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INTRODUCTION

It is a privilege and a pleasure to have this opportunity to talk to you about progress in vertical and short takeoff and landing (V/STOL) aircraft technology. I must admit at the outset to some trepidation in accepting the invitation of the Society to speak on a subject that was successfully pioneered in the United Kingdom and brought to its current operational state largely because of the enduring faith of the Harrier team. However, I hope that the more modest progress that has been made on a variety of STOL and VTOL concepts will also be of interest to you; at the very least, this talk will identify some of the blind alleys to be avoided and, with a little luck, point out some new directions for future research. I will confine myself largely to the V/STOL technology with which I have been involved over the 1970-1980 period at Ames Research Center.

By way of historical introduction, it may be said that man's interest in vertical takeoff is as old as his first attempts to emulate the flight of birds; indeed, many of the early concepts of flying machines faithfully tried, entirely without success, to duplicate the flapping mode of flight. It was not recognized that the short and vertical takeoff capability of birds is in large measure made possible by their low wing-loading, which is a natural result of their small size. It is interesting to plot wing-loading (pounds per square foot) against wing span (feet) for a variety of birds and then to characterize them in terms of VTOL, STOL, or conventional (CTOL) flight modes (fig. 1).

Most birds (tree birds) have wingspans of about 1 foot, which correspond to wing loadings of less than 1 lb/ft^2; these birds can be classified as VTOL types. At the other extreme are birds of very large wing span (10 ft or more) — the extinct pteradactyl (actually a reptile), the condor, and the permanently grounded ostrich. These can be thought of as the conventional fliers — the CTOL types. In between these extremes are birds of intermediate sizes and wing loadings, primarily water birds. This group, which includes birds ranging from the sea gulls to Canadian geese, can be classified as STOL types. For obvious reasons, the STOL birds thrive in regions where there is ample space for their more or less horizontal takeoffs. Relative to the VTOL birds, the number of STOL species is rather limited.

Despite the lesson in survivability that he might have learned from the preponderance of VTOL birds, man has in general opted for CTOL

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flight. As David Hazen of Princeton University so aptly put it in a recent paper in which he discussed the survivability element inherent in VTOL capability: "Apparent as this fact may be to a bird's brain, it is by no means widely accepted by military planners — a fact to which many V/STOL enthusiasts attach significance."

In tracing the branch point between bird flight and manned flight we need go back only to Sir George Cayley who was the first to recognize the importance of distinguishing lift from thrust, and in particular to recognize the fact that for level flight, the required thrust is one or two orders of magnitude less than the required lift. Since, at that time, the technology for thrust-producing propulsion hardly existed, whereas that for lift-producing aerodynamics was rapidly evolving, it is hardly surprising that the first manned aircraft used a minimum of propulsion and were, therefore, CTOLs. Even when, over a 100 years later, vertical flight was achieved, it was an aerodynamic solution (i.e., a rotary wing) rather than a propulsive solution, that was first developed. Clearly the ingredient that was missing for so long in the quest for a feasible fixed-wing VTOL aircraft was a suitable propulsion system. The significance of the Pegasus Engine lies not only in its role as the powerplant for the Harrier but in being the first operational demonstration that a propulsion system could be built with sufficient thrust, and at a reasonable fraction of the total aircraft weight, to permit controlled vertical flight. It accomplished the step of combining the lift and thrust functions during takeoff and landing, which had been separated almost irrevocably since the time of Cayley.

I would like to turn now to the topic of research and development relating to V/STOL aircraft at Ames Research Center. The Center was established in 1940 as an aeronautical laboratory of the National Advisory Committee for Aeronautics (NACA), the predecessor agency to NASA. One of the first major facilities to be built at Ames was the 40- by 80-foot wind tunnel, which permitted the full-scale testing of aircraft, including their engines, to speeds of 200 knots (fig. 2). This capability to conduct combined aerodynamic/propulsive test programs made the facility a natural one in which to conduct research on V/STOL concepts. The sea-level location and usual lack of wind were also ideal for flight testing experimental aircraft, particularly those with marginal thrust-to-weight ratios and handling qualities. During the 1950s a variety of concepts were researched in the 40- by 80-foot tunnel and subsequently explored in flight-test programs. Some of these are illustrated in figures 3-5; they include STOL and VTOL aircraft depending on such thrust devices as the augmentor, the fan-in wing, the tilt-rotor, and the rotating cylinder flap. By 1970, the question was not "Can we conceive aircraft capable of V/STOL flight" but "of all the VSTOL concepts being investigated, which ones have the potential of being developed into feasible commercial or military aircraft?"

In attempting to define an R and D strategy for the 1970-1980 period, a number of V/STOL alternatives were assessed and an approach conceived to further the technology of the more promising concepts. The 1970 assessment can be summarized as follows:

1. The thrust augmentor (ejector) was potentially capable of providing a thrust increase of 60% to 70% for either STOL or VTOL applications, although these high augmentation ratios would probably require large diffusers and therefore result in packaging difficulties, particularly for VTOL aircraft.

2. The upper-surface-blown (USB) wing was potentially capable of substantially increasing $C_{L,approach}$ for STOL aircraft and was compatible with high-bypass ratio engines having high cruise efficiency, although questions remained regarding engine-out low-speed performance and controllability.

3. The tilt rotor was potentially capable of vertical takeoff with reasonably low disc-loading and with cruise speeds up to 350 knots, although questions remained regarding rotor stability and high cruise speed.

4. The lift fan was efficient in vertical flight but incorporation of the fan into the wing led to poor performance in STOL operation, structural deficiencies, and adverse pitching moments.

In order to pursue an aggressive program to improve and demonstrate V/STOL technology at reasonable cost, the following strategy was adopted:

1. Extensive use of large-scale testing in wind-tunnel and flight simulation facilities

2. Development of low-cost research aircraft using, wherever possible, modified airframes/or engines

3. Involvement of other agencies and industry contractors in joint technical and funding arrangements.

The advantages of this strategy were twofold: the cost of research and development was shared and therefore less likely to become a casualty of budgetary cutbacks; and the involvement of user agencies and industrial contractors influenced the configurations toward aircraft that were likely to have operational usefulness beyond their generic research value.

STOL INVESTIGATIONS: 1970-1980

Rotating Cylinder Flap

Early in the 1970s a very modest program to explore STOL performance in flight was undertaken, using the rotating cylinder flap concept. A rotating cylinder, placed at the trailing edge of the wing (fig. 6), acts as a boundary-layer control device, accelerates the flow over the flap, and, in conjunction with the propeller slipstream, produces the lift and drag characteristics required for steep approaches and short landings. A YOV-10 light observation aircraft (fig. 7) was borrowed from the U.S. Army and modified by incorporating the Alvarez-Calderon rotating cylinder flap system, installing Lycoming T53-L-11 engines, cross-shafted for single-engine safety, and larger propellers.

This aircraft, after modification by North American Rockwell, was tested extensively in the wind-tunnel and subsequently taken into a series of flight tests. The primary characteristics of the aircraft are given in figure 8; it had an aspect ratio of 4.75 and a wing loading of 45 lb/ft^2. In its modified form the propeller slipstream covered 55% of the wing and provided a thrust-to-weight ratio of 0.48 at 50 knots. The rotating cylinder, 12 in. in diameter, had an adjustable rotational speed; it was determined from the wind-tunnel tests that a speed of 7500 kept the flow attached over the flaps.

Some of the conclusions from the test program were as follows:

1. The aircraft had low lateral-directional stability in the approach to landing. Roll control, aided by differential propeller augmentation, was satisfactory and reduced adverse yaw in rolling maneuvers.

2. From a research point of view there were some interesting differences between wind-tunnel and flight tests, particularly with respect to airplane pitching moment. The unstable pitch-up, found in flight test, was a strong function of flap deflection, cylinder operation, engine power, and airspeed.

3. The lift and downwash determined in flight test were higher than those found in the wind-tunnel tests, and high descent angles (8°-12°) were achieved in flight. The differences between wind-tunnel and flight tests were attributed to wind-tunnel wall interference effects which are accentuated at low speed.

The overall usefulness of the aircraft as a research tool was limited by the low wing-loading, marginal stability characteristics, and its inability to carry a second crew member to act as a safety pilot.

Augmentor Wing

The second STOL research aircraft program undertaken in the 1970s was a cooperative program between Ames Research Center and the Canadian Government (the Defense Research Board and the Department of Industry Trade and Commerce). The program initially involved wind-tunnel research and subsequently, in 1972, became focused on a research aircraft utilizing the augmentor wing. This concept (fig. 9) uses an augmentor flap, installed along the trailing edge of the wing, which is supplied with bypass air from the engine. This arrangement produces an increase in thrust, accelerates ambient air into the augmentor flap, and directs it downward to produce lift. The configuration is cross-ducted so that the lift remains balanced in the event of engine failure, and the augmentor flap has a choke to provide additional roll control.

