NASA Contractor Report 177619

Summary of Lift and Lift/Cruise Fan Powered Lift Concept Technology

Woodrow L. Cook (Retired NASA Ames Researcher)

NASA Ames Research Center
STOVL/Powered-Lift Technology Branch
Moffett Field, CA 94035-1000

Prepared for
Ames Research Center
CONTRACT A25364D
August 1993

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

TABLE OF CONTENTS

SURVEY OF LIFT AND LIFT/CRUISE FAN TECHNOLOGY

A summary is presented of some of the lift and lift/cruise fan technology related to performance, fan stall, ground effects, ingestion and thrust loss, design tradeoffs and integration, control effectiveness and several other areas related to V/STOL aircraft conceptual design. The various subjects addressed while not necessarily pertinent to specific STOVL supersonic designs being considered, are of interest to the general field of lift and lift/cruise fan aircraft designs and may be of importance in the future.

The various wind tunnel and static tests reviewed in the following summary are 1.) the Doak VZ-4 ducted fan, 2.) the 0.57 scale model of the Bell X-22 ducted fan aircraft, 3.) the Avrocar, 4.) the General Electric lift/cruise fan, 5.) the V/STOL lift engine configurations related to ingestion and consequent thrust loss, 6.) the XV-5 and other fan-in-wing stall considerations, 7.) hybird configurations such as lift fan and lift/cruise fan or engines and the various conceptual design studies by air-frame contractors. Other design integration problems related to a small and large V/STOL transport aircraft will be summarized including lessons learned during more recent conceptual design studies related to a small executive V/STOL transportaircraft.

Much of the analysis was based on meeting the requirements for steep decelerating descents for the XV-5 as established by Ron Gerdes (Ref.1) and also for the Dornier DO-31 flown by Bob Innis (Ref.2). In these investigations the need for -0.05"g" to -0.15"g" deceleration during part of the descent to landing and for a -2 to -3° additional descent angle capability for maneuvering were determined to be a requirement for satisfactory control and performance of steep approaches to landing. In addition the guidelines and criteria (Attachment A) for the conceptual design of the lift/cruise fan technology demonstrator aircraft was utilized for many conceptual designs of military type aircraft or modified for civilian type aircraft and used herein in the summary for design integration and tradeoffs.

DOAK VZ-4 DUCTED FAN WIND TUNNEL TESTS

A single ducted fan from the Doak VZ-4 VSTOL (Fig.1) aircraft was tested in the Ames 40X80 ft. wind tunnel with the fan mounted on a semispan wing for a range of wing angles of attack and angles of rotation varying from a zero degree duct angle to angles up to 90°. Test results were obtained for a range of forward velocities from 0 to 140 knots, for a range of power settings and for fan rotational speeds from 1800 to 4800 rpm. Tests were also made for a range of fan blade angles 11° to 43° which were manually set between test runs and also for a range of inlet guide vane settings from 0° to 24° (Ref.3,4, 5,6 and 7).

Performance - The results indicated that the hover figures of merit had a value of about 78% from 11° to 23° of blade angle and fell off to values of about 74% for 30° and 60% for 40° of blade angle.

The efficiency at forward speed varied from about 52% at a blade angle of 11° to a value of about 57% to 58% at a blade angle of 23° at an advance ration of about 0.6 and remained essentially constant up to the maximum blade angle tested of 43°atanadvance ratio of 1.0. The fan had blade stall at hover at the maximum blade angle of 43° tested which became unstalled at forward speed at an advanced ratio about 0.5.

Inlet Guide Vane - Although the Doak fan did not have variable blade pitch capability the blade angle could be adjusted manually in the wind tunnel so that the effectiveness of variable blade pitch for fan thrust control and for lateral control compared to the inlet guide vanes which were utilized on the Doak airplane. The thrust variation per degree of blade angle change was about 80 pounds/degree (Fig.2) whereas the inlet guide vane provided about 12 pounds/degrees only about 15% as effective as variable blade pitch for lateral control power and height control near hover for the Doak VZ-4 airplane.

The effectiveness of the inlet guide vanes for the Doak VZ-4 airplane is illustrated in (Fig.3) and indicates the value of lateral control power and damping compared to previous standards that had been established at that time. It should be noted that other inlet vane designs having greater numbers of vane and more vane area would increase the effectiveness of the inlet vanes for varying thrust.

Exit Vane and Cascades - A single exit vane and two different cascade vane designs were also investigated to determine the effectiveness of these vanes for turning the airflow and providing forces to overcome high pitch-up moments caused by the duct at forward speed and at tilt angles. The single vane shown in (Fig.1) along with ducted fan mounted on semi-span wing in the wind tunnelwas avariable incidence vane with a 25% chord flap. The results of the tests are shown in (Fig.4) and indicate the effectiveness of the vane and flap in reducing the maximum duct pitching moment as forward speed increased from hover. The most effective setting was the main vane at 10° with the flap at 20°. The maximum out of trim moment was reduced about 50% at the foregoing setting and required about a 3% power increase.

Descent, Deceleration and Inlet Stall - The exit vanes also provided a means of reducing the required duct angle during transition where duct lip stall restricted the ability of the Doak VZ-4 Aircraft to conduct steep, decelerating approaches and let down from about 70 knots to hover. With the plain duct (no exit vane) the maximum descent angle at about 50 knots with .05g deceleration would be about -3° with no margin of descent angle for maneuvering. With the single flapped vane the descent angle could be increased to about -7° with .05g deceleration and a 2° descent angle margin for maneuvering. Cascades of exit vanes could increase the descent capability further and are shown in (Fig.5) for mounting angle of 0° to 45°. The effect of exit vanes over a range of transition speeds for the 0° cascade mounting on the lip stall boundary are shown in (Fig.6) and are compared to the vanes off case of the original Doak duct. The descent rate capability can be increased significantlyby a factor of about 2.5 andimproved the descent margin and deceleration capability considerably during approach and letdown to landing.

The exit vanes and cascades would also improve the Doak VZ-4's ability to decelerate at low speeds when approaching hover at speeds from about 40 knots to hover, with the ducted fans near vertical the deceleration forces would be increased by a factor of about 4 to values above -0.3g or about -10 ft/sec^2 and hence give much better air braking when approaching hover over a spot.

The lack of deceleration with steep descent angle capability was a common problem with many types of V/STOL Aircraft and made the use of lift and lift/cruise fans with single or cascades of exit vanes or louvers an effective design tool for these type of aircraft, where flight in transition speed range from0 to conversion speed, the drag forces are very low or nonexistent for air braking and flight path control during let down.

Small-Scale Duct - Comparison of the 4-foot diameter ducted fan and a 5/16-scale model are shown in (Fig.8). In the tests of the small scale model, because of the lower Reynold's number, lower lip stall occurred at a steady level flight conditions at low forward speeds causing large increases in power required and reductions in the pitch-up moment at forward speed compared to those of the full size airplane ducted fans. To prevent the occurrence of the small-scale duct inlet stall it was necessary to increase the upstream inlet lip radius by a factor of two.

WIND TUNNEL TESTS OF X-22 LIFT/CRUISE FAN AIRCRAFT MODEL

A 0.57 - scale model of the X-22 was constructed and tested in the 40X80 foot wind tunnel utilizing the four Doak 4-foot diameter lift/cruise ducted fans. The model is shown in (fig. 8 & 9). Tests were conducted over a range of forward velocities, angle of attack, ducted fan tilt angles from about 0° to 90° and a range of power settings. Tests were also conducted at various heights above ground for a range of velocities, duct tilt angles and model angles of attack. The effects of the variables on the longitudinal lateral and directional characteristics to different angles for longitudinal control and along with the variable deflection single flap upward and downward in each duct exit provided sufficient pitch control for significant center of gravity changes and pitch control at forward speeds during transition flight. The duct exit flaps provided additional lateral control at transition speeds when deflected assymetrically on each side together. (Ref. 8 & 9)

Descent Angle - The X-22 aircraft had essentially the same aerodynamic duct design as the Doak but did have fans with variable pitch blades unlike the Doak fans. The downwash effect of the tilted front ducts on the aft ducts reduced the duct lip stall & deceleration capability was therefore established by the front duct lip stall. (Fig. 10 & 11) The stall boundaries could be improved to some degree by utilizing the single exit vanes deflected in a downward direction for obtaining a larger range of descent velocities in the transition speed range while remaining within the longitudinal and trim requirement for the exit vanes and/or variable pitch of the fan blades at the fore and aft ducts for longitudinal trim and control. Whereas, the maximum descent angle attainable at constant velocity let down varied between -6° to -10° without duct lip stall between about 50 to 70 knots, with the requirement for -.05g deceleration and a margin of -2 or -3° for maneuver the descent capability would be reduced to very small values of 0 to -2° or -3° and would be of very little practical use during terminal area operation. This would not allow considering steep, decelerating descent with low noise levels. These values of descent angle with deceleration and a maneuver margin could be improved upon by a significant amount (about -5°) by utilizing lower tilt angles on the front ducts and less up deflection angle of the exit flaps and larger tilt angles and exit flap angles on the aft ducts. Although in (Fig. 11) untrimmed flight is shown at the lower velocities of transition with the fixed pitch angle blades of the Doak ducts, trimmed flight could be established with variable blade pitch fans.

Ground Effect - The X-22 model was also tested at three heights above ground 1,2 and 3 fan diameters (4-feet).. The results in general showed a favorable ground effect for lift, drag and power required as lower heights were examined, however there was an indication that a reversal of control would be required for trim at one and two fan diameters above ground and possible less power would be required at two fan diameters than at one fan diameter above ground (Fig. 12 and 13) for hover and 48 knots.

Performance - The cruise and climb performance (Fig.14) was very poor as the aerodynamic L/D value were exceedingly low without a good wing for higher L/D's. Also the propulsion system match for cruise was poor as high fuel consumption would be obtained with 4-large diameterfans operating at relatively low thrust. The low power required for the engines compared to the design value for hover would result in high specific fuel consumption.

Therefore, it was learned that the more efficient design would require a wing for cruise, climb, and letdown. The propulsion system should be better matched for cruise speeds with much lower, total fan area utilized in cruise, flight, hence much higher pressure ratio fans.

Full-Scale X-22 Ducted Fan - The Hamilton Standard 7-foot diameter ducted fan built for X-22 Aircraft (Fig.15). The duct aerodynamic design was very similar to the 4-foot diameter Doak duct and the results for duct lip stall very similar. The fan had variable angle control of the fan blades, thus allowing large changes in duct thrust at constant RPM and therefore better descent capability than the Doak Airplane as duct angle and thrust could be varied fore and aft thus minimizing the lip stall on the forward ducts particularly with downward deflection of the exit vanes of the forward ducts. (Ref.10) Varying the blade pitch of the fore and aft ducted fans depending on the c.g. location could accomplish the trimming requirement of the aircraft.

AVROCAR

The AVROCAR was an 18-foot-diameter flying saucer like wing powered by three J-69 turbojet engines that drove a 5-foot-diameter lift fan through tip turbines as shown in (Fig.16,17 and 18) and described previously in Wally Deckert's paper. This summary discusses the wind tunnel tests of the full-scale AVROCAR in the Ames 40X80 foot wind tunnel and indicates, from the results, reasons that caused the failure of the system to accomplish the performance and control anticipated by the manufacturer. (Fig.16 a) shows the AVROCAR mounted in the wind tunnel on the ground effect struts at minimum test height of 0.15 diameters or 2.7 feet. Shown in (Fig.16 b) is the AVROCAR mounted at the maximum test height of about 0.7 diameters with the horizontal tail mounted at the aft portion of the AVROCAR for some of the forward speed tests for cruise flight. (Ref.11 and 12)

Jet Flow - Shown in (Fig.17) are sketches of the fan flow regimes produced by various positions of the control system for hover, the initial transition stage, mid-transition stage all in the presence of the ground and (d) the cruise flight stage out of ground effect. The ducting for the flow of a mixture of the turbine exhaust and cold lift fan air and the control system was divided in 3 - 120° quadrants, the forward 120° quadrant, the two 60° (120° total) quadrants on each side and the aft 120° quadrant. (Fig.18). The side quadrants and part of the aft quadrants had cascades to turn the air when flowing through the alternate nozzle with the transition doors in the cruise flight position as shown in (Fig.18 b).

Ground Effect - The effect of ground on the lifting capability of the AVROCAR with circular nozzle are shown in (Fig.19) and at the lowest height tested 0.15 height to diameter ratio (2.7-feet) at the low forward speed near hover and high Cj of 3.0 there is about 250% increase in lift capability.

The data for ground effect in (Fig.19) was normalized for Cj and the extropolated CL at h/d-1.0 and are shown in (Fig. 20) indicating that accounting for C_L varying from values of 1.0 to 3.0 shows fair correlation of the effect of ground and the 250% increases in lift performance from a height over diameter ratio of 1.0 to a value of 0.15,h/d,for the three Cj's tested 1.0, 2.0 and 3.0. This ground effect phenomena has been utilized by number of hover craft and ground effect or air cushion machines since that time.

Performance - (Fig.21 a,b,and c) show the results of the data for transition at a ground height of 0.15 h/d and for the cruise configuration at a ground height of 0.7 h/d and comparison of low power transition with constant jet momentum transition. The significant result shown by this data is the lower power requirements of low speed flight in ground effect compared to the power requirements in cruise flight out of ground effect and the resulting low forward speed capability of this air vehicle. From the data it was determined that large increase of inlet momentum drag and the large duct losses were two of the major reason for the poor forward speed performance. The maximum forward speed out of ground effect would have been about 59 knots at a weight of 4500 pounds whereas in ground effect it would have been significantly greater at much higher weights.

Duct Losses - The second factor was the large loss in jet momentum due to duct losses as shown by the results in (Fig.22). At 96% of the radius the large loss in Cpt shown for 180% point of the circumference and the requirement for downward vectoring of the jet left very low values of jet momentum in the horizontal direction for thrust available for cruise flight out of ground effects. Therefore at cruise flight configuration the AVROCAR had neither the forward thrust, the pitch control capability or the lift capability necessary to fly the aircraft above about 70 knots out of ground effect at the design weight of 5650 pounds.

The horizontal tail was installed on the AVROCAR to improve stability and pitch down control during cruise flight and thus alleviate the large nose down angle of attack and low aerodynamic lift. Very little tail effect was found due to its location in the wake of the circular plan form and the high in-flow at the fan inlet.

GENERAL ELECTRIC - LIFT/CRUISE FAN

Full-scale wind tunnel tests were conducted of the General Electric, 1.1 pressure ratio, ducted lift/cruise fan. The fan was the tip turbine fan of a previous fan-in-wing driven by the exhaust of a jet engine (J-85) mounted above the fan as shown in (Fig.23 and 24)/ The fan diameter was 62.48 inches and had 36-blades. The tests were conducted throughout the speed range from 0 to 180 knots with the fan speed varied from 1200 to about 2400 rpm to allow a large range of tip speed ratios. Duct angles from -4 to +80° were investigated. At higher forward speeds and low duct angles five exit areas were tested to determine the effectiveness of exit area on fan performance utilizing a fan with fixed blade angles. (Ref.13)

Effect of Exit Area on Static Performance - The static performance is shown in (Fig.25) indicating a maximum thrust would be attainable at 2640 rpm with the maximum exit area of 19.57 sq. feet. (Area Ratio, Ae/Ae,s=1.0). The reduction in thrust measured with the exit area ratio reduced to 0.8 was about a 20% loss in thrust. As the area ratio was reduced to 0.74, 0.62 and 0.56 larger thrust losses at lower speeds were measured and at 0.56 the static thrust loss was of the order of 50% below that of the exit area ratio of 1.0. Shown in (Fig.26) are the variation of lift and drag at several forward speeds from 21 to 121 knots throughout a range of duct angles and fan rpm's and show the effectiveness of the duct for varying lift drag and thrust (horizontal) with airspeed and duct angle.

Effect of Exit Area on Performance at Forward Speed - The results of data for five exit area configurations of thrust to static thrust ratio for a range of forward speeds are shown in (Fig.27). These results indicate that at the higher forward speeds the exit area ratio between 0.62 and 0.74 show the largest increase in effective thrust and could result in about a 40 to 50 knot increase in forward speeds. Lower values of thrust ratio were indicated at all speeds for the area ratio 0.56 exit and below 190 to 220 knots for area ratio 0.74 and 0.62 exit respectively, the values of thrust ratio were less than for area ratio 1.0 exit, indicating the need for a variable area exit nozzle for a fan with fixed blade angles instead of variable blade angles.

Duct Drag - The effect of duct external drag was determined by measuring and integrating the boundary layer total pressure at the duct trailing edge indicating a relatively high overall duct external drag coefficient of 0.11 as shown in (Fig.28). Whereas at the bottom of the duct the external drag coefficient based on the boundary layer measurements would have been 0.04 as a result of no interference effects due to wind tunnel mounting to the struts and the jet engine mounted on the to duct upper surface. The results are compared at area ratios of 1.0 and 0.62 to a zero drag duct drag $C_d=0$ in (Fig.28) and indicates the increase in potential forward speed between a duct drag of 0.11 and 0.04 particularly for the area ratio 0.62 exit which shows a potential 40 knot increase in speed.

Duct Stall - The effect of lower lip duct stall on the descent performance at nondecelerating flight conditions for three wing loadings are shown in (Fig.29) and although they are of reasonable value, with the inclusion of the margin factor of about 2° and the deceleration factor of about -.05"g" the values are less than -10°for all conditions of speed and duct angle of 50° or greater. The lip stall was limited to the lower lip quadrant and no stall occurred at duct angles of less than 40°. The effects of hysteresis on the aerodynamic characteristics of the duct are shown in (Fig.30) where once the duct lip stalled by reducing rpm and tip speed large increases in rpm were necessary to unstall the lip.(Fig.30) The use of tip speed ratio, u_t, as a correlating factor for various fan tip speeds and forward velocities are shown in (Fig.31) for the exit area ratio of 0.56. Similar good correlation existed for all other exit area ratios and other velocities as well.

REINGESTION CHARACTERISTICS OF V/STOL LIFT-ENGINE FIGHTER MODEL

This research although done with jet engines and hot gas may in some cases have a bearing on lift fan and lift/cruise fan aircraft or mixture of lift fan and vectored thrust engines having higher pressure ratio fans in the hover and transition mode of flight. (Ref.14) During these tests the reingestion of exhaust gas into engine inlet during hover and inlet flow distortion with the associated loss in total pressure recovery during transition were studied using a large scale generalized lift-engine fighter model powered by J-85 jet engines. Exhaust gas ingestion during hover was tested on a static test facility and inlet flow distortion and total-pressure loss were measured at forward speeds in the 40X80 foot wind tunnel (Fig.32). Some of these results were summarized previously by David Hickey in his paper. These tests included internally fixed and swiveling retractable arrangements of lift/engines as shown in (Fig.33 and 34).

Three different lift engine exit nozzles the conical, the bifurcated and the slotted shown in (Fig.35) for the internally fixed configuration and did have different effects on hover inlet temperature rise and thrust loss.

Thrust Loss - The effects of exhaust vectoring on temperature rise and thrust loss with the swiveling, retractable configuration are shown in (Fig.36) and indicates the largest temperature rise and loss of thrust and lift at height to diameter ratio 5.0 will occur with the thrust angle from horizontal near 90° or near vertical. It was found that vectoring the lift engines to a small forward angle and the lift/cruise engines aft from vertical to balance the aircraft would alleviate exhaust gas ingestion and thrust losses. The aircraft could takeoff and land with decelerating approaches surrounded by exhaust but relatively free of ingestion effects and losses.

All configurations tested swiveling and internally fixed lift engines experienced excessive thrust loss and compressor stall when the thrust was vectored 90° from horizontal. Of the three exhaust nozzles with the internally fixed lift engines, the slotted nozzles produced (Fig.37) somewhat lower temperature gradients and average inlet temperatures and therefore less lift loss than the conical or bifurcated nozzles, but at angles of 80 and 90° to the horizontal engine stall occurred regardless of the exhaust nozzle installation. Although no forward vectoring was accomplished with the internally fixed configuration because of limitation in the vectoring system it was believed that forward vectoring of the lift engine thrust and aft vectoring of the lift/cruise engines thrust for balance would produce the same result as found with the swiveling lift engines discussed previously. That is to alleviate exhaust gas reingestion and allow takeoff and landing within an area surrounded by hot exhaust but relatively free from ingestion effects.

Although these results are for jet-engine hot gas exhaust the results should be of general value to higher pressure ratio fans where exhaust air of the lift and lift/cruise fans are impinging upon each other underneath the fuselage and wings. For, example the general effect of forward vectoring the lift fan thrust while aft vectoring of the lift/cruise fan could reduce or eliminate the suck down in approaching the ground and reduce the reingestion of fan flow into the engines as for the XV-5 aircraft where no adverse thrust loss effects were encountered near the ground during takeoff or approach to landing at hover conditions.

GRUMMAN-698-111 TILT NACELLE V/STOL MODEL

A full-scale powered model of a subsonic, tilt nacelle V/STOL aircraft concept was tested in the 40X80 foot wind tunnel and on the Ames outdoor Static Test Stand at three heights above the ground plane, 18 ft. 7 inches, 6 ft. and 4 ft. 2 inches. The model is shown in **(Fig. 38a)** in the cruise mode mounted in the wind **tunnel and in the hover mode mounted on the static test stand (Fig. 38b).**

I have no first hand experience with the test results. Therefore, my comments and conclusions are based entirely on analysis of the data in the **Grumman** Report 098-33 (Ref.15) to the Navy under contract N00019-80-C15 and the reference sketch of the model mounted in the wind tunnel as shown in (Fig.39) and indicates the general size of the model and the method of tilting the nacelles and engines forward of the wing. The later motion of the nacelles during transition cause a large change in the center-of-gravity (c.g.) location of the aircraft as shown in (Fig.40). This amounts to a total movement of about 9-inches at the landing weight configuration of the aircraft and has a significant bearing on control power available after trimming out the moments for c.g. shift. This magnitude of c.g. shift during transition is very unusual for V/STOL aircraft.

<u>Transition Performance</u> - The descent performance of the aircraft is shown in (Fig.41) for several nacelle tilt angles from 20° to 68° at the landing weight of 13,654 pounds and at constant velocity conditions. Also shown are inlet fan stall limited points at angles of attack of 4° and 12°. The points indicate that the aircraft is trimable over wide ranges of nacelle deflections, angle of attack, velocity and flight path angle.

<u>Transition Control</u> - Although the aircraft is trimable over the transition range the large nose up pitching moments reduces the control available for maneuvering to about 50% of what has been determined as acceptable as shown in (Fig.42). Shown are the longitudinal control available in radians per second^2 over a range of transition velocities from about 58 knots to 88 knots for 50,60 and 68° of nacelle tilt, for 4 and 12° angle of attack and for the takeoff and landing gross weights. It is indicated that a large reason for the large pitch up moments is due to the long inlet at the high position above the c.g. and also the large area of unprotected wing center section over the fuselage between the nacelles. It was concluded that reducing the inlet length by one foot would reduce the pitch up moment sufficiently to provide acceptable pitch down control moments for maneurering. However, during the ground effect and inlet ingestion tests at static conditions the lack of ingestion and thrust losses was attributed to some degree to the high location of the inlet. Reducing the inlet length by a foot or so could increase the ingestion problem at hover and low forward speeds during transition.

Descent Capability - The maximum descent angles(Fig.42), indicated at 60 knots and 68° nacelle deflection, to -14.5° to -19.2° at 60° nacelle deflection in the 70 to 80 knot speed range and from -8.8° to -15.8° descent angle for 50° nacelle deflection in 75 to 88 knot range during transition. Although those descent angles appear quite adequate the requirement for maneuver margin of -2° or -3° and requirement for deceleration of -0.05 to -0.01 "g" reduces the available usable values of descent angle by about -6° to a maximum of -10° or -12° depending on the amount of deceleration required. See Table I.

FAN-IN-WING STALL BOUNDARIES

The fan-in-wing as in the XV-5 was subject to fan stall as well as wing stall that affected fan stall and vice versa. During some of the wind tunnel tests with the 5.2 foot diameter fans, fan stall was penetrated several times, sometimes inadvertently but also on purpose. The fan operation personnel became very good at determining how far they could go with increased forward speed at constant fan tip speed or reducing tip speed at constant velocity without stalling the fan (Ref. 16 and 17,etc). (Fig.43) shows the stall of lift fans (co-rotation) with tip speed ratio for different inlets and right and left fan fans mounted in a generalized model. These results are at and angle-of-attack of 0° and an exit louver angle of 0° or vertical. The results in (Fig.44 & 45) show the effect of wing angle-of-attack at various tip speed ratios on fan stall. As can be seen, wing conditions with adverse pressure gradients result in large reductions in thrust occurs as well as total lift (Fig.45). These data points were taken from tests with different wings, but the same 5.2-foot diameter fan having fixed blade angle of about 36°.

Tip-Speed and Wing Angle of Attack - For the particular aircraft such as the XV-5 the stall boundaries can be roughly established from the data obtained in the wind tunnel for a given tip speed of the fan blades. The stall boundary in (Fig.46) is based on a number of test points and show the variations of tip speed ratio for stall with angle-of-attack with the aircraft flown level at a -10° descent angle at about 70 knots and the other at a slightly higher tip speed with aircraft flying parallel to the -10° descent path. As can be seen at 10° angle-of-attack with deck level approach the margin to stall is small about 2° to 3° in angle-of-attack and about 10 knots in forward speed which would be critical to gust or maneuver requirements. With the deck parallel approach about 12° angle-of-attack margin will exist and at least a factor of two up to 150 knots could be flown before reaching the stall boundary at an angle-of-attack of near zero degrees and constant fan RPM. The boundary at 0° angle-of-attack would be at a higher velocity or tip speed ratio than shown in (Fig.46).

CONCEPTUAL DESIGN CONSIDERATIONS

During the 1960's and 70's a number of conceptual designs studies were undertaken by NASA personnel and by airframe and engine contractors. The studies for lift fan and lift/cruise fan STOL aircraft were made of commercial transports, military multi-mission aircraft and of a technology demonstrator (originally called proof-of-concept) aircraft representing the commercial or military aircraft conceptual designs in principal particularly for the V/STOL design aspects. During these studies design guidelines and criteria for design of the various technology demonstrator aircraft were established over several years by NASA. Attachment A is a copy of the 1975 version "Design Guidelines and Criteria for the Design Definition of the Lift Cruise Fan Technology V/STOL Aircraft". Hervey Quigley, Curt Holzhauser and L.S. Rolls started the Criteria document, first, for the Augmentor Wing Research and Technology Aircraft Project second, for the XV-15 Tilt Rotor R and T Aircraft and finally Quigley, W. Deckert and Rolls for the Lift/Cruise Fan R and T Aircraft.

Contractor Studies - A number of airframe and engine contractors such as Boing, McDonnel-Douglas, Lockheed, North American-Rockwell, LTV, General Electric, United Technologies Corporation and others participated in the study efforts as shown by some of the configuration in Wally Deckert's paper.

A number of the conceptual designs were hybrid type, that is lift fans primarily for vertical thrust, low speed control and acceleration requirements combined with lift/cruise fans or integral lift/cruise engines primarily for cruise but also for some part of the vertical thrust and low speed control and acceleration requirements (Ref. 18,20 & 21). In the design of fan-in-wing aircraft, the results indicated that placing the fans in the wings of high subsonic speed aircraft caused a severe penalty in wing weight and the thickness of the wing required to house the lift fans. The wing thickness was considerably greater than the thickness required for flight at Mach no.'s of the order of 0.8. However, the effectiveness of lift fans mounted in the horizontal mode with exit louvers to provide accelerataion at low speeds of transition and deceleration at steep descent angles as well as for providing some of the control functions at low speeds made lift fans an important if not necessary part of the designs with 3 or more fans where lift/cruise fans or integral hi-bypass fan engines are also used. Experimental results showed that a statorless fan could be utilized in a fan-in-wing design with very small thrust loss and allow thinner wings to be used. With the statorless fan, the wing thickness ratio could be reduced by 1 to 1½% depending on the wing geometry and chord length. It was hypothesised that the cascade louver system below the fans did much of the work of the aft stators resulting in the small losses. The problem of wing thickness was minimized with a low aspect ratio triangular wing (Ref.19) that could be capable of lower supersonic speed flight where the chord length of the wing was sufficient to give the thickness and depth for mounting fans in the wing without penalty at high speeds. The penalty of lost volume in the wings for fuel storage existed in all fan-in-wing designs.

