Large Capacity
Oblique All-Wing Transport Aircraft

Thomas L. Galloway
James A. Phillips
Robert A. Kennelly, Jr.
NASA Ames Research Center
Moffett Field, CA

Mr. Mark H. Waters
Thermosciences Institute, ELORET Corp.
Palo Alto, CA

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INTRODUCTION

Dr. R. T. Jones first developed the theory for oblique wing aircraft in 1952, and in subsequent years numerous analytical and experimental projects conducted at NASA Ames and elsewhere have established that the Jones' oblique wing theory is correct. Until the late 1980's all proposed oblique wing configurations were wing/body aircraft with the wing mounted on a pivot. With the emerging requirement for commercial transports with very large payloads, 450 - 800 passengers, Jones proposed a supersonic oblique flying wing in 1988. For such an aircraft all payload, fuel, and systems are carried within the wing, and the wing is designed with a variable sweep to maintain a fixed subsonic normal Mach number. Engines and vertical tails are mounted on pivots supported from the primary structure of the wing. The oblique flying wing transport has come to be known as the Oblique All-Wing transport (OAW).

Initial studies of the OAW were conducted by Van der Velden first at U.C. Berkeley(1) in 1989 and then at Stanford in collaboration with Kroo(2) in 1990. A final document summarizing this work is given in the thesis by Van der Velden(3). Many issues regarding the design were identified in these studies, among them the need for the OAW to be an unstable aircraft.

Also at Stanford, Morris had successfully built and flown a powered model with a 10 foot wing span and a fixed 30 degree wing sweep during this same period. His intent was to study low speed handling of an OAW during taxi, takeoff, low speed maneuvering, and landing. To the extent that this model demonstrated that such a vehicle can fly, the project was successful. But with no instrumentation the results were strictly qualitative. In mid-1990, Morris and Kroo of Stanford along with R. T. Jones proposed to NASA Ames to build an instrumented model with an on-board computer. The wing was to have a wing span of 20 feet and have the capability to vary the wing sweep from 0 to 45 degrees. This proposal was accepted, and it stimulated additional in-house work at NASA Ames to study the total concept of the OAW as a commercial transport, and to design and build a wind tunnel model for test in the Ames 9 by 7-ft Supersonic Wind Tunnel. The decision to proceed with the OAW project led to the following in-house and industry activities over the period from early 1991 to the end of 1994.

	Completed
Systems Analysis Study at NASA Ames	7/91
Conceptual Design by Frank Neumann of Boeing	12/91
AIAA Papers — Structures/Aero & Economics by NASA Ames(4)(5)	8/92
Configuration & Airport Interface Study by Boeing(6)	6/93
Design study by the University of Kansas	6/93
Wind Tunnel Test Design Team established at NASA Ames	7/93
Aerodynamics & Stability-Control by McDonnell-Douglas(7)	10/93
20' Model Ground & Flight Test by Stanford University(8)	5/94
Supersonic Wind Tunnel Test at NASA Ames	8/94
Mission Analysis Study by McDonnell-Douglas(9)	12/94

This presentation gives the highlights of the total project. The references listed at the end of this Introduction are all the documents that have resulted from the project. The remaining document to be completed and undoubtedly the most important is the report of the wind tunnel test which will not only present test results but demonstrate the agreement that was obtained between CFD studies and the test data.

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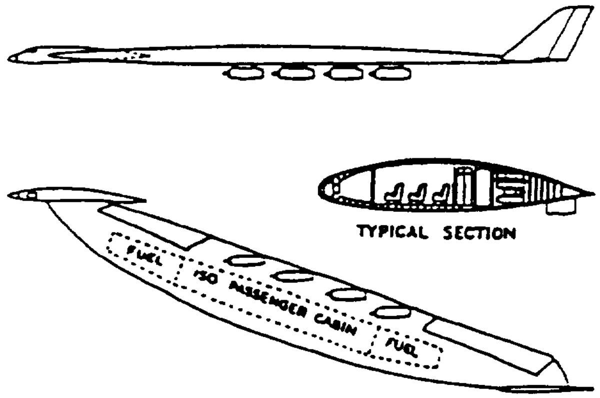
Figure 1 Recent Oblique All-Wing Transport Activities

The concept of an oblique all wing aircraft was first proposed by Lee(10) in the early 1960's, but subsequent research on oblique wing aircraft up to the mid 1980's concerned oblique wing/body aircraft with the oblique wing pivoted from a conventional fuselage. The 3-view sketch below shows the concept proposed by Lee.

With the emerging requirement in the mid-1980's for commercial transports with very large payloads, 450 - 800 passengers, Dr. R. T. Jones proposed an oblique flying wing. His work was carried on at Stanford University in 1988 - 1990 with grants from NASA Ames. In 1991, NASA Ames became directly involved. The Ames work included in-house studies in collaboration with Stanford, funded studies at both the Boeing Commercial Airplane Company and the McDonnell-Douglas Corporation, a contract with Stanford to build and fly a radio controlled 20 foot model, the design, construction, and supersonic wind tunnel test of a 7.5 foot span fully instrumented model, and finally a second contract with McDonnell-Douglas. The work at the University of Kansas was done independently as part of a grant from the NASA Advanced Design Program(11).



Oblique All Wing Concept
(Circa 1961)

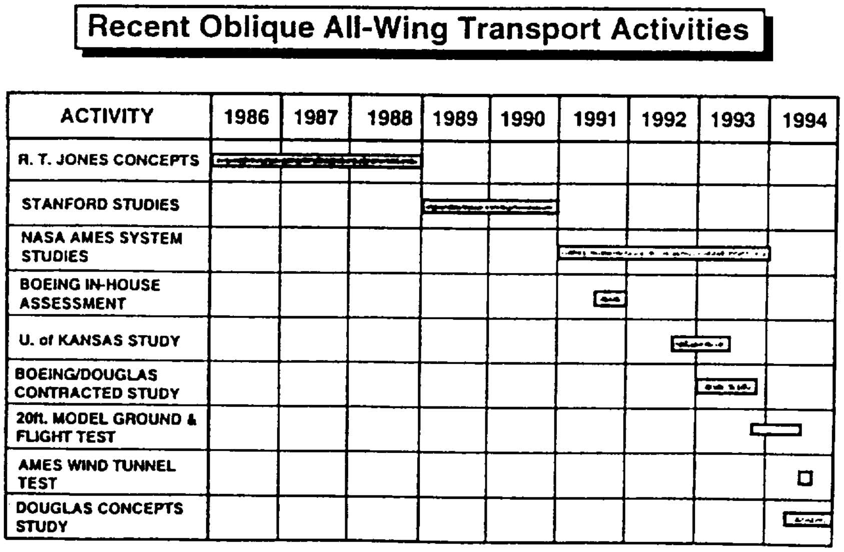


Figure 2 Original Stanford Configuration

The 3-view given below is the final arrangement for the OAW that evolved from the studies at Stanford completed in 1990. This work established the general arrangement for the OAW with the cabin in the center section toward the leading edge of the wing, the fuel tanks outboard of the cabin in both wings, four pivoting engines mounted on the front spar of the wing, multiple strut landing gear with approximately an equal distribution of weight between the forward and aft gear, and multiple vertical fins mounted on top of both the leading and trailing wings. This design shown in the figure below is for a cruise Mach number of 2.0, and with a design Mach number of 0.68 normal to the wing, a wing sweep of 70.1° is required. The unswept span of the wing is approximately 425 feet. The aircraft is designed to takeoff at a sweep angle of 35 - 40°. The passenger cabin has a lobed structure to take the pressure loads, and the seats are arranged so that the passengers face the leading wing tip.

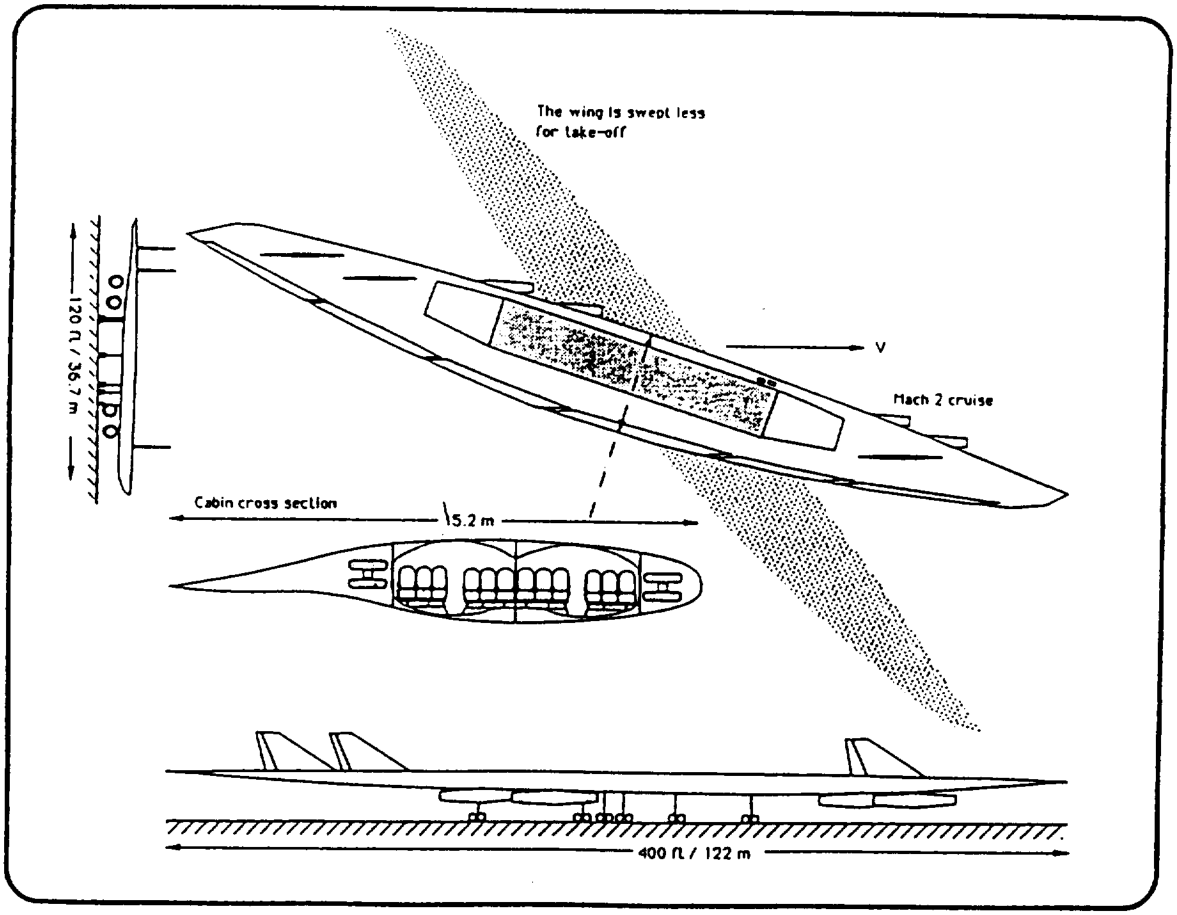
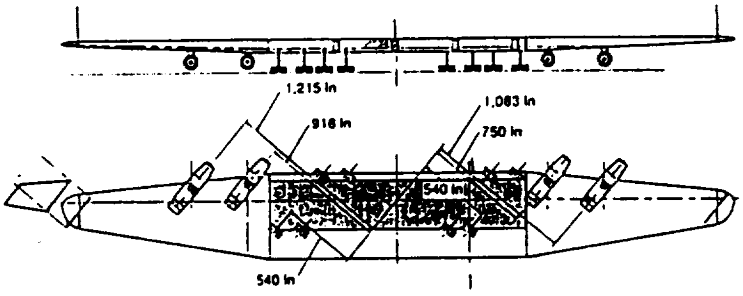