The details of the research aircraft were established on the basis of a 0.6-scale wind-tunnel model (fig. 10), utilizing a J-85 General Electric engine which powered two Rolls Royce Viper compressors, and on extensive flight-simulator investigations. In 1972, a DeHavilland C8A (Buffalo) aircraft was modified into a powered-lift airplane; the wing and tail were rebuilt by Boeing, and the Spey engines modified by DeHavilland and Rolls Royce of Canada to replace the original turboprop engines. Pegasus jet pipes and bifurcated nozzles were also installed to provide additional vectoring capability, using the engine hot-flow. The end result was an airplane with a 78-foot wingspan, an aspect ratio of 7.2, and a wing loading of 60 lb/ft^2 (fig. 11). This ungainly looking aircraft, with its fixed landing gear and instrumented nose boom, was nevertheless the means for conducting flight research for a period of almost 10 years. Figure 12 shows the modified Buffalo aircraft in flight.

Some of the results of the wind-tunnel, flight-simulator, and flight-test programs conducted with the Augmentor Wing Aircraft are summarized below; these results apply primarily to the landing configuration with flap angles in the vicinity of 70°.

1. Duct losses in supplying bypass air to the Augmentor were about 5% of the thrust; this was more than overcome by an augmentation of approximately 1.37 (including a nozzle efficiency factor of 94%) for the wind-tunnel model and 1.27 for the aircraft. The inability to achieve, in the flight vehicle, the higher augmentation ratio achieved in the wind-tunnel model seems to be symptomatic of large-scale augmentor hardware.

2. The maximum lift and stall characteristics experienced in flight generally agreed with trends predicted from the wind-tunnel tests. Three dominant factors were present when the stall condition was approached: entrainment of the secondary flow into the augmentor flap provides very effective boundary layer control; the onset of stall occurs at the wing fuselage junction but is confined to the wing root area because of jet entrainment; and the growth of the disturbance at the wing root causes changes in downwash at the tail resulting in a post-stall, nose-down, pitching moment. These characteristics produce a very gentle stall (as seen in fig. 13), with a large angle-of-attack margin of about $\Delta\alpha = 20^\circ$ between the approach and stall conditions.

3. A substantial amount of flight simulation was conducted throughout the development of the research aircraft, using a large moving-base simulator. Data from the wind-tunnel investigations were used to define the stability derivatives, including the effects of powered lift, and it was gratifying to learn that the aircraft handling qualities were very close to those experienced in the simulator. A notable exception to this agreement was found in the flare and touchdown characteristics.

The aircraft experienced a positive ground effect, resulting in a more gentle and accurate touchdown than that experienced in the simulation. The simulation was based on wind-tunnel results which had predicted adverse ground effect.

The flight program conducted on this research aircraft by a joint NASA-Canadian team was also concerned with the definition of automated landing procedures; an experimental automatic flightpath control system was developed by NASA and Sperry for this purpose. The system permitted curved steep approaches and landings, with pilot participation varying from fully piloted to fully automatic.

Recently, after a successful joint flight program lasting almost 10 years, the Augmentor Wing Aircraft was transferred to the Canadian government for further flight investigations in support of a potential medium-range military transport development employing the augmentor concept. The aircraft would be designed for use into short, unimproved airstrips.

Upper-Surface-Blown Flap

In 1974 a further step was taken to explore STOL technology in flight, with the initiation of the Quiet Short-Haul Research Aircraft (QSRA) program. A second modified Buffalo aircraft, which incorporated conventional high-bypass-ratio engines, was used. This concept, the upper-surface-blown flap (fig. 14) directs the engine exhaust over the upper surface of the wing and over a large Coanda flap, thereby producing additional wing circulation and lift. Again, the details of the research aircraft were established on the basis of large-scale wind-tunnel tests (fig. 15). It was decided that a four-engine version was desirable in view of its ability to provide high, propulsion-induced lift, and its greater ability to balance the lift in the event of engine failure without the necessity for cross-ducting across the fuselage.

In 1976, the Boeing company, under contract to NASA, initiated final design of a new wing-propulsion system, and in 1978 delivered the aircraft to Ames Research Center (fig. 16). The primary characteristics of the wing and propulsion system are shown in figure 17. It has a wing span of 73-ft, an aspect ratio 9.0, and 15°-sweep. Large inboard flaps redirect the exhaust flow from the four Lycoming YF102 engines (acquired as surplus from the U.S. Air Force). The engines have bypass ratios of 6 and each produces 6,225 lb of thrust. At a weight of 50,000 lb, the aircraft has a nominal uninstalled thrust-to-weight ratio of about 0.5.

Two features of the QSRA are of particular interest: the high-lift characteristics and the small noise footprint. These two features make the aircraft an ideal tool with which to explore a variety of flightpaths during approach and to demonstrate quiet operation in the terminal area. The small turn-radius and short-field landing capability that result from the high lift-coefficient also make the QSRA ideal for investigating takeoff and landing modes for military STOL aircraft, including operations from carrier decks. Some of the conclusions derived from numerous flight investigations are as follows:

1. A maximum lift coefficient of 11 was achieved in flight with USB flaps set at 50° and at a thrust-to-weight ratio of 0.38.

2. An operating lift coefficient of about 5.5, with wide operating margins ($\Delta\alpha = 20°$ and one engine inoperative), can be achieved readily (fig. 18).

3. The noise footprint during takeoff and landing is described by a 90 EPNdB contour enclosing an area of about 1 square mile (fig. 19).

4. An approximate 30% reduction in takeoff and landing distances can be achieved by use of the USB flap, at a thrust-to-weight ratio (about 0.25) and wing loading equal to those for a conventional aircraft.

5. A powered-lift USB aircraft is not difficult to fly and generally has better handling qualities and performance characteristics than a comparable conventional aircraft.

In addition to the NASA research conducted with this aircraft, it has also been used to demonstrate powered-lift landing techniques and in familiarization training for industry. Among the most interesting of these familiarization programs was a demonstration of unassisted carrier landings and takeoffs made by NASA and Navy pilots. The Navy pilots had extensive carrier experience with fighter aircraft but none with transport aircraft, except 3 weeks of simulator and flight training provided at Ames. Landing distances of about 650 ft with zero wind-over-deck and about 170 ft with wind-over-deck of 30 knots have been achieved. Of particular interest are the vertical and horizontal dispersions during approach and touchdown: sink rates of 7 ±1.5 ft/sec were typical for the several pilots who took part in the program; wheel height at the carrier ramp was 17 ±1.6 ft, and main gear touchdown distance dispersions were ±10 ft. In these precision landings, a Fresnel lens, a radar altimeter, and no-flare landings were used at approach angles of 4.5° and approach velocities of 65 knots.

To summarize, it can be said that recent progress in STOL aircraft technology is the result of careful research in ground facilities and in flight. The rate of progress sometimes appears to be slow; nevertheless, in retrospect, the level of confidence that we have acquired in the use of powered-lift in short-field aircraft operations is markedly improved over that of 10 years ago. The means of generating lift have improved to the point that very high lift-coefficients can be obtained while still providing wide margins to protect against gusts, cross-winds, and engine failure. [illegible] many takeoff and landings accumulated in these research programs under various conditions, including night landings, carrier deck landings, and fully automated landings amount to several thousand in number; they provide a firm basis for both design criteria and certification criteria for future STOL aircraft.

A somewhat unexpected result from the flight research at reduced thrust levels is that substantial reductions in field length can be achieved with high-bypass-ratio engines at thrust levels equivalent to those normally used by CTOL aircraft (e.g., a thrust-to-weight ratio of 0.25). The short-field advantage of the powered-lift aircraft can be traded for other parameters of merit; for example, payload, range or fuel consumption. The implication is that a powered-lift aircraft can be used in a conventional mode (CTOL), a conventional takeoff and short-landing mode (CTOSL), and in a short-takeoff and landing mode (STOL) without compromise to the aircraft design.

VTOL INVESTIGATIONS: 1970-1980

Tilt-Rotor Aircraft

In the early 1970s a review was conducted of the status of technology related to the tilt-rotor concept. The problems associated with the XV-3 aircraft, notably the aeroelastic (whirl flutter) instability of the rotor at high forward speeds, had been thoroughly researched during the intervening years in the wind tunnel, and a new rotor had been designed and tested at large scale (fig. 20). The results of those tests showed that it should be possible to design a tilt-rotor aircraft with maximum cruise speeds in excess of 350 knots. In 1972 the technical program at Ames was focused on the development of a research aircraft; the size of the aircraft was chosen so as to permit testing in the 40- by 80-ft wind tunnel before the aircraft was taken into forward flight, and sufficiently large to permit extrapolation of results to an aircraft of useful operational size.