There were many other areas of design studied such as 1.) gas flow driven lift and lift/cruise fans versus shaft driven fans, 2.) control by utilization of variable fan blade pitch for lateral, longitudinal and height control versus fixed blade pitch fans of gas coupled systems, 3.) the need for fan out controllable fight to landing as well as engine out for civil aircraft, 4.) the need for high negative thrust vectoring for steep decelerating approaches to landing and sufficient air braking forces during level flight at low speeds approaching hover, 5.) the remotely controlled fans versus integral high by pass fan engines and the need for fan inter connect.

1.) Fan Drive Systems - Contractor conceptual design studies by McDonnell-Douglas and Boeing during the NASS/NAVY program for potential development of the Research and Technology Lift/Cruise Aircraft representing the NAVY multi-mission aircraft of the future. The results of those studies presented lift/cruise fan propulsion concepts that utilize either mechanically-coupled transmission or gas-coupled systems. Either system could accomplish the goals and guidelines of the studies.

The following: Concluding Remarks from Reference 20 - The analysis of the basic characteristics of both a gas-coupled and a shaft-coupled lift/cruise fan propulsion system has shown that either propulsion system concept would be suitable for development for a Lift Fan research and technology aircraft, (LFRTA). For the aircraft and propulsion systems analyzed the research potential is similar except for the following considerations. The gas-coupled system has a larger thrust-to-weight ratio which may equate to higher thrust margins or greater payload capability and this system offers greater design flexibility with its transmission systems. The shaft-coupled system has faster response to thrust modulation commands and greater attitude control power.

Both propulsion system concepts have an adequate data base to initiate development. There are, however, technical risks for both systems that would be associated with the LFRTA development. For the gas-coupled system, there is a risk in the timely development of (1) large-diameter, high-temperature valves for the primary control system, (2) high-temperature, low-pressure loss ducting to interconnect the fans and gas generators, and (3) a power-management-control system complicated by the requirement to automatically recognize the compensation for an engine failure. For the shaft-coupled system, there is a risk in the timely development of (1) a thrust modulation control system with the mechanical reliability required of an aircraft primary control system and (2) high-horse-power transmission components, particularly a clutch for decoupling the nose fan of a three fan configuration.

For an operational aircraft the advantages or disadvantages of either system will include many of the items discussed and will also depend on the aircraft mission, operational guidelines and aircraft configuration." End of Concluding Remarks.

2.) Other specific Comparisions.- The proposed LFRTA a modified T-39 aircraft with lift/cruise fans to provide sufficient thrust and control for VTOL flight is illustrated in (Fig.47) for the two propulsion concepts gas-coupled and shaft-driven transmission systems. The 3-fan with 3 engines systems are shown in (Fig. 48 & 49). The McDonnell designs also included a shaft-driven system. It was concluded that the shaft driven system was 6 to 7% more efficient than the gas-coupled system but the higher weight of the shaft driven system offset some of the difference. The McDonnell Aircraft had thrust vectoring with D-nozzles whereas Boeing had tilting integral fan engines mounted on the aft fuselage. The gas-coupled system had fixed blade pitch fans whereas the shaft driven fans had variable blade pitch which offered a number of advantages in performance, control and reversed thrust which will be discussed more completely later.

The primary unsolved problem in the design of the shaft driven transmission for the LFRTA (Research and Technology Aircraft) of 1975 in my opinion was the fatigue life and qualification requirement of the gears. The gear tooth bending stress and contact stress as a function of gear pitch line velocity are shown in (Fig. 50a & b). For both companies aircraft. Boeing and McDonnell the pitch line velocities are high compared to most other gears for helicopters of that time particularly for the bending stresses. It was estimated some three years of development time and large costs would be required to qualify the gear boxes for the LFTRA. The development of the large ducts and valves at high temperatures for the gas-flow coupled transmission system was less of a problem and hence the time and cost for development would be less than that of a shaft-driven system development. At that time the forgoing shaft-drive transmission development time and costs were not warranted for a Research and Technology aircraft although could be reasonable for a NAVY prototype of a Production multipurpose aircraft. Therefore, at that time my decision would have been to proceed with a gas-coupled drive system with fixed blade pitch fans for the LFRTA at gross weight of about 26,000 pounds. However, at this time some 17 years later my choice depending on the developments on gear boxed during those years and the many advantages of variable blade pitch fans, my decision would probably be for a shaft-driven transmission system particularly for smaller less than 5000 pound aircraft to be discussed later, where the volume available for ducts is not sufficient for a gas-coupled transmission system. In either case for the large aircraft the choice is still subject to tradeoff studies and recent developments for both cases shaft and gas-drive transmission systems.

2.) Control Comparisons. - The response characteristics of the variable blade pitch fans for control would be 0.1 second or lower for the smaller fans with light weight blades compared to about 0.3 second for fixed blade pitch fans where fan rotational speed changes are necessary as in the ETC system. Thrust spoiling as used on the XV-5A aircraft could be used to improve the control response characteristics of the gas-coupled ETC system at the expense of thrust loss depending on the degree of spoiling required. The magnitude of fan thrust loss with large variations of control required for simultaneous lateral, pitch and height control would be significantly less with the variable fan blade pitch control system than other fixed fan blade pitch systems.

3.) Fan out flight. - For military designs of lift/cruise fan VSTOL aircraft ejection seats or cockpits make it unnecessary to provide engine out or lift or L/C fan out safe, controllable flight to landing at hover or low speeds below conversion speed. However, for civil small aircraft or civil tranport aircraft where passengers are without parachute capability it becomes very necessary to have engine or any lift fan out controllable flight to landing. In the designs of some of the STOL transports this was accomplished by having more fans than required for hover and shutting off a opposite fan for lateral or pitch control and increasing the thrust of the remaining fans to provide the necessary thrust to weight ratio and control forces for a safe let down to landing. Utilization of reversal thrust at low speeds of transition to hover to accomplish one fan out safe flight will be discussed later.

4.) Thrust vectoring. - In nearly all the study efforts the requirement for a large degree of horizontal thrust vectoring both negative and positive for acceleration and climb as well as steep descent, deceleration and angle of attack and speed margins were necessary to provide accurate and short time transition flights for military aircraft and quieter and smaller transitional terminal flight areas with accurate flight to final landing spots. Since this has been discussed in more detail previously, no more will be written herein about thrust vectoring except to point out that with lift fans mounted in the horizontal position and with exit louvers deflected to -30° in the forward direction deceleration forces were much greater and more effective than by simply defecting or tilting the cruise fan or engine thrust.

5.) Integral high-bypass ratio fan engines. - The conceptual designs of the NAVY Multimission Aircraft by Boeing and later by McDonnell utilized integral high-bypass lift/cruise fan engines resulted in considerably longer nacelles (Fig. 47,48 and 49) than for remotely driven lift/cruise fans. (Ref. 20) The integral fan engines also required fan interconnect to allow one engine out safe flight for three fan aircraft. In the case of four or more lift and lift/cruise fans aircraft interconnect was also necessary for fan out safe controllable flight. The loss of an integral fan engine would cause a larger thrust loss than a remotely powered fan due to the loss of super-charging effect on that the engine was depending on, resulting also in larger control losses as well.

There are a number of other design considerations by the contractor during their design studies that are pointed out by Wally Deckert, Jack Franklin and Lary Gertsma and will not be discussed in this paper. However the effectiveness of variable blade pitch for cruise performance of the lift/cruise fans is much greater than for a fixed pitch fan with variable exit area in cruise as on the previously discussed General Electric lift/cruise fan.

TECHNOLOGY UTILIZATION FOR CONCEPTUAL DESIGN STUDIES

I. Horizontally mounted Lift Fans (Hickey & Kirk)
  A. Data from static and wind tunnel tests for following:
    1. Fan sizing and thickness
    2. Wing sizing function of fan size
    3. Hydrid Configuration - effect of fan downwash on aft wing
    4. Fan induced lift, drag and pitching moments
    5. Determination of lift fan stall boundaries with cross flow and angle-of-attack
    6. Inlet requirements for vane, and closure door or vanes
  B. Geometric characteristics of lift fans dependent on number of fan blades and blade area

II. Lift/Cruise Fans (Hickey and Kirk)
  A. Data from static and wind tunnel tests of tilting ducted fans
    1. Stall boundaries over range of tilt angles of a function of forward speed
    2. Effect of single vanes and cascade on duct pitch up moments and lower lip stall boundaries during steep descent to hover landings
    3. Variable blade pitch fans for control (pitch, roll and height) along with Lift Fan with variable pitch and the potential of reversed thrust on the L/C Fans by either variable pitch or target type or clamshell type thrust reverses.

III. Control systems and Simulation (Franklin and Cooper)
  A. Control system and power integration during transition speed range particularly during steep, decelerating descents during part of letdown from conversion speed at altitude to hover near ground.(Ref. 24,25,26 & 27)
    1. Initially utilized flight tests powered Lift QSRA and augmentor wing STOL aircraft and simulation.
    2. Later and at present work on simulator and flight tests of XV-5B, XV-15 and Harrier aircraft
  B. Use of Cooper-Harper Rating during simulation to establish handling qualities. (Ref. 28)

IV. Flight Tests - (Gerdes and Innis)
  A. Initially XV-5B and Dornier DO-31 flight test established many of the requirements for conversion and transition during takeoff and landing.
  B. Also flight tests data of X-14, XV-15 and Harrier were examined and in some cases introduced to the design, for example
    1. Rate of change of exit louver deflection for acceleration or deceleration
    2. Flight path angles during descent and aircraft duct angles.

   3. L/C Fan rate of tilt angle during takeoff and landing transition
   4. Rates of deceleration
   5. Control power requirements
   6. Control System requirements

V. Structural weight & Materials (Zutech & I. Spiker)

   A. MAD Report - Initial utilization of San Diego Aircraft Engineering (Ref. 23) Report for Mission Analysis Division, (Ames)
   B. Airframe design programs for aircraft in cruise mode initially, wih V/STOL airframe, propulsion and control requirements integrated into the design later to provede initial weight and c.g. range.

VI. Lift plus Lift-Cruise Fan model Wind Tunnel tests.(Hickey & Kirk)

A large scale transport model with tilting lift-cruise fans and three positions of lift fans mounted on the fuselage forward of the wing are shown in figures 51 and 52. These lift fans represented fold out fans that would fold into the fuselage during normal aircraft flight. The data shown in figure 52b indicate that the least loss of lift due to downwash on the aft wing during transition would occur with the lift fans mounted in the low position on the fuselage. These data were used extensively in the conceptual design studies of the small executive V/STOL normal category aircraft conducted during the past 10 years.

VII. Conversion

With Tilting Lift/Cruise Fans for both lift near hover and horizontal thrust during transition at all velocities and variable blade angle for controlling Lift Fan thrust to low values allows for smooth conversion from cruise mode to powered lift mode at conversion and vice-versa.

Conversion can be made over a speed range from 70 to 120 knots thus allowing large margins in velocity and angle-of-attack for fan or wing stall. Large margins will also exist during decelerating descents with the aircraft paralleled to flight path. This will be discussed further by, Ron Gerdes.

VIII. Control and Stabilization Systems

Control with fixed blade pitch with a gas-coupled (ETC) system compared to variable blade pitch fans with shaft-drive system.

   a. Lower time constant with variable blade pitch fans at constant RPM.

b. If thrust spoiling used on ETC system to improve response time, higher thrust fans and hence power will be required to over come thrust spoilage in control neutral positions for pitch and roll.

c. Detection and anticipation of engine out with ETC System to speed up fans for one engine out condition for retaining vertical thrust component with little or no initial loss.

2. Control and Stabilization system designs looked at based on previous work by Jack Franklin and his group.

a. For the ideal system to allow operation under IFR conditions, a limited authority fly-by-wire digital attitude hold system with flight path and airspeed command control in the loop would be necessary. Automation of some of the parameters during decelerating descents to landing such as power,exit louver and duct tilt, flight path and speed control. Fig. B-10(a&b) and Fig. B-11.

b. During an emergency engine out, lift fan or lift/cruise fan out for control a full authority system should be available.

c. The first series of aircraft would be VFR and perhaps a simpler systems may be adequate which could be studied with the TDA (Technology Demonstrator Aircraft).

d. Jack Franklin will discuss these areas more completely.

IX. Technology Demonstrator Aircraft

A. The geometric size and aerodynamic shape and details would be the same or as close as possible to the Prototype and Productin aircraft.

B. The structural strength of airframe and components would be designed to max speed of about 235 Knots rather than 350 Knots. This corresponds to a dynamic pressure of about 182 pounds per square foot rather than 405 pounds per square foot.

C. The TDA would be designed for 2-place with an instrumentation package for all the initial flight testing to prove the aircraft technically prior to demonstration flying and later flight as a 3-place aircraft with about one half the fuel load of the following production aircraft.

D. These and other simplifications that are weight and cost effective would result in the TDA weight being about 22 to 25% less than the final aircarft.

1. The lift and lift/cruise fans would be designed for the thrust requirements for the final aircraft but flown on the TDA initially at about 75% of the final design thrust of the fans thus requiring considerably

lower initial power requirements as well.

2. As the development testing of the fans was completed to the maximum design value the weight of the aircraft could be increased toward the final production aircraft weight for final evaluation and demonstration of the vertical thrust and control system.

X. Conceptual Design Tradeoffs.
A. Airframe
1. Canard Vs. aft horizontal tail
2. 2,4 and 6-place VTOL aircraft
3. 2/4 and 4/6 V/STOL place aircraft
4. TDA - 1 or 2-place VTOL with instrumentation package
B. Propulsion System
1. Gas coupled vs. shaft driven transmission systems
2. Fan sizing and power requirements
3. Reciprocating vs. turbo shaft engines
a. 2-cycle, 4-cycle and Wankel engines
b. Twin Pack turbo-shaft engines
4. 2,3 or 4 engines
5. Remote engines vs. integral hi-bypass engines
6. 2 LF's + Cruise Fans vs. 2 LF's vs. 2 L/C Fans.
C. Safety vs. Complexity
1. One engine out
2. One lift fan or lift cruise fan out
D. Conversion and transition control and performance with variable blade pitch fans and more or a dual change of lift fan thrust and less aircraft angle-of-attack change with time over conversion speed range.
E. Lift fan inlet guide vanes, closure doors and rate of inlet opening as closure during conversion.

XI. Potential military use.
A. V/STOL Trainer, 2-place (TDA)
B. VIP and other transportation to undeveloped areas as 4/6-place V/STOL 300 MPH short range aircraft. Production aircraft.

TABLE I.- GRUMMAN 698 - DESCENT ANGLES FOR THREE NACELLE TILT ANGLES

Nacelle Tilt Angle (Velocity*)	Descent, γ, No Deceleration, or γ Margin	Descent, γ, No Deceleration, -3, γ, Margin	Descent, γ, -0.1"g" Deceler And -3° Margin
50° (75 to 88k)	-8.8° to -15.8°	-5.8° to -12.8°	0° to -7.0°
68° (65 to 80k)	-10.7° to -15.2°	-7.7° to -12.2°	-1.9° to -6.4°
68° (~ 60k)	-14.5° to -19.2°	-11.5° to -16.2°	-5.7° to -10.4°

* Velocity in knots.

REFERENCES

1. Gerdes, Ronald M. and Hynes, Charles S.: Factors Affecting Handling Qualities of a Lift-Fan Aircraft during Steep Terminal Area Approaches. NASA TM X-62,424.

2. Holhauser, Curt A., Morello, S.A., Innis, Robert C. and Patton, James M.: A Flight Evaluation of a VTOL Jet Transport under Visual and Simulated Instrument Conditions. TN D-6754.

3. Yaggy, Paul F. and Mort, Kennth W.: A Wind-Tunnel Investigation of a 4-Foot-Diameter Ducted Fan Mounted on the Tip of a Semispan Wing. NASA TN D -776.

4. Yaggy, Paul F. and Goodson, Kenneth W.: Aerodynamics of Tilting Ducted Fan Configuration. NASA TN D-785.

5. Mort, Kenneth W. and Yaggy, Paul F.: Aerodynamics Characteristic of a 4-Foot-Diameter Ducted Fan Mounted on the Tip of a Semispan Wing. NASA TN D-1301.

6. Mort, Kenneth W.: Performance Characteristics of a 4-Foot-Diameter Ducted Fan at Zero Angle-of-Attack for Several Fan Blade Angles. NASA TN D-3122.

7. Mort, Kenneth W. and Gamse, Burt: A Wind Tunnel Investigatin of a 7-Foot-Diameter. NASA TN D-4142

8. Giulianetti, Demo J., Biggers, James C. and Maki, Ralph L.: Longitudinal and Lateral-Directional Aerodynamic Characteristics of a Large-Scale, V/STOL Model withe Four Tilting Ducted Fans Arranged in a Dual Tandem Configuration. NASA TN D-3490.

9. Giulianetti, Demo J., Biggers, James C. and Maki, Ralph L.: Longitudinal Aerodynamic Characteristics in Ground Effect of a Large-Scale, V/STOL Model with Four Tilting Ducted Fans Arranged in a Dual Tandem Configuration. NASA TN D-4218.

10. Mort, Kenneth W. and Gamse, Berl: A Wind-Tunnel Investigation of a 7-Foot-Diameter Ducted Propeller. NASA TN D-4142.

11. Greif, Richard K., Kelly, Mark W. and Tolhurst, William A.: Wind Tunnel Tests of a Circular Planform in Proximity to the Ground. NASA TN-317.

12. Greif, Richard K., and Tolhurst, William H.: Large-Scale Wind Tunnel Tests of a Circular Planform with Peripheral Jet for Lift, Thrust and Control. NASA TN D-1432.

13. Giulianett, Demo J., Biggers, James C. and Corsiglia, Victor R.: Wind-Tunnel Test of a Full-Scale, 1.1 Pressure Ratio, Ducted Lift-Cruise Fan. NASA TN D-2498

14. Kirk, Jerry V. and Barrack, Jerry P.: Reingestion Characteristics and Inlet Flow Distortion of V/STOL Lift-Engine Fighter Configuration. NASA TN D-7014.

15. Full-Scale Tests of Grumman Design 698-411 Tilt Nacelle V/STOL Model at NASA Ames, Grumman Aerospace Corporation Report for Naval Airsystem Command, N 00019-80-C-0116.

16. Hickey, David H, and Hall, Leo P.: Aerodynamic Characteristics of a Large-Scale Model with Two High Disk-Loading Fans Mounted in the Wing. NASA TN D-1650.

17. Kirk, Jerry V., Hickey, David H. and Hall, Leo P.: Aerodynamic Characteristics of a Full-Scale Fan-In-Wing Model Including Results in Ground Effect with Nose-Fan Pitch Control. TN D-2368.

18. Hall, Leo P., Hickey, Davie H., and Kirk, Jerry V.: Aerodynamic Characteristics of a Large-Scale VSTOL Transport Model with Lift and Lift Cruise Fans. NASA TND-4092.

19. Hodder, Brent K., Kirk, Jerry V. and Hall, Leo P.: Aerodynamic Characteristics of a Large Scale Model with Lift Fans Mounted in a 5% Thick Triangular Wing. NASA TND-7031.

20. Lampkin, Bedford A. and Staff: Propulsion System Project Office, Lewis, Analysis of Propulsion System for V/STOL Lift/Cruise Fan Research and Technology Aircraft. NASA TMX-73,237.

21. Kirk, Jerry V., Hodder, Brent K. and Hall, Leo P.: Large-Scale Wind Tunnel Investigation of a V/STOL Transport MOdel with Wing Mounted Lift Fans and Fuselage Mounted Lift Cruise Engines for Propulsion. NASA TND-4233.

22. Kirk, Jerry V., Hall, Leo P. and Hodder, Brent K.: Aerodynamics of Lift Fan V/STOL Aircraft. NASA TMX-62,086.

23. San Diego Aircraft Engineering Inc., Potential Structural Materials and Design Concepts for Light Airplanes. NASA CR-73258, Oct 1968

24. Franklin, J.A., Innis, R.C., Hardy C.H. and Stephenson, J.D. Design Criteria for Flight Path and Airspeed Control for the Approach and Landing of STOL Aircraft. NASA TP-1911.

25. Franklin, J.A. and Hunes, C.S. Flight Evaluation of Highly Augmented Controls and Electronic Displays for Precision Approach and Landing of Powered Lift Aircraft. AIAA Journal of Guidance Control and Dynamics Vol. 12 No. 4 July-Aug. 1989.

26. Franklin, J.A., Stortz, M.W., Englland, S.A., Hardy, G.H., Martin, J.L. and Gerdes, R.M. Simulation Evaluation of Transition and Hover Flying Qualities of Mixed-Flow, Remote-Lift STOVOL Aircraft. SAE T.P.S. 892284 Sept.25-28, 1989.

27. Franklin, J.A. and Engelland, S.A. Design and Piloted Evaluation of Integrated Flight/propulsion Controls for STOVL Aircraft. AIAA -91-3108 Sept. 23-25, 1991.

28. Cooper, G.E. and Harper, R.P. The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities NASA TN-5153.

29. Holzhauser, C.A., Quigley H. and Innis, R.C. - NASA TN-5594

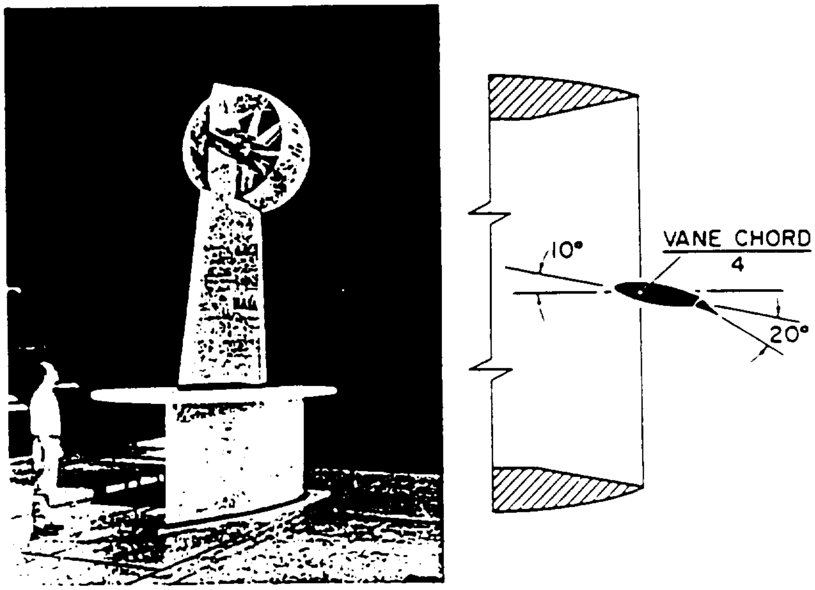


Figure 1. Model with duct exit vane.

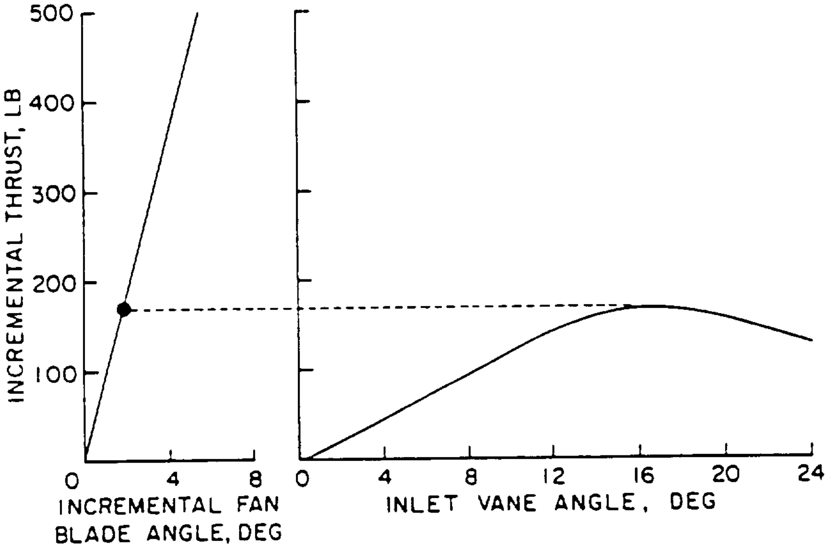


Figure 2. Two methods of thrust control.

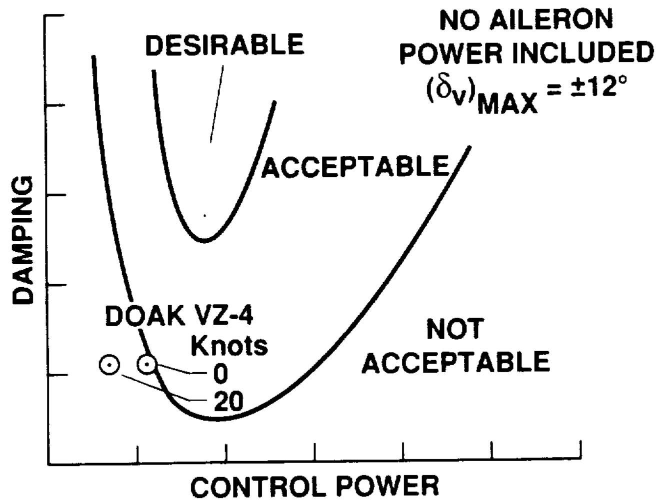


Figure 3. Lateral control available with inlet vanes.

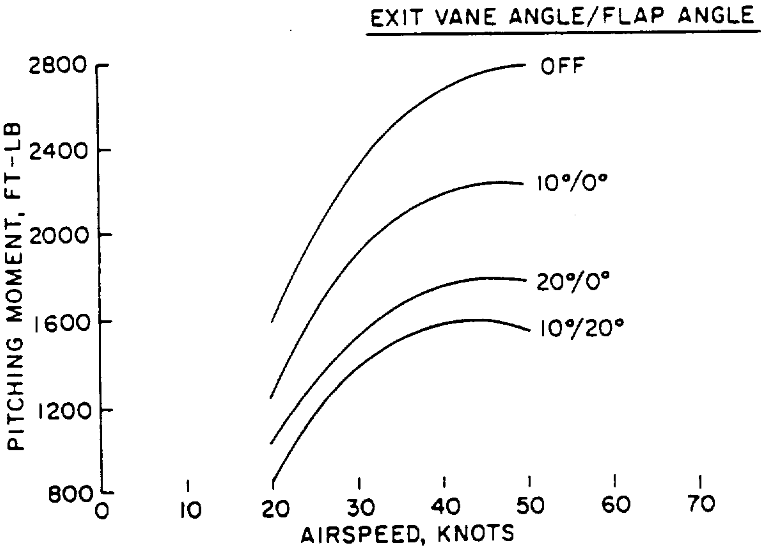
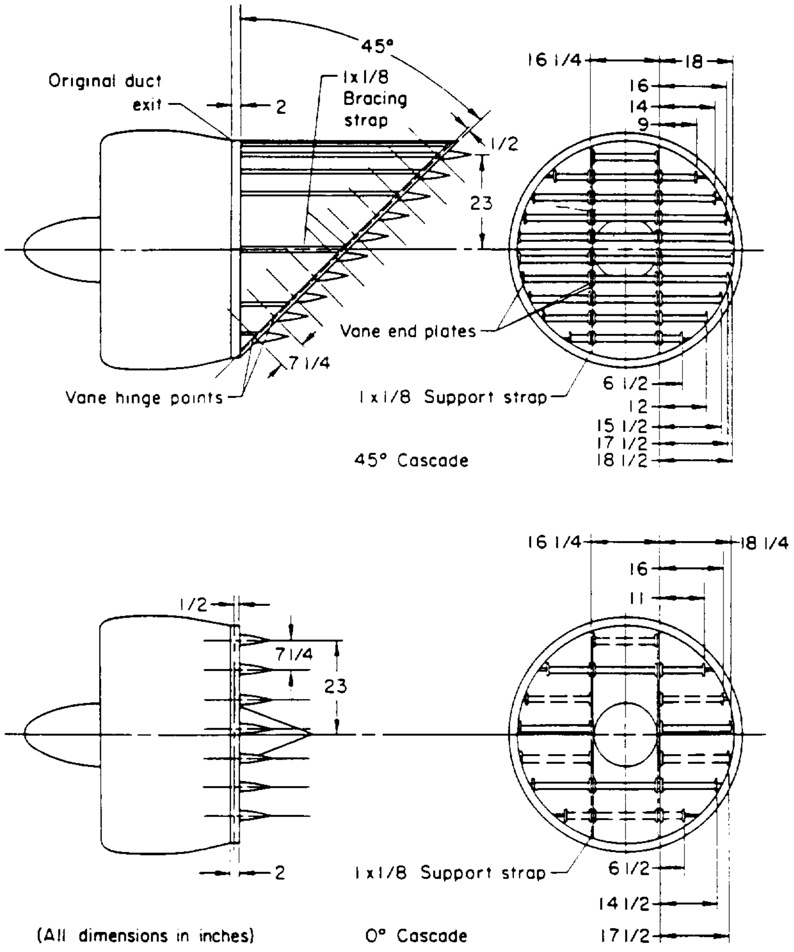


Figure 4. Reduction in pitching moment due to duct exit vane deflection.