Figure 3 NASA Ames Configuration — 8/92

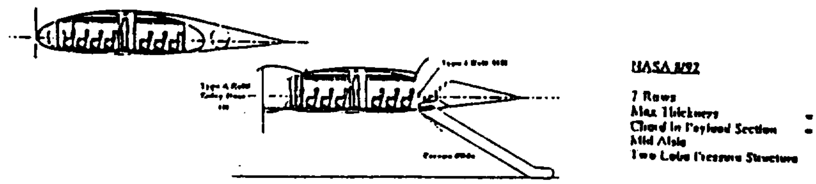
The in-house studies at NASA Ames which began in early 1991 resulted in the configuration shown below. This work was reported in an AIAA paper in August, 1992. The general arrangement established by Stanford was preserved, but with more attention to details such as ingress and egress, landing gear design and stowage, cockpit design, etc. The major change is that the seats are oriented to face the passengers toward the wing leading edge. This requires multiple bays for seating with a center main aisle and cross aisles into each bay. Two large galleys are shown in the aft cabin, and the cockpit is arranged in the center of the cabin and oriented for a takeoff sweep angle of 37.5°.

Main and emergency doors are designed to meet FAA requirements. There are four main doors which have to be at least 72 inches high, and there is an emergency exit at the rear of each cabin bay. These doors are 48 inches high. The leading edge has a clam-shell design for primary door access and egress, and at the rear of the cabin the emergency slide chutes are accessed through the bottom of the wing, and there are stairs, as shown, up to the top of the wing.

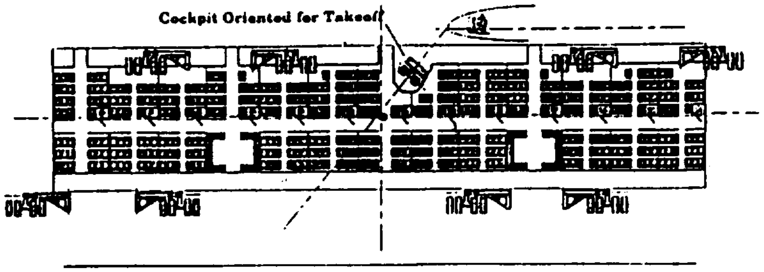
There are eight landing gear struts with four wheels on a single axle for each truck. The design was based on pavement loading criteria, and the intent of the single axle design is to simplify the stowage problem. Even with this design, the gear do not fit in the wing leading edge ahead of the front wing spar. This is a serious design flaw.



OAW CONFIGURATION -- SECTION


NASA 8/92

7 Rows
Max Thickness = 98.6 inches
Chord in Payload Section = 616 inches
Mid Aisle
Two Lobe Pressure Structure



Cockpit Concept for the OAW Aircraft

Figure 4 Boeing Configuration — 5/93
General Arrangement — OAW Configuration No. 2

The major focus of the Boeing study was to address the design from a configurator's point of view — a standard starting point for the design of a new commercial transport. The result was that the project moved from a discussion of a concept to the definition of a preliminary design which addressed most design integration, operational, and safety/regulatory issues. This was a crucial step which should have been taken earlier in the project. As a lesson learned, any innovation that must stand up to this mixture of issues should strive to establish a point design early in the project and include as much detail as possible.

A good example is the seating arrangement. There is a current FAA requirement (FAR Part 25.785) that passengers be oriented to within 18° of the direction of flight for takeoff and landing unless an energy absorbing rest or a safety harness is used to support the head. Having cabin bays angled to wing leading edge was considered, but Boeing finally decided to have the OAW aircraft takeoff straight. This meant that no yaw control was possible with the vertical fins. Instead split drag rudders provide yaw control as is done on the B-2 bomber. The drag rudders are part of the elevons in wing center section (the two panels just in-board of the wing fold).

The OAW aircraft may have too much span for a straight takeoff, Boeing shows the design with folded wing tips. The concern is violating the "obstacle free zone" (OFZ) requirements between runways and taxiways. Boeing also assumes the aircraft will taxi with zero sweep whereas previous work at NASA Ames assumes the aircraft will taxi end-on. Even with folding wing tips, there may a violation of the OFZ. Needless to say, folded wing tips is a major design consideration, and there is much difference of opinion on this subject. (continued next page)

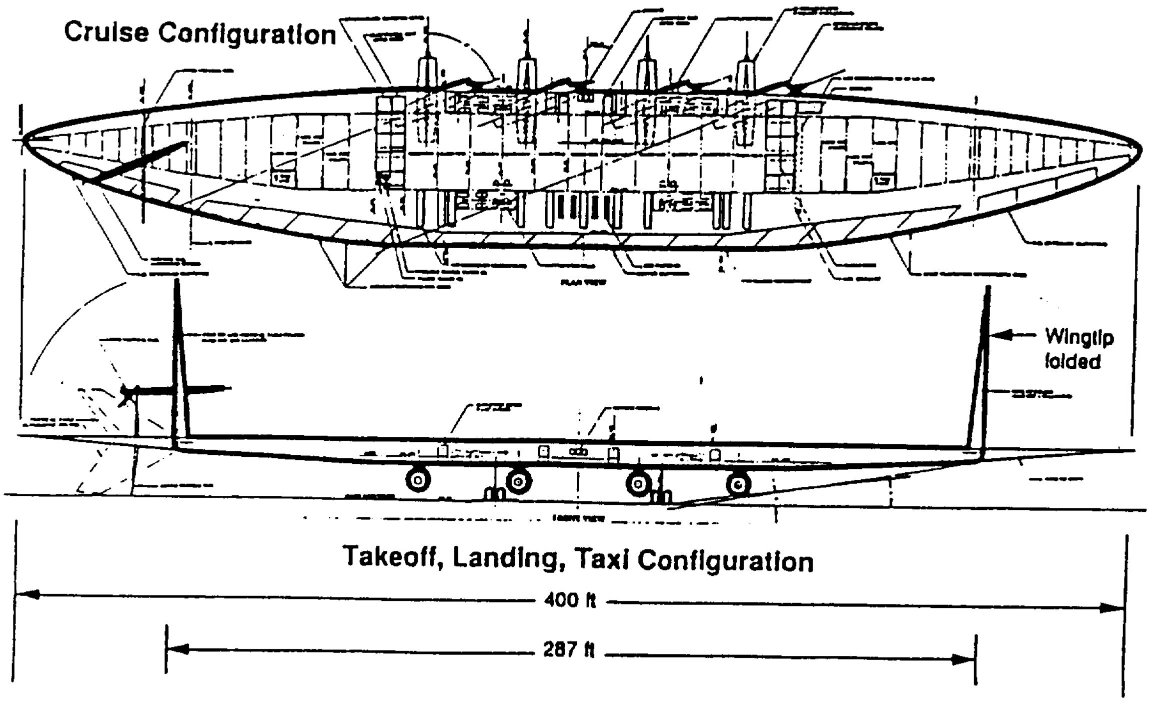


Figure 4 Boeing Configuration — 5/93
General Arrangement — OAW Configuration No. 2
(cont.)

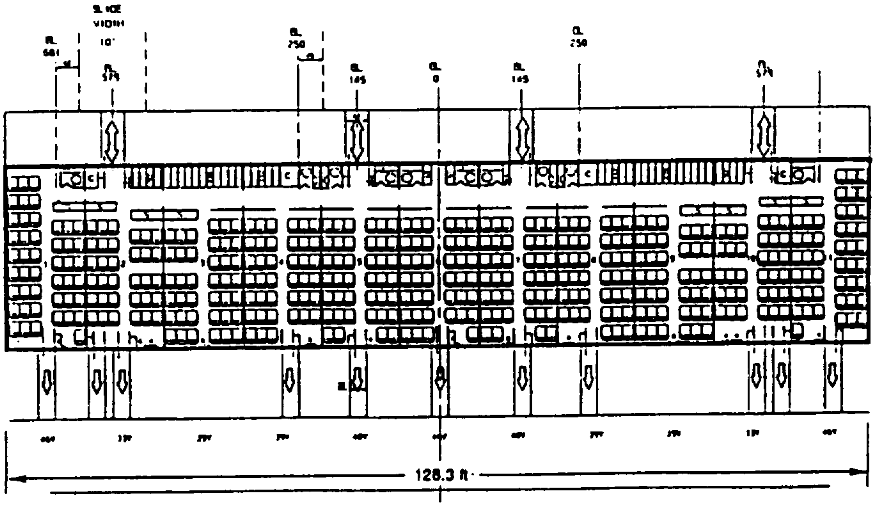
Also, note that the engines are located in-board in the region of the cabin. The previous NASA and Stanford designs placed them outboard away from the cabin. However, Boeing felt there is more of a safety concern if engines are located near fuel tanks. In addition, it was discovered at NASA Ames that with the engines outboard the yawing moment with one engine inoperative was excessive, and it is questionable if a reasonable drag rudder system could be designed. Thus, the design shown below. The integration of the engine pivots and the landing gear into the leading edge proved to be a difficult design integration problem. To highlight this fact, the airplane designed as shown must takeoff with zero sweep because otherwise there is an interference problem between engines and landing gear.