The resulting XV-15 Tilt-Rotor Research Aircraft (fig. 21) was developed between 1972 and 1977 by a team from NASA, the U.S. Army, and Bell Helicopter Corp.; two aircraft, designed at a gross weight of 13,000 lb each, were built and brought to flight status. The aircraft are powered by twin Lycoming T-53 turboshaft engines that are connected by a cross-shaft and drive three-bladed, 25-ft-diam metal rotors (the size extensively tested in the wind tunnel). The rotors have a blade twist of 45° and are gimbal-mounted to the hub with an elastomeric spring for flapping constraint. At the design weight of 13,000 lb, the wing loading is 77 lb/ft^2, and the disc loading is 13 lb/ft^2. The design maximum speed is 300 knots at an altitude of 16,000 ft. The two aircraft have accumulated over 400 hr of flight testing, and the program is now being directed toward establishing the suitability of the concept for various civil and military applications.

The XV-15 research flight envelope is shown in figure 22, in terms of density-altitude and true airspeed, for level flight. The predicted envelope is shown with flight-test conditions superimposed; based on flight-test results to date, the demonstrated flight envelope is expected to coincide with the predicted envelope. Flight hovering performance

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agrees well with predicted performance, and sideward and rearward flights to 25 knots have been conducted with favorable results. As originally expected, one-engine-out hovering is possible at lower gross weights, and the aircraft has demonstrated a maximum cruise speed of 300 knots. The aeroelastic rotor stability boundary is also shown in the figure; flight-test results show that damping ratios are equal to or higher than predicted levels. Further tests, with the aircraft in a shallow dive, are planned.

The shaft-horsepower of the rotor, as a function of calibrated airspeed, is shown in figure 23 for (1) the helicopter mode (nacelle angle of 90°), (2) two tilt-rotor modes (nacelle angles of 60° and 30°), and (3) the airplane mode (nacelle angle of 0°). Also shown is the single engine maximum power line for this aircraft. The speed-power curve for the helicopter mode is typical of helicopters, and the curve for the airplane mode is typical of that for fixed-wing turboprop airplanes. The buckets of the helicopter mode speed-power curve (and all tilt-rotor-mode curves) occur at approximately the same power level, that is, at about 920 rotor shaft-horsepower per rotor. This phenomenon leads to a total minimum power envelope that is essentially flat in the calibrated airspeed range of 50 to 170 knots. Thus, there exists an airspeed range of 120 knots that can be flown at minimum power by using the nacelle tilt angle appropriate to the desired airspeed. Figure 23 has several implications. Flight at minimum fuel flow occurs anywhere within the 120-knot-wide minimum power envelope. This characteristic is of interest for a wide variety of flight conditions; for example, it would provide flexibility and endurance for search and rescue missions and efficient near-terminal operations. Other favorable implications pertain to such characteristics as noise and vibration level, STOL performance, life of component parts, and single-engine conversion, and reconversion, in level flight. It may be of interest for some military missions to note that the cruise speed of the tilt-rotor aircraft, with one engine inoperative, is much higher than that of a typical helicopter under full power.

Turbofan VSTOL Technology

The use of large fans for vertical lift was researched extensively at Ames through the 1960s; the high propulsive efficiency of the large-diameter fan, however, was offset by the difficulty of packaging it into a configuration that remains aerodynamically efficient in horizontal flight. This problem was further compounded by the need to interconnect the engines in order to balance the aircraft in the engine-out situation. Considerable effort was expended on a variety of configurations to find suitable solutions to the packaging and engine-out problems for proposed VTOL transport concepts; some of these are illustrated in figure 24.

During the early 1970s, an attempt was made to design a research aircraft having three fans, exhausting behind the wing near the root and at the nose. Two propulsive concepts were considered: (1) tip-driven fans interconnected to two gas generators to provide engine-out capability, and (2) mechanically driven fans cross-shafted for engine-out capability. Both of these approaches were complex and ultimately proved too costly to permit approval of a research aircraft development program. Work continued on mechanically connnected fan concepts, however, and by the late 1970s the effort became focused on a concept devised by Grumman Corp. (fig. 25). The design incorporates two tilting turbofan engines with controllable inlet guide vanes and a system of control valves placed in the engine exhaust flow to provide control moments during vertical and transitional flight. This approach minimizes complexity by reducing the number of engines and by integrating the propulsion and control system into a separate module that can be adapted to different mission-specific aircraft. A large-scale model, using two General Electric TF-34 (bypass ratio 6), engines shown in figure 26, has been tested extensively in the wind tunnel and on the hover test stand.

Inlet airflow separation has been investigated and flight boundaries, in terms of nacelle angle versus airspeed, established from wind-tunnel data, show that a fairly wide transition-speed corridor is available without the occurrence of separation. The effect of nacelle interference on lift has also been investigated; evidently the positive increment of lift from this interference more than offsets the negative effect of the exhaust flow on the wing lift, at least for nacelle angles up to 60°. Control-vane effectiveness in the turbofan airstream has also been determined: the control moment was found to be quite linear with vane deflection and provides adequate power for maneuvering at low speed. Lift in ground effect is not degraded, despite some meandering of the exhaust flow fountain, and there is no evidence of high-temperature gas injection into the engine.

The development of a propulsion/control module that can be adapted to various aircraft configurations may be of considerable interest in the future. It could be used for a small carrier-on-board delivery aircraft, or for a larger transport aircraft by incorporating several two-engine modules fore and aft of the wing. Such modules could be based on existing or modified high-bypass-ratio commercial engines.

Direct Jet Lift

Direct jet lift has been applied successfully to the Harrier aircraft and is now being considered for application to future supersonic fighter aircraft. The integration of a VTOL propulsion system into a supersonic aircraft that retains good performance at high speed is a much more difficult task than for subsonic aircraft, however, and substantial work remains to be done before an airplane with satisfactory performance can be built. In the late 1970s a comprehensive program was started at Ames to acquire low-speed and high-speed data on a variety of supersonic VSTOL configurations proposed by the U.S. airframe industry. A detailed evaluation of the alternative configurations, and an assessment of the performance penalties that result from incorporating VTOL capability, should then be possible. These penalties can then be weighed against the advantages that accrue from the flexible basing modes made possible by the V/STOL capabilities of the aircraft.

Thus far in the program, wind-tunnel tests have been conducted on several twin-engine configurations. Two of these, proposed by General Dyanmics Corp. and Northrop Corp., are shown in figures 27 and 28. The General Dynamics concept (fig. 27) is a wing-canard configuration, in which jet augmentors (ejectors) are used for vertical lift, and a vectored engine-over-wing propulsion system is used to provide transonic maneuvering and STOL performance. The engine airflow is directed over the wing aft surface to provide jet-flap effect; this can be combined with spanwise blowing, at high angles of attack, to produce leading-edge vortex augmentation. The Northrop configuration (fig. 28), incorporates variable cycle engines, a remote augmented lift system (RALS) to provide lift through the forward nozzles, and deflector exhaust nozzels to provide for thrust vectoring. This concept also is a wing-canard design but with two vertical tails mounted on twin afterbodies. The clipped delta-wing has variable camber with automatically phased leading- and trailing-edge flaps. The canard is high-mounted and all-movable. The complexity of those designs reflects the difficulty of providing simultaneously for VTOL low-speed stability, good transonic maneuverability, and adequate supersonic performance.

Tests have been conducted in the 40- by 80-ft tunnel; in the 12-ft high-Reynolds number, subsonic tunnel; in the 11-ft transonic tunnel; and in the 9- by 7-ft supersonic tunnel. In this way, the Mach number range from 0.2 to 2.0 was covered. The test results, and comparisons of test results with those predicted by the design teams and NASA, have been published in several technical papers of the AIAA and the SAE; they are too extensive to review here.

A similar program is now under way to establish a data base for single-engine configurations, which are typified by the McDonnell Douglas and General Dynamics configurations shown in figures 29 and 30, respectively. The McDonnell Douglas concept has four swiveling nozzles to provide thrust vectoring for vertical flight and for in-flight maneuvering. It has a close-coupled canard mounted on the side inlets and a single vertical tail. The propulsion system has a twin-spool gas generator augmented by fan-stream burning. The evolution of this concept from the successful Harrier is self-evident. The General Dyanmics single-engine V/STOL fighter concept combines vectored thrust and a thrust augmentor (ejector) for vertical flight. The aerodynamic planform is a crank-arrow design with a single vertical tail and no horizontal tail. These concepts are still evolving and should be developed for wind-tunnel testing this year (1982).

It is not yet clear which of the several design approaches to a supersonic VSTOL fighter will emerge as the most promising, but the extensive data base now being established on twin-engine and single-engine concepts should permit a decision in the mid-1980s and will support the development of such an aircraft by 1990.