(a) Vane mounting detail

Figure 5. Exit vane dimensions and arrangement.

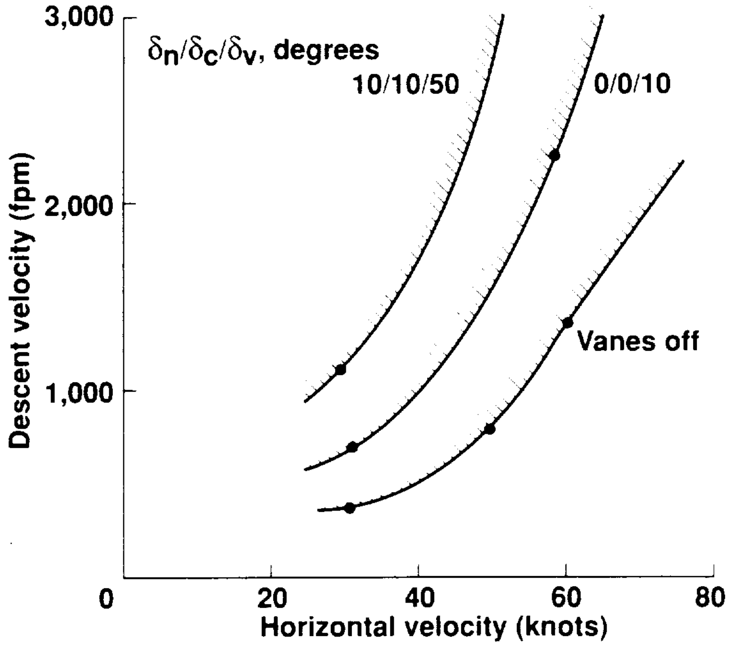


Figure 6. Descent velocity boundary due to stall of the upstream duct lip for the vehicle at 0° wing angle of attack using the 0° cascade with a vane chord-to-gap ratio of 0.83.

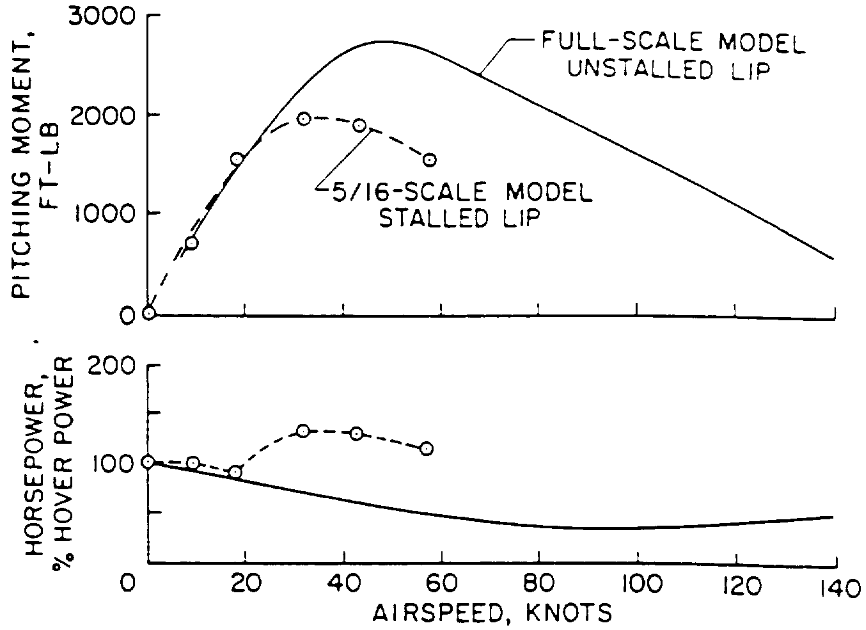
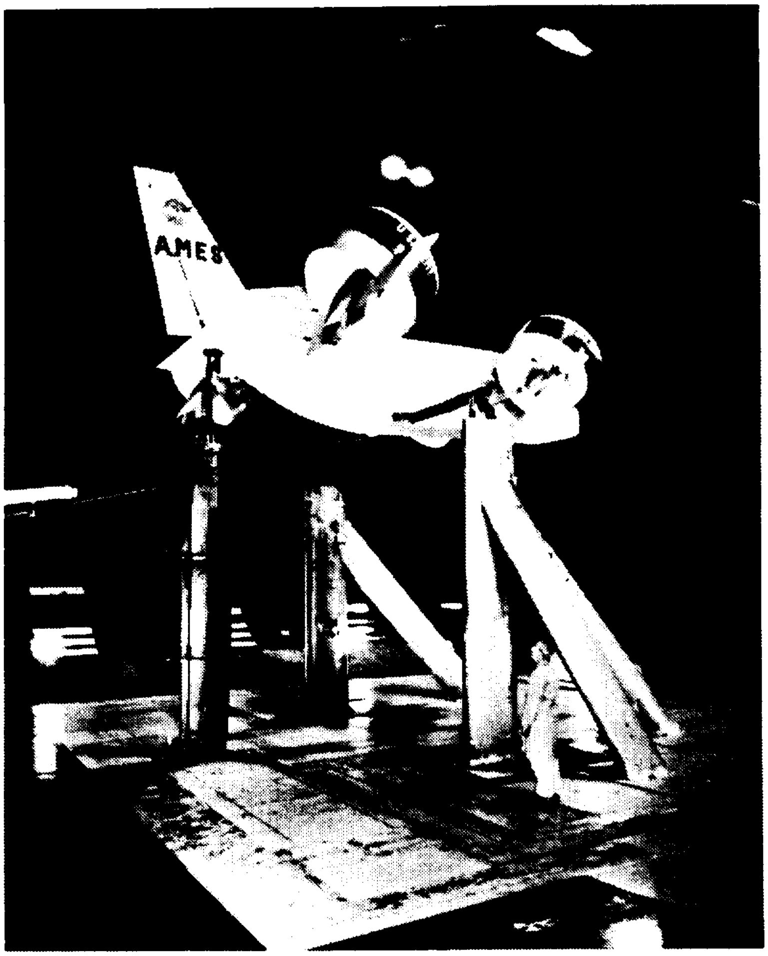
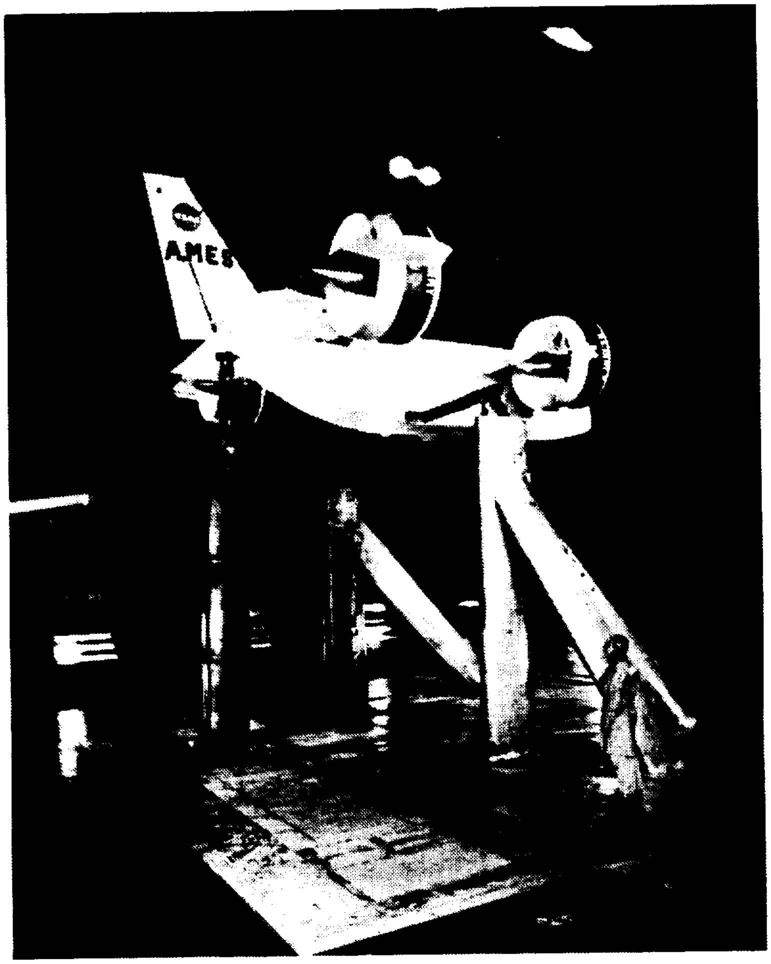


Figure 7. Effect of lip stall on pitching moment and horsepower.



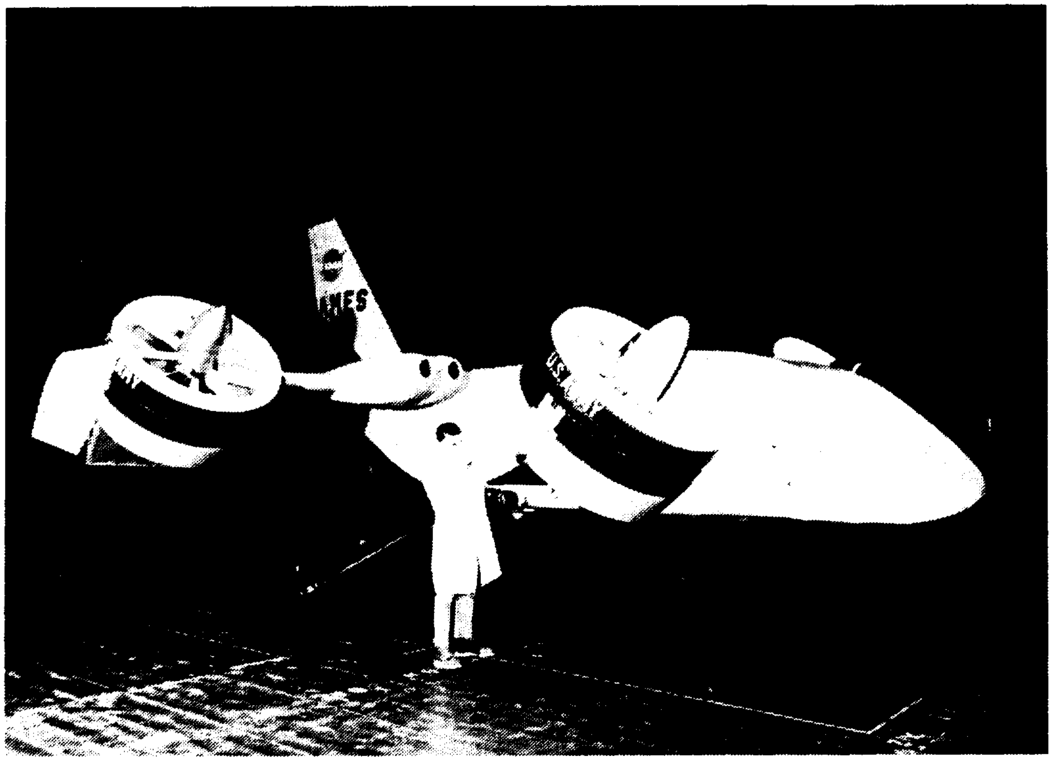
(a) Transition duct configuration: $\delta_D = 45°$, $\delta_{e_f}/\delta_{e_a} = -20°/20°$

Figure 8(a). X-22 model mounted on main struts in 40 × 80 ft wind tunnel.



(b) Cruise duct configuration: $\delta_{D_f}/\delta_{D_a} = 5°/0°$, $\delta_{e_f}/\delta_{e_a} = 0°/0°$

Figure 8(b). X-22 model mounted on main struts in 40 × 80 ft wind tunnel (concluded).



$\delta_D = 45°, \delta_{e_f}/\delta_{e_a} = -20°/20°$

Figure 9. X-22 model mounted on variable height ground effect struts.

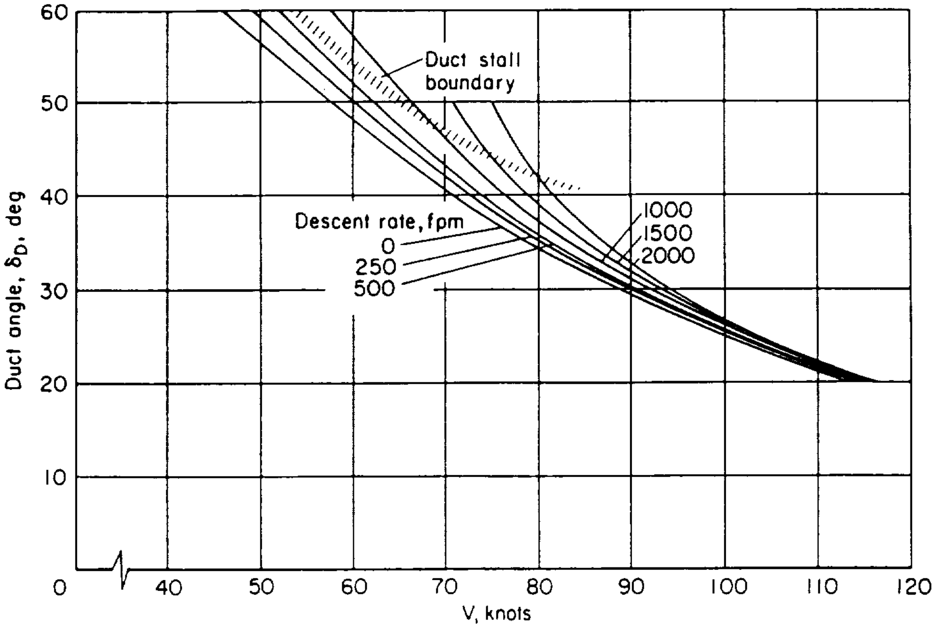


Figure 10. Maximum descent velocities as limited by front duct stall; pitching moments trimmed, lift = 6500 lb, α = 0°.

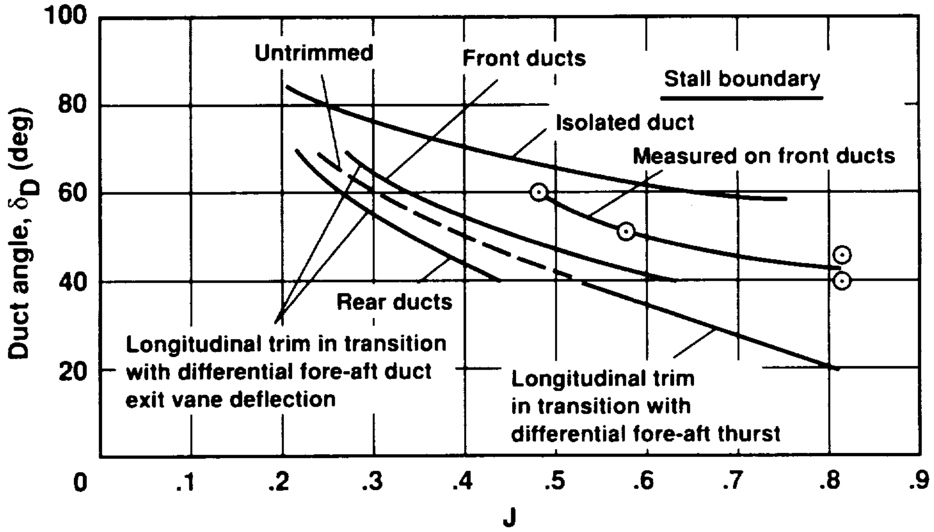
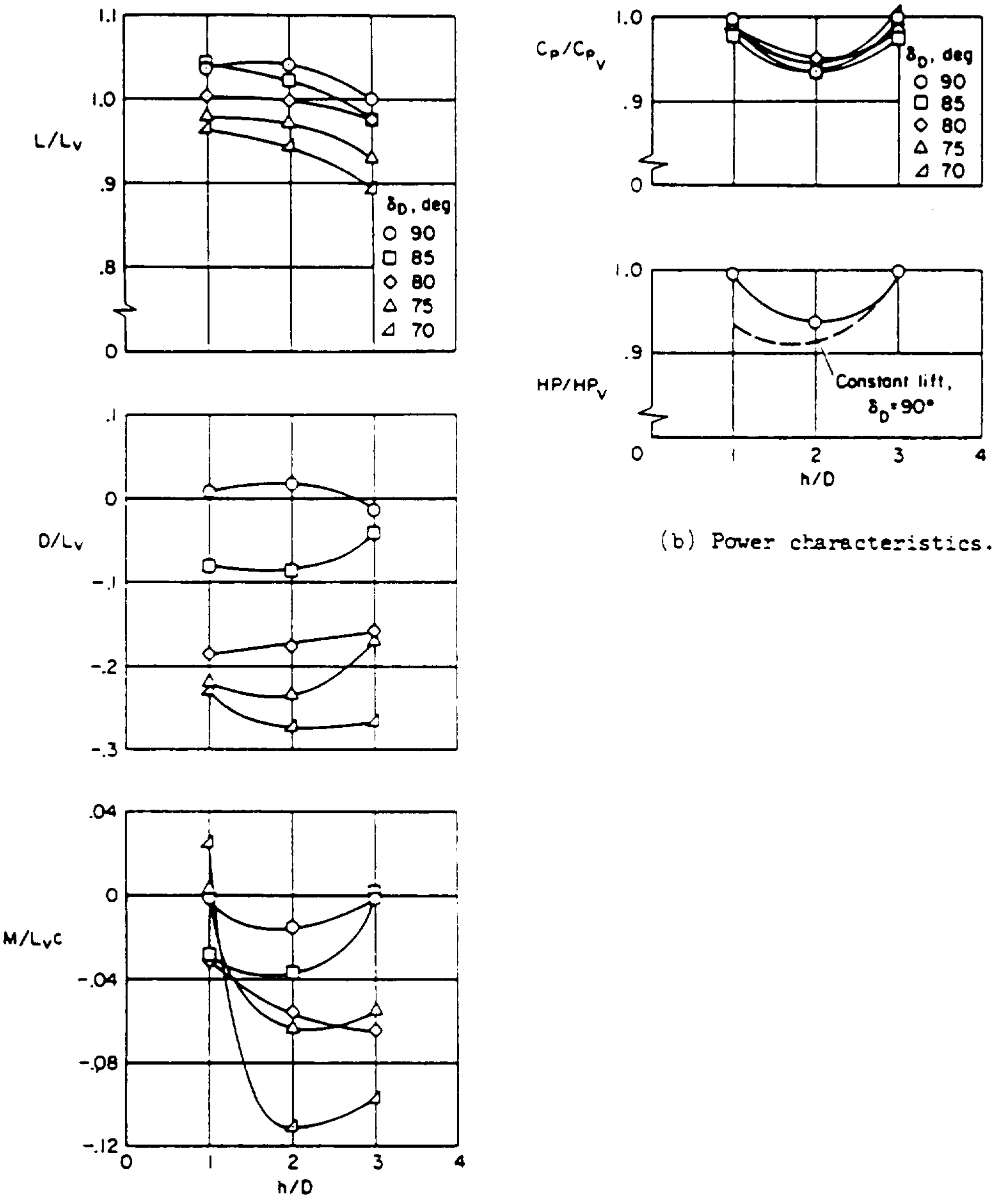


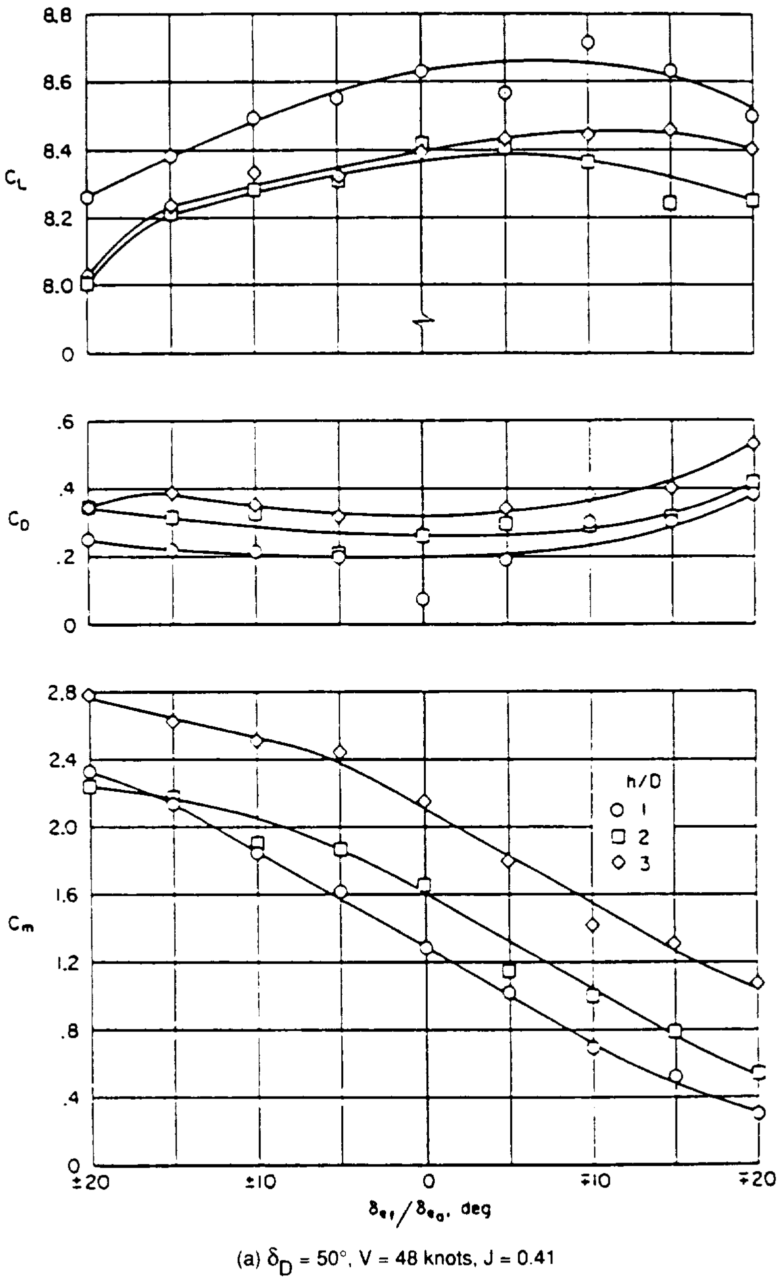
Figure 11. Estimated duct stall margins at level, unaccelerated transition flight conditions; lift = 6500 lb, α = 0°.



(a) Longitudinal aerodynamic characteristics.

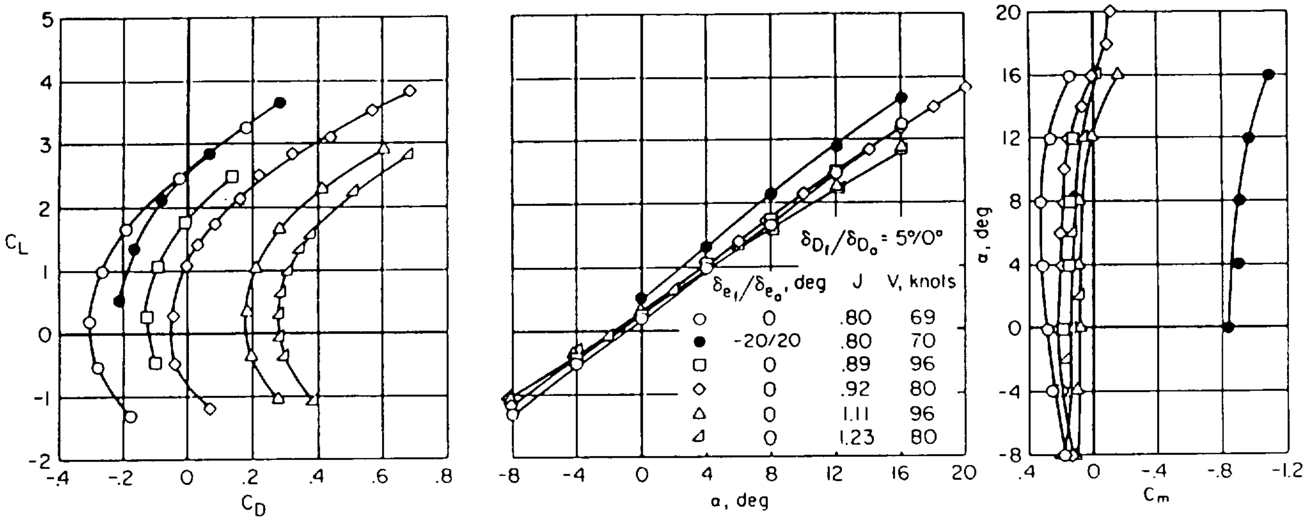
(b) Power characteristics.

Figure 12. Performance at hover and zero forward speed; $\alpha = 0°$, N = 3020 rpm, $\delta_{e_f}/\delta_{e_a}$.



(a) δ_D = 50°, V = 48 knots, J = 0.41

Figure 13. Longitudinal pitch control effectiveness of differential fore-aft duct exit vane deflection; $\alpha = 0°$.



(a) Cruise duct configuration.

Figure 14. Longitudinal aerodynamic characteristics of the model with differential fore-aft duct incidence settings; $\beta = 0°$.

3/4 rear view with duct at 0° angle of attack

Figure 15. Hamilton standard 7-ft diameter ducted fan.