Figure 5 Boeing Configuration — 5/93
Passenger Seating & Ingress / Egress— OAW Configuration No. 2

More definition of the passenger seating and ingress / egress arrangement is given in the drawings below. The base design is for 434 passengers in an all tourist seating configuration. Four main boarding doors are located in the wing leading edge which opens in a clam shell design. The main aisle, which runs almost the length of the cabin span, is located in front of the cabin bays, and the services and lavatories are between this aisle and the front wing spar. Emergency exits are located at the rear of the cabin bays. In two bays there are no exits because of the location of the landing gear stowage bays. For each of these bays, there is a cross aisle into the adjacent bay as shown in the drawing.

The emergency slide chutes are shown from the leading edge and from the top of the wing trailing edge. This is a departure from the NASA design which located the rear slide chutes below the wing. An above wing location is preferred for emergency ditching on water. There is a ramp at a 15° angle to get to the top of the wing at the rear, and there is some concern that this angle is too steep to meet handicapped access requirements.

Passenger Seating in 11 Cabins



434 passengers—all tourist

Passenger Cabin, Boarding Doors, Emergency Egress

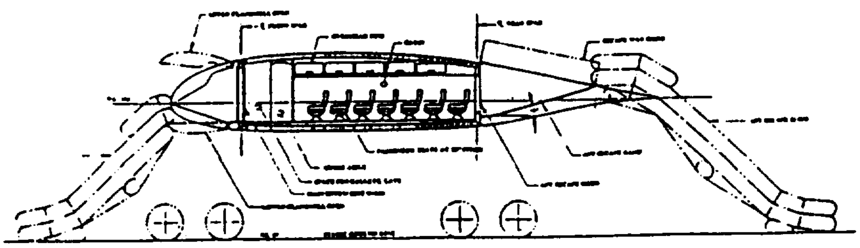


Figure 6 Boeing Configuration — 5/93
Landing Gear— OAW Configuration No. 2

A great deal of attention was given by Boeing to the landing gear design. It was determined that four gear posts with four wheels each using 54" diameter tires can support airplane gross weights up to 1 million pounds without exceeding permissible pavement loading criteria. The load distribution is approximately 55% on the forward gear and 45% on the aft gear, so smaller diameter tires are possible on the aft gear. However, it is likely that all the gear would be identical for commonalty. Boeing evaluated the single axle four wheel gear proposed by NASA Ames and found it was not viable because of the requirement for a "knee joint." The gear design shown below is more conventional in that it has two axles per truck with two wheels per axle. However, there are several unique features in the design. For example, the gear are steerable up ± 20° to provide the capability for ground maneuvering and cross wind landings. Also, the centerline of the truck is 22.5 inches forward of the oleo strut to allow the truck beam to be rotated into a vertical position for stowing. Being able to stow the forward gear into as small a chordwise space as possible (keeping it ahead of the forward spar) is critical to thickness requirements of the wing.

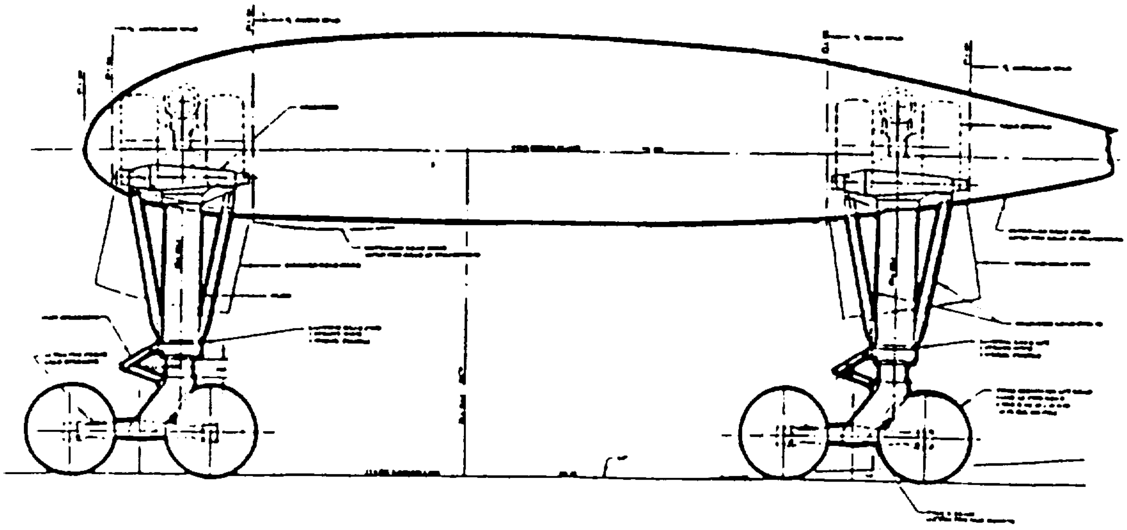


Figure 7 Boeing Configuration — 5/93
Engine Installation— OAW Configuration No. 2

The engine installation is shown in the lower drawing. Work on the engine cycle and inlet design was a collaboration between Boeing and NASA Ames. In the course of the work it was found that the original engine/inlet design, which used a mixed-flow turbofan engine with a design point bypass ratio of 1.5 and a normal shock inlet, was over penalizing in terms of engine size and inlet losses. As can be seen from the drawing, the engine diameter dictates the length of the landing gear. The final design shown below is a mixed flow turbofan having a design point bypass ratio of 0.6, and the inlet is an external compression conical inlet with a fixed 16° cone. The pivoting strut that supports the nacelle is cylindrical with actuators mounted from the front spar. A fairing over the full length of the nacelle encloses the pivot. In later aerodynamic work at NASA Ames, it was found that these fairings create excessive drag, and an alternative design by Boeing uses a rectangular support mounted as a piano hinge from the front spar.

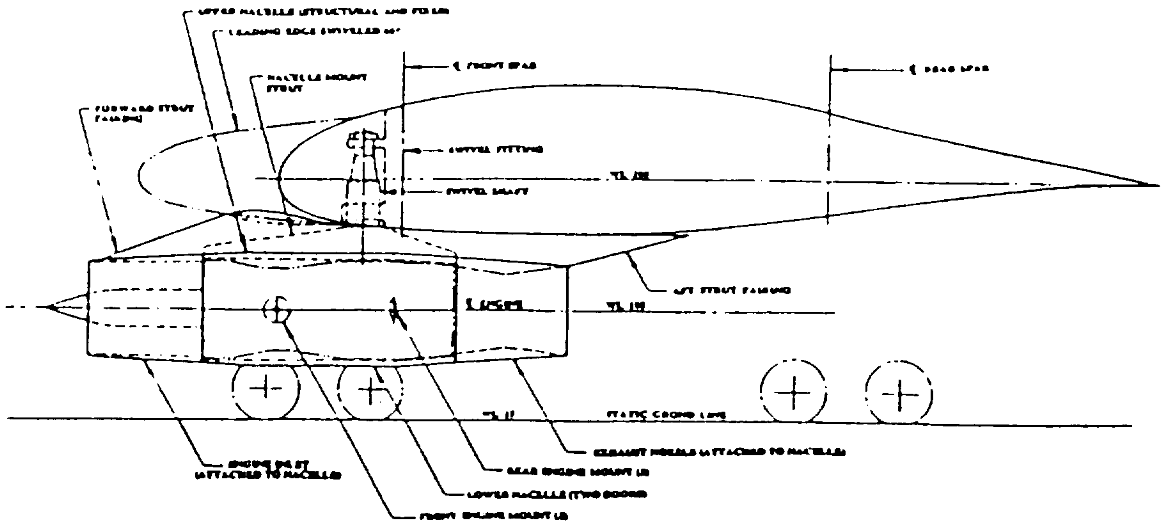


Figure 8 Economic Potential for the Oblique All-Wing Transport

To estimate the economic viability of commercial transports, NASA Ames has developed a model that addresses the return on investment (ROI) for both the airplane manufacturer and the airline. For the OAW analysis it was assumed that both achieve an ROI of 12% and that this return is achieved with a 500 unit production. Although the airplane is designed for a range of 5000 N.Mi. with full payload, a mean trip is defined to compute the economics of the airline. In this case, the range is assumed to be 3800 N.Mi. with a 65% passenger load factor. In addition, it is assumed that the aircraft is utilized for 5000 hours per year over a 15 year period.

The price of the aircraft necessary for the manufacturer to achieve a 12% ROI is determined, and using this price the passenger revenue required for the airline to achieve a 12% ROI is computed. In the chart below, the OAW is compared with an advanced subsonic transport. The values of 9 - 10 cents/revenue passenger mile for the advanced subsonic transport is consistent with average yields reported by the airline industry. For the OAW, the advantage for increased size is obvious. At a design payload of 300 passengers, the required yield for the OAW is approximately 30% greater than the advanced subsonic. At the design point of 434 passengers, the increment is a 14% increase, and at the largest design payloads considered in this study (550 passengers) the increment is approximately 9%. These values are computed assuming manufacturing complexity factors of 2.0 for the wing, vertical tail, and nacelles. The use of these complexity factors represent a large unknown for the use of advanced materials for any airplane design in the future. If the complexity factors are reduced to 1.0, the required revenue increment drops from 14% to approximately 10% at the 434 passenger design point (open square symbol on the figure below).

