included not only sitting at an angle with respect to the direction of flight (which also varied), but the angle of attack necessary for the OAW to achieve efficient performance during flight would also tilt the seats in unnatural directions. This also necessitated steps throughout the cabin, since the "forward" seats would be higher than the rear seats. Making the aircraft large enough to mitigate the above problems resulted in very large aircraft that would have been extremely expensive and cause potentially unsolvable problems for airport operations. In part due to the conclusions of the study by both Boeing and McDonnell Douglas (which merged with Boeing in 1997), the OAW concept was dropped as a viable passenger transport.

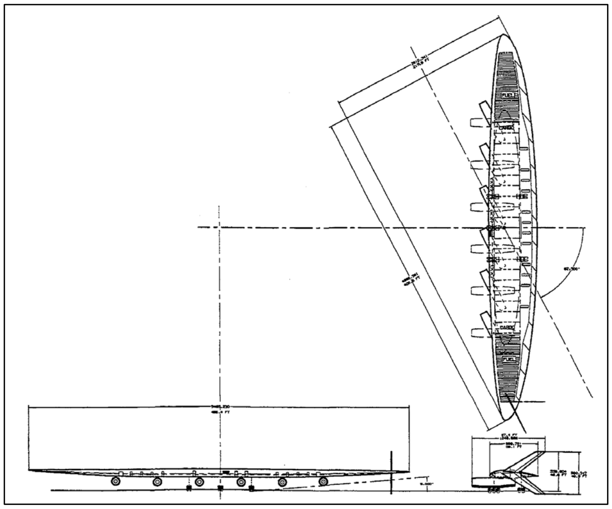

Figure 47. 1994 McDonnell Douglas design for a Mach 1.3 OAW.[74]

X. Morris OFW Flight Testing

During the above studies, NASA Ames funded Steve Morris at Stanford University to build and fly two small-scale OFW aircraft; these were the first powered oblique flying wing flight demonstrations. NASA's grant allowed Morris to develop these demonstrators in order to study handling qualities, investigate control algorithms for stability augmentation, and demonstrate the feasibility of the inherently unstable configuration and its applicability to the full-scale OAW transport discussed above (specifically to emulate the 1991 design depicted in Figure 43). In support of the F-8 OWRA program, Morris had previously analyzed the lateral accelerations of the AD-1 simulation results and found a way to simultaneously optimize the aerodynamic configuration and the handling qualities of oblique wing aircraft. Morris research in support of his thesis addressed issues discovered during the OWRA program including aeroelastics, stability and control, and aerodynamic issues of oblique wing aircraft.[75]

The first model (Figure 48) was a 10 ft span radio controlled aircraft powered by a single propeller, capable of pivoting to effect the vehicle sweep angle between 25° and 65°. Aircraft characteristics are given in Table 14. The model was statically stable in pitch and had no flight computer for stability augmentation, being manually controlled using radio control.*

For control, the aircraft used three trailing edge surfaces and a single all-moving vertical fin. It crashed on its first flight due to pitch effects of the single large vertical tail: the

Figure 48. Steve Morris' 10 ft OFW (first flight 1993). It flew at sweep angles of up to 65°. (Photo courtesy of Steve Morris. Used with permission.)

Table 14. Morris 10 ft OFW aircraft characteristics. *

Wingspan (0°)	10 ft	3.0 m
Minimum Sweep	25°	
Maximum Sweep	65°	
Weight	10 lb	4.5 kg
Engine Type	0.40 cubic inch 2 stroke	

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* Morris, Stephen, correspondence with the authors, December 2005.

aerodynamic load centroid of the fin was too far above the plane of the wing, producing a significant pitching moment that overpowered the pitch authority of the flaps. A vortex lattice code was used to model this and to explore ways of correcting this phenomenon. Morris' studies showed that if the fin was canted, the aerodynamic force vector from the fin could go through the pitch axis, decoupling the force. Many vertical tail configurations were tested with a final result of using two smaller fins. The model was flown extensively over a 6 month period, as shown in Figure 49, eventually flying up to sweep angles of 65° briefly to verify that there was adequate control authority to trim the aircraft at this flight condition. During several of the flights, Morris attached long streamers to the trailing edge to see the sweep angle in flight. [75-77, *]