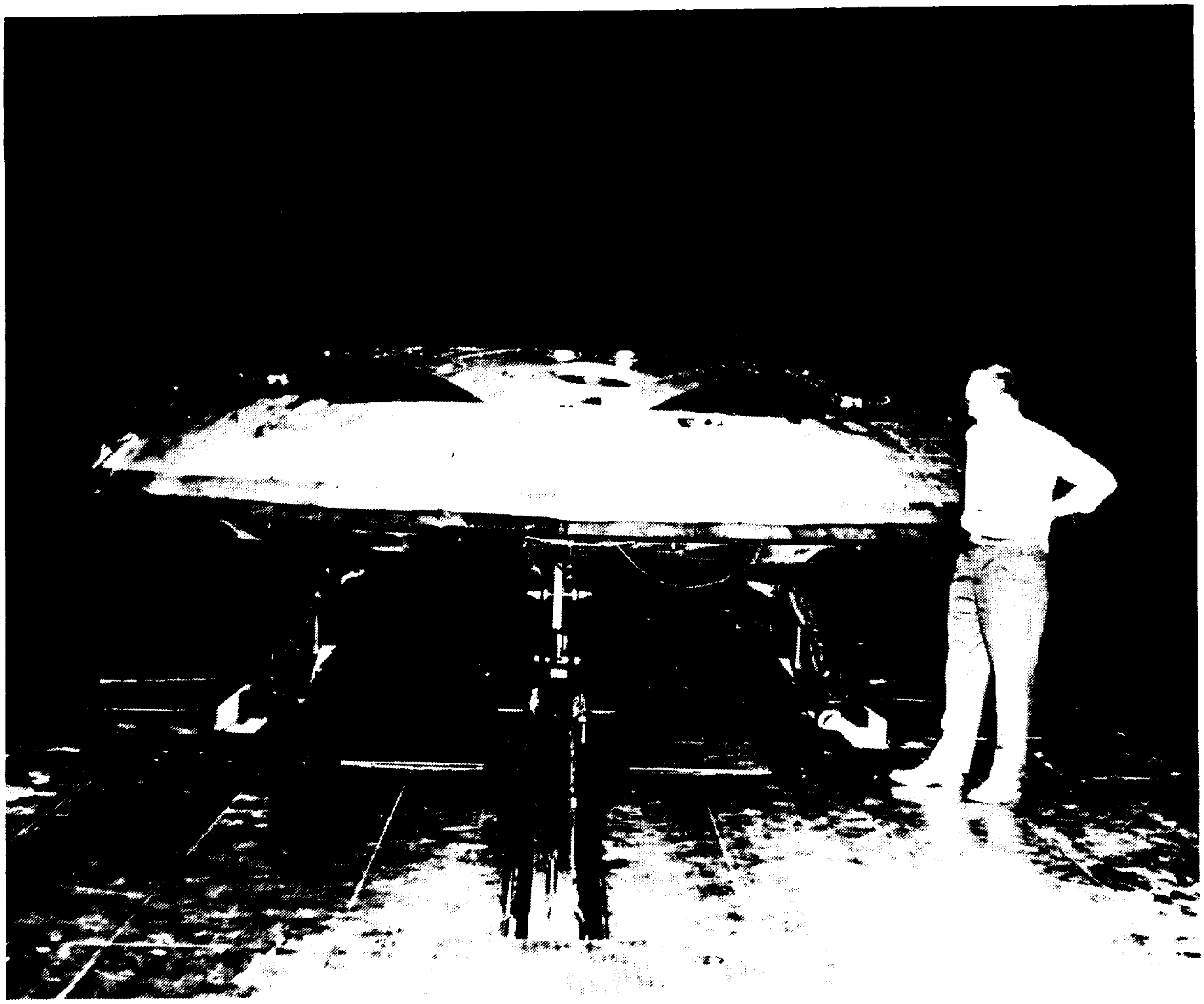


Figure 16(a). Rear view at minimum test height.

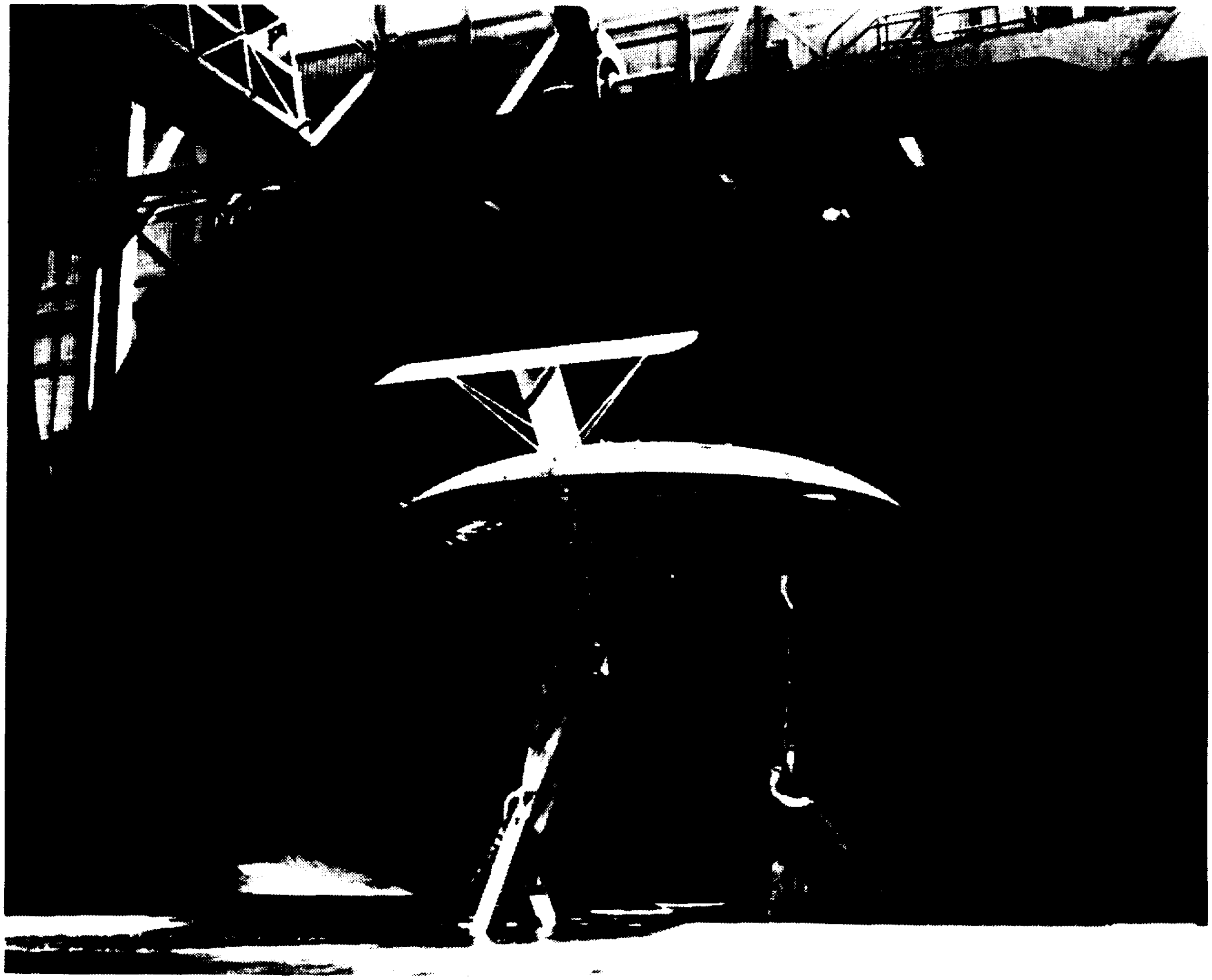
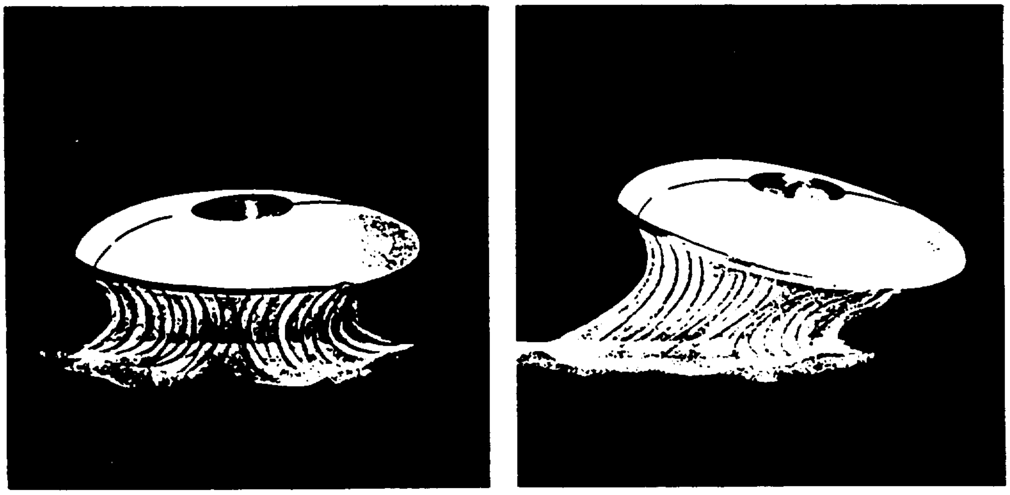
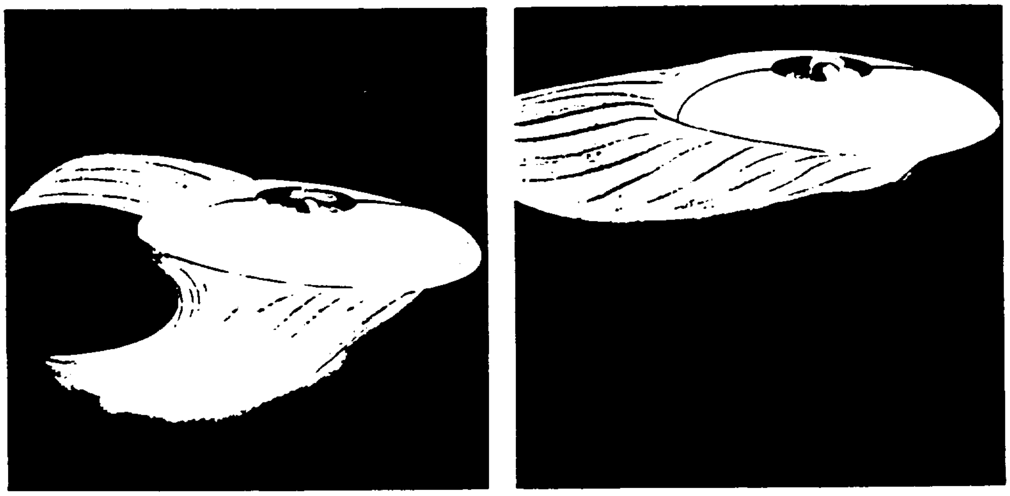


Figure 16(b). Three-quarter rear view at maximum test height (with horizontal tail) (concluded).



(a) **Hover configuration**
Transition doors closed.
Focusing ring neutral.
Pitch and roll controlled by
movement of focusing ring.

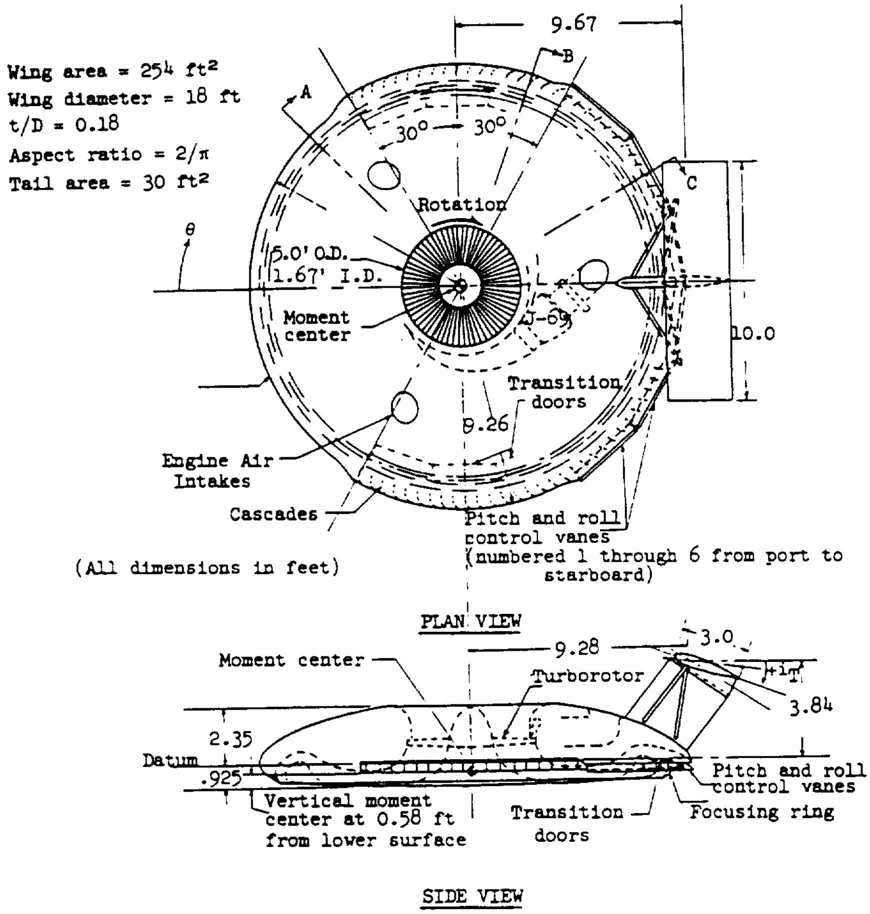
(b) **Initial transition stage**
Transition doors closed.
Focusing ring moved aft, but
with reserve travel for pitch
and roll control.



(c) **Mid-transition stage**
Rear transition doors closed.
Pitch and roll controlled by
movement of focusing ring.

(d) **Cruise flight out of ground effect**
All transition doors open.
Pitch and roll controlled by
movable vanes located in rear
120° of thrust nozzle.

Figure 17. Sketch of the jet flow regimes produced by the control system during various flight phases.



(a) General details.

Figure 18(a). Geometrical details of the aircraft.

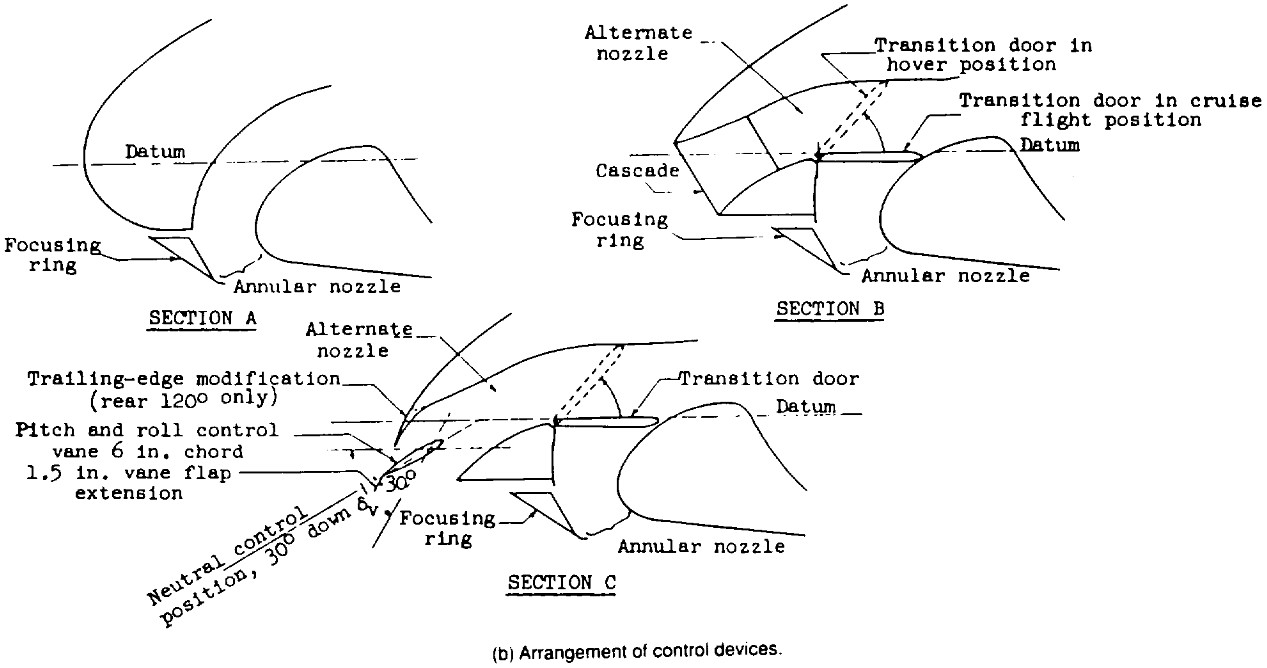


Figure 18(b). Arrangement of control devices (concluded).

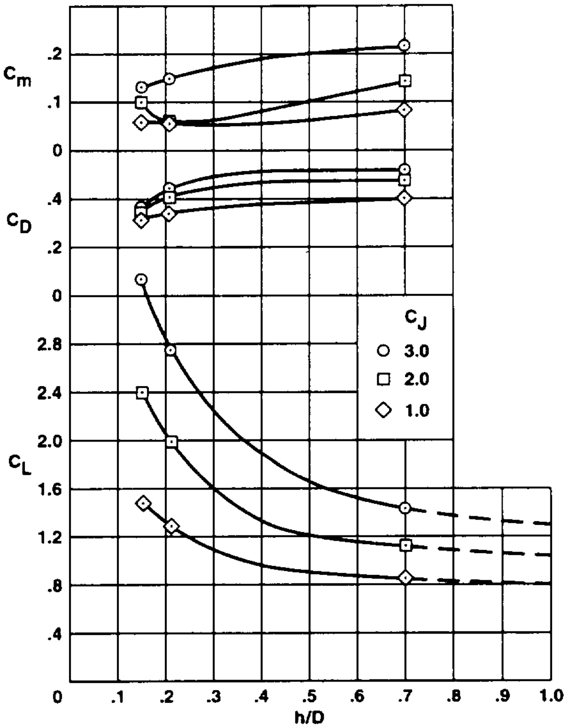


Figure 19. Effect of ground height on the longitudinal characteristics of the hover configuration at $\alpha = 0$ and $J_E = 0$.

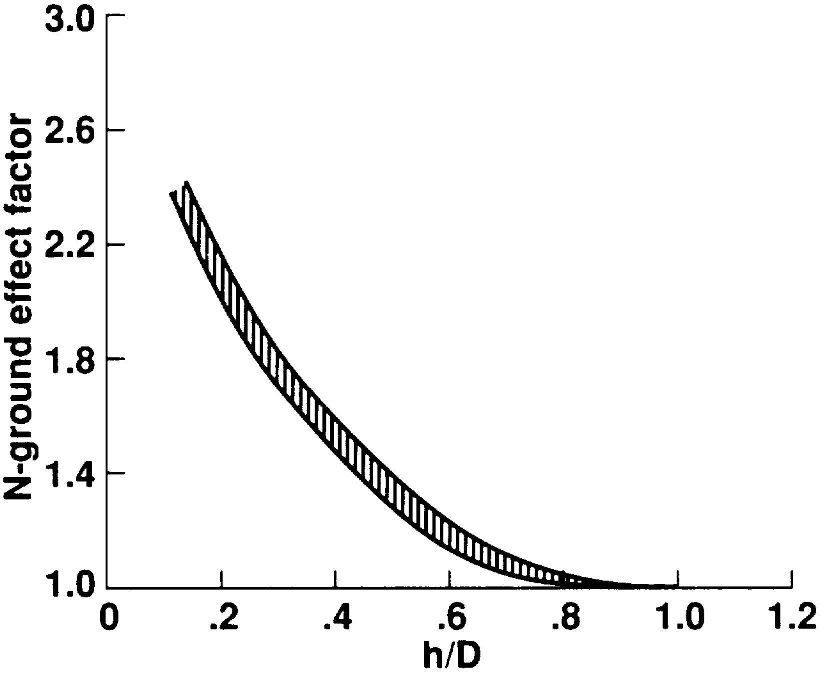
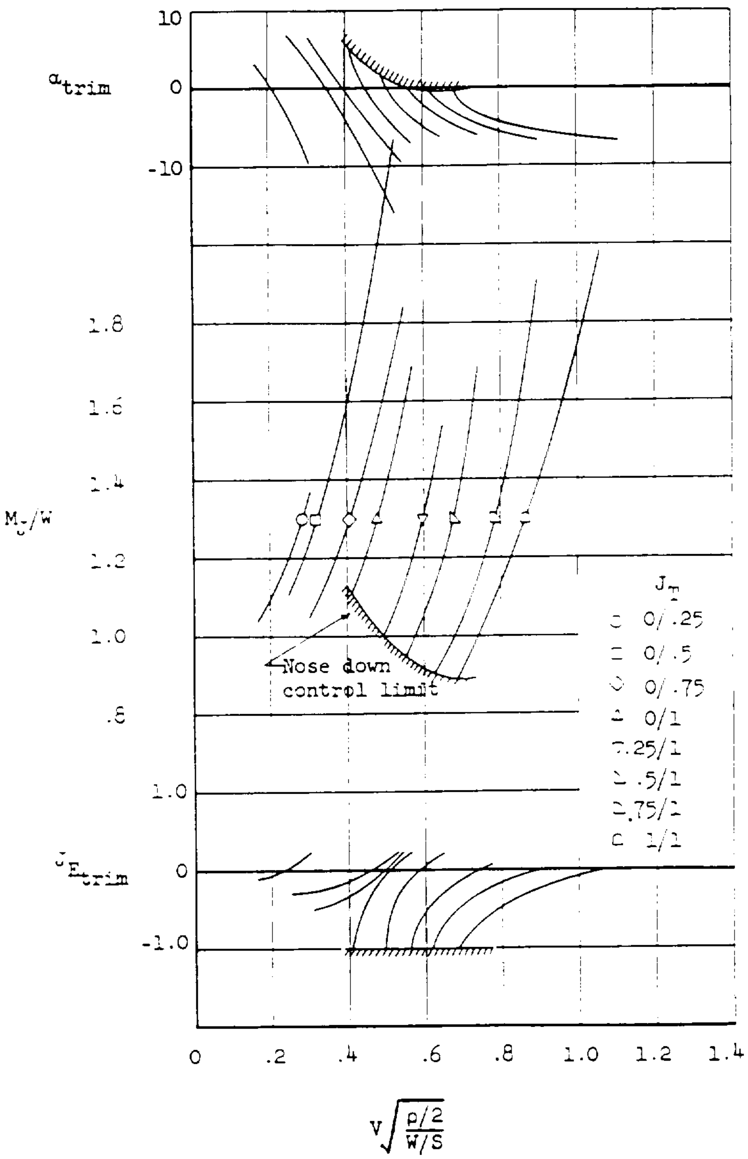
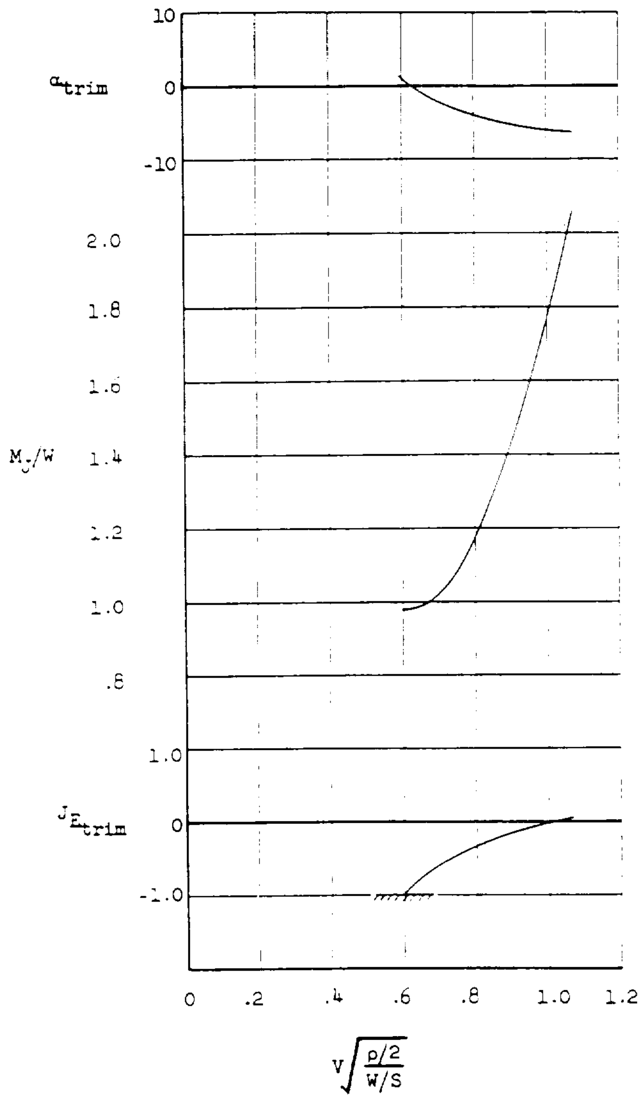


Figure 20. Variation of ground effect with height to diameter ratio.



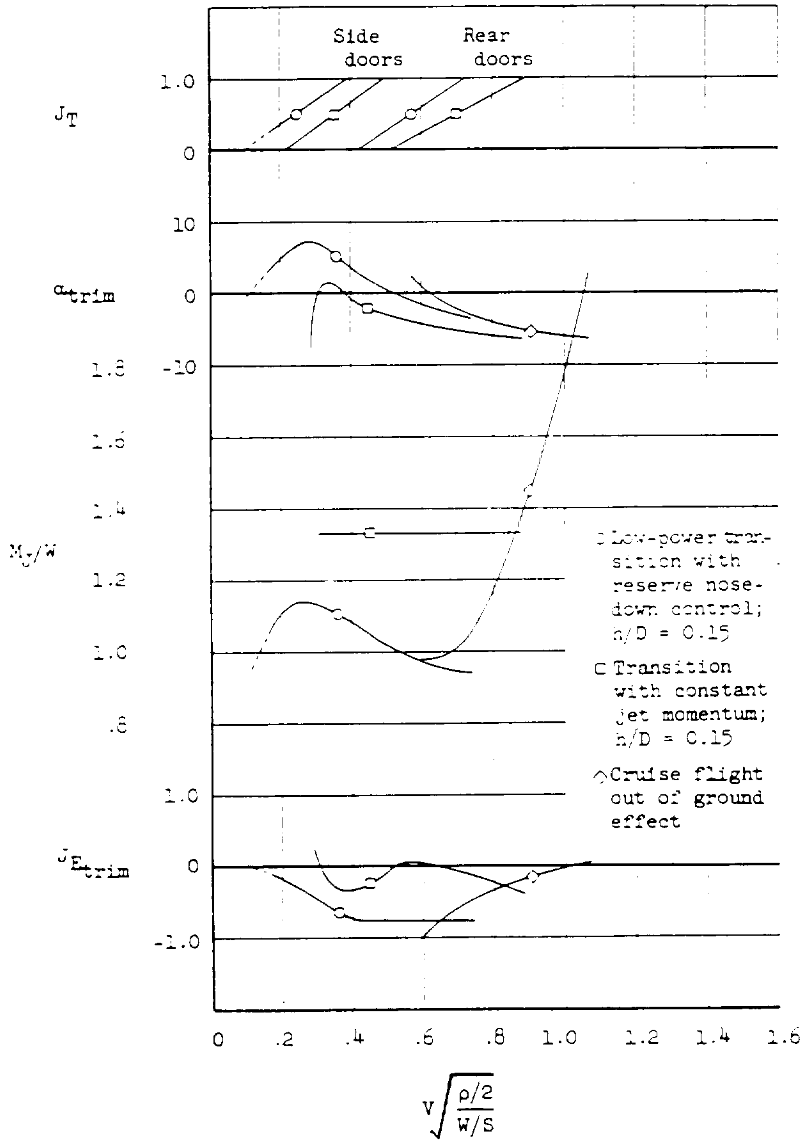
(a) For transition configurations at h/D = 0.15.

Figure 21(a). Performance summary showing the variation of basic aircraft variables required for trimmed, level, unaccelerated flight. Tail off configuration with modified trailing edge.