SOME PROJECTIONS FOR THE FUTURE

In discussing the future, I will confine myself to those missions and configurations that could emerge by the year 2,000. Such a near-term projection requires little imagination and its correctness will probably depend more on changes in the perceptions and attitudes of civil and military planners than on revolutionary changes in technology. Given the large physical and emotional investment in the present air system, it seems more likely that those perceptions will be changed by the imposition of new requirements rather than by a strong desire to take advantage of new technology.

Turning first to the military use of V/STOL aircraft, the primary question over the next 20 years concerns the nature of air warfare and the role of aircraft in direct engagement. It is not difficult to postulate a future in which real-time data acquisition using space-borne and high-altitude sensor platforms, combined with highly accurate long-range standoff tactical missiles, will make fixed bases, whether on land or at sea, the least attractive places from which to conduct military operations. It seems quite probable that the debate now taking place over the vulnerability of ICBM sites will soon be extended to air bases and aircraft carriers, and the question of credible basing modes will be raised in the context of tactical weapons.

In such a threat environment, V/STOL aircraft may be most effective in the role of situation assessment and weapons designation, rather than in the direct delivery of munitions; their effectiveness in this role will depend on an ability to respond quickly to changing battlefield conditions and to operate from dispersed locations within easy reach of the battle area. Similarly, sea-based V/STOL aircraft operating from dispersed ships forward of the main battle force would provide early warning of enemy attack and targeting of ship-launched missiles.

In civil aviation, a significant long-term question relates to the way air transportation will interact with urban development. Since the introduction of jet transport aircraft into commercial aviation in 1960, air transportation has played an increasingly important role in intercity trade and commerce. In the process, however, a necessary element of air transportation, the airport, has become a source of noise and congestion — an unwanted neighbor of the city it serves — and the ground segment of the journey now requires an ever-increasing fraction of the total journey time and cost.

This inefficiency is particularly serious for short-haul flights, and the problem will be overcome only when the airport becomes small, quiet, and conveniently-sited. The solution will require STOL and VTOL aircraft, compatible with an interconnected system of short-haul airports; and clearly these aircraft must retain or improve upon the cruise efficiency of current aircraft if they are to compete successfully. The need for a versatile air transportation system of this kind has been recognized for many years, of course, but it now appears feasible to design suitable alternatives to the pure helicopter, with its inherently poor cruise efficiency, and to the conventional transport aircraft with its need for long runways.

Typical of the air vehicles that may be in service by the year 2,000 are the following:

1. A 40-passenger, tilt-rotor aircraft capable of scheduled service over distances up to 400 miles, and capable of operation to oil rigs and between ships at sea.

2. A 150-passenger CSTOL military/civil transport aircraft capable of takeoff and landing on 3,000-ft runways and having a cruise efficiency comparable to that of current jet transports.

3. A supersonic STOVL fighter/attack/interceptor aircraft, capable of operating from dispersed sites on land and from small carriers at sea.

4. A large, short-range VTOL military transport aircraft capable of supporting the rapid redeployment of heavy equipment, including ground-based missiles.

Much of the technology necessary to such developments is essentially available today; the specific mission/user requirements have not yet been established, however, and will be determined by the response to the changing military threat and by the needs of the commercial marketplace.

CONCLUDING REMARKS

Progress in the rate of development of V/STOL aircraft over the past 30 years seems disappointingly slow to the enthusiasts of this form of flight among whom I count myself. Only two kinds of V/STOL aircraft have achieved operational maturity: the helicopter and the direct-lift Harrier. Yet, when we look more closely at the state of the art, it is clear that our understanding of the technology has improved immeasurably in this period; for example, the level of lift enhancement derivable from aerodynamic/propulsive interactions, the trade-offs involved in optimizing overall performance in VTOL aircraft design, and the minimum control margins necessary to assure acceptable landing qualities for STOL and VTOL aircraft.

Equally important, there now appears to be a growing recognition that the vulnerability of military assets to long-range attack will require distributed basing in order to assure their survival. In civil aviation the saturation of terminal airspace can be expected to force the development of aircraft that are quiet, capable of short takeoffs and landings, and efficient in cruise flight. When specific missions and their requirements finally evolve I believe the technology base will be adequate to support suitable V/STOL aircraft developments. The results will change dramatically both air transportation and air warfare.

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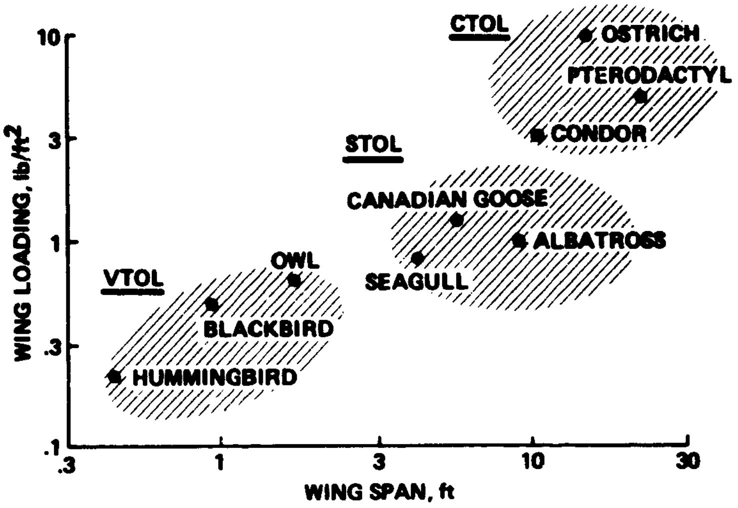

Figure 1.- Takeoff and landing characteristics of birds.

Figure 2.- Construction of 40- by 80-foot wind tunnel (1944).

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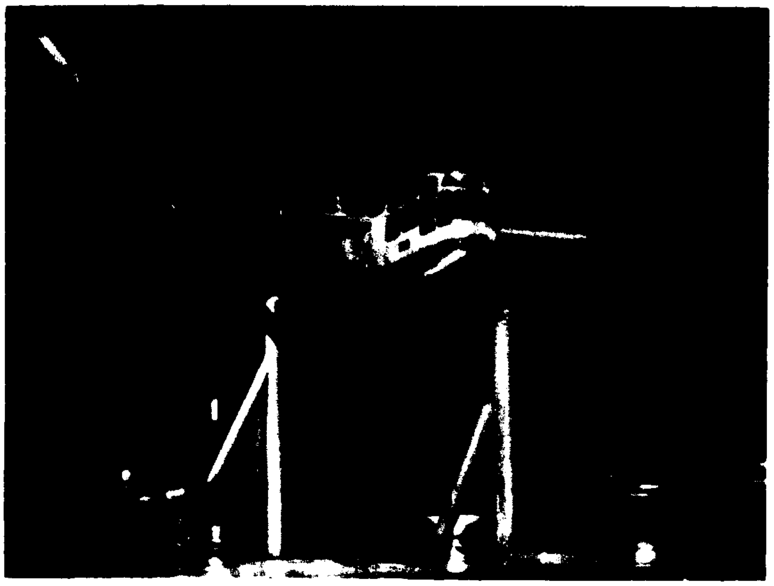

Figure 3.- Early tilt-rotor aircraft, XV-3 (1950s).

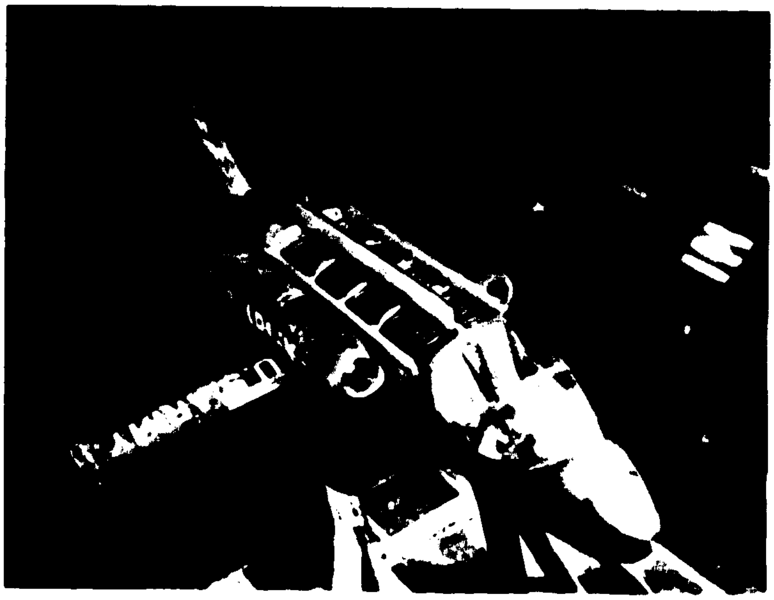

Figure 4.- Augmentor VTOL aircraft, XV-4 (1960s).

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Figure 5.- Lift-fan VTOL aircraft, XV-5, (1968).