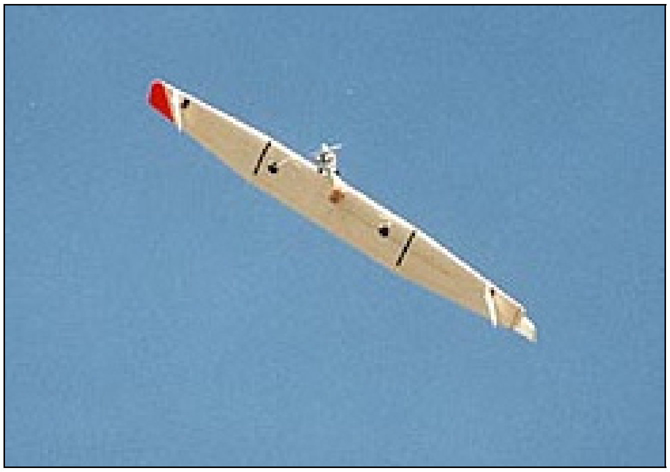

Figure 49. Steve Morris' 10 ft OFW in flight. (Photo courtesy of Steve Morris. Used with permission.)

The second aircraft had a 20 ft (unswept) span and used 10 trailing edge control surfaces, as well as two all-moving vertical fins. The aircraft was sized to be a 5%-scale model of the full-scale 400 passenger OAW (Figure 43). Trailing edge surfaces were sized to be 25% of the local wing chord in order to produce the most control authority within a reasonable size. The vertical fins were sized for sufficient control authority in the event of an engine failure, but the centroid of the loading was kept close to the surface of the wing in order to avoid pitch coupling.

The second aircraft weighed 80 lb and was powered by two radio control model aircraft 5 hp single cylinder engines driving ducted fans that produced 12.3 lb of thrust at 23,000 rpm; the fans could pivot to effect the variable sweep in flight from 35° to 68°. The 48 oz of fuel was sufficient for about 6 minutes of flight time. The landing gear was a fixed, quadracycle gear arrangement with four wheel steering to allow the aircraft to taxi. The model used three flight sensors: a 3-axis rate gyro, an angle of attack, and angle of sideslip vane, and a wind turbine air speed indicator. Figure 50 shows a general comparison of the two aircraft.

The airframe was constructed of an aluminum spar with steel sub-spars to support the landing gear, engines and fins. Wing ribs covered by Kevlar and foam molded skin formed the aircraft surface. The leading edges were formed from balsa and fiberglass; the entire trailing edge was comprised of the balsa control surfaces, which were sized by the maximum torque that the servos could produce.

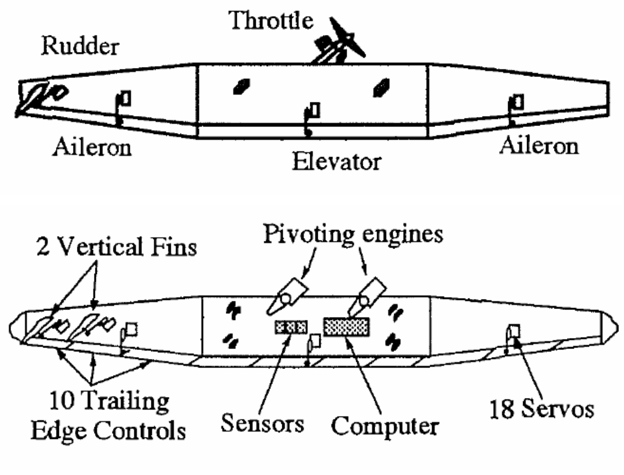

Figure 50. Comparison diagram of Morris' 10 ft OFW model (final fin configuration) with the 20 ft model (not to scale). [76]

Prior to flight, the model was evaluated in a captured "flight" affixed on a universal three-degree of freedom pivot on top of an automobile. The vehicle was driven at the full range of flight speeds, exposing the aircraft to a realistic environment with aerodynamic forces and moments approximately equivalent to those in flight. This testing was used to verify the desired function of the stability augmentation system, control surface authority, and trim settings prior to first flight. Ten series of tests were conducted at Moffett Field/Ames Research Center, providing a thorough investigation of the aircraft's aerodynamic behavior and its stability augmentation system with a variety of control gain settings.