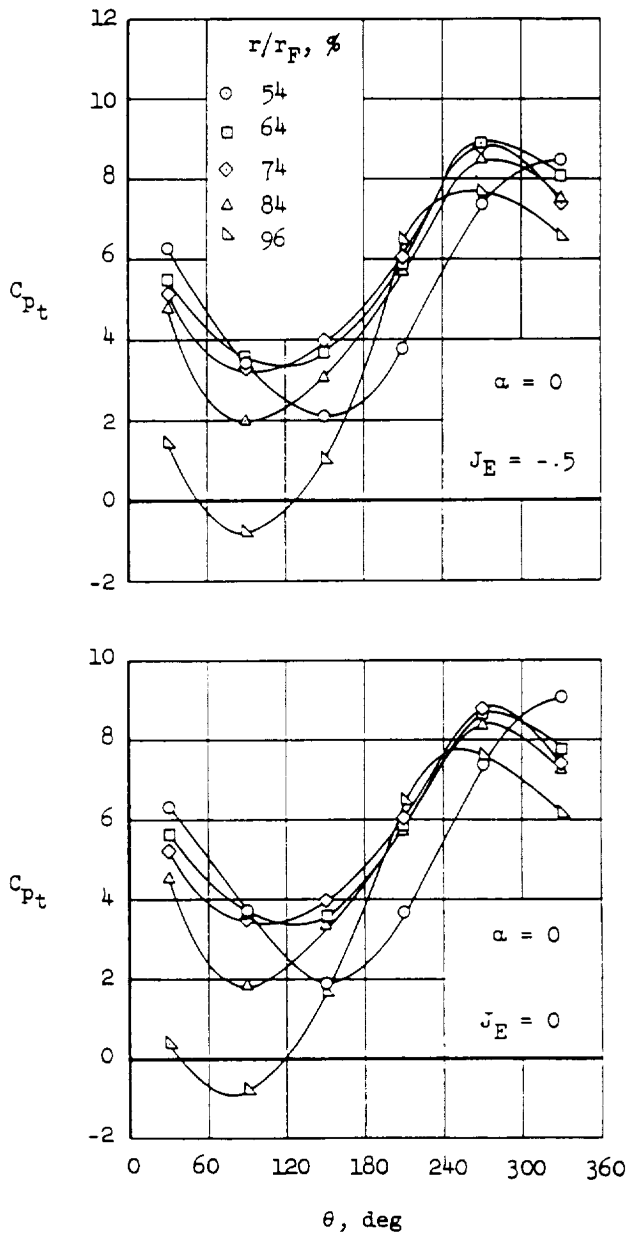
(b) For the cruise configuration out of ground effect (h/D = 0.70).

Figure 21(b). Performance summary showing the variation of basic aircraft variables required for trimmed, level, unaccelerated flight. Tail off configuration with modified trailing edge (continued).



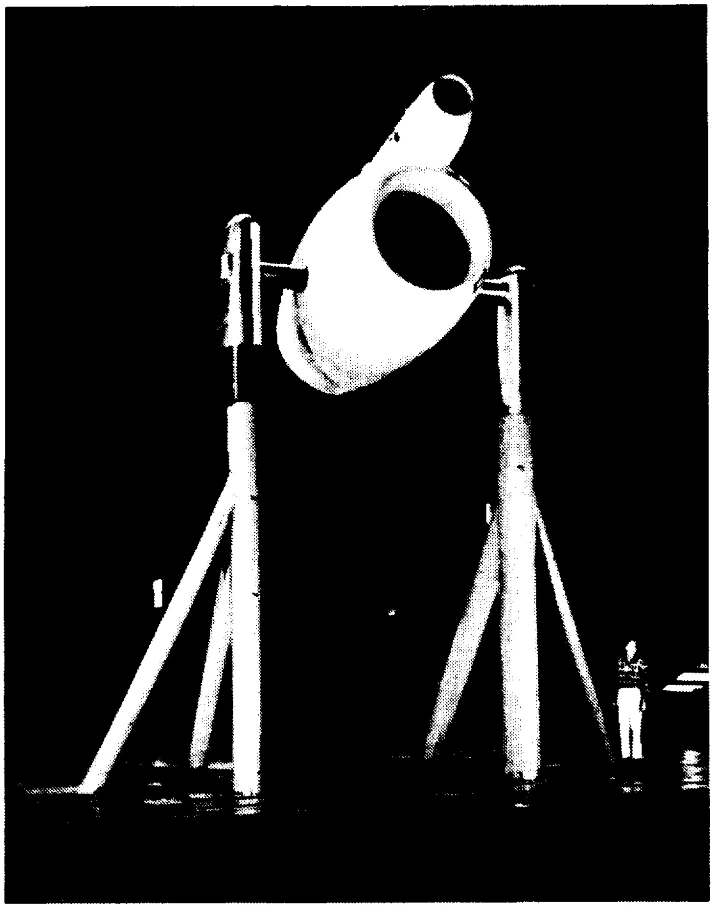
(c) Cross plots of figure 4(a) showing two variations of trim conditions for transition flight.

Figure 21(c). Performance summary showing the variation of basic aircraft variables required for trimmed, level, unaccelerated flight. Tail off configuration with modified trailing edge (concluded).



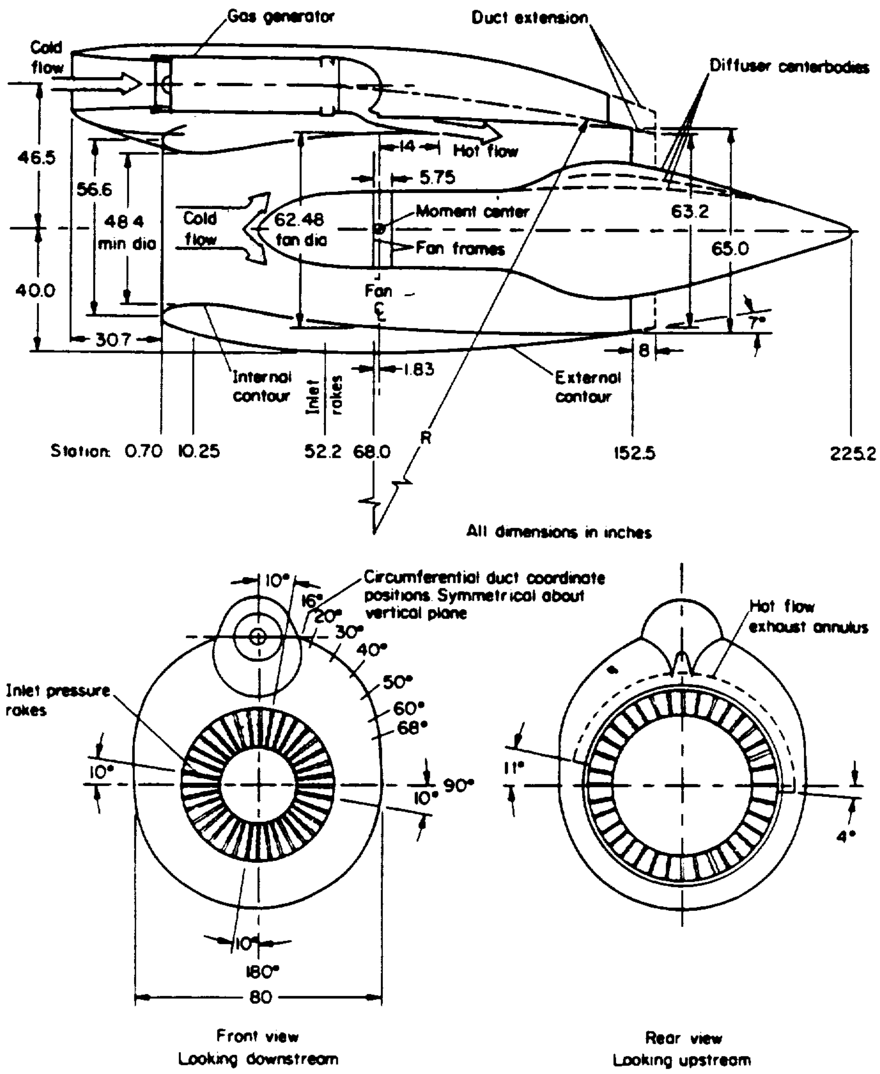
(c) C_J = 0.45 - Concluded.

Figure 22. Duct losses.



Front view of model

Figure 23. Model mounted in the test section of the Ames 40 × 80 wind tunnel.



Exit area sq ft	Exit area Ratio
19.57	1.00
15.67	.80
12.16	.62
18.28*	.93
14.44*	.74
10.95*	.56

*Lengthened duct

Figure 24. Model dimensions and geometry.

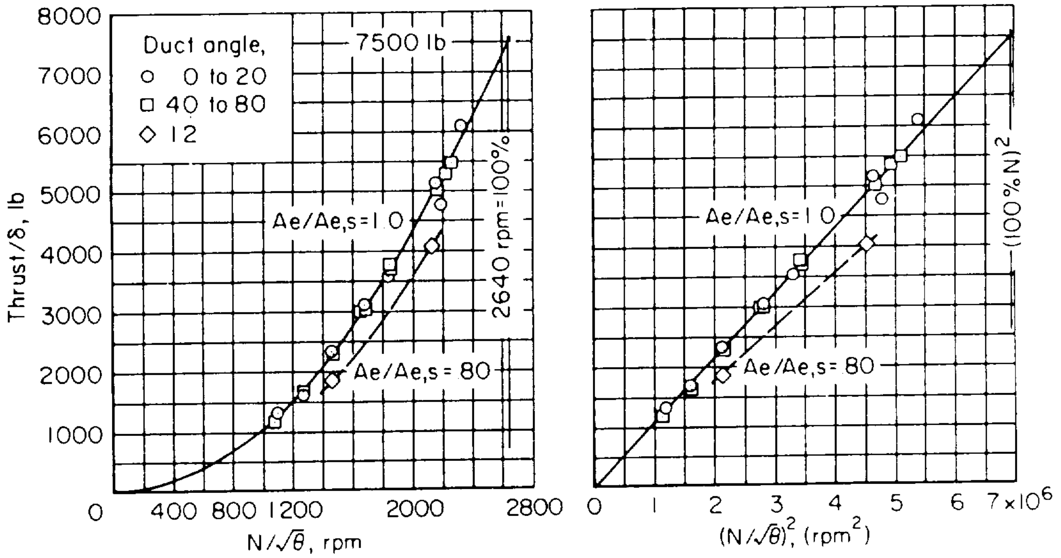
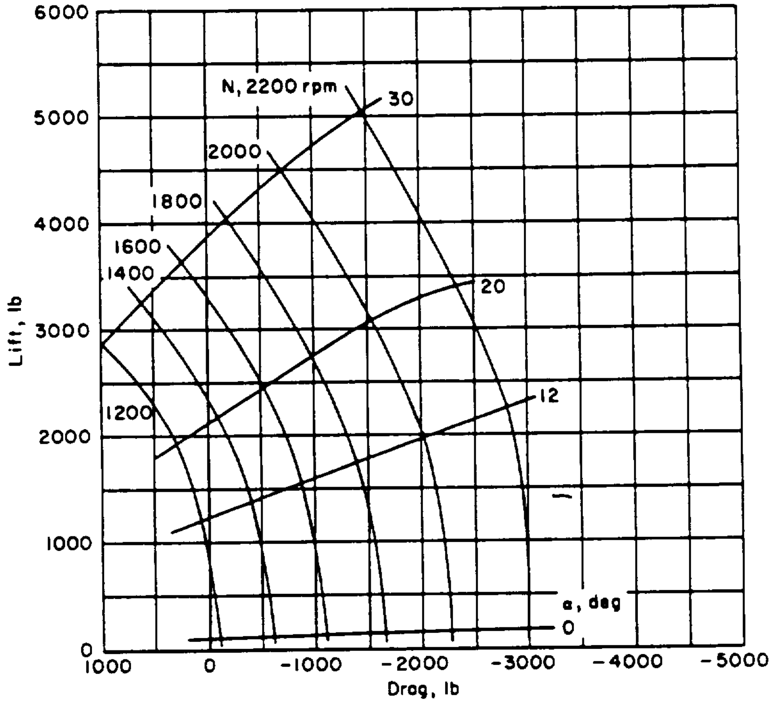
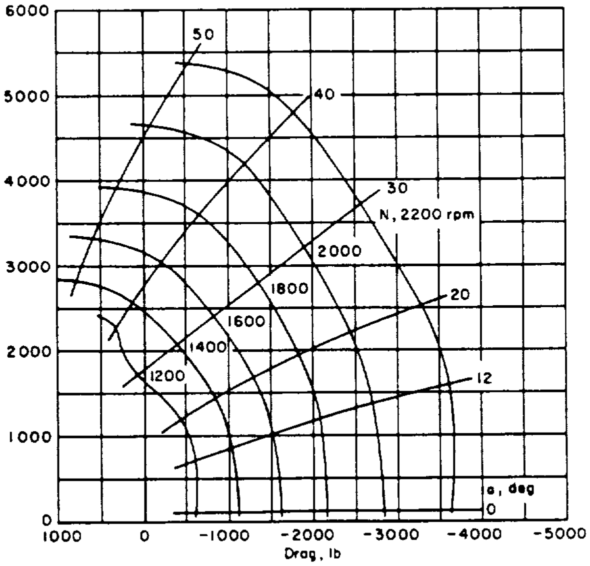


Figure 25. Fan performance at zero forward speed with the fan installed in the duct.



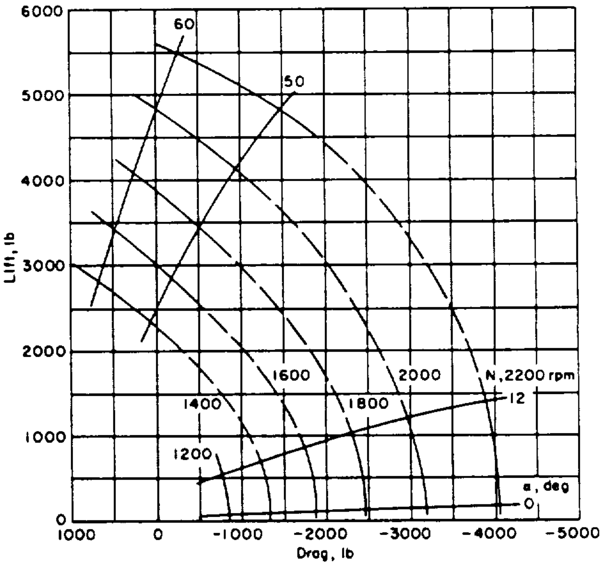
(a) V_{∞} = 121 knots.

Figure 26(a). Longitudinal force characteristics of the model; $A_e/A_{e,s}$ = 1.0.



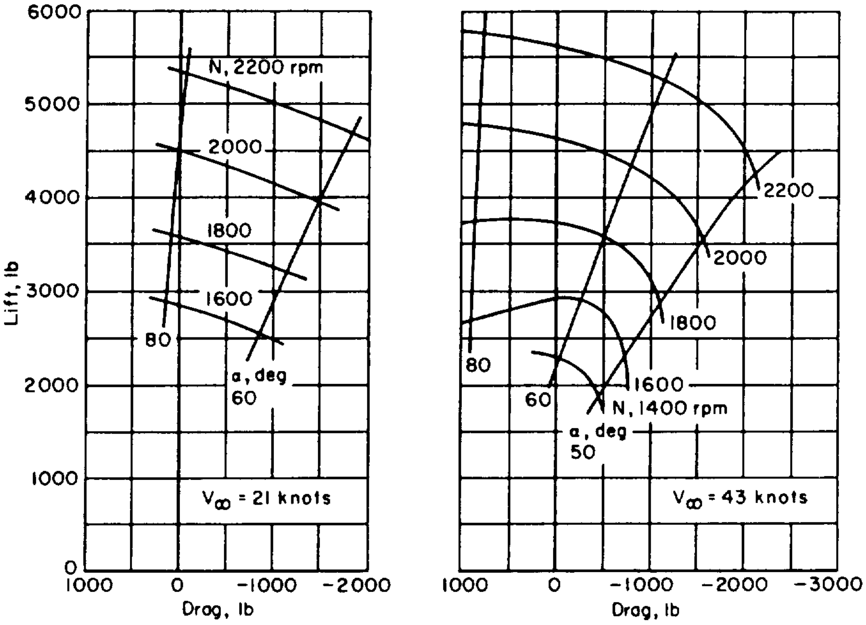
(b) V_∞ = 80 knots

Figure 26(b). Longitudinal force characteristics of the model; $A_e/A_{e,s}$ = 1.0.



(c) V_∞ = 61 knots

Figure 26(c). Longitudinal force characteristics of the model; $A_e/A_{e,s}$ = 1.0 (continued).



(d) V_∞ = 21 and 43 knots

Figure 26(d). Longitudinal force characteristics of the model; $A_e/A_{e,s}$ = 1.0 (concluded).

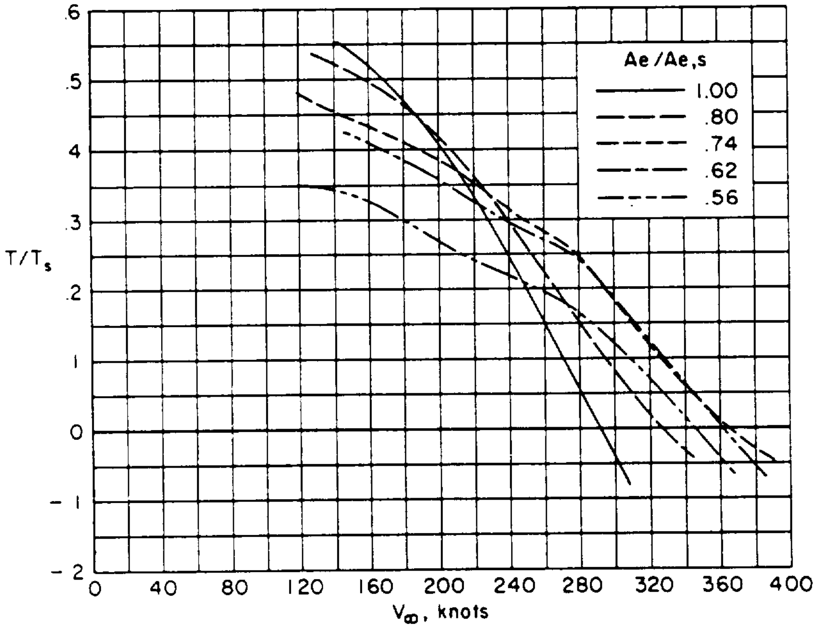


Figure 27. Model performance showing the effect of duct exit variation on net thrust with forward speed; α = 0°, N = 100 percent.

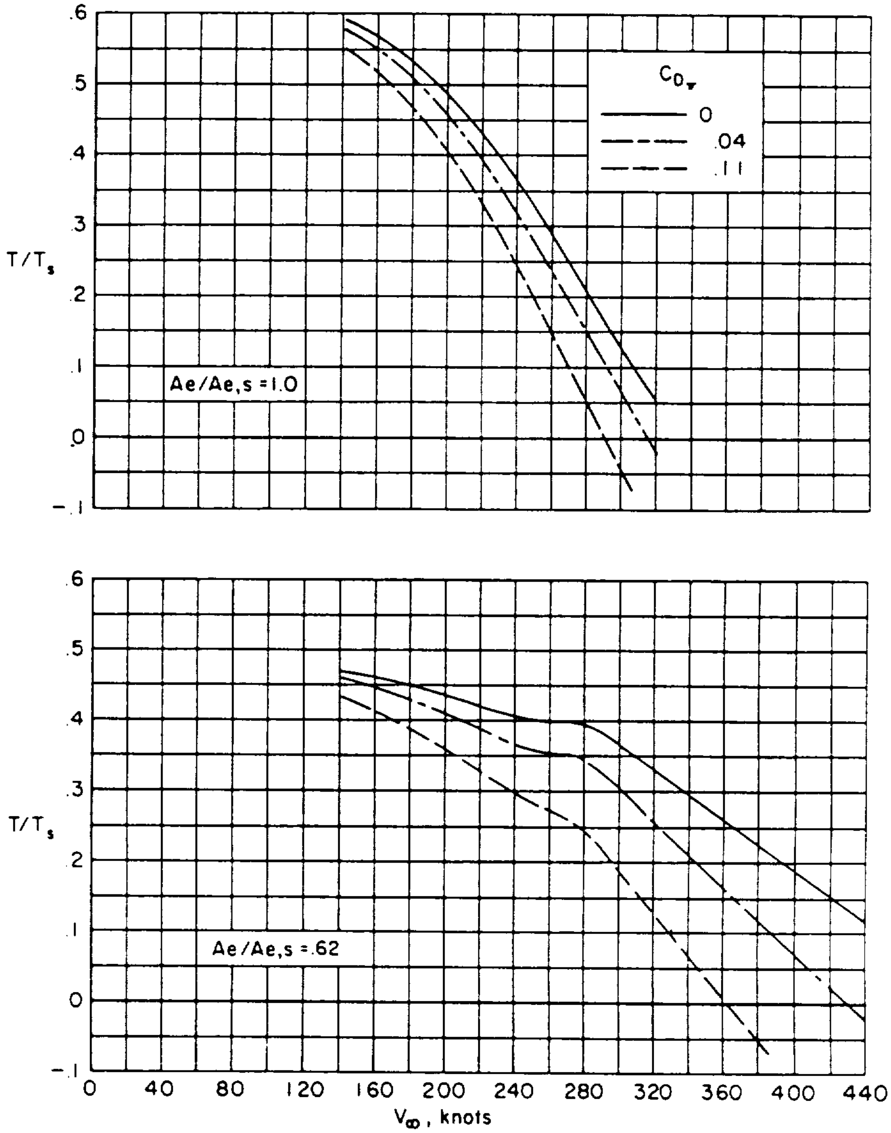


Figure 28. Model performance showing the effect of external duct drag variation on net thrust with forward speed; α = 0°, N = 100 percent.

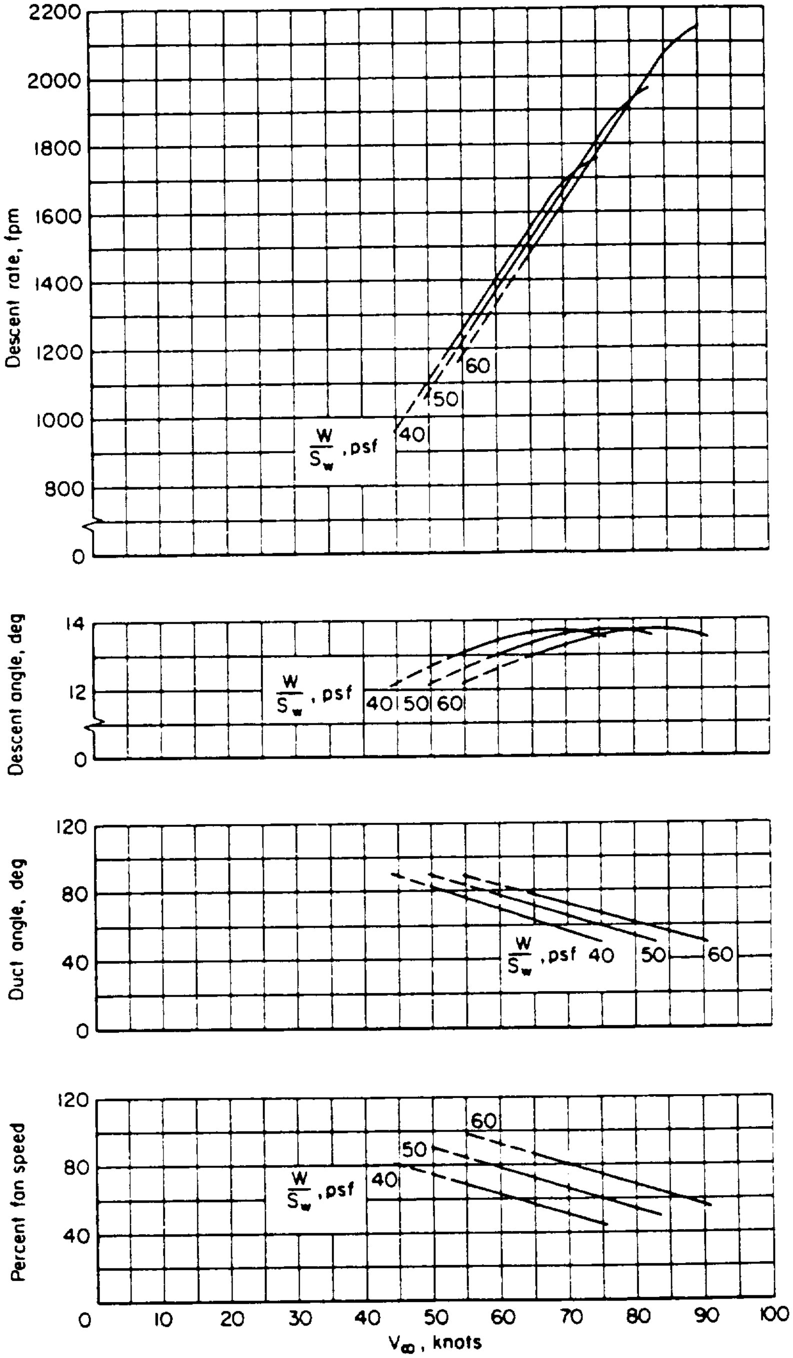


Figure 29. Maximum descent conditions due to duct inlet stall for an airplane having two ducted lift-cruise fans; $A_e/A_{e,s} = 1.0$.

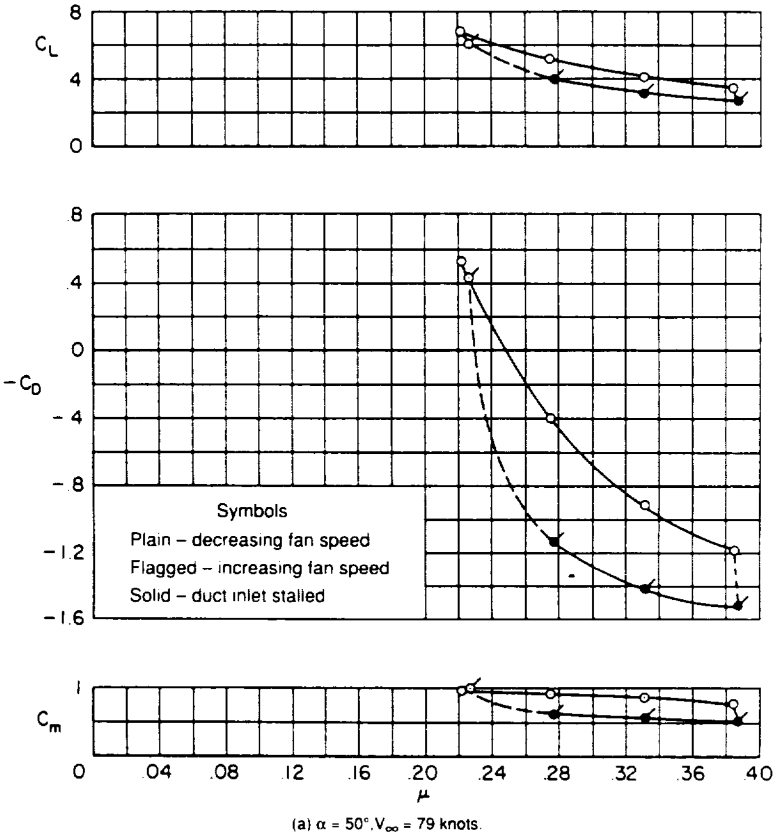
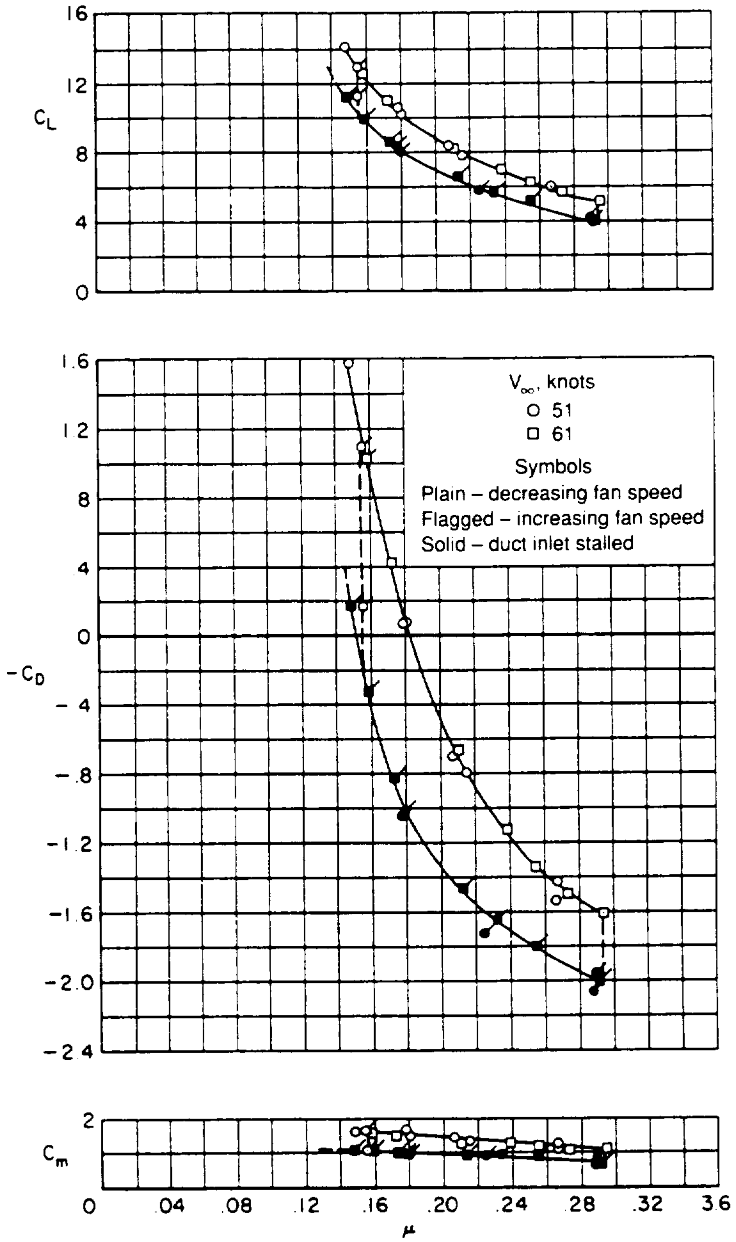


Figure 30(a). Effect of duct inlet stall on the variation of model longitudinal aerodynamic characteristics with fan tip speed ratio; $A_e/A_{e,s} = 0.93$.