A large issue not included in this study is the demand elasticity — would there be a shift in appeal to the supersonic aircraft such that the average load factors for the supersonic airplane would exceed that for the subsonic airplane so that the required yield would be nominally the same. The assessment of the results given below gave rise to much optimism for the potential of a large passenger capacity supersonic OAW airplane at the time of this study in August, 1992.

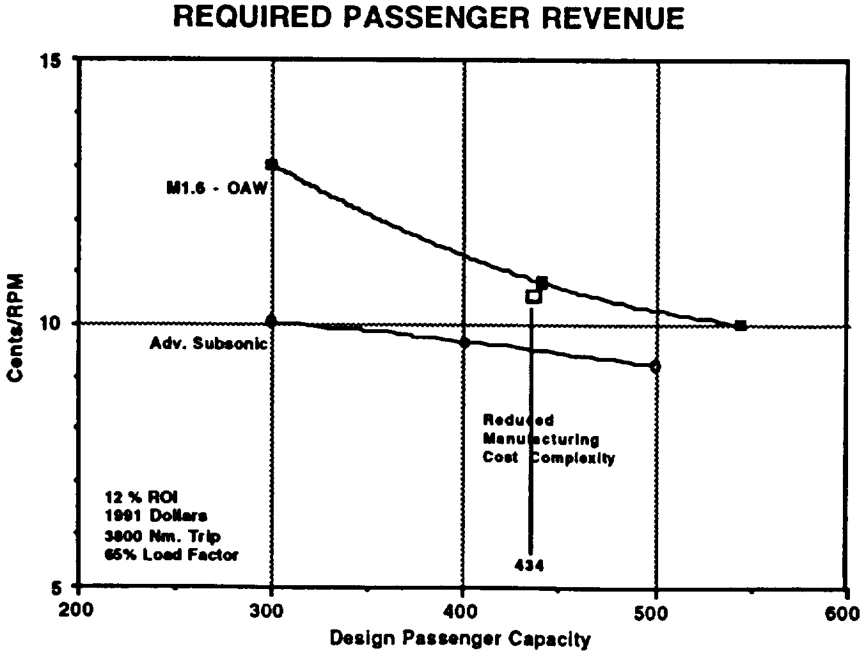


Figure 9 OAW Airfoil Geometric Requirements

An airfoil shape and section dimensions had been defined in the NASA Ames studies, but it became clear in the Boeing study that these dimensions were unrealistically low. The airfoil given in the sketch below is not a shape defined by aerodynamic analyses. Instead, it is a sketch that serves to define geometric control points defined by Boeing. These control points were used by NASA Ames and McDonnell Douglas in all of their subsequent aerodynamic CFD studies and in the design of the wind tunnel model. The definitions for the control points are summarized as follows:

Space to stow the forward landing gear	
• Distance from the leading edge to the forward spar	80"
• Wing thickness (outside dimension) at the front of the forward spar	92"
Location of the front edge of the pressurized cabin (inside of the cabin)	
• Distance from the leading edge to the front edge of the cabin	95"
• Wing thickness (outside dimension) at the front edge of the cabin	96"
Location of the rear edge of the pressurized cabin (outside of the cabin)	
• Distance from the leading edge to the aft edge of the cabin	420"
• Wing thickness (outside dimension) at the aft edge of the cabin	87"
Location of the rear edge of the aft landing gear bay (outside the bay)	
• Distance from the leading edge to the aft edge of the bay	499"
• Wing thickness (outside dimension) at the aft edge of the bay	59"

AIRFOIL WITH DESIRABLE FEATURES

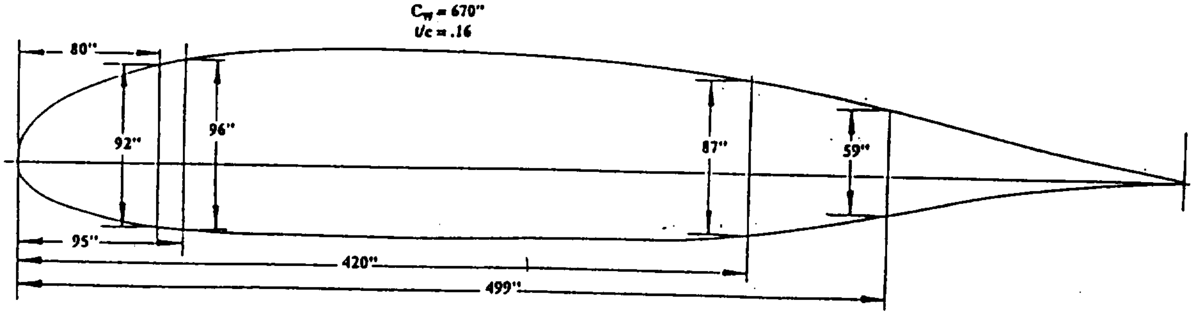


Figure 10 OAW Airfoil CFD Studies

The figures below hardly do justice to the large body of work conducted at both NASA Ames and McDonnell-Douglas on CFD analyses of the wing. The report prepared by Cheung[12] is an excellent summary of the analytical studies conducted at NASA Ames which led up to the final design for the wind tunnel model.

In the work at NASA Ames and McDonnell-Douglas it was found that viscous effects were very important, and Euler codes were not sufficient for an acceptable design. McDonnell-Douglas compared results on a baseline wing using four different Navier-Stokes codes all using a common grid and the same turbulence model, and the closeness of the results were "surprisingly excellent" as stated by the MDA author. Shown below are particle traces in the boundary layer flow for an interim NASA Ames design but computed at McDonnell-Douglas. The figure on the left represents the planned wind tunnel Reynolds number of 5.7 million, and the one on the right is representative of the Reynolds number in flight — 200 million. The Reynolds number (Re_c) is based on the wing centerline chord normal to the wing leading edge. It is apparent that the flow is highly three dimensional at the low Re_c, and a shock wave has formed near the trailing wing tip. In contrast, no separation is apparent at the flight Re_c.

McDonnell Douglas also conducted CFD analyses using inverse methods where the airfoil section shape is perturbed locally to achieve a desired pressure distribution. These results are promising in that they were able to improve aerodynamic smoothness.

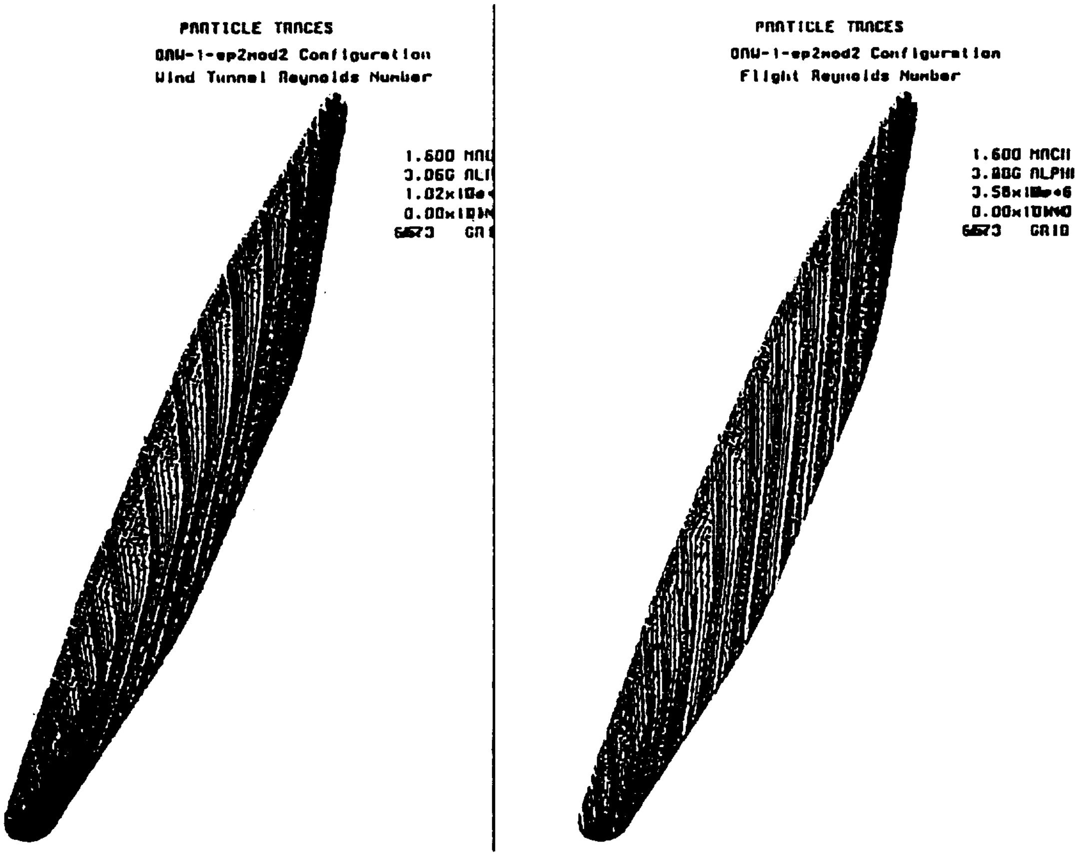


Figure 11 OAW Idealized Cruise Lift-Drag

At the outset of the OAW work at Stanford and in the initial studies at NASA Ames, there was much optimism in the aerodynamic cruise performance of the OAW transport. The figure below is taken from a contractor study done by Stanford for the NASA, and as can be seen the OAW was predicted to have excellent lift-drag ratio (L/D) over the complete flight regime. At a flight Mach number of 2, the value of the L/D for the OAW is comparable to that for a double-delta supersonic transport. From this figure, the estimate for the L/D at a flight Mach number of 1.6 is approximately 13. The Mach number normal to the wing leading edge was chosen to be 0.68, and thus the required wing sweep is about 65° at this condition.