The model was 1.5-1.7% statically unstable in pitch. Initially, it was intended to be 7% unstable (to match the proposed operational vehicle), but during the vehicle testing, the off-the-shelf servos were determined to be too slow to control the vehicle

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[*] Morris, Stephen, correspondence with the authors, December 2005.

adequately. In addition, vehicle testing also showed that the ducted fans created a pitching moment, because their thrust line passed below the aircraft center of gravity. It had been hoped that the resulting induced flow over the control surfaces would increase their effectiveness sufficiently that a small flap deflection would correct this moment. Vehicle tests, however, showed that at full power, the thrust-dependent pitching moment was too great to be trimmed by a flap deflection. As a result, deflecting vanes were placed in the fan efflux, reorienting their thrust through the center of gravity. Once these were installed, the vehicle tests proved that there was no change in pitch trim with throttle changes. The final series of vehicle-mounted "flights" were conducted to verify the stability and trim settings. The controls were set so that the aircraft would have no rolling moment at the lift-off conditions of 10° angle of attack and 35° sweep, in order to minimize the danger of losing the aircraft during take-off.

The 20 ft model performed a single flight in May 1994 at Moffett Field, adjacent to NASA Ames (Figures 51 and 52). During a 23 second take-off roll, the aircraft accelerated to 45 mph and then rotated for lift off. It flew to an altitude of 150 ft and made a left hand turn around the airfield. The model was flown at speeds from 25 to 65 mph (at 35° sweep). During the second circuit, the wing sweep was momentarily increased to 50°. At the end of this pass, the model was landed to ensure it didn't run out of fuel. Total flight time for this flight was only 4 minutes. Budget constraints precluded additional flight testing.

NASA had hoped to follow the supersonic wind tunnel tests and Morris' small OFW tests with a 1/10th-scale supersonic unmanned demonstrator, but sufficient interest and funding did not materialize.[67]

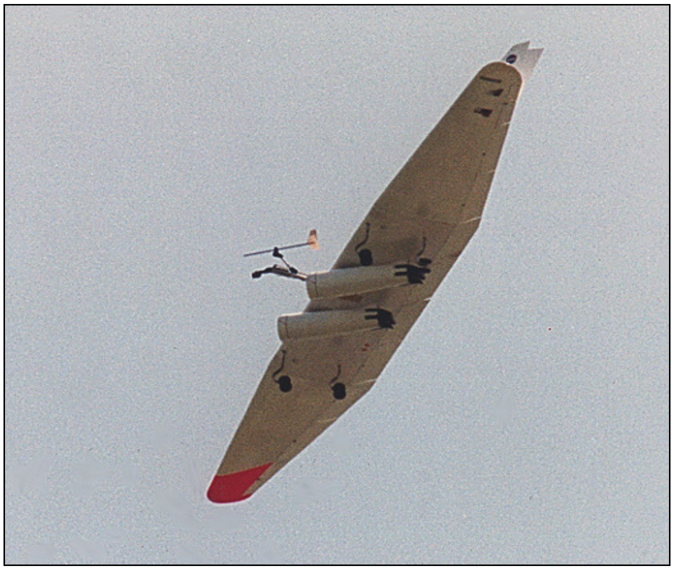

Figure 51. Morris' 20 ft OFW in flight. (Photo courtesy of Steve Morris. Used with permission.)

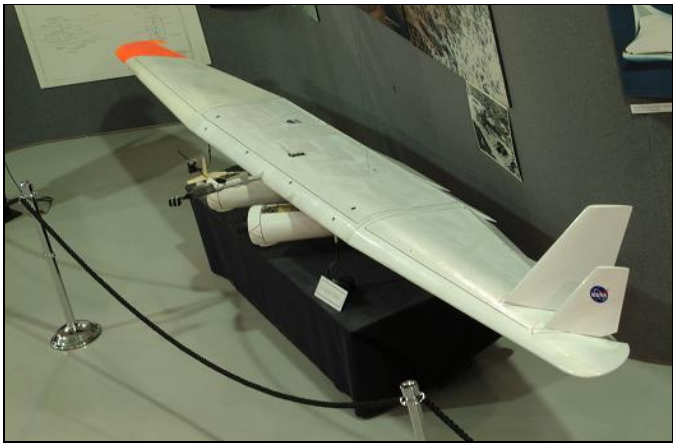

Figure 52. Steve Morris' 20 ft OFW (first flight 1994). It was designed to fly at sweep angles between 35° and 68° and a maximum speed of about 65 mph. (Photo courtesy of the Hiller Aviation Museum. Used with permission.)