(b) α = 60°

Figure 30(b). Effect of duct inlet stall on the variation of model longitudinal aerodynamic characteristics with fan tip speed ratio; $A_e/A_{e,s} = 0.93$ (concluded).

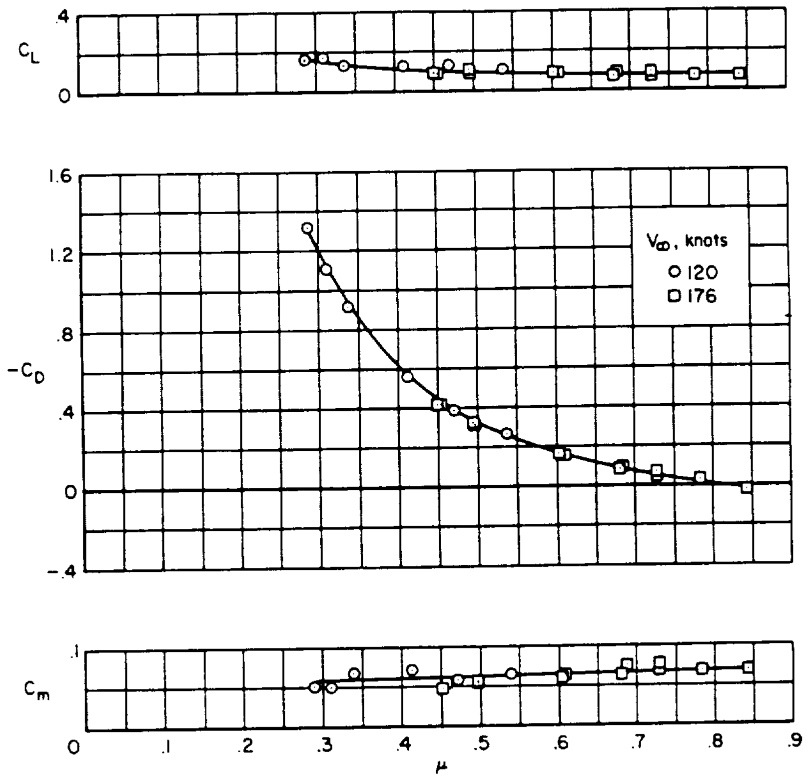
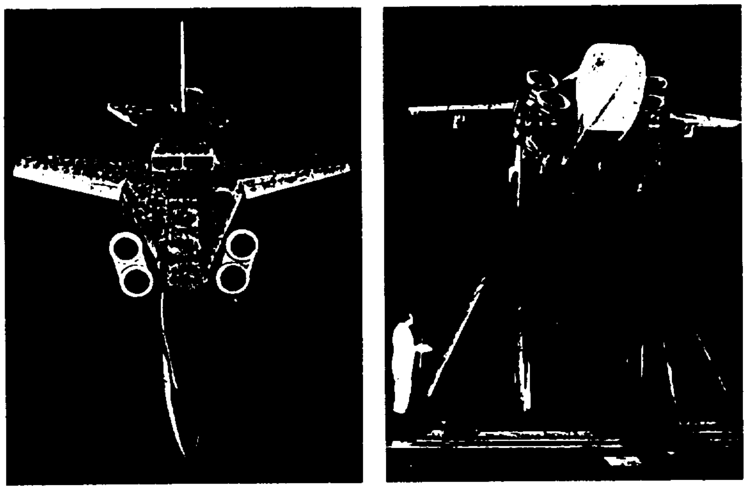
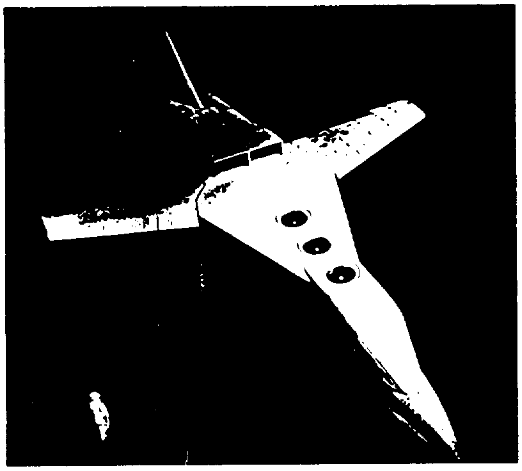


Figure 31. Variation of model longitudinal aerodynamic characteristics with fan tip speed ratio; $\alpha = 0°$, $A_e/A_{e,s} = 0.56$.

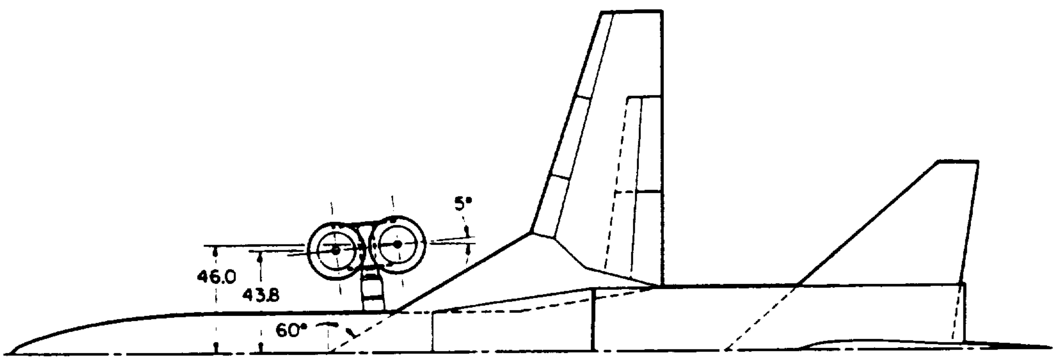


(a) Swiveling, retractable configuration in 40- by 80-foot wind tunnel.

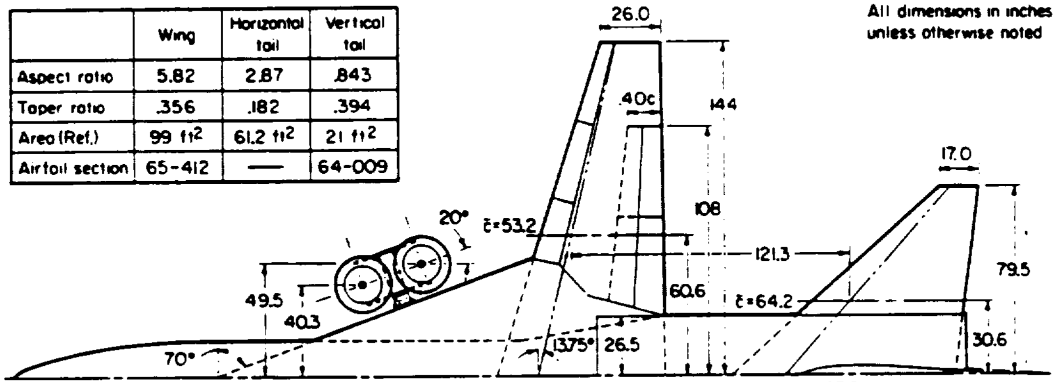


(b) Internally fixed configuration in 40- by 80-foot wind tunnel.

Figure 32. Lift engine model mounted in wind tunnel.



5° Swivel plane, lift-cruise engine duct extension



	Wing	Horizontal tail	Vertical tail
Aspect ratio	5.82	2.87	.843
Taper ratio	.356	.182	.394
Area (Ref.)	99 ft²	61.2 ft²	21 ft²
Airfoil section	65-412	—	64-009

20° Swivel plane

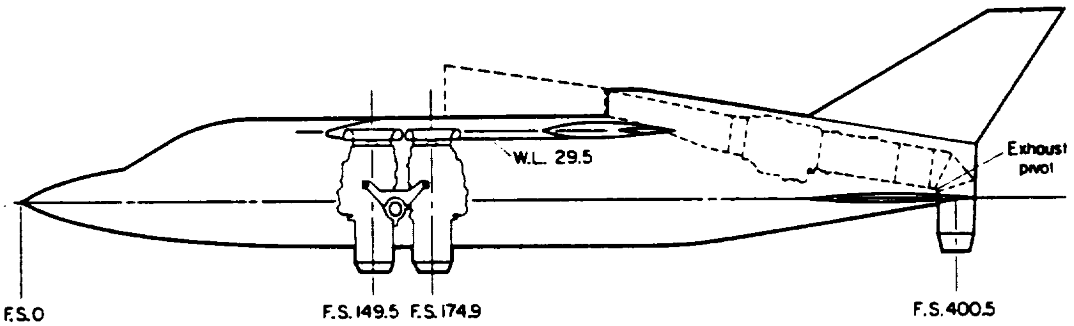


Figure 33. General arrangement of the swiveling, retractable configuration.

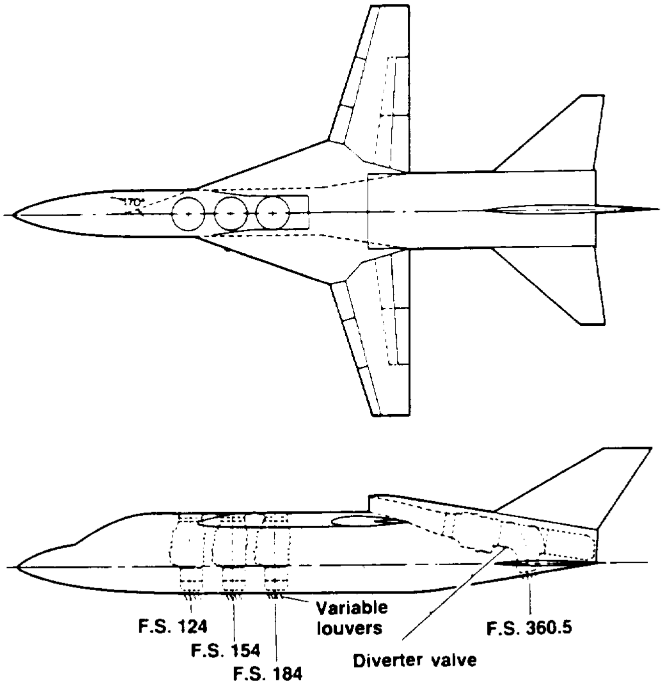
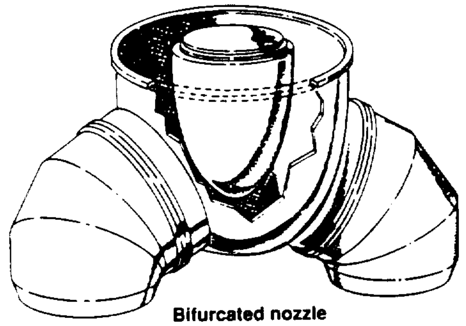
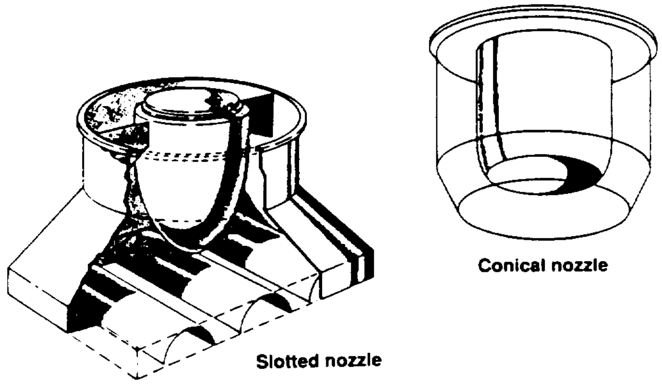


Figure 34. General arrangement of the internally fixed configuration.



Bifurcated nozzle



Conical nozzle

Slotted nozzle

Figure 35. Lift-engine exit nozzles tested with the internally fixed configuration.

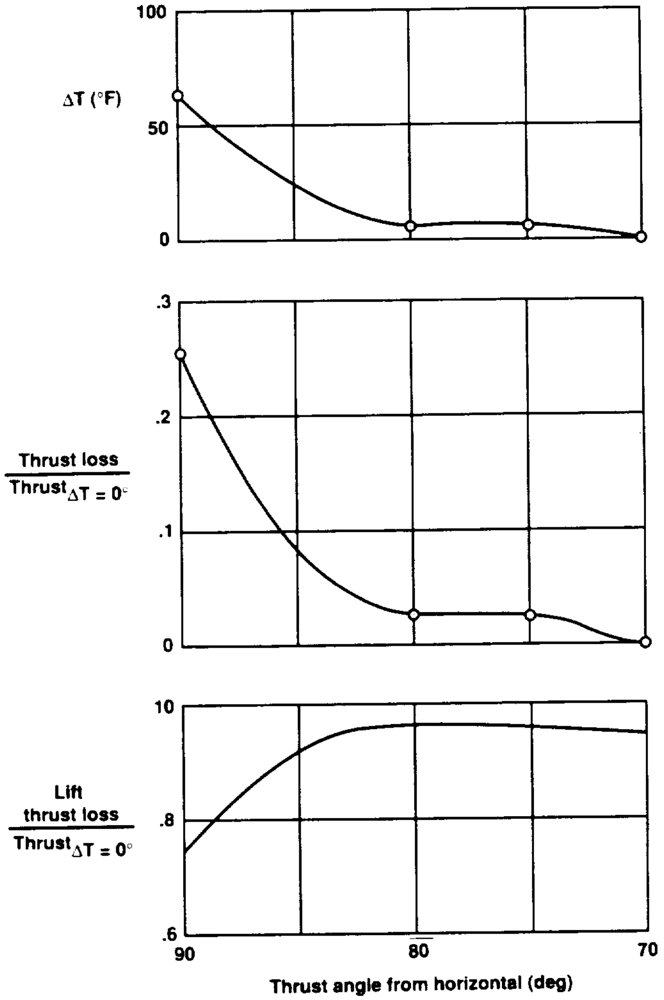


Figure 36. The effect of exhaust vectoring on temperature rise and thrust loss; swiveling retractable configuration, H/D = 5.0.

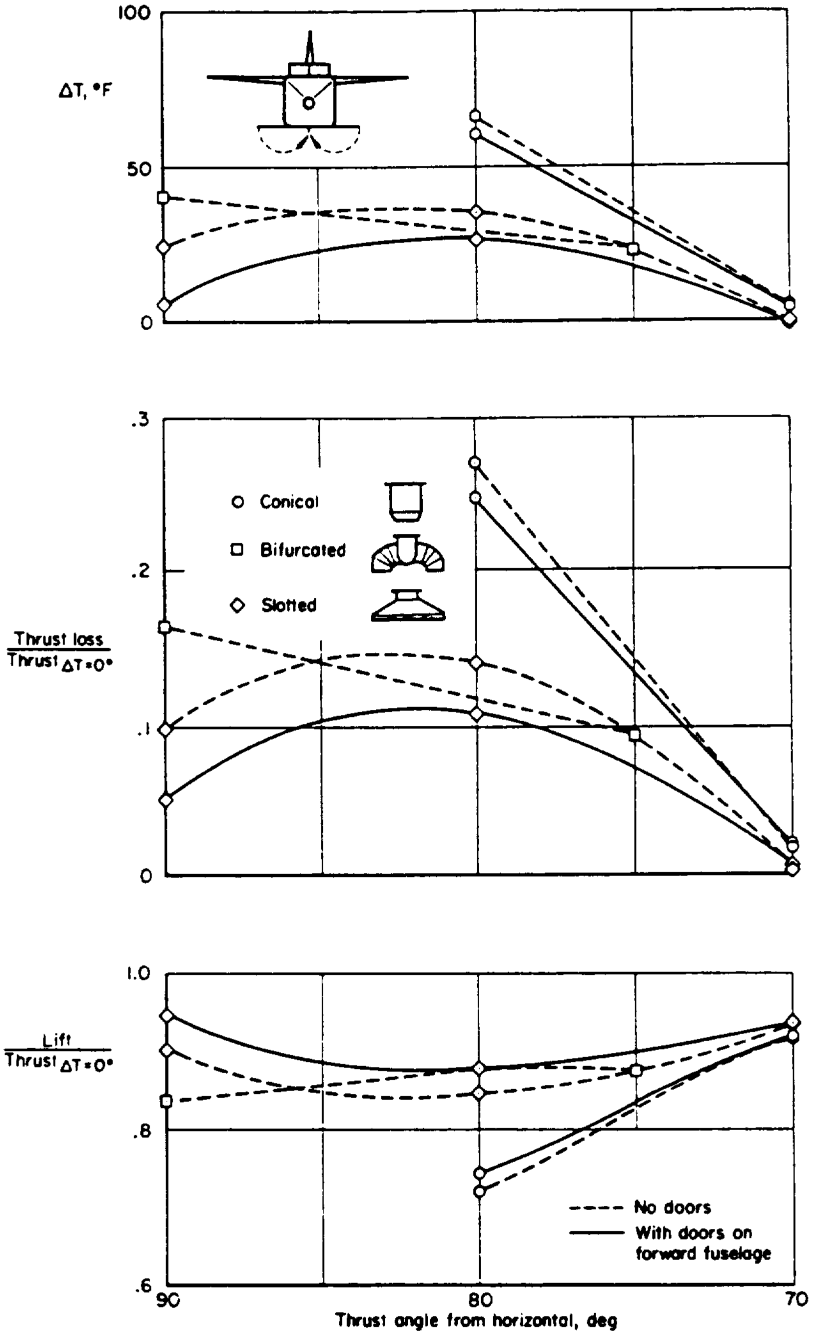


Figure 37. The effect of exhaust vectoring on temperature rise and thrust loss; internally fixed configuration, H/D = 5.0.

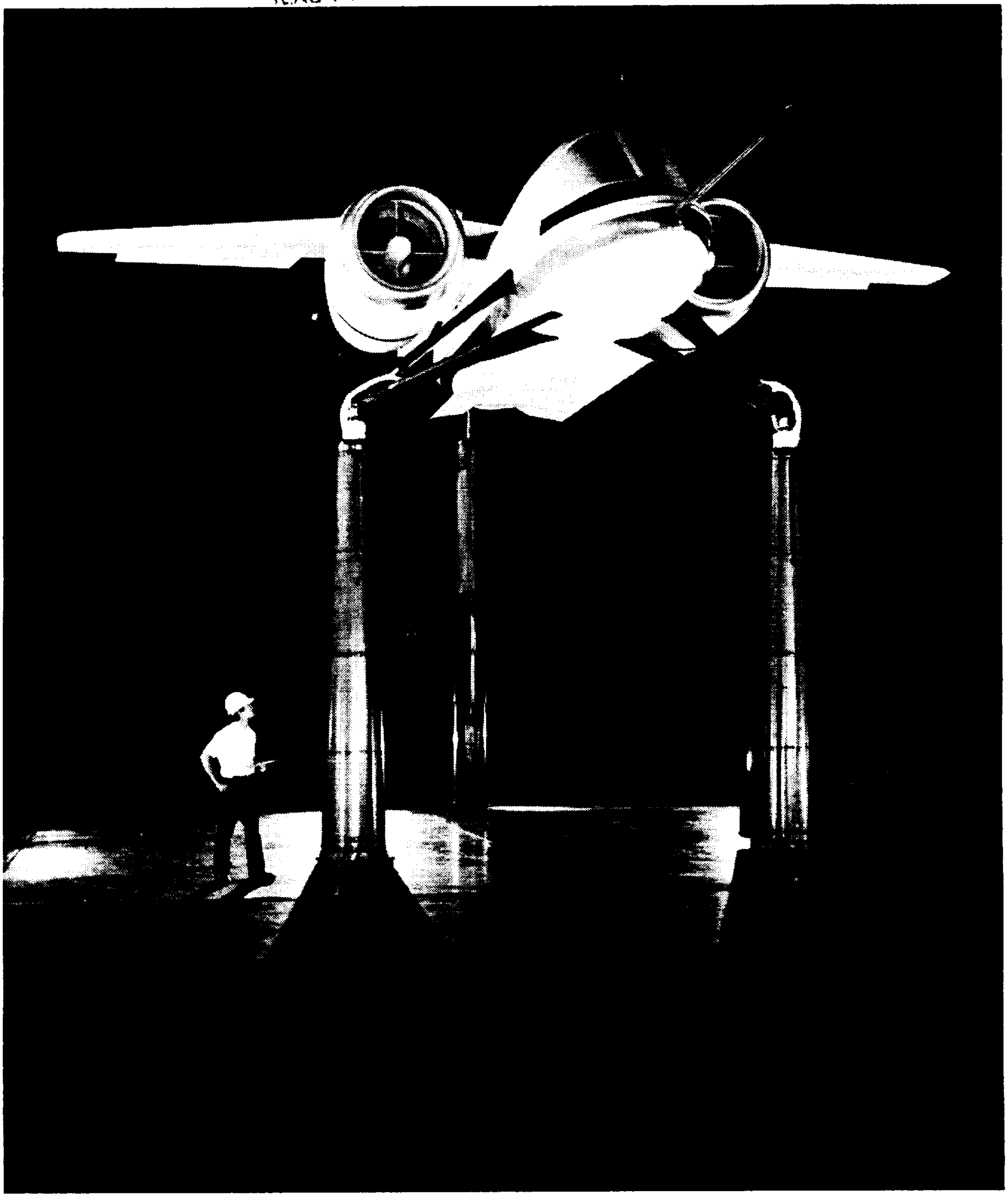


Figure 38(a). Full scale Grumman model 698 in the Ames 40 × 80 Wind Tunnel.

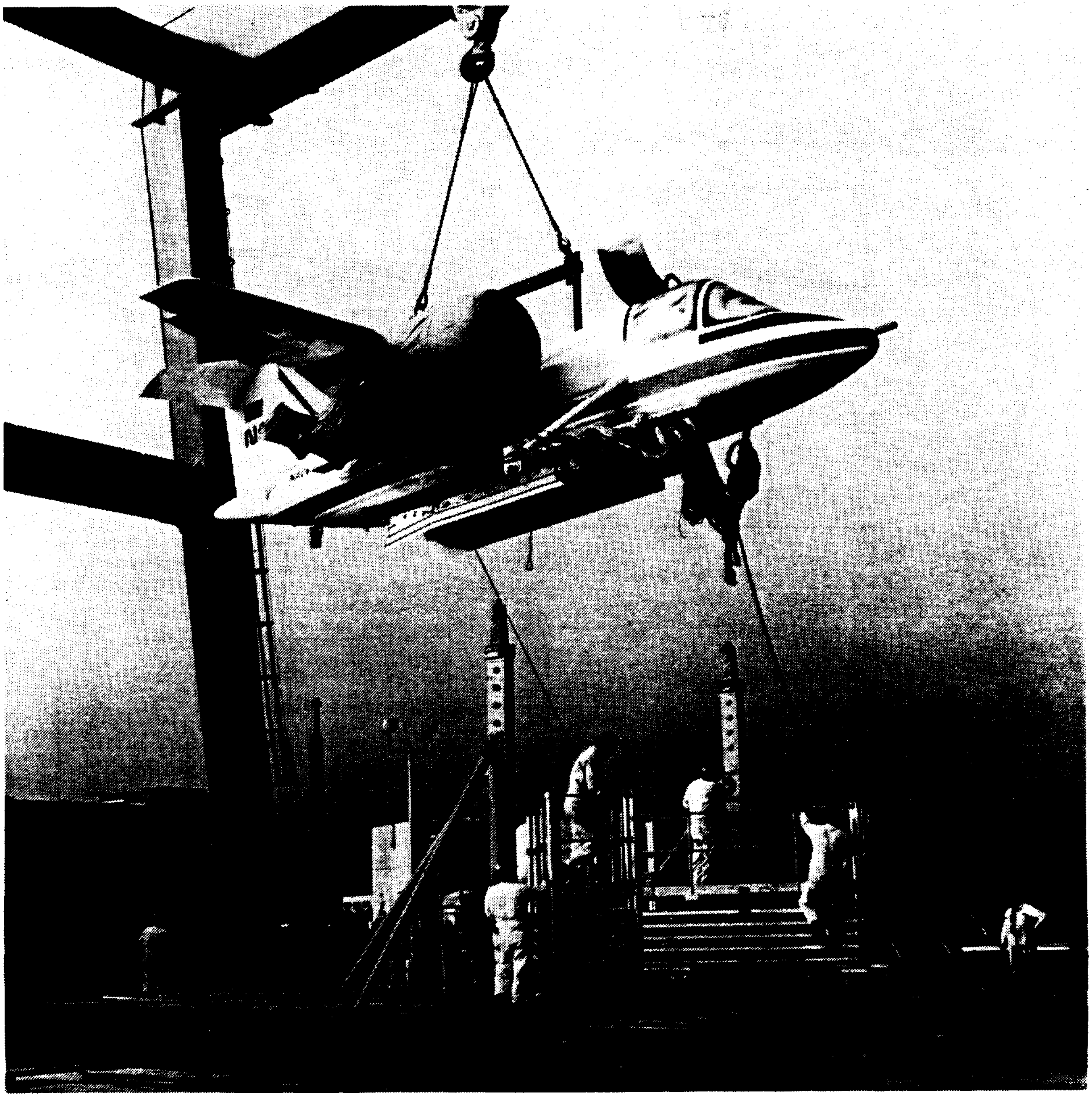


Figure 38(b). Full scale Grumman model 698 on the Ames Outside Aerodynamic Research Facility (concluded).