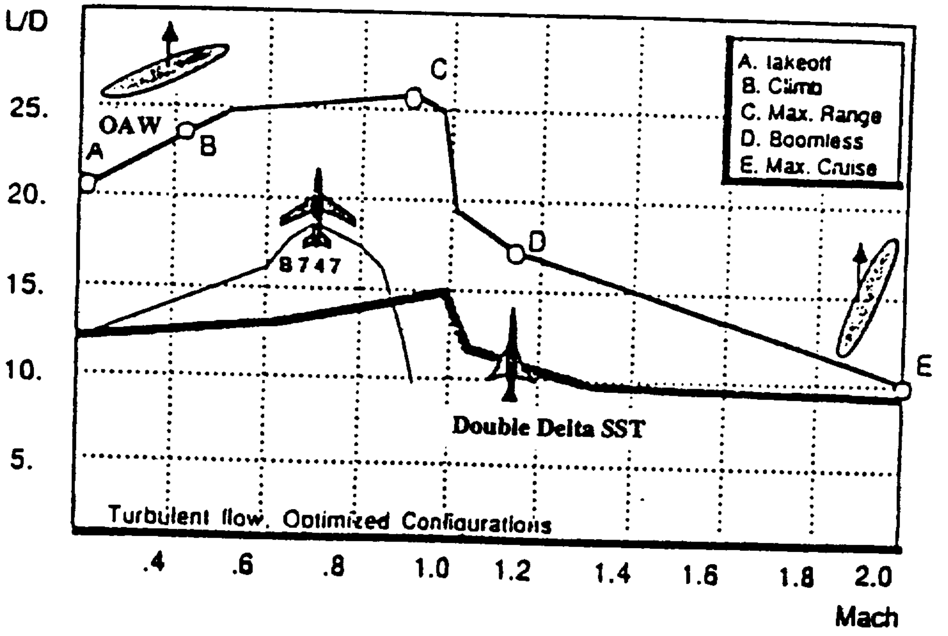
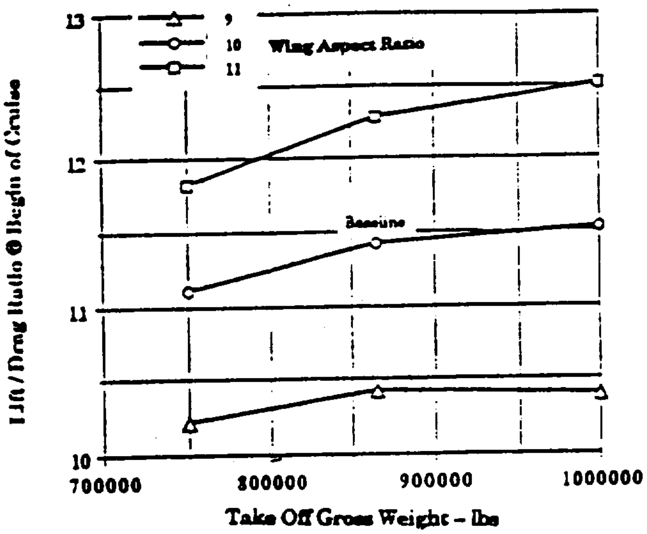


Figure 12 OAW Cruise Lift-Drag Evolution @ NASA Ames

The NASA Ames parametric results from the AIAA paper presented in August, 1992 are given in the figure below. The effect of airplane size (Reynolds number effects) and wing aspect ratio on L/D are shown, and the baseline design has an L/D of 11.46. The buildup of drag in the first column of the table is for this baseline. There are several factors that can help explain the reduction in L/D from that of the Stanford studies. These include an increase in the thickness ratio of the wing section, and more careful bookkeeping of the vertical tail and nacelle drag.

The second two columns in the table give the estimated drag buildup by NASA Ames at the conclusion of the Boeing study in May, 1993. At this time much more information was known about the size of the wing, and CFD work at Ames had identified nacelle and pylon profile drag as significant drag factors. Also, estimates of trim drag on the vertical fins had been computed. The net result is a L/D slightly greater than 10 at the Mach 1.6 cruise point. Estimates based on the wind tunnel tests have yet to be determined.



OAW Transport Aircraft Aerodynamic Drag Buildup

	NASA 8/92		NASA 5/93 (fix gross wgt)		NASA 5/93 (fix CL)	
Wing Area	16542 ft2		17261 ft2		17261 ft2	
Cruise Mach	1.6		1.6		1.6	
Cruise Altitude	52000 ft		52000 ft		52000 ft	
Dynamic Pressure	396.7 psf		396.7 psf		396.6 psf	
Weight @ begin Cruise	821750 lb		821750 lb		865000 lb	
Lift Coefficient	.12522		.1200		.12522	
Wing Drag	.00990		.01054		.01086	
Parasite		.00351		.003990		.003990
Volume Wave		.00215		.002420		.002420
Induced		.00361		.003500		.003671
Wave due to Lift		.00061		.000610		.000749
Compressibility		.00002		.000020		.000020
Vertical Tail Drag	.00021		.00045		.00045	
Parasite		.000175		.000138		.000138
Wave		.000035		.000028		.000028
Trim		.0		.000284		.000284
Nacelle Drag	.00080		.00094		.00096	
Nacelle Parasite		.00056		.000328		.000337
Nacelle Cowl Wave		.00007		.000164		.000169
Nacelle Boattail Wave		.00010		.000189		.000194
Nacelle Lip Bluntness		.0		.000015		.000015
Nacelle Base		.00001		.000044		.000044
Pylon Parasite		.00005		.000080		.000082
Pylon Wave		.00001		.000020		.000021
Nacelle-Wing Interference		.0		.000100		.000100
Surface Gaps (Wing & Tail)	.00002		.000030		.00003	
Total Drag @ Begin Cruise	.01093		.01194		.01230	
Lift / Drag @ Begin Cruise	11.46		10.05		10.18	

Figure 13 Idealized Bending Loads for a Span-Loaded Aircraft

The sketch below defines simply the potential advantage for any span loaded airplane in flight. With a conventional airplane, much of the gross weight is concentrated in the fuselage and combined with the lift on the wing large bending moments result at the wing root. In an idealized spanloader, weight is distributed over the wing span thus reducing the maximum bending moment considerably.

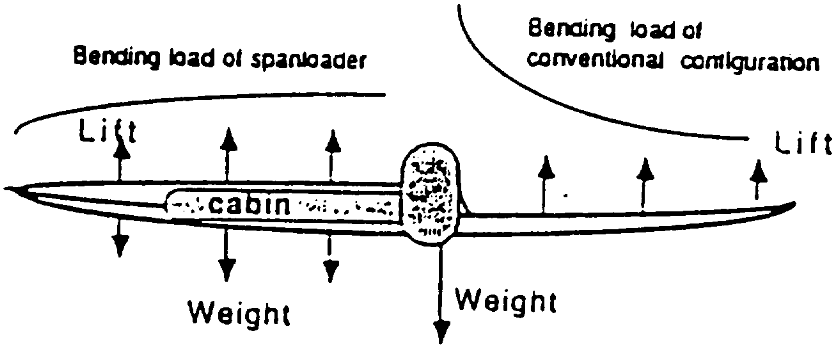
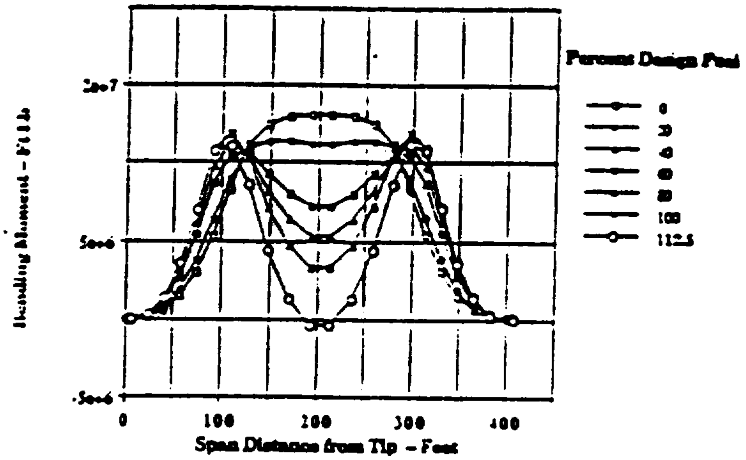


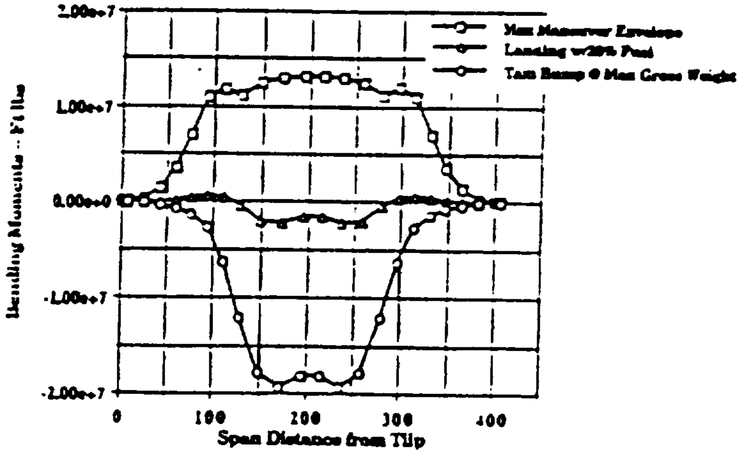
Figure 14 OAW Bending Loads & Wing Unit Weight

In the NASA Ames design of August, 1992, the outer edge of the fuel tanks were approximately 100 feet from the wing tip, and as can be seen from the set of curves on the left, there is an interesting family of bending moment curves with the aircraft in flight depending on the amount of fuel on board. The envelope for these data are given in the upper portion of the curves on the right, and indeed the bending moment distribution is nominally that of a span loader.