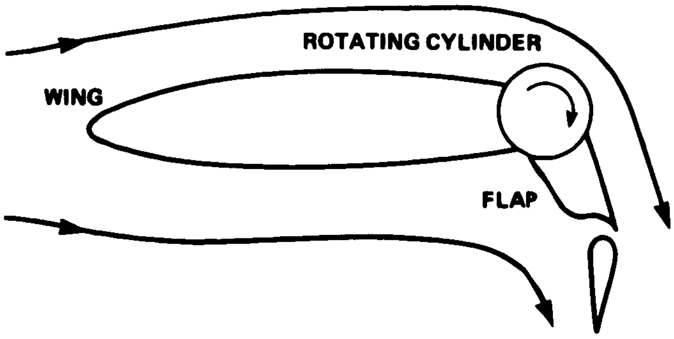

Figure 6.- Rotating cylinder flap concept.

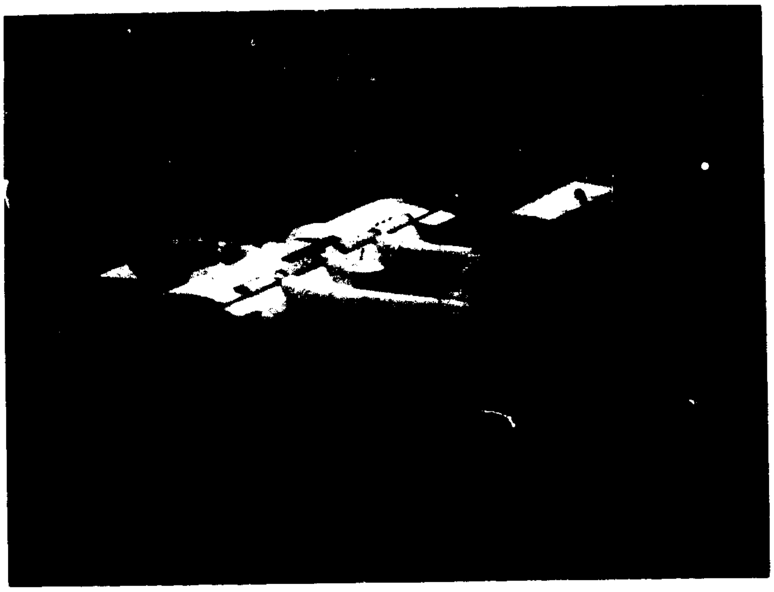

Figure 7.- Modified OV-10A.

PRIMARY CHARACTERISTICS – MODIFIED OV10A

TAKE-OFF GROSS WEIGHT	11,844 lb
WING SPAN	34 ft
WING LOADING	45 lb/ft^2
ASPECT RATIO	4.74
PROPELLER (4 BLADED), diam	9.4 ft
ENGINE THRUST (2, T53 L-11)	2200 lb
ROTATING CYLINDER, diam	12 in.
ROTATING CYLINDER, LENGTH	62 in. (PER SECTION)

Figure 8.- Primary characteristics — modified OV-10A.

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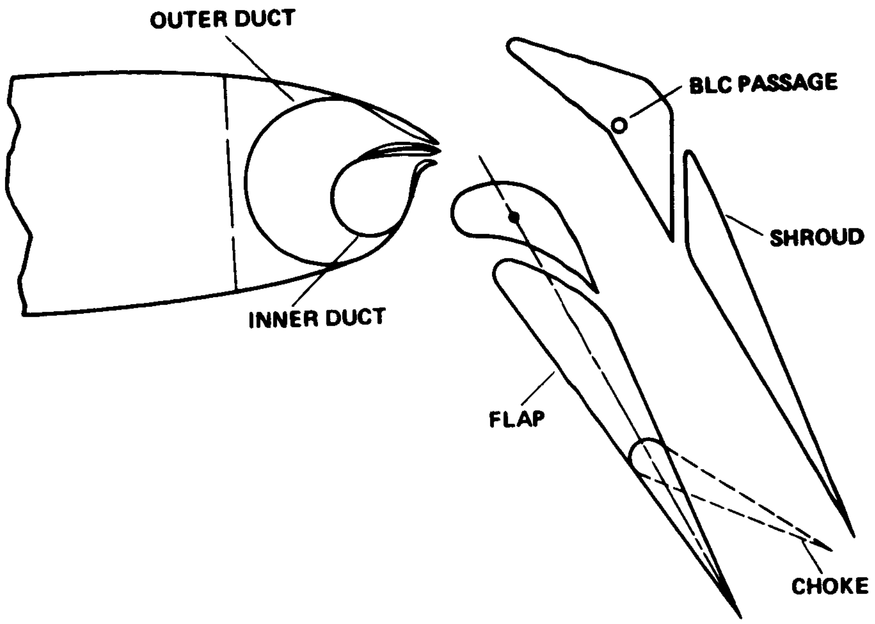

Figure 9.- Augmentor wing concept.

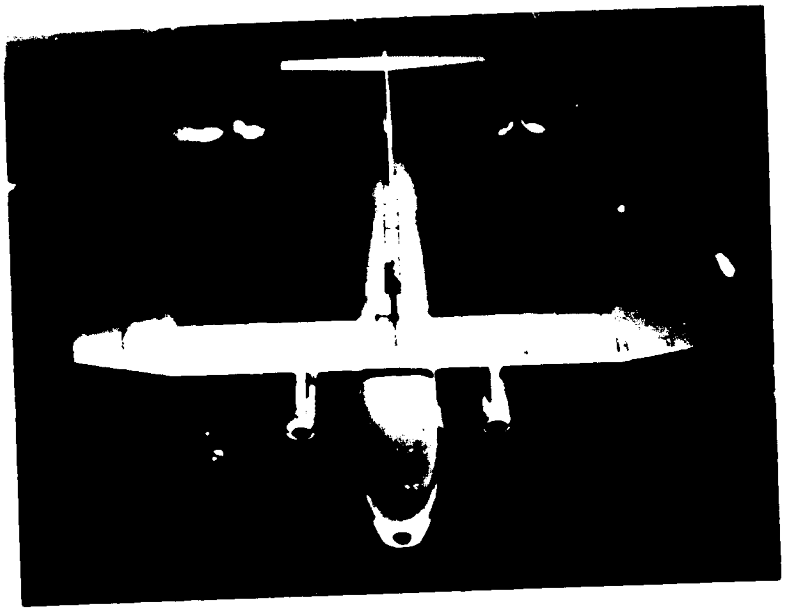

Figure 10.- Wind-tunnel model of augmentor wing aircraft.

TAKE-OFF GROSS WEIGHT	50,000 lb
WING SPAN	78 ft
WING LOADING	60 lb/ft^2
ASPECT RATIO	7.2
ENGINE THRUST (2 MODIFIED SPEY)	26,000 lb
AUGMENTOR FLAP, LENGTH	23.5 ft
AUGMENTOR FLAP, CHORD	3 ft

Figure 11.- Primary characteristics — modified DeHavilland C8-A aircraft.

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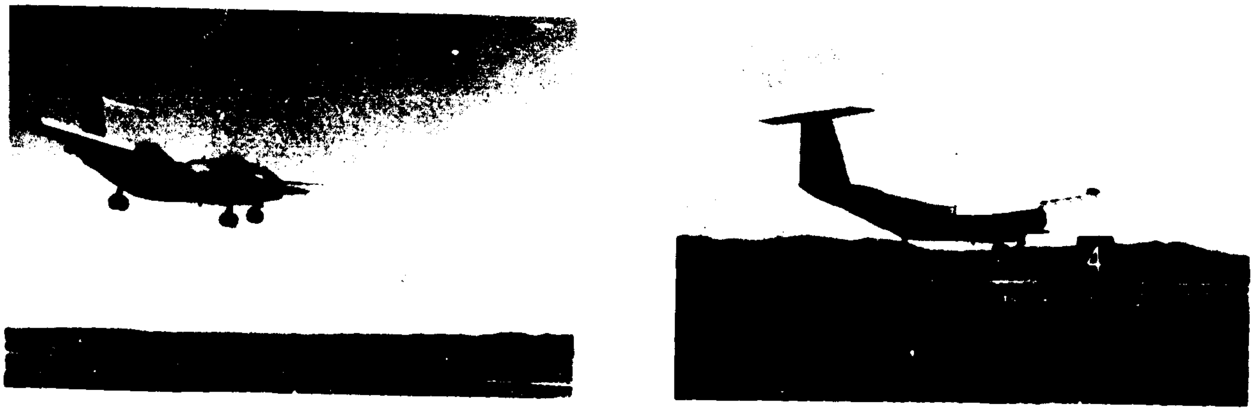

Figure 12.- Augmentor wing aircraft in flight.