XI. Neblett OFW Flight Testing

Evan Neblett graduated with a Bachelor of Science degree from Virginia Polytechnic and State University in 2003. During one of his undergraduate courses, he was exposed to the idea of an oblique flying wing. Following graduation, he built and flew several oblique flying wing gliders, followed by two small radio controlled OFW models. The gliders had an aspect ratio of 8 and a wing span of 10 inches (with a constant 45° sweep). Neblett cut out sections of the trailing edges and deflected them to study the behavior of the gliders in flight.*

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* Neblett, Evan, http://filebox.vt.edu/users/eneblett/OFW and http://www.evanneblett.com, December 2006.

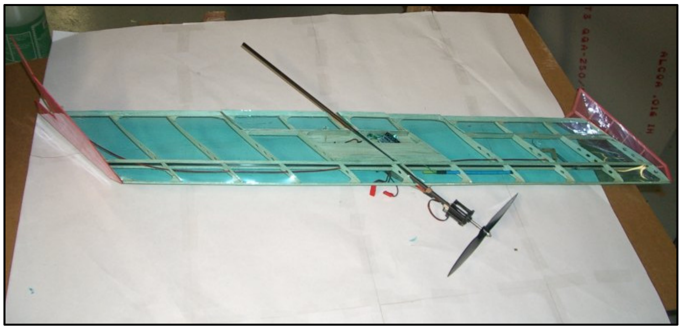

Figure 53. Neblett AV1. First flight was July 2003. (Photo copyright Evan Neblett. Used with permission.)

The first aircraft (shown in Figure 53) was a simple proof of concept demonstrator that he used to see if the second, larger aircraft was feasible. Multiple control surfaces and a stability augmentation system as used on Morris' OFW was beyond the capability of the relatively inexpensive radio equipment that Neblett had available.

The XFOIL program was used to analyze the performance of various airfoil shapes; Neblett selected a reflex airfoil to minimize the pitching moment, since it was a tailless configuration. The model flew at a fixed sweep of 45°, with resultant aspect ratio of 3.6.[*]

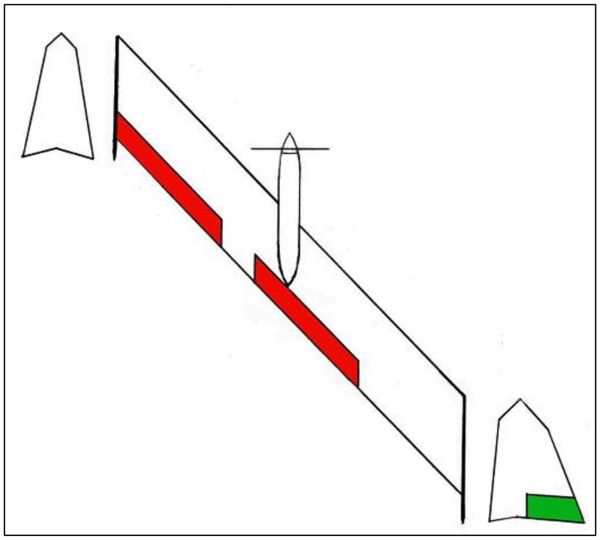

Figure 54. Neblett OFW control architecture, showing elevon, elevator, fins and rudder. (Copyright Evan Neblett. Used with permission.)[*]

Neblett hand-launched the model, which was powered with an electrically-driven propeller. A small fin on the left wing tip extended above and below the wing, and a larger fin on the right wing tip was primarily situated above the wing; this included a rudder for the entire height above the wing. The structure was composed of balsa stringers, with a monokote skin, and a carbon rod wing spar. Another carbon rod was used to support the propeller and extended about 6 inches beyond the rear of the wing to facilitate hand launching.[*]