On the ground a different situation arises. Conventional transport aircraft with conventional landing gear are designed for a taxi bump with a design load factor of 2.0 (i.e., the weight acts with two times the acceleration of gravity). A study at NASA Ames concluded that the use of a double acting oleo (like that used on the C5 military transport) operating on standard commercial runways could reduce the required taxi bump design load factor to 1.24. Using that factor and a gear track of 90 feet, the bending moment distribution shown in the lower portion of the curve on the left was computed. As shown, the bending moment distribution for the taxi bump is more severe than for the flight loads. This is reflected in the estimate for wing unit weight (structural weight / wing surface area) which is shown on the following page. (continued next page)



Maneuver Bending Moments for
Different Fuel Loads

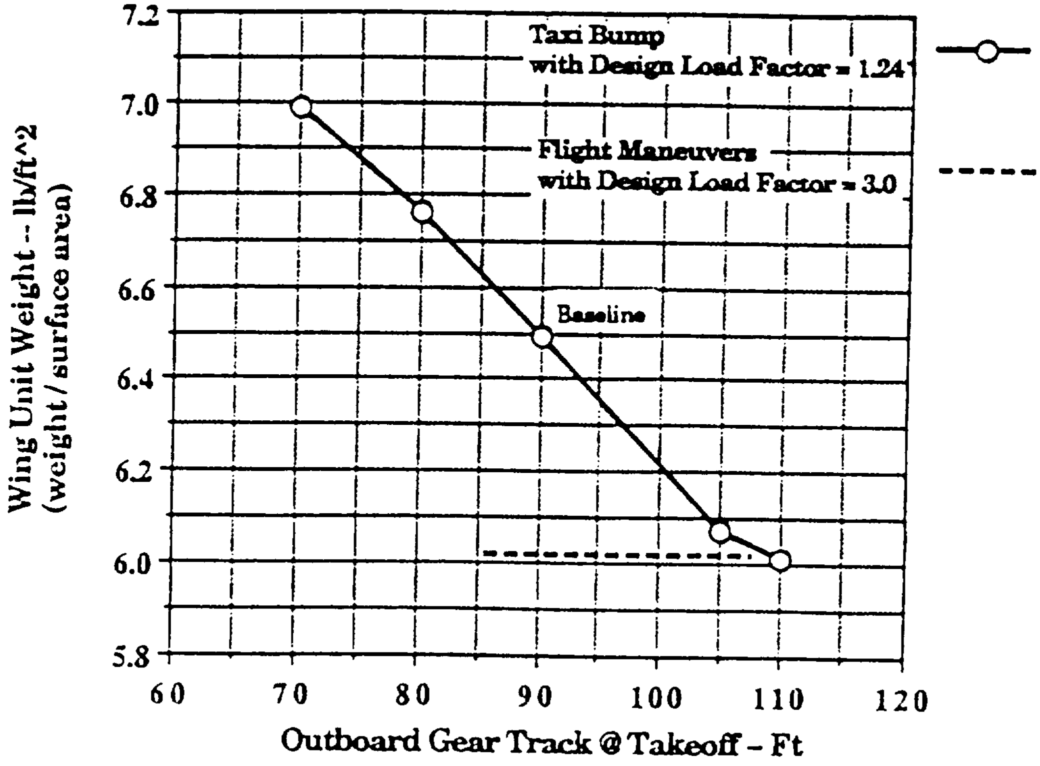


Bending Moments for
Maneuvers, Landing, and Taxi Bump

OAW Aircraft Bending Moments

Figure 14 OAW Bending Loads & Wing Unit Weight (cont.)

The bending loads due to a taxi bump are unquestionably a major concern for the OAW transport. The load factor may have to increased above the estimate of 1.24. Increasing the track of the landing is an obvious solution to the problem, but there are limits due to width of existing runways which vary from 150 to 200 feet at major airports. Airlines desire 50 feet from the landing gear to the edge of the runway which would allow a track of 100 feet for a runway width of 200 feet. The Boeing design did not consider this problem, and the gear track in their design is 58.3 feet. This can be increased to approximately 80 feet if the gear are designed to swing toward the centerline when stowed rather that away from the aircraft centerline as was done by Boeing. However, it is not clear if other design factors would preclude such a change.



OAW Aircraft Wing Unit Weight with Landing Gear Track

Figure 15 OAW Stability and Control Issues

The concern for stability and control issues was the original impetus for Stanford to propose the OAW project to NASA Ames, and this subject was a major part of the first contract with McDonnell Douglas. This is a difficult subject to resolve with just an analysis, but it is safe to say enough has been learned to pose intelligent questions and propose a plan for continued work in this area. The following text is a summary of the assessment given by McDonnell Douglas in their final report.

OAW Airplane Controls

Pitch Control	Midspan and inboard elevons (pitch about the long axis)
Roll Control	Outboard Elevons
Yaw Control	Vertical Fins for High Speed Split Drag Rudders for Low Speed (takeoff with zero sweep) (Drag rudders are outboard flaps on both wings which operate functionally as a rudder)

General Positive Statements

- A stable and controllable OAW is feasible. However, aeroelastics have not been addressed, and this could present high speed problems.
- Wingtip folding appears quite controllable
- The low wing loading and attendant lack of high lift devices means that the controls are not forced to cope with severely non-linear aerodynamics.
- The static instability (-7% MAC) produces a high trimmed lift-curve slope which keeps the approach angle of attack the same as that for conventional transports and provides a CLmax way beyond that required to meet the approach speed targets. Thus, stall problems are minimized.

(continued next page)

Figure 15 OAW Stability and Control Issues (cont.)

Areas of Concern or Unknown

- Aeroelastic effects may have a significant impact on cruise trim and maneuvering, especially in roll. Further, flexibility in general may produce structural mode coupling or ride quality problems
- Gust Sensitivity & Center of Rotation effects: The low wing loading and short pitch coupling of the OAW may yield poor flying and ride qualities in turbulence. In addition, cockpit placement at the wing leading edge will result in a relatively short distance from the pilot to the center of rotation which is not desirable.
- Fin Placement: Current design places the upper fin on the trailing wing in a region of extreme streamline curvature which is undesirable because the fin must rotate. In addition, the boundary layer is very thick at this location and flow separation may occur. Alternative fin locations including multiple fins on the upper surface need to be explored. For close coupled multiple fins, interference is a potential problem..
- Drag Rudder Performance: These devices often suffer from linearity and reversal problems. Wind tunnel tests are required.
- Alternate C.G. location: The current design (32% MAC) does not heavily tax the pitch controls. The effect of further aft C.G. on the airfoil design and cabin packaging may prove to be beneficial to L/D.
- Post Stall Tumbling: The OAW appears to have a solid margin between the required minimum stall speed and aerodynamic stall. However, if technology advances allow an increase in the wing loading, this will become a major issue.

Figure 16 OAW Transport Potential for Sideline Noise @ Takeoff

In the original NASA studies, the engine cycle was a mixed flow turbofan with a design point bypass ratio at sea level of 1.5. The engine was sized for cruise at Mach = 1.6, and because of the engine lapse rate, the engines were greatly oversized for takeoff. As a result the required takeoff distance could easily be achieved with the engines at part power, and the takeoff noise was very low. The estimate was made that potential Stage IV goals could be made with any of the possible airplane configurations — straight wing unfolded, straight wing folded, or swept wing (40° sweep). In all cases, the engines could have conventional convergent-divergent nozzles without noise suppressers of any kind.

As the study evolved, it became obvious that a large nacelle diameter had a strong negative effect on the design both in terms of drag and the required length of the landing gear. The engine cycle for the final design is a mixed flow turbofan with a design point bypass ratio at sea level of 0.6. As can be seen in the table below, the best that can achieved with this engine cycle is current Stage III noise levels, and not even that if the wing is swept 35° to 40° at takeoff. If the bypass ratio is 0.8, the noise performance is improved, but again only Stage III levels are achieved. All of these estimates are with engines having conventional convergent-divergent nozzles without noise suppressers, so even with the bypass ratio 0.6 engines the noise performance is considered to be very good.

OAW Transport Aircraft Potential for Sideline Noise @ Takeoff

Engine	Straight Wing Unfolded	Straight Wing Folded	Swept Wing (40 degrees)
SLS Bypass Ratio = 0.6	Stage III	Stage III w/PLR	No Can Do
SLS Bypass Ratio = 0.8	Stage III	Stage III w/PLR maybe w/o PLR	No Can Do
SLS Bypass Ratio = 1.5	Stage IV	Stage IV	maybe Stage IV w/PLR

Stage III	Sideline Noise @ Takeoff --	102.5 EPNdB. Measuring point 21323 feet from brake release
Stage IV	Sideline Noise @ Takeoff --	Stage III - 4 or 5 EPNdB
PLR	Programmed Lapse Rate	Throttle reduction during gear retraction -- begin @ 35 ft altitude