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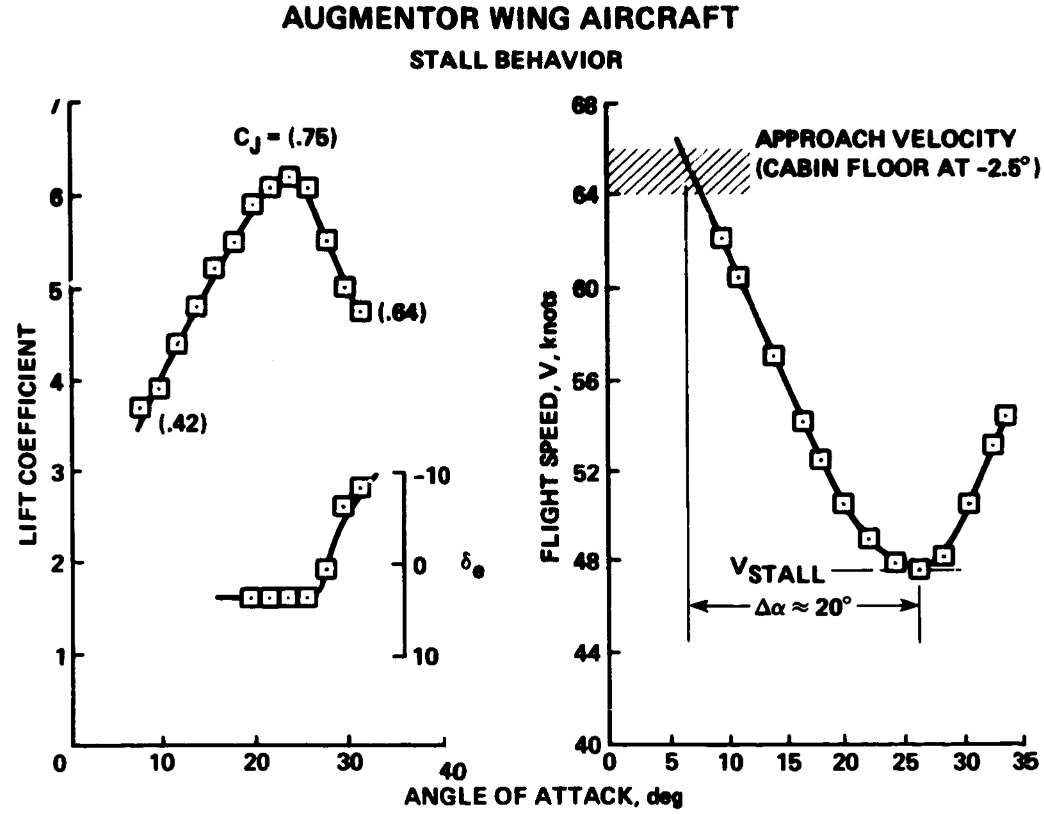

Figure 13.- High-lift and stall characteristics — augmentor wing aircraft.

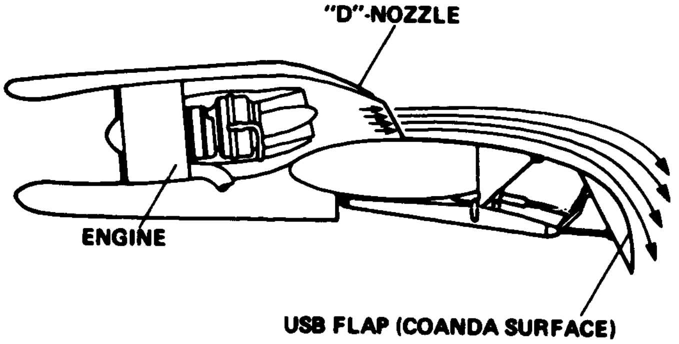

Figure 14.- Upper-surface blown flap concept.

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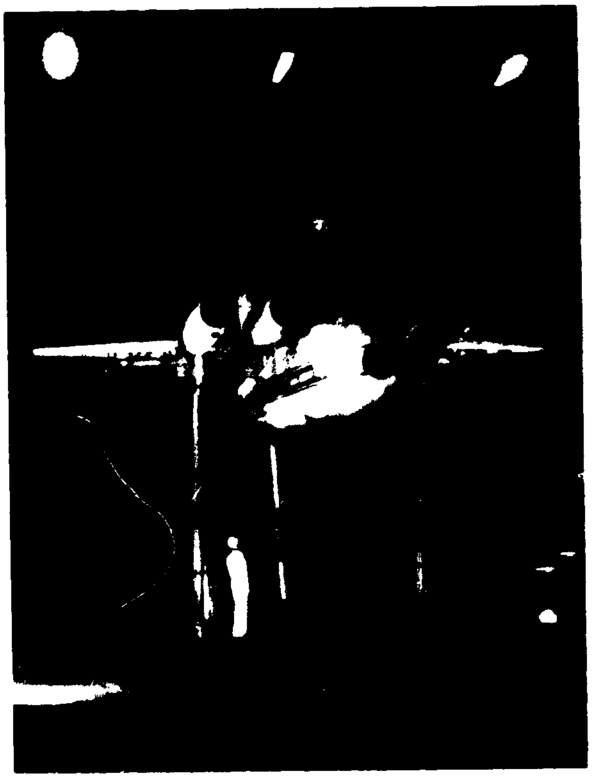


Figure 15.- Wind-tunnel model of USB aircraft.

Figure 16.- NASA/Boeing Quiet Short-Haul Research Aircraft (QSRA).

TAKE-OFF GROSS WEIGHT	50,000 lb
WING SPAN	73 ft
WING LOADING	60-100 lb/ft^2
ASPECT RATIO	9
ENGINE THRUST (4 LYCOMING YF102)	24,900 lb
ENGINE BYPASS RATIO	0.6

Figure 17.- Primary characteristics of QSRA.

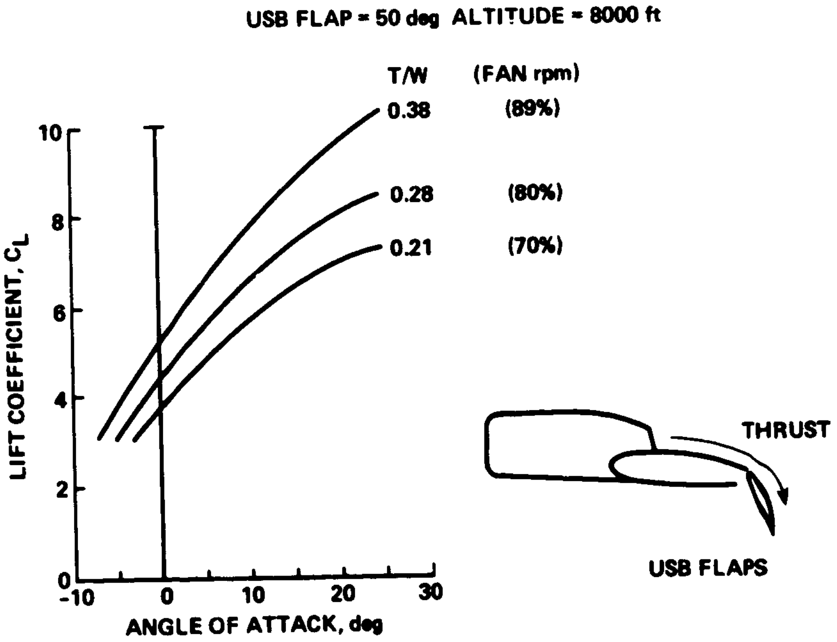
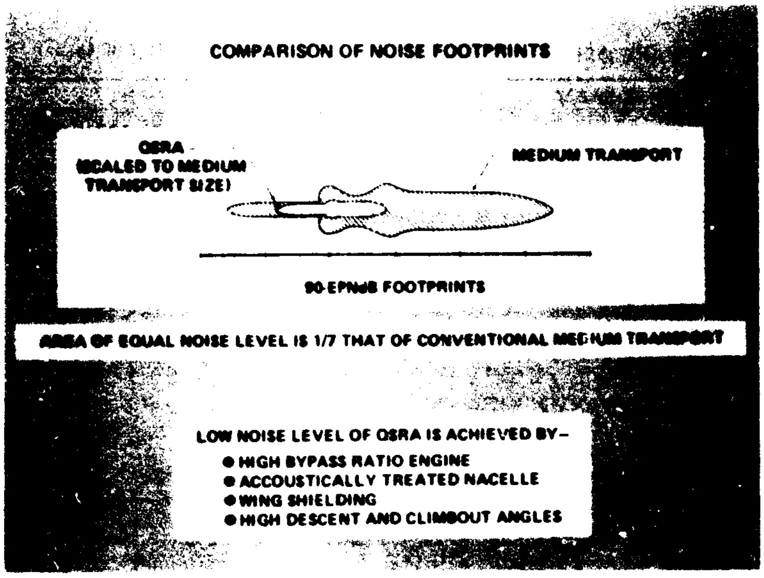


Figure 18.- High-lift characteristics of QSRA.