The aircraft had a wingspan (at the fixed 45° sweep) of 21.2 inches (53.8 cm) and used a Park Flyer Electric 8.4V motor and weighed 6 oz (170 g). Control inputs included motor/propeller speed, an elevon on the left (forward) wing tip, an elevator roughly on the thrust centerline, and a rudder on the right (trailing) fin. The first flight was conducted on July 24, 2003. The propeller did not provide adequate thrust, so a larger propeller was installed, with four successful flights the next day, and several more shortly thereafter. Design, construction and first flight of AV1 were all conducted within three weeks.[*]

Since initial flights were promising, Neblett decided to build a larger and more complicated second aircraft. The second aircraft (AV2) used the same control philosophy, depicted in Figure 54, but was scaled up by a factor of 1.5, was more structurally sound and used a gasoline-powered propeller and a retractable, tricycle landing gear. The structure was composed mainly of balsa wood with some plywood reinforcement; a carbon rod ran the full span of the wing. Wingspan (at 45° sweep) was 33 inches (53.8 cm). The model weighed 28 oz (800 g) and was powered by an ASP .12 ABC engine.[*]

Figure 55. Neblett AV2. First flight was in January 2004. (Copyright Evan Neblett. Used with permission.)

As a result of the flight testing on AV1, two degrees of twist were added to AV2, distributed evenly along the wingspan to help counteract a natural left roll characteristic. First flight was January 23, 2004. Several more flights were conducted on March 14th and subsequently.[*]

Flight tests of AV1 and AV2 proved the design to be controllable in both pitch and roll. Neblett states, "The elevon mixing is standard symmetric

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[*] Neblett, Evan, http://filebox.vt.edu/users/eneblett/OFW and http://www.evanneblett.com, December 2006.

and the aircraft responds equally to left and right inputs. There is some slight roll coupling associated with up and down elevator. I believe this can be eliminated with fine tuning of the elevon mixing."[*]

XII. DARPA OFW Program

In March 2006, the Defense Advanced Research Projects Agency (DARPA) initiated an Oblique Flying Wing (OFW) program. Northrop Grumman was awarded a contract for risk reduction, testing and preliminary design of an OFW X-Plane demonstrator aircraft. The DARPA OFW program is focused on the design issues associated with a tailless, variable sweep, supersonic flying wing, including aerodynamics, aeroelasticity and controllability.[7]

If successful, the current preliminary design effort may be followed by a second phase that would finalize the detailed design, and build and flight test an X-plane.[7]

The X-Plane demonstrator would take off from a runway, be jet powered and achieve a Mach number of 1.2 while demonstrating variable sweep in flight.[7]

Figure 56. Artist's concept of the Northrop OFW X-Plane. (Painting courtesy of Northrop Grumman.)

XIII. Summary

Research into oblique wing aircraft over the past half-century has made significant progress in understanding the aerodynamic and operational benefits of an oblique wing, as well as the technical challenges associated with making the concept practical.

Decades of research on oblique wings and oblique flying wings has indicated that significant advantages may result from the use of such planforms. In addition, it "has provided an extensive database for future oblique wing design and has not uncovered the unexpected problems that many expected." [2]

Through wind tunnel tests, small scale and manned oblique wing flight testing, the basic feasibility of oblique wing aircraft has been repeatedly evaluated. Efforts since the late 1980s – including small-scale supersonic wind tunnel testing – have furthered the belief that a supersonic oblique flying wing is possible. Current efforts are again investigating this concept, nearly 50 years after first proposed by R.T. Jones.

Acknowledgements

This historical summary was greatly assisted by Steve Smith (NASA Ames) and Ilan Kroo (Desktop Aeronautics), who provided a plethora of reference material as well as comments on a draft of this paper. This work was also significantly benefited by the generosity of the following people: Tony Landis (at NASA Dryden), Lynn Albaugh (at NASA Ames), Rod Bailey (at NASA Ames), Ron Smith (NASA Ames, Ret.), Steve Morris (MLB Company) and Willie Turner (Hiller Aviation Museum), as well as Evan Neblett, Thomas Müller, Ken Scott and Gregory Omelchenko. The authors are particularly grateful for the custom artwork of Jens Baganz to illustrate many of the poor quality original graphics.

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