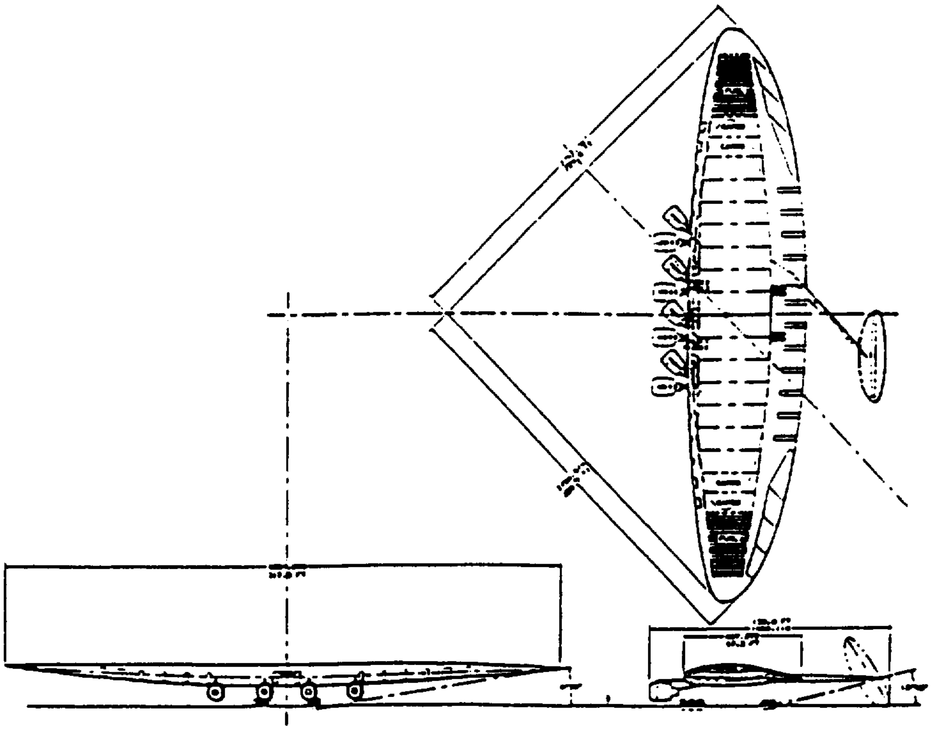
Figure 17 The OAW as a Subsonic Transport

In their second study[9], McDonnell-Douglas developed a generalized computer model for the OAW aircraft, and evaluated two flight Mach numbers — 0.85 and 1.3. They found that the economics of the OAW drove them to airplane designs with large payloads. For the detailed design study, a payload of 800 passengers was selected for both vehicles.

The Mach 0.85 transport pictured below is designed for a range of 7000 N.Mi. The general arrangement is similar to that defined in the Boeing study with four forward pylon mounted engines, and a four-poster landing gear. The centerline wing chord is 67.3 feet, and unswept wing aspect ratio is 6 which results in a wing span of 317 feet. The engines are conceptual ADP (advanced ducted prop) engines with a sea level design point bypass ratio of 21.9.

The most obvious deviation from the OAW designs studied previously in this project is the addition of a boom-mounted stabilizer. During unswept flight at low speed the stabilizer is rotated to the horizontal position so that it functions as a horizontal stabilizer with elevator control. During high speed flight, the stabilizer is rotated to the vertical position as shown in the side view below. This permits it to provide a yawing moment to counteract the fundamental tendency of the OAW to yaw toward zero sweep angle. There are good reasons to have the boom mounted stabilizer from the standpoint of control, but there are structural and aerodynamic drag problems which have not been evaluated.

The taxi bump case which was found in the NASA studies to size the structure was not evaluated in this study. With a relatively narrow gear track, and with payload and fuel further out toward the wing tips, this could be a serious problem. If so, smaller payloads would be desirable to reduce the span of the cabin and move the fuel tanks closer to the landing gear.



General arrangement of Mach 0.85 OAW.

Figure 18 Ground Tests of the Stanford 20' Subsonic RC Model

Before committing to flight tests, a low risk method of ground testing was developed by Stanford. The aircraft designed for flight was mounted on a ground vehicle (a Volkswagen Scirocco with a sun-roof). The mounting was a shaft bolted to the car with a universal pivot on top attached to the airplane at the center of gravity. The arrangement is shown in the pictures on the following page. When the ground vehicle is driven at flight speeds, in this case up to 40 mph, the aircraft experiences aerodynamic forces and moments identical to those experienced in flight, and it is free to pivot in roll, pitch, and yaw. There is the additional force on the aircraft due to the interaction with the vehicle vertical motion. As a result, controlling the aircraft in a ground test such as this is considered more difficult than control in flight.

Two important discoveries during these tests which proved to be vital to the subsequent flight test:

- Initially, the model was designed with a static margin of 7% unstable to match the planned design of the full scale OAW. Ground vehicle tests of the 20' model demonstrated that the servos were too slow to permit this level of instability. The custom servos required to meet the necessary bandwith requirement were beyond the timescale and budget of the project so the C.G. was moved forward reducing the level of static instability to 1.8%. The aircraft's open loop motion is still a very fast 0.5 second time-to-double, and an active control system is vital for flight.
- It was discovered that the engines caused an excessive pitching moment because the thrust line passes below the aircraft C.G. The ground vehicle test performed with both engines at full throttle showed that the thrust-dependent pitching moment easily overpowers the trim capability of the control surfaces. By mounting deflecting vanes in the engine exhaust, the engine thrust could be made to act through the aircraft C.G. thus eliminating the thrust dependent pitch moment, at a small loss in axial thrust.

(continued on following page)

Figure 18 Ground Tests of the Stanford 20' Subsonic RC Model (cont.)

A final round of ground vehicle tests were carried out to verify the stability and trim settings of the model. The controls were adjusted so that the aircraft would be trimmed at 10° angle of attack, 35° sweep, and have zero rolling moment.

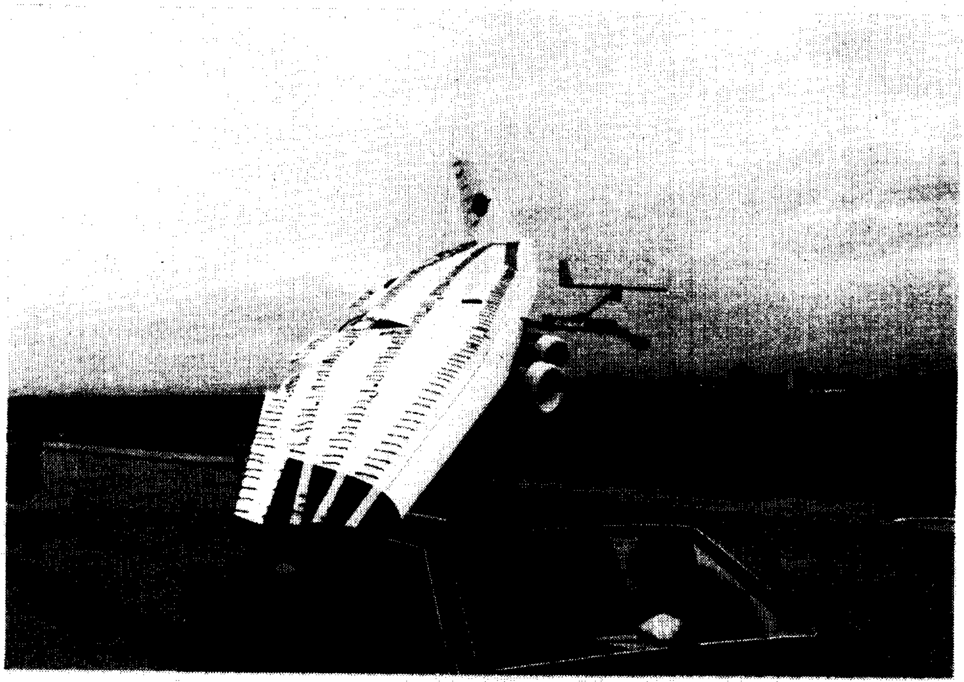


Figure 19 Flight Tests of the Stanford 20' RC Model

A four minute flight was completed above the Moffett Field runways in May, 1994. The flight began with a 23 second takeoff roll where the aircraft accelerated to 45 mph and then lifted from the ground after the pilot rotated the airplane with a pitch up command. The model climbed to an altitude of 150 feet and entered into a left hand pattern with speeds as low as 25 mph and as high as 65 mph with the wing sweep held constant at 35°. During the second left pattern the wing sweep was increased briefly to 50°, and at the end of this pattern the model landed safely on the runway centerline. This remarkable flight was watched by many nervous people from Stanford and NASA Ames, and the success of the flight and the whole RC model program is a testimonial to the model designer, builder, and pilot Dr. Steve Morris and his collaborator Dr. Ben Tigner. The flight test verified the aerodynamic analyses done for the model and the results determined from ground testing. An extensive flight test program was planned, but unfortunately budgetary constraints limited the flight testing to a single flight.