COMPARISON OF NOISE FOOTPRINTS

QSRA
(SCALED TO MEDIUM
TRANSPORT SIZE)

MEDIUM TRANSPORT

90-EPNdB FOOTPRINTS

AREA OF EQUAL NOISE LEVEL IS 1/7 THAT OF CONVENTIONAL MEDIUM TRANSPORT

LOW NOISE LEVEL OF QSRA IS ACHIEVED BY–

- HIGH BYPASS RATIO ENGINE
- ACCOUSTICALLY TREATED NACELLE
- WING SHIELDING
- HIGH DESCENT AND CLIMBOUT ANGLES

Figure 19.- Noise footprint of QSRA.

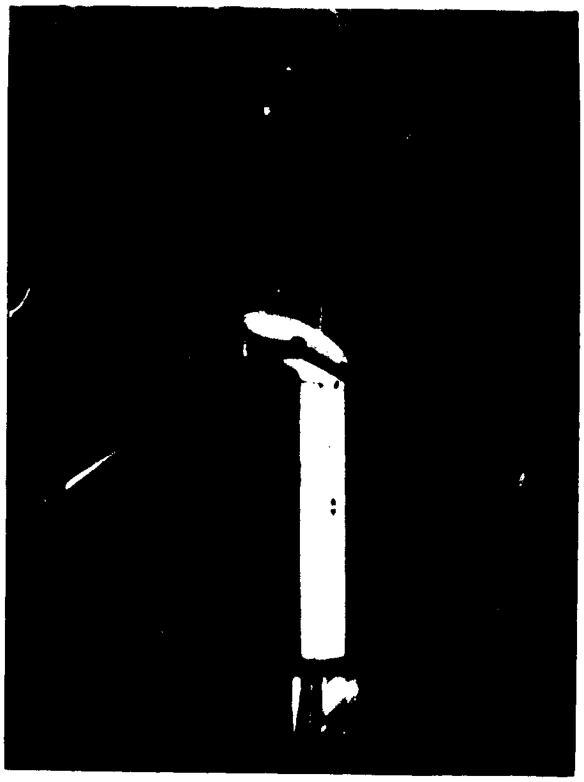


Figure 20.- Wind-tunnel test of 25-ft-diameter rotor.

Figure 21.- XV-15 tilt-rotor research aircraft.

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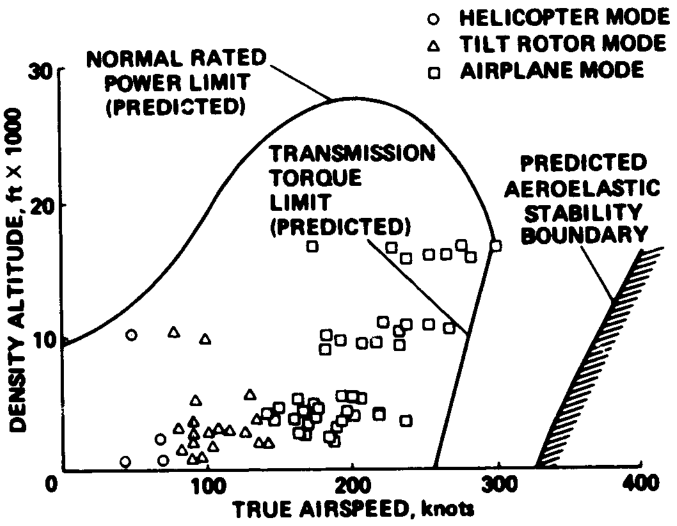

Figure 22.- XV-15 flight envelope.

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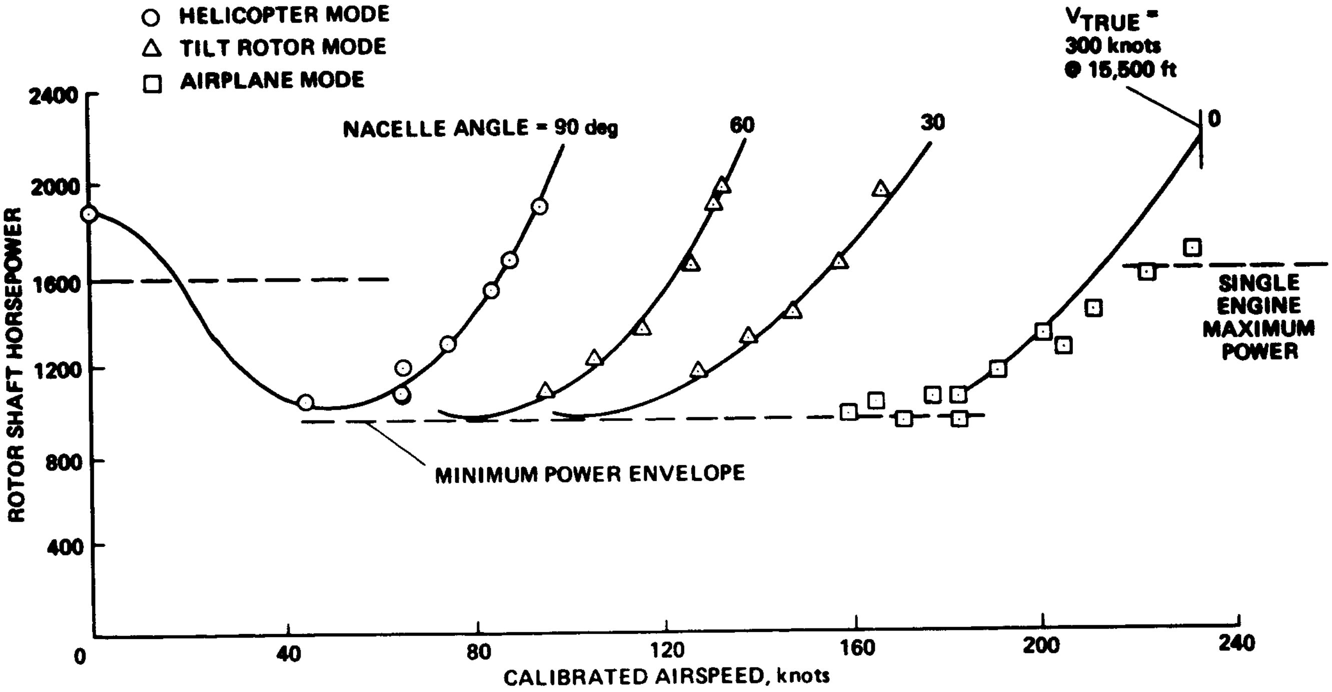

Figure 23.- XV-15 power-airspeed characteristics.

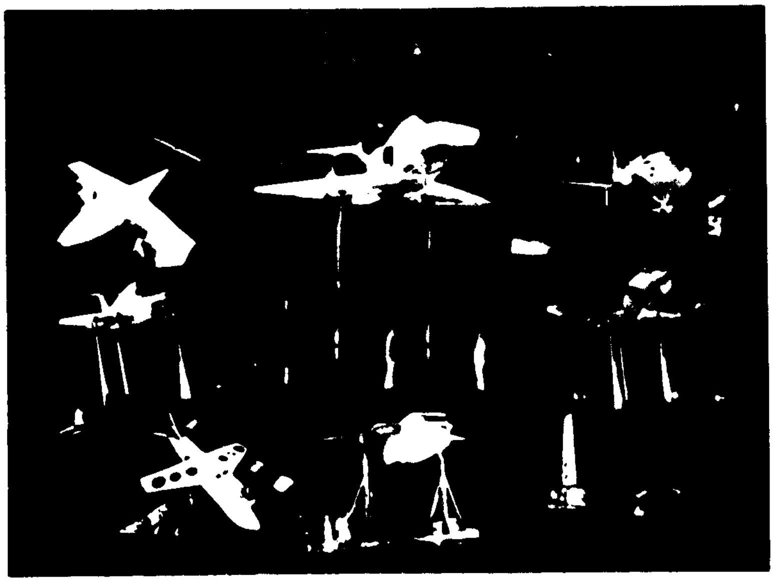

Figure 24.- Wind-tunnel investigations of several lift-fan concepts.

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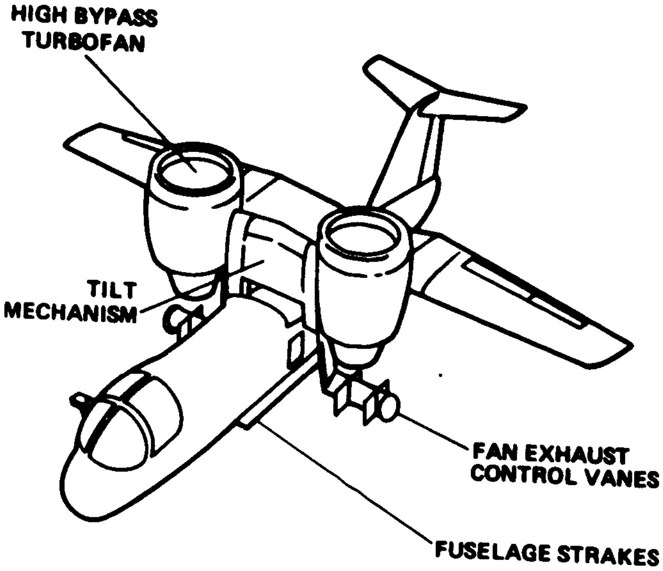

Figure 25.- Tilt-nacelle aircraft concept.