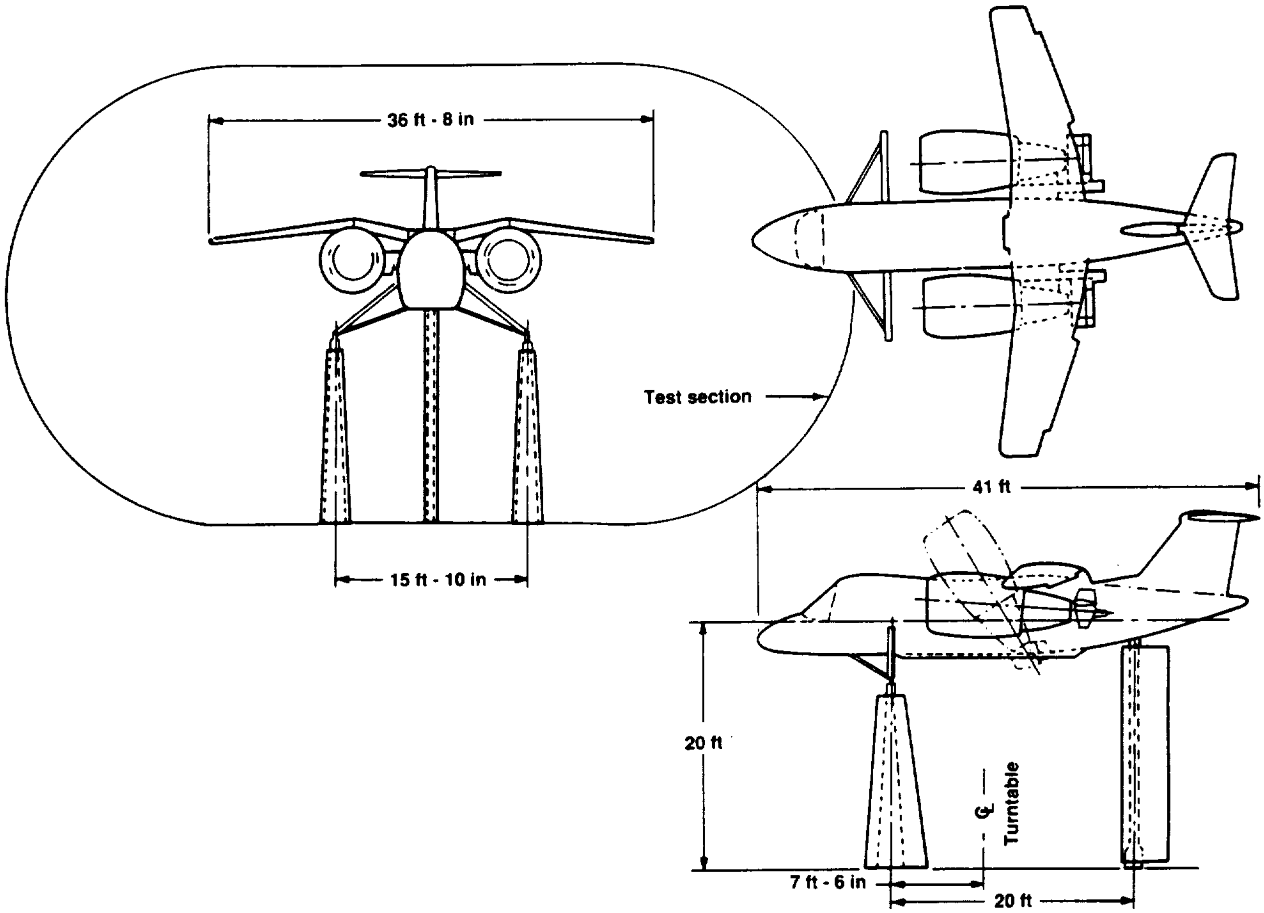


Figure 39. V/STOL model in 40 × 80 wind tunnel.

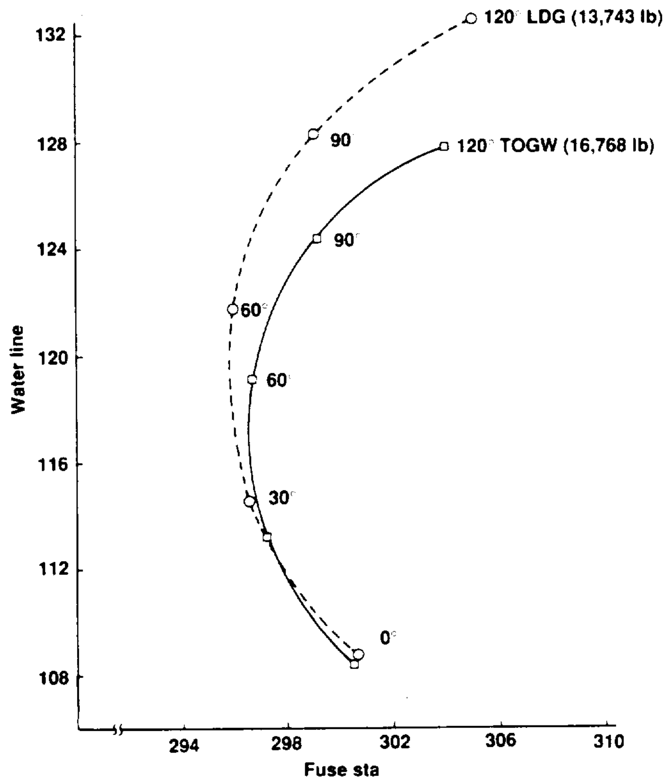


Figure 40. Aircraft cg vs. nacelle deflection.

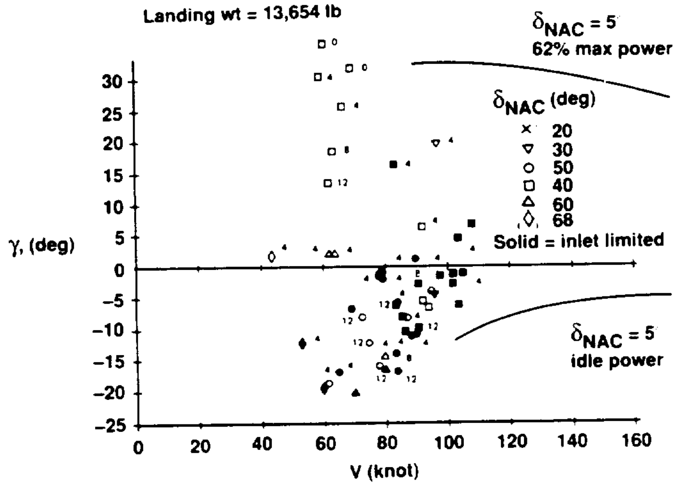


Figure 41. Trimmed performance.

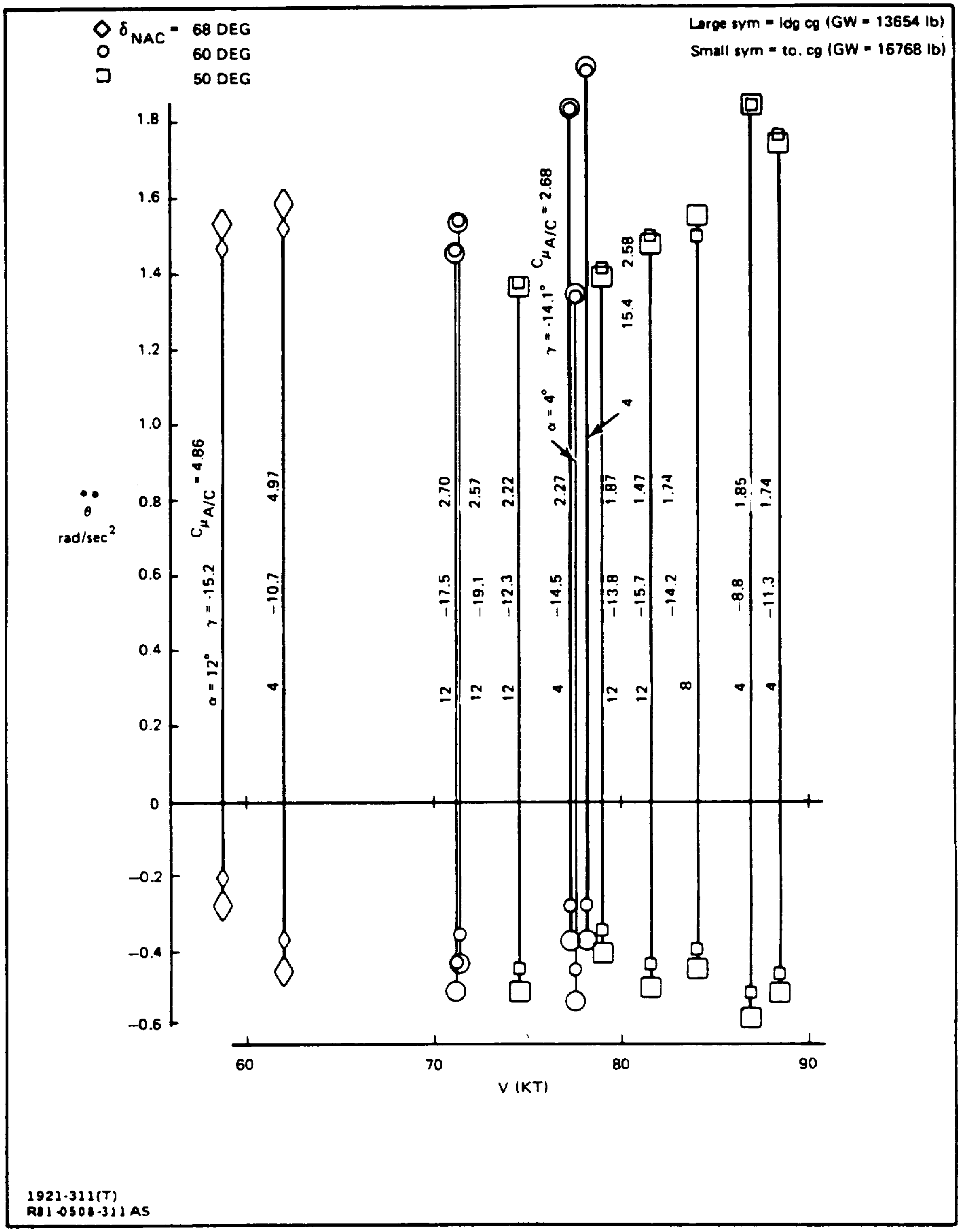


Figure 42. Longitudinal maneuvering capability.

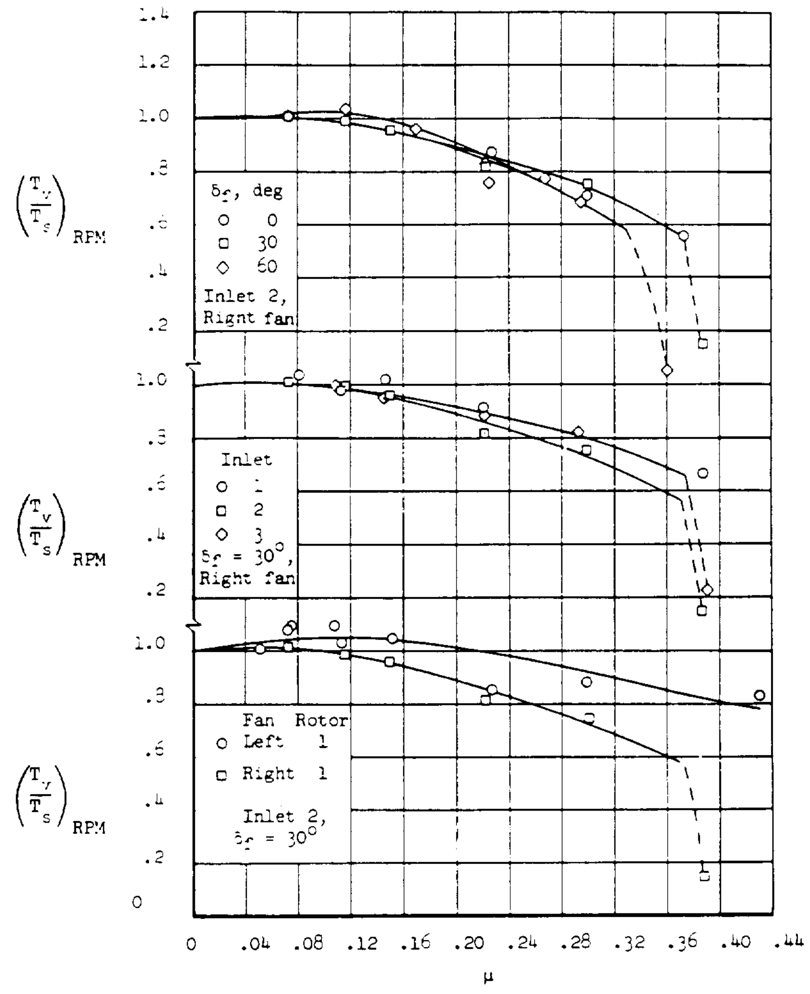


Figure 43. The effect of airspeed (tip speed ratio) on fan thrust; α = 0°, β = 0°, 1100 to 2400 rpm.

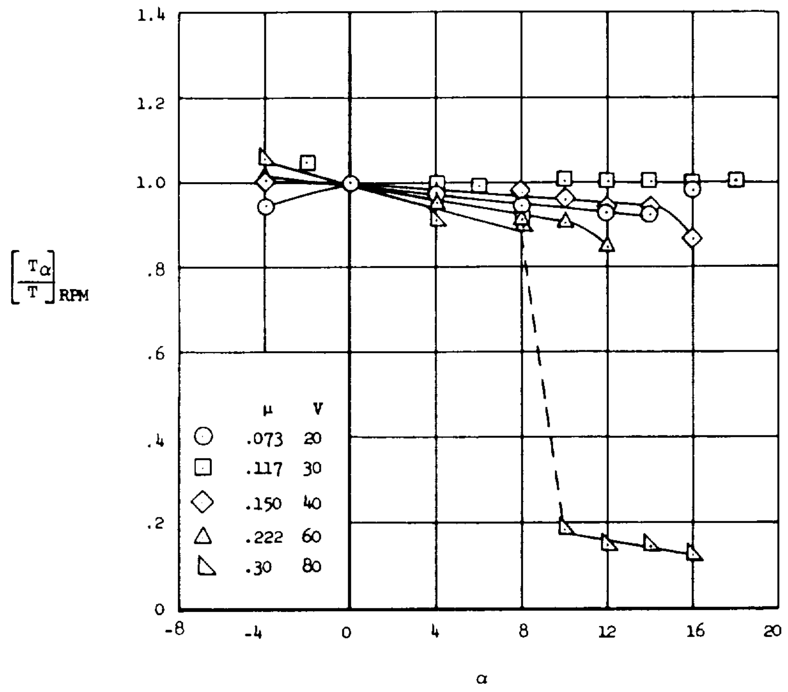
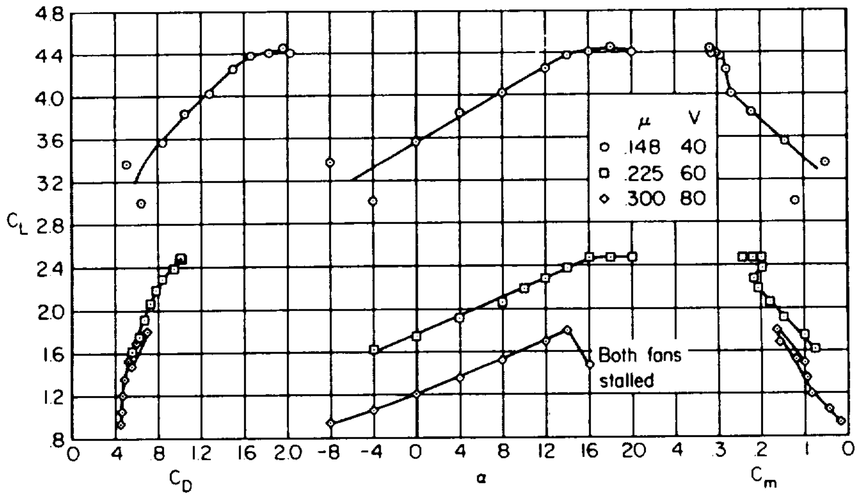


Figure 44. The effect of angle of attack on thrust of right fan at several forward speeds; β = 0°, δf = 30°, 1700 rpm.



(a) β = 0°, δf = 30°

Figure 45. Longitudinal characteristics with fans operating; h/D = 3.85, tail off, straight louvers, 1700 rpm.

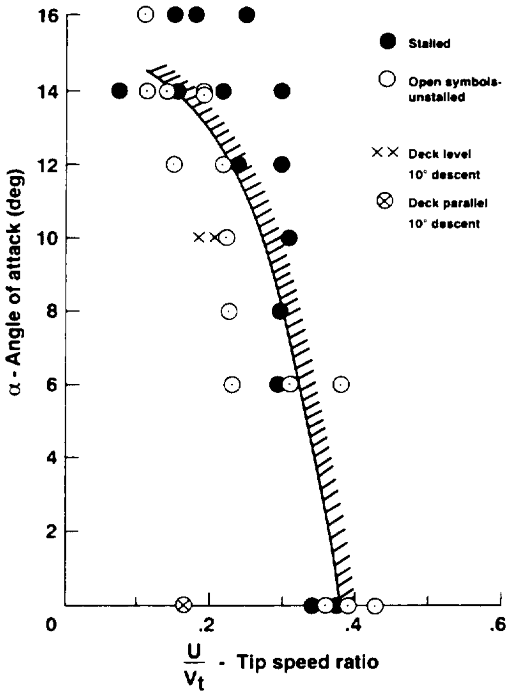
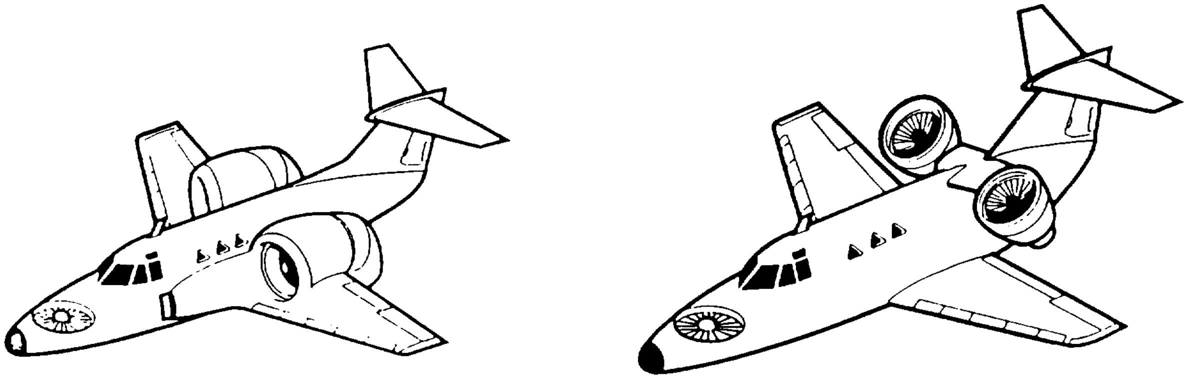
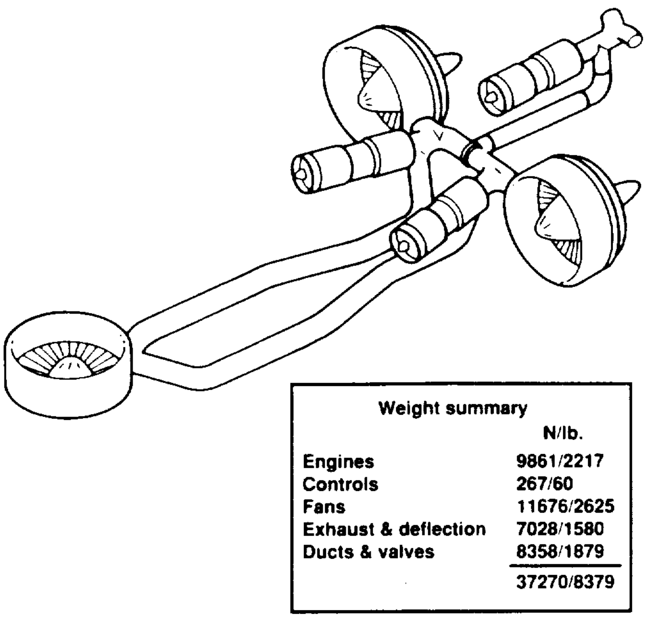


Figure 46. Effect of angle-of-attack on tip speed ratio stall boundaries.



- THREE FANS
- 110,000 TO 130,000 N (25,000 TO 29,000 lb.) VTOL GROSS WEIGHT
- 42,000 N (9,500 lb.) USEFUL LOAD

Figure 47. T-39 modification.



Weight summary	N/lb.
Engines	9861/2217
Controls	267/60
Fans	11676/2625
Exhaust & deflection	7028/1580
Ducts & valves	8358/1879
	37270/8379

Figure 48. Gas drive system.

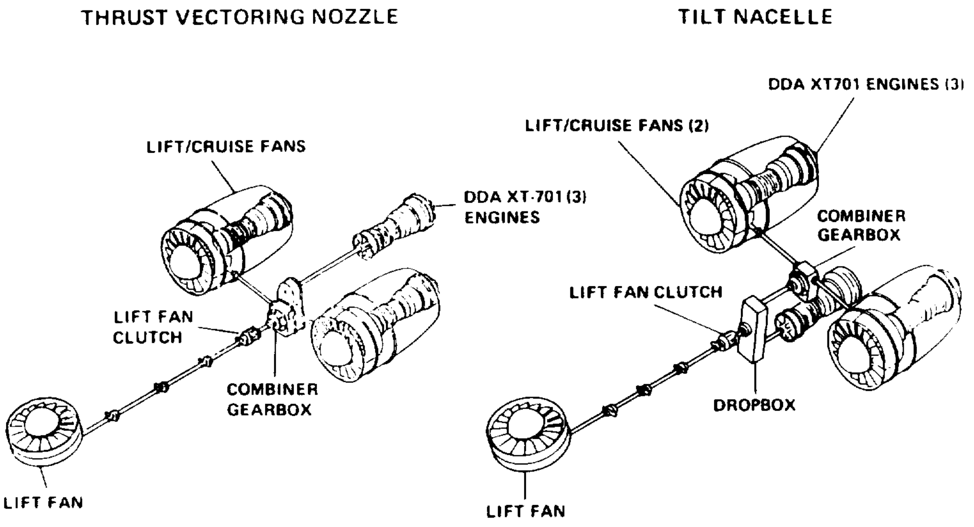


Figure 49. Shaft drive systems.

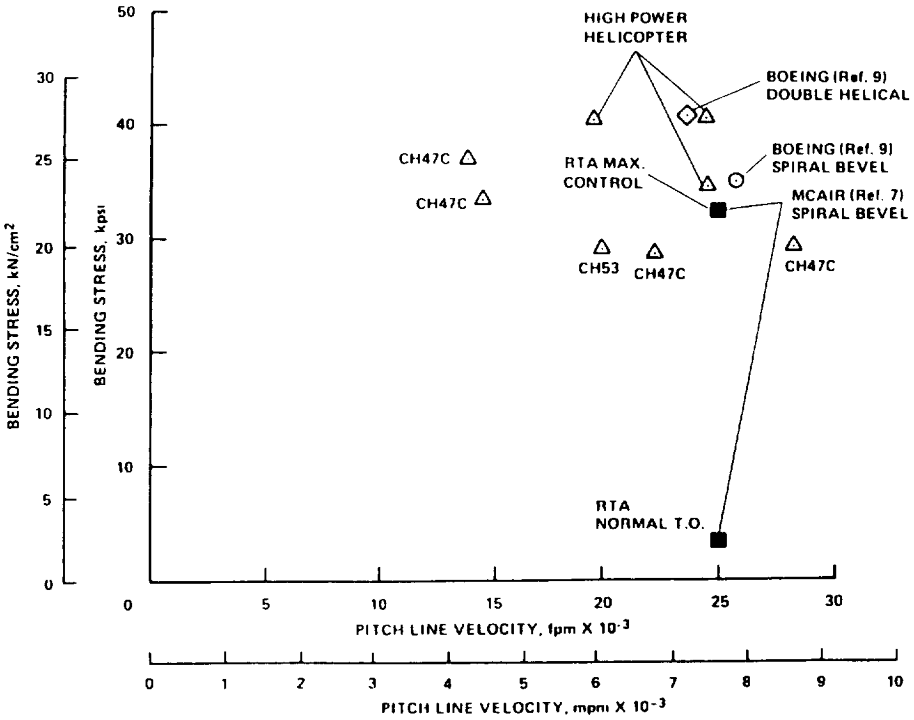


Figure 50(a). Effective pitch line velocity on stress levels...bending.

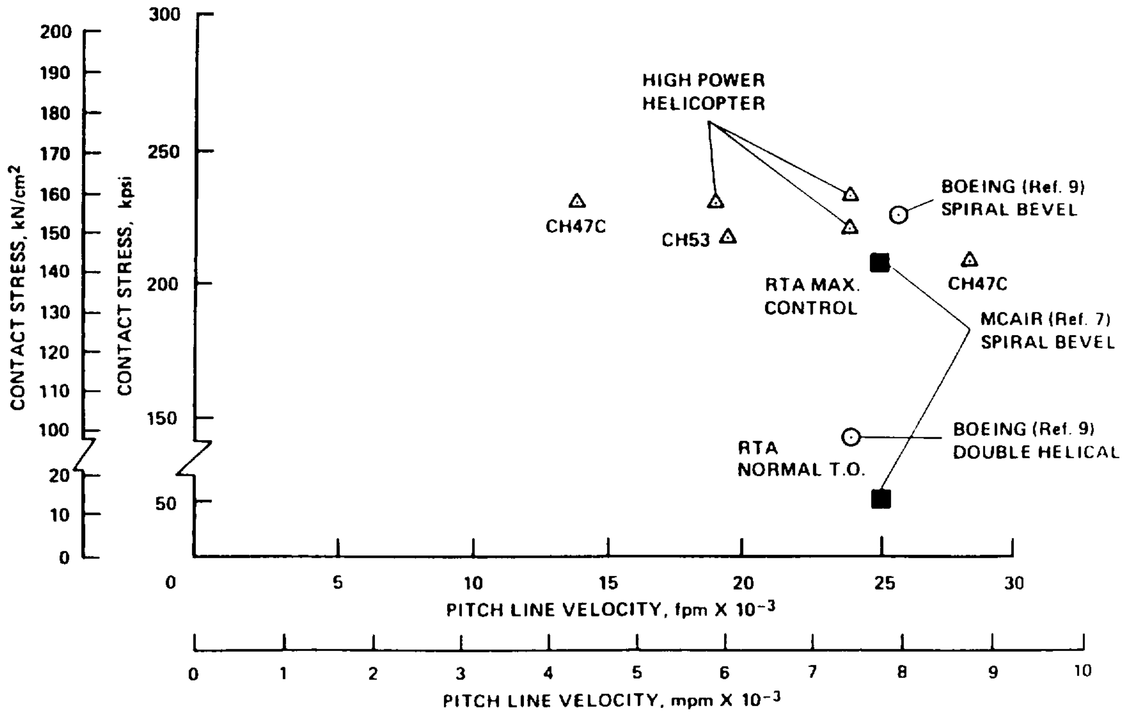


Figure 50(b). Effective pitch line velocity on stress levels...contact.