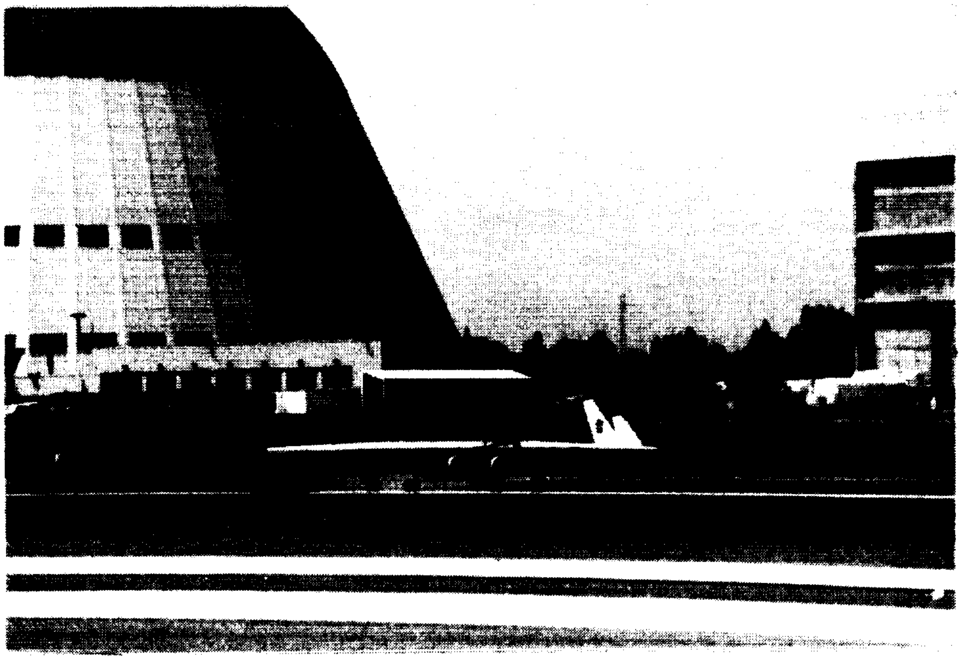
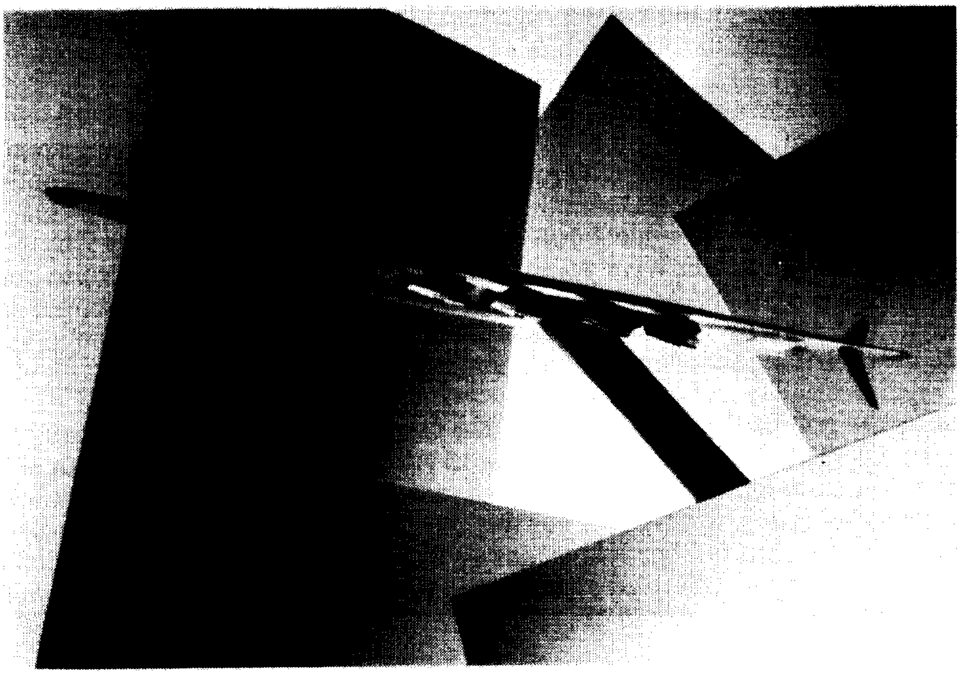


Figure 20 Wind Tunnel Test

A wind tunnel test was conducted on two models both having wing spans of 7.5 feet. These tests were conducted during June-July, 1994, in the NASA Ames 9 by 7-ft Supersonic Wind Tunnel. One model was designed to match the final configuration developed at NASA Ames, and the second model was a design developed at McDonnell-Douglas. An impressionistic view of the Ames model is given below, and as can be seen, the model is configured with both vertical fins and nacelles. Tests were conducted with the clean wing, with wing and fins, with wing and nacelles, and with wing, fins and nacelles. The second model had an elliptical planform and was tested as a clean wing only.

The test conditions included Mach numbers from 1.56 to 1.80, unit Reynolds numbers from 1.0 to 4.5 million/foot, and angles-of-attack from 0° to 6°. Because this work was concerned primarily with cruise performance, only a single sweep angle of 68° was tested. Force and moment data were obtained from a specially designed "flat" balance and surface pressure data from taps and pressure sensitive paint. A coordinated series of Navier-Stokes calculations for the bare wing and for the wing-nacelle-fin configuration, with and without blade support, was performed prior to the test. The quality of agreement obtained between the calculations and the test, observed in both surface pressure comparisons and the forces and moments, was very good.

There was an interesting sidelight to the test. A new scheme for interacting with wind tunnel users (termed "Remote Access Wind Tunnel") is under development at NASA Ames, and a prototype application of this digital network-based technology was successfully demonstrated during the test. A three-way video-conference was established among the interested parties at NASA Ames in Moffett Field, Boeing in Seattle, and McDonnell-Douglas in Long Beach to keep them apprised of test progress and to allow them to provide feedback on results. The interaction featured "live" audio, video, and shared access to a whiteboard, and it was supplemented by near realtime transfers of reduced data in a format suitable for plotting. This form of remote collaboration shows great promise: it was convenient, effective, and inexpensive.



CONCLUDING REMARKS

The work on the Oblique All-Wing supersonic transport outlined in this presentation is best described as an ad-hoc project at the Ames Research Center which evolved over the four year period from 1990 to 1994. An exception was the wind tunnel test. Once the decision was made to proceed with the test, careful plans were made and followed to design and build the models in time to meet the scheduled entry into the tunnel. The overall sequence of events that took place is probably very typical of the promotion of new technical ideas particularly when the concept involved is intended to improve on existing, well established configurations. The project was marked by strong advocacy on the part of dedicated proponents and sharp criticism on the part of numerous people within and without of NASA. This too is to be expected, and in the long run it is an important part of the process. Proponents must develop sufficient technical and economic data to defend their claims and justify continued development.

As outlined in the Introduction, this project was stimulated by a proposal from Stanford University to build and fly small scale radio control models to evaluate low speed stability and control issues. Before agreeing to fund this proposal, NASA Ames conducted an in-house systems study to evaluate the technical and economic viability of OAW aircraft as a supersonic commercial transport, and initial results were very promising. However, many technical issues including stability and control were identified, and along with agreeing to proceed with the Stanford proposal, the extremely important step to involve the aerospace industry was undertaken.

Boeing Commercial Airplane Company personnel argued strongly that details of the configuration must be carefully evaluated — layout of the cabin interior and integration of the landing gear were two items they emphasized. A contract with Boeing resulted in a configuration that identified geometric considerations of the OAW which lead to a clear understanding of the required size of the wing section in the region of the cabin. They also emphasized the need to understand the interface between the OAW aircraft and the airport. Boeing studied this problem as well, and clearly the airplane and the airports of today are not a good match. To reject the OAW transport on this basis alone is not justified. However, it is apparent that wider runways and greater separation between runways and taxiways are desirable and perhaps mandatory for the operation of the OAW transport.

The keys to OAW performance gains are improved cruise lift-drag ratio and reduced airplane empty weight due to the distribution of weight over a great portion of the wing span — the effect of span loading. The evaluation of the cruise aerodynamics was a major effort both at NASA Ames and in the contract with McDonnell-Douglas. Both organizations conducted extensive CFD studies, and two 7.5 foot models were designed and tested in the Ames 9 by 7-ft Supersonic Wind Tunnel. Although results have yet to be finalized, it is apparent that cruise performance is less than the original estimates by both Stanford and NASA Ames for a passenger carrying configuration. The need for a thicker wing section, trim drag effects, and nacelle wave drag and interference all contribute to reduced aerodynamic performance.

Understanding the potential weight benefit of the OAW transport remains a major shortcoming of the studies. Dr. Robert Liebeck of the Douglas Aircraft Company pointed out early in the project that an accurate model of weights is mandatory for any aircraft sizing studies. There is virtually no weights data base to turn to for this type of aircraft, and a detailed structural design study is required. This has not been done, and as a result further refinement is needed to properly size the aircraft as a function of payload size and range for different cruise Mach numbers. Any future work on OAW studies should give a structural analysis the highest priority.

Stability and control issues, the original impetus for the project, remain in spite of excellent work at Stanford, McDonnell-Douglas, and in-house at NASA Ames. An important point is that no "show stoppers" related to stability and control have been identified. In their evaluation of a subsonic version of the OAW, McDonnell Douglas opted for a boom mounted stabilizer for low speed pitch control and high speed yaw control. This would certainly not be appropriate for supersonic flight, but the fact that such a stabilizer has been proposed at this time highlights the need for continued stability and control work.

Beyond the documentation of the recent wind tunnel test results, there are no current plans within the NASA to continue this project. The following statements provide a brief summary of the OAW status as a result of this project.

- A baseline OAW configuration for carrying 400 - 500 passengers at a cruise Mach number of 1.6 was defined including the planform geometry of the wing which has an aspect ratio of nominally 10, the cross section geometry of the wing required for passengers, provision for ingress and egress, and the location of vertical fins, engines, landing gear, fuel tanks, and sub-systems.

- Problems in the interface between the aircraft and the airport were identified, but not solved. Introduction of an OAW transport would likely dictate some changes in airport design.

- The aerodynamic performance of the OAW at supersonic Mach numbers between 1.5 and 1.8 was developed in some detail both through CFD analyses and wind tunnel test. Initial estimates of very high lift-drag ratio at a flight Mach number of 1.6 have proven to be overly optimistic because the effects of nacelle and vertical fin integration were not properly identified. Without question there is room to improve the integration of the nacelles with the wing and thereby regain some of the lost aerodynamic performance. It is likely that a flight Mach number of 1.6 is an upper limit for an OAW transport, and lower cruise Mach numbers may be desirable. A subsonic OAW transport remains a possibility.

- Important structural loading conditions have been assessed but there is insufficient analysis to establish the weight of the OAW primary structure. It is apparent that pressure loads rather than bending loads are dominant in flight. On the ground, the bending loads during a taxi bump will be severe if the wing span is large with respect to the gear track. A wide gear track would provide a much better distribution of the landing gear loads, but this will require wider runways — a prospect that should not be discounted.

- Economic analyses have demonstrated that the OAW is most attractive for a large passenger capacity, nominally 800 passengers. However, this level of payload drives the airplane to a large size — particularly span which aggravates the airport interface problem. In addition, a large span may aggravate structural requirements as discussed above. Thus, there is insufficient data to establish a "best" payload size.

- The important stability and control issues have been identified through analysis and subsonic scale-model flight test, and no "show stoppers" exist. However, there is much work to be done to understand all the important effects such as aeroelasticity and gust sensitivity.

- The OAW transport has the potential for good to very good takeoff noise characteristics.

In retrospect, there are lessons to be learned from the OAW project that go beyond the pure technical results, and they apply to the evaluation of any proposed advanced concept, particularly one that must interface with an existing infrastructure and compete with well developed subsonic jet transports.