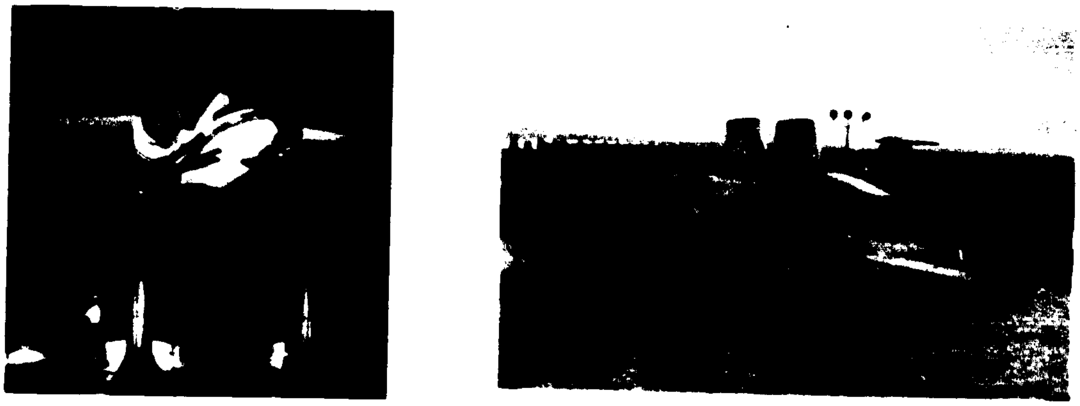

Figure 26.- Wind-tunnel model of Grumman tilt-nacelle aircraft.

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Figure 27.- General Dynamics twin-engine V/STOL Aircraft: model in 11-ft wind tunnel.

Figure 28.- Northrop twin-engine V/STOL aircraft: model in 11-ft wind tunnel.

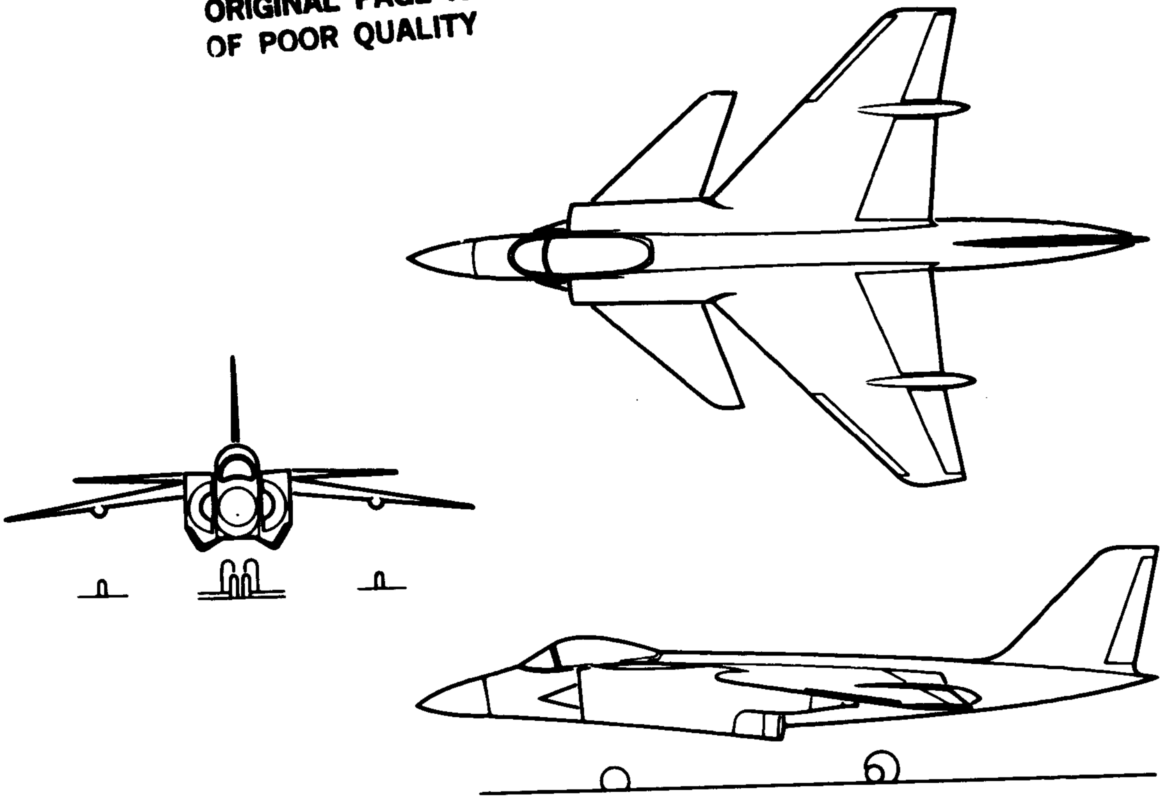

Figure 29.- McDonnell Douglas single-engine V/STOL fighter concept.

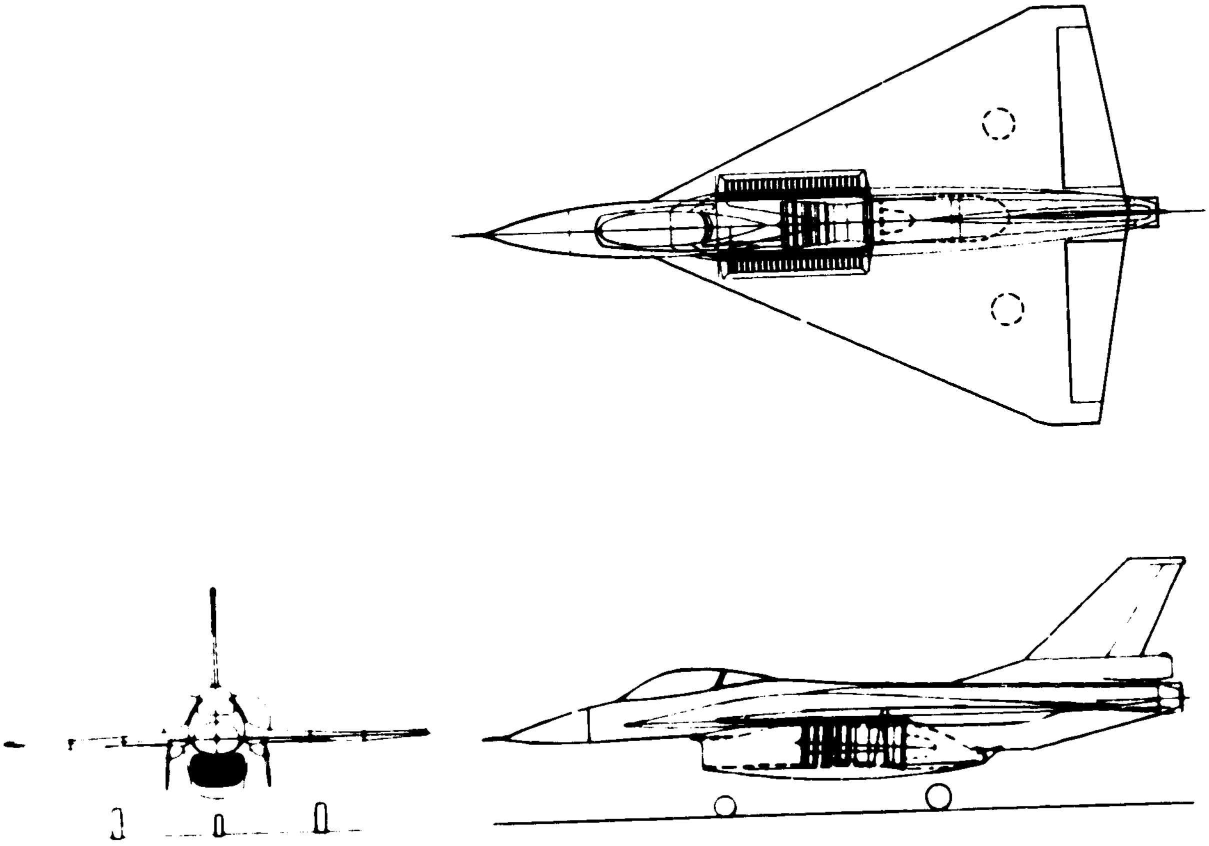

Figure 30.- General Dynamics single-engine V/STOL fighter concept.