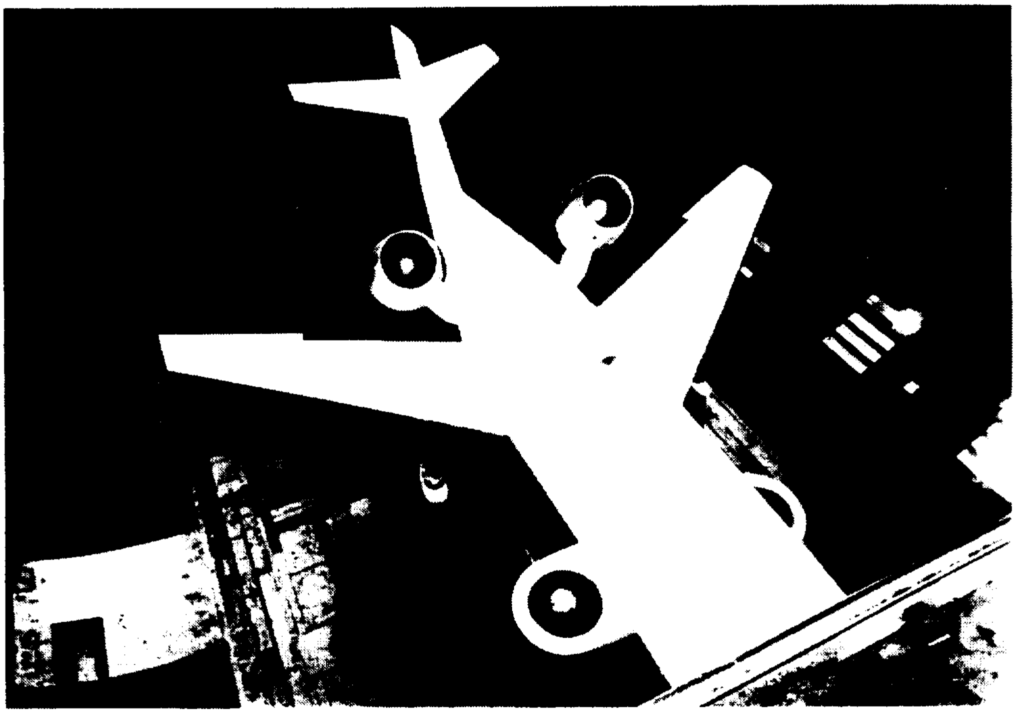
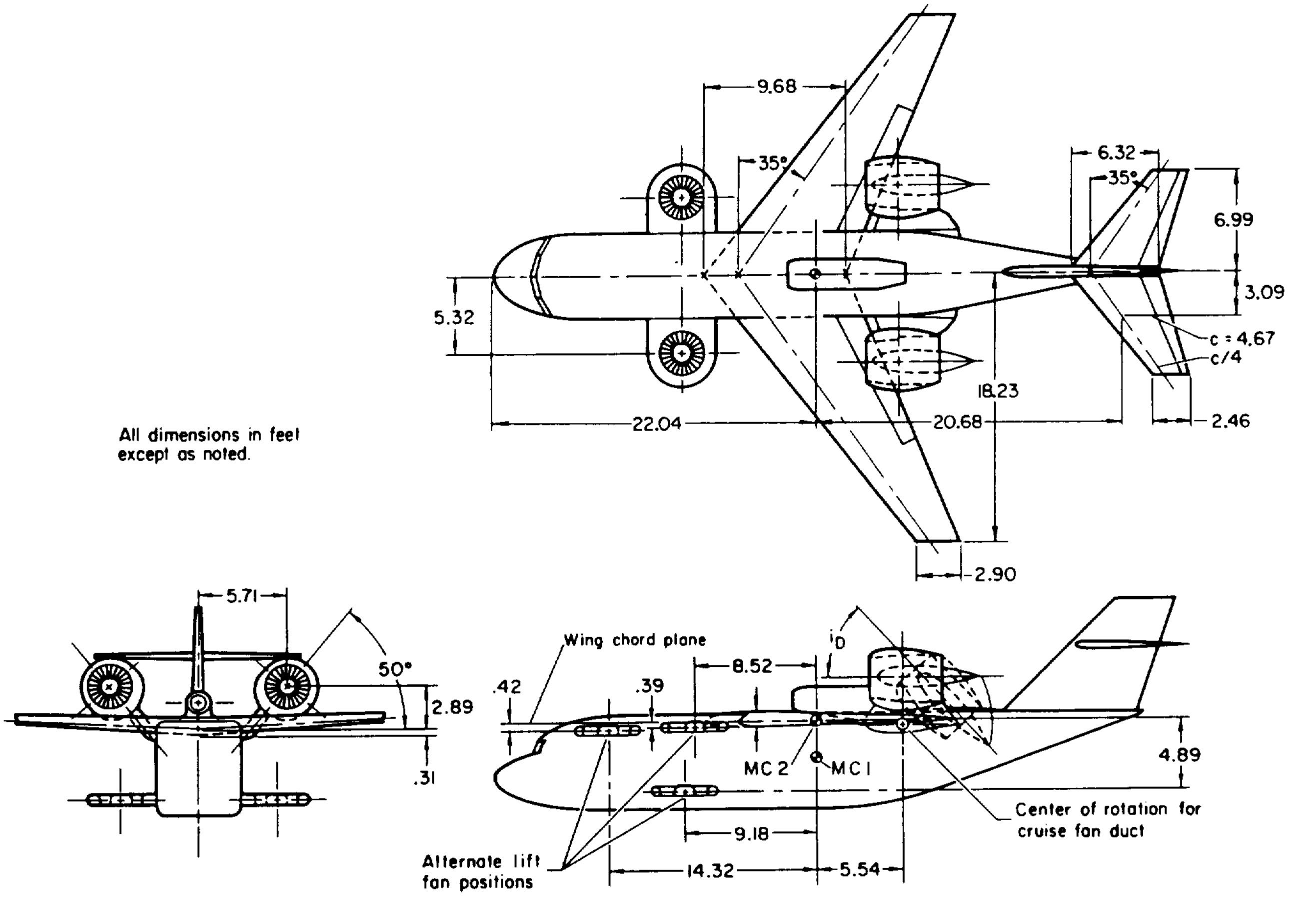
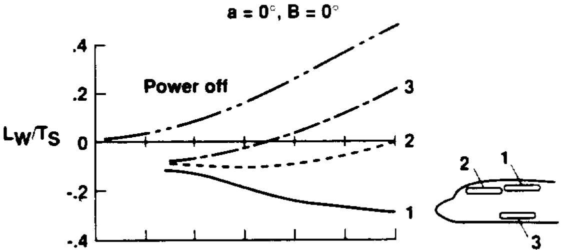


Figure 51. Lift-cruise fan model mounted in the Ames 40 x 80 wind tunnel.

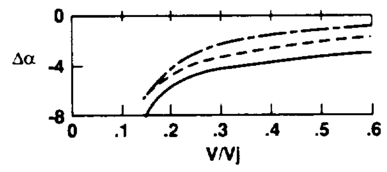


(a) Lift-cruise fan configuration

Figure 52(a). Geometric details of lift-cruise fan model.



(a) Wing lift



(b) Average reduction in wing angle of attack

Figure 52(b). Geometric details of lift-cruise fan model (concluded).

ATTACHMENT A

DESIGN GUIDELINES AND CRITERIA
FOR
DESIGN DEFINITION STUDY OF A
LIFT CRUISE FAN TECHNOLOGY V/STOL AIRCRAFT

DECEMBER 1975

The purpose of these guidelines is to provide a basis for comparing the conceptual designs of V/STOL Technology aircraft using the lift/cruise fan propulsion system. These guidelines will provide direction for only those items required for conceptual design considerations. This is not an attempt to provide criteria for either the preliminary or detail design of military aircraft.

Except where specific criteria are given, handling qualities shall be consistent with the intent of AGARD-R-577-70 and MIL-F-83300. Under MIL-F-83300, the aircraft will be considered in the class II category. Two levels of operation will be considered. Level I is normal operation with no failures. Level 2 is operation with a single reasonable failure of the propulsion or control system.

Upon any reasonable failure of a power plant or in the control system, the aircraft shall be capable of completing a STOL flight mode takeoff and continuing sustained flight. With failure of the most critical power plant, Level 2 performance shall be achieved at sea level and at 90°F under the following conditions: (a) STOL Mode - capability for continuing flight on a flight path 1 1/2° above the horizontal at a weight which shall include 2500 lbs. payload and fuel sufficient for 11 STOL test missions; (b) VTOL Mode - capability for a thrust to weight ratio of 1.03 without altitude control at a weight which shall include 2500 lbs. payload and fuel sufficient for 2 VTOL test missions. Fan failure during low speed flight is not a design requirement (as similarly the case for rotor type or propeller-driven concepts), althought consideration of a turbo-engine failure is a design requirement.

1.0 Flight Safety and Operating Criteria

1.1 Handling Qualities Criteria (low speed powered lift mode)

Definitions of the two levels are as follows:

Level 1: Flying qualities are satisfactory for research and technology demonstration missions when flown by an engineering test pilot.

Level 2: Flying qualities are adequate to continue flight and land. The pilot work load is increased but is still within the capabilities of an engineering test pilot.

1.1.1 Attitude Control Power (S.L., 90°F).

Applicable for all aircraft weights and at any speed up to V_{con}. For purposes of this study, the VTOL values will apply near hover (0 to 40 kts); where the STOL values will apply when operating above 40 knots. The Tables list minimum values, higher levels are desirable for research purposes.

Level 1: The low speed control power shall be sufficient to satisfy the most critical of the three following sets of conditions:

Conditions (a) -- to be satisfied simultaneously,

(1) Trim with the most critical CG position.

(2) In each control channel provide control power, for maneuver only, equal to the most critical of the requirements given in the following table.

Axis	Maximum Control Moment / Inertia		Attitude Angle in 1 sec after a Step Input	
	VTOL	STOL	VTOL	STOL
Roll	± 0.9 rad/sec^2	± 0.6 rad/sec^2	± 15 deg	± 10 deg
Pitch	± 0.5 rad/sec^2	± 0.4 rad/sec^2	± 8 deg	± 7 deg
Yaw	± 0.3 rad/sec^2	± 0.2 rad/sec^2	± 5 deg	± 3 deg

These maneuver control powers are applied so that 100% of the most critical and 30% of each of the remaining two need occur simultaneously.

Conditon (b) -- At least 50% of the above control power shall be available for maneuvering, after the aircraft is trimmed in a 25 knot crosswind.

Condition (c) -- At least 90% of the control power specified in condition (a) shall be available after compensation of the gyroscopic moments due to the maneuvers specified in condition (a). This condition includes trim with the most critical CG positon.

Level 2: The low speed control power shall be sufficient to satisfy, simultaneously, the following:

(1) With the most critical CG position trim after any reasonable single failure of power plant or control system.

(2) In each control channel, provide control power, for maneuver only, equal to at least the following:

Axis	Control Moment / Inertia		Attitude Angle in 1 sec after a Step Input	
	VTOL	STOL	VTOL	STOL
Roll	± 0.4 rad/sec²	± 0.3 rad/sec²	± 7 deg	± 5 deg
Pitch	± 0.3 rad/sec²	± 0.3 rad/sec²	± 5 deg	± 5 deg
Yaw	± 0.2 rad/sec²	± 0.15 rad/sec²	± 3 deg	± 2 deg

Simultaneous maneuver control power need not be greater than 100% - 30% - 30%.

1.1.2 Flight Path Control Power (SL to 1000 ft., 90°F).

1.1.2.1 VTOL (0-40 kt TAS and zero rate of descent)

At applicable aircraft weights and at the conditions for 50% of the maximum attitude control power of critical axis specified in para. 1.1.1 it shall be possible to produce the following incremental accelerations for height control:

Level 1:
(a) In free air ± 0.1g
(b) With wheels just clear of the ground -0.10g, + 0.05g

Level 2: (a) In free air -0.1g, +0.05g

(b) With wheels just clear of the ground

-0.10g, +0.00g

It shall also be possible to produce the following horizontal incremental acceleration, but not simultaneously with height control.

Level 1: ± 0.15g

Level 2: ± 0.10g

At applicable aircraft weights it shall be possible to produce the following stabilized thrust-weight ratios without attitude control inputs.

Level 1: $\frac{F}{W}$ = 1.05 in free air (Takeoff power rating)

Level 2: $\frac{F}{W}$ = 1.03 in free air (Emergency power rating)

With the most critical engine failed, Level 2 performance shall be achieved at a weight which shall include 2500 lbs. payload and fuel sufficient for 2 VTOL test missions (figure 1a).

1.1.2.2 VTOL and STOL Approach (40 kts. to V_{CON})

At the applicable landing weight the aircraft shall be capable of making an approach at 1000 FPM rate of descent while simultaneously decelerating at 0.08g along the flight path.

It shall be possible to produce the following incremental normal accelerations by rotation alone (angle of attach change and constant thrust) in less than 1.5 seconds at the STOL landing approach airspeed where reasonable rotation (angle of attack changes) will produce at least 0.15g's.

Level 1: ± 0.1g

Level 2: ± 0.05g

It shall be possible to produce the following normal accelerations in at least 0.5 seconds for flight path, flare, or touchdown control by either thrust changes on combined thrust changes and rotation at STOL landing a approach speeds below which 0.15g's can be produced by reasonable rotation alone.

Level 1: ± 0.1g

Level 2: ± 0.05g

1.1.3 VTOL and STOL Low Speed Control System Lags (S.L. to 1000 ft. 90°).

The effective time constant (time to 63% of the final value) for attitude control moments and for flight path control forces shall not exceed the levels given in the following table.

	Level 1	Level 2
Attitude Control Moments	0.2 sec	0.3 sec
Flight Path Control Forces	0.3 sec	0.5 sec

With a step-type input at the pilot's control the commanded control moment or force shall be applied within the following:

Level 1: 0.3 seconds for 0.5 inches of pilot's control

0.5 seconds for full pilot's control

Level 2: 0.5 seconds for full pilot's control

1.1.4 Stability (S.L. to 1000 ft., 90°F)

1.1.4.1 Hovering

The frequency and damping of the airframe/control system dynamics, in the hovering condition, shall be within the following limits for the three rotary axes:

Level 1: Optimum damping and frequency zone established from the Ames six-degree-of-freedom moving base simulator (figure 2).

Level 2: The zone given in figure 2. The boundary of this zone corresponds to a damping factor of 0.166 for values of ω_n above 1 rad sec.

1.1.4.2 Low Speed

Level 1: The dominant oscillatory modes shall be maintained as close as possible to the optimum zone specified in section 1.1.4.1 while maintaining other oscillatory modes damped. Aperiodic modes, if unstable, shall have a time to double amplitude of greater than 20 sec.

Level 2: The dominant oscillatory modes shall be maintained within the Level 2 zone given in figure 2. Other oscillatory modes may be unstable provided their frequency is less than 0.84 rad/sec and their time to double amplitude greater than 12 sec. Aperiodic modes, if unstable, shall have a time to double amplitude of greater than 12 sec.

1.1.4.3 Cruise

The aircraft as configured for cruise flight shall be statically stable at all gross weights with a stability margin of 0.05 at the critical center of gravity without stability augmentation.

1.2 STOL Takeoff Performance

The climbout gradient in the takeoff configuration, at takeoff gross weight, with gear down and most critical power plant failed at lift off shall be positive and the aircraft will continue to accelerate.

During takeoff wing lift shall not exceed 0.8 CL_{MAX}. No catapults or arresting gear will be utilized. The rolling coefficient of friction will be 0.03. (for calculations)

1.3 Conversion Requirements (STOL and VTOL)

It must be possible to stop and reverse the conversion procedure quickly and safely without undue complicated operation of the powered lift controls.

The maximum speed in the powered-lift configuration shall be at least 20% greater than the power-off stall speed in the converted configuration for level 1 operation and the speed in the powered lift configuration shall be at least 10% greater than the power off stall speed for the level 2 operation.

2.0 Mission

2.1 Mission Summary

2.1.1 Land Operation -- The VTOL and STOL test missions are described in figure 1.

- Minimum Mission Time - Level 1

VTOL Missions	1/2 hour
STOL Missions	1 hour
Cruise/Endurance Mission	2 hours
- Payload (not including crew)	2500 lbs (minimum) 50 cu. ft.

2.1.2 Shipboard Operation -- The aircraft shall be capable of operating from the deck of a naval aircraft carrier.

2.2 Minimum Cruise Speed

- 300 KEAS at sea level and 0.7 at 25,000 ft.

3.0 General Design Guidelines

3.1 Austerity is to be stressed but not by compromising safety.

3.2 The limit load factor will be no less than +2.5g, -0.5g at design gross weight.

3.3 Sufficient attitude control power will be available to perform research on control requirements. The contractor shall indicate those axes where greater control power than required in section 1.0 would be made available for research purposes.

3.4 New aircraft components will be designed for approximately 500 flight hours.

3.5 Additional Information

- Crew	2 pilots (flyable by one pilot only, or by either pilot)
- Sink rate at touchdown	12 fps at max landing weight, 15 fps desired

- Pressurized cockpit is desired but not required
- Oxygen required
- Cockpit Environmental System Minimum
- Pilot's Primary Flight Controls Stick and Pedals
- Ejection System for both pilots
- Maximum possible visibility

3.6 The contractor shall furnish as a minimum:

a. Conceptual design aircraft layout drawings.

b. Mil Std. 1374 Part 1 shall be used to show the empty weight breakdown into the usual structural and system group including additions and deletions to the original aircraft.

c. Low speed performance envelope at design gross weight.

d. Conceptual definition of proposed aircraft low speed control and stabilization system.

e. Control moment coefficients and control power about each axis with all gas generators operating and with most critical gas generator failed.

f. Engine and fan data which were used to calculate mission performance in all flight modes.

4.0 Summary of Costing Information required for the Research and Technology Aircraft

The Cost Breakdown is for a two airplane buy. The Cost Breakdown shall be stated in five pricing elements; engineering labor, manufacturing labor, materials and purchased items, other direct costs, and spares (if any). A listing of Government Furnished Equipment (GFE) assumed in the costing shall be included. It is intended that the costing information shall be complete in that the total costs of the subitems listed in paragraphs 4.1 thru 4.8 shall equal the total costs of the aircraft excluding the GFE items.

4.1 Airframe Design and Modification including:

- ° Landing Gear
- ° Subsystem and conventional controls
- ° Cockpit
- ° Ejection seats
- ° Wings
- ° Fuselage
- ° Empennage
- ° Miscellaneous

4.2 Propulsion system including:

- ° Components in 5.0
- ° Transmission components
- ° Transmission subsystem
- ° Thrust vectoring
- ° Miscellaneous

4.3 Control System including:

- ° Fly-by-wire controls
- ° Augmentation systems
- ° Miscellaneous

4.4 Propulsion System Testing including:

- ° Components in 5.0
- ° Transmission components
- ° Thrust vectoring

° Qualification tests

° Aircraft ground tests

° Miscellaneous

4.5 Control System Aircraft Testing including:

° Component tests

° System integration

° Aircraft ground tests

4.6 Aircraft Ground Tests

° Excluding aircraft ground tests in sections 4.4 and 4.5

4.7 Ejection Seat Tests

4.8 Flight Tests

° Contractor Flight Test

4.9 Government Furnished Equipment including:

° NA265-40 basic airframe

° Airframe components

° Fans

° Engines

° Research instrumentation

° Miscellaneous

5.0 Summary of the Costing Information required for the high risk propulsion components

The costs for each component shall be stated in four pricing elements; engineering labor, manufacturing labor, material and purchased items, and other direct costs. For each of the pricing elements, the component costs shall be stated for the following categories: data base requirements (effort required to accumulate required data before detail design including data search, analysis, tests, etc.), design and manufacture, component testing, and unit qualification testing. Thus each component costs shall be stated in a four by four matrix.

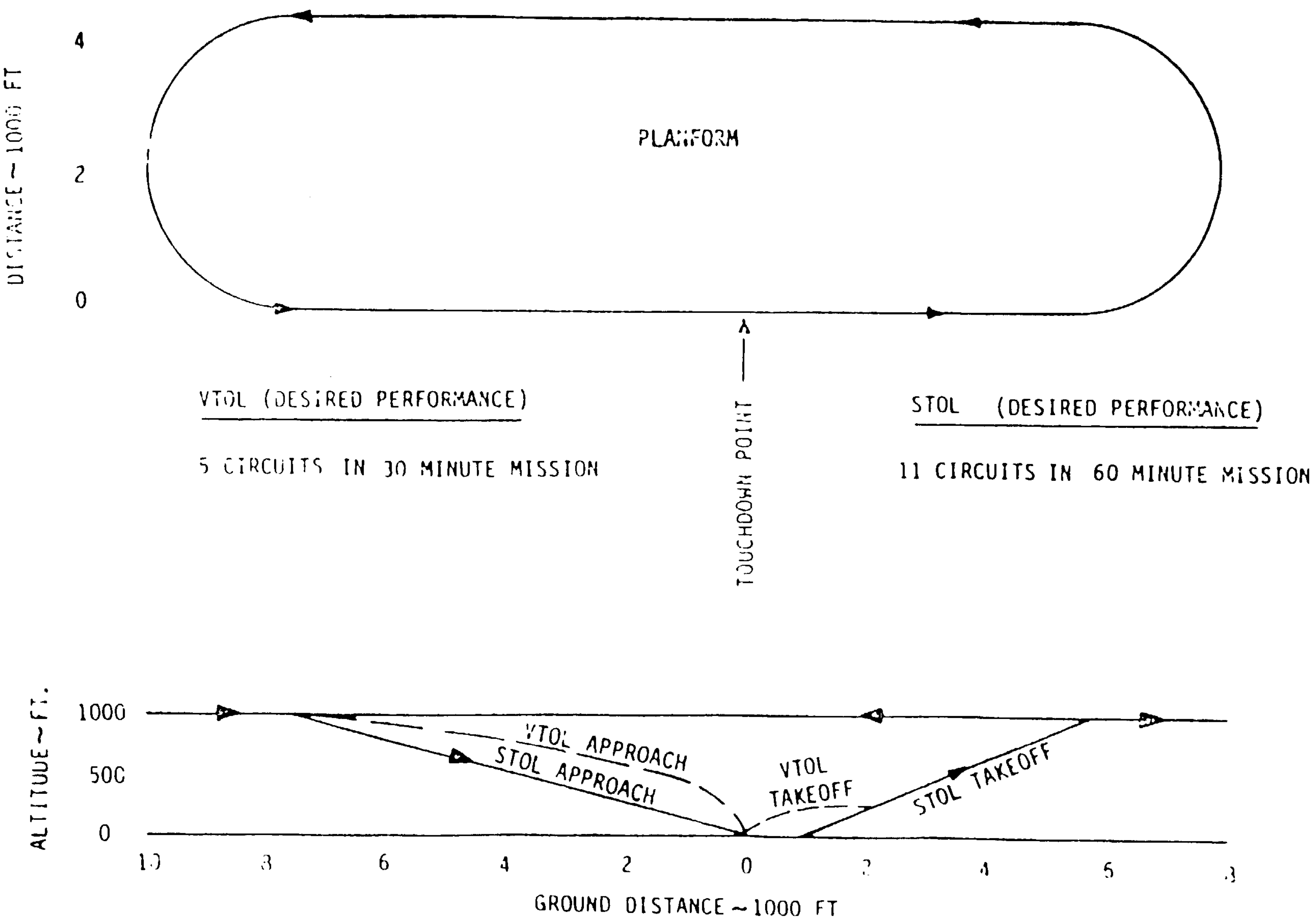


Figure 53. Typical VTOL and STOL test missions.

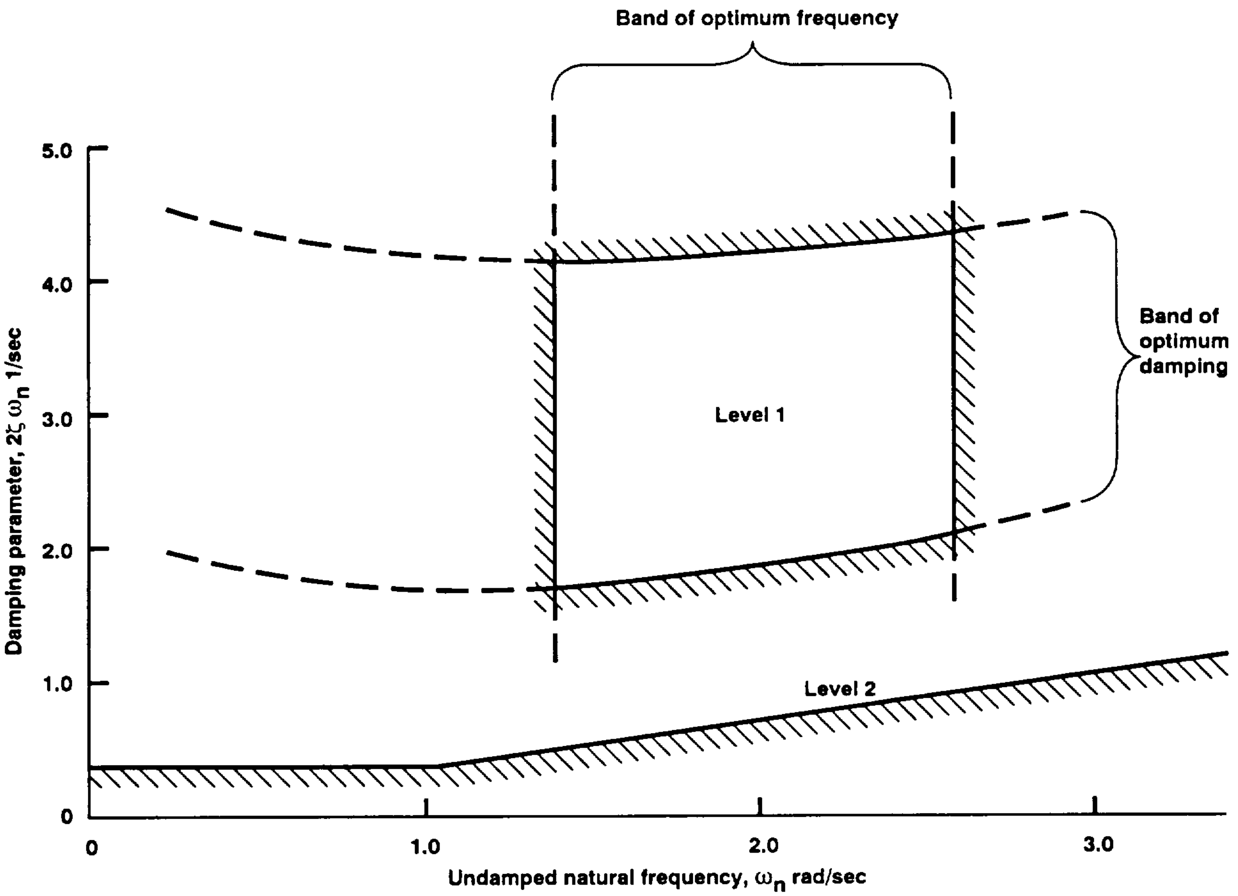


Figure 54. Dynamic Stability Criteria.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE August 1993	3. REPORT TYPE AND DATES COVERED Contractor Report

4. TITLE AND SUBTITLE Summary of Lift and Lift/Cruise Fan Powered Lift Concept Technology	5. FUNDING NUMBERS A25364D
6. AUTHOR(S) Woodrow L. Cook	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Ames Research Center STOVL/Powered-Lift Technology Branch Moffett Field, CA 94035-1000	8. PERFORMING ORGANIZATION REPORT NUMBER A-93113
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA CR-177619

11. SUPPLEMENTARY NOTES

Point of Contact: K. Clark White, Ames Research Center, MS 237-3, Moffett Field, CA 94035-1000,
(415) 604-5653

12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified — Unlimited Subject Category 05	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A summary is presented of some of the lift and lift/cruise fan technology including fan performance, fan stall, ground effects, ingestion and thrust loss, design tradeoffs and integration, control effectiveness and several other areas related to vertical short takeoff and landing (V/STOL) aircraft conceptual design. The various subjects addressed, while not necessarily pertinent to specific short takeoff/vertical landing (STOVL) supersonic designs being considered, are of interest to the general field of lift and lift/cruise fan aircraft designs and may be of importance in the future.

The various wind tunnel and static tests reviewed are: (1) the Doak VZ-4 ducted fan, (2) the 0.57 scale model of the Bell X-22 ducted fan aircraft, (3) the Avrocar, (4) the General Electric lift/cruise fan, (5) the vertical short takeoff and landing (V/STOL) lift engine configurations related to ingestion and consequent thrust loss, (6) the XV-5 and other fan-in-wing stall consideration, (7) hybrid configurations such as lift fan and lift/cruise fan or engines and (8) the various conceptual design studies by air-frame contractors. Other design integration problems related to small and large V/STOL transport aircraft will be summarized including lessons learned during more recent conceptual design studies related to a small executive V/STOL transport aircraft.

14. SUBJECT TERMS Lift-fan, Powered-lift, Short takeoff/vertical landing (STOVL)	15. NUMBER OF PAGES 98
	16. PRICE CODE A05

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT