High-Performance Jet-V/STOL Development

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Recent aircraft sizing and experimental studies of future high speed V/STOL aircraft are examined. Mission studies indicate that for supersonic strike/fighter missions the lightest weight and lowest cost aircraft is one powered by a lift-plus-lift/cruise propulsion system, sized for the high-speed mission, supplemented by a low specific weight and volume lift-producing device (e.g., a jet lift engine). This type of aircraft introduces unique design problems. Recent technology developments aimed at solving these problems are discussed in the key areas of aircraft/propulsion design concepts, engine arrangements and sizing, V/STOL aerodynamics, hot gas effects, and control concepts.

Introduction

REQUIREMENTS for future Navy and Marine Corps supersonic fighter/attack V/STOL aircraft are being studied at various government and industry installations. The need for such studies has been prompted by the growing challenge to the Navy abroad and at home. Overseas, we are witnessing the growth of a sophisticated and well-coordinated Soviet naval force, which is oriented towards a disruption of our use of the seas as an operational base and a disruption of our vital logistic links. On the home front, a limited-defense-oriented dollar has resulted in a reduction in the size of our Naval forces. To compound the problem, the increasing loss of overseas bases places a constraint on the rapidity and scope of support which we can provide to our Allies. One of the proposed solutions to these problems is a dispersed force concept.[1,2] A brief review of this concept provides some insight to the need for high-speed V/STOL tactical aircraft.

Dispersed-force concepts apply to both sea and amphibious operations. The essence of the concept at sea, as it relates to the traditional aircraft carrier role, is the use of VTO-capable supersonic fighter/attack and subsonic ASW/AEW aircraft. The aircraft would be deployed on widely dispersed air capable platforms. The use of smaller and more numerous ships, spread over greater ocean areas, not only complicates enemy targeting and dilutes his offensive resources, but decreases our time to react to the threat and provides operational continuity in the face of heavy losses in one concentrated area.

Navy-funded studies[2,3] have shown that the supersonic V/STOL fighter, acting in a VTOL mode from dispersed platforms, can provide significant economies over the current fleet air-defense concept. The current concept requires large numbers of aircraft to maintain a quick-reaction posture; VTOL interceptors operating in a ground loiter mode on dispersed sites provide favorable reaction-time factors (i.e., relative distance to the threat and rapid intercept time).

Projection of power ashore, primarily in support of amphibious operations, is also enhanced by providing the Marine Corps with tactical aircraft capable of rapid response to the battlefield commanders' need for air support. Here again, the concept is one of ground loiter vs air loiter to provide rapid response. Dispersing the air element on shore and placing it closer to the area of conflict again provides quicker reaction time, reduced vulnerability, and air cover without the need for large carriers.

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The lift-plus-lift/cruise ($L+L/C$) design illustrated in Fig. 1 is one of the supersonic V/STOL aircraft concepts we have been studying for both the Navy and Marine Corps applications discussed above. This type of design will be used to discuss: lift vs cruise-engine thrust selection tradeoffs; propulsion considerations for selecting and integrating the deflector nozzle which converts the cruise engine to a lift/cruise thrust; combining VTOL and conventional takeoff and landing (CTOL) requirements into one design with multimission capability; unique jet V/STOL aerodynamic phenomena; and control concepts.

Lift-Plus-Lift/Cruise ($L+L/C$) Design Concepts

Figure 2 illustrates four variations of the basic $L+L/C$ design concept—lift/cruise engines fitted with deflection capability for lift thrust, and supplemented by direct-lift engines (DLE's) which are used only during V/STOL operations. Figure 2a is a symmetric $L+L/C$ design, similar to the FRG VAK-191, in which neither DLE nor L/C operation causes pitch imbalance for VTOL. Figure 2b, 2c, and 2d are asymmetric $L+L/C$ designs, whose basic differences are due to the location, type and number of L/C engines.

Cruise-Engine Selection

The first order of priority is the proper choice of L/C engine cycle. Our concept of proper means basing the selection on the propulsion and aerodynamic characteristics required to satisfy the desired high-speed mission and maneuvering constraints. After such a selection, the additional lift and control power required for vertical, or STO, operation should be explored for the purpose of minimizing attendant weight and cost penalty (i.e., minimizing the V penalty). For both fan and jet DLE, this approach appears to lead to viable high-subsonic and supersonic V/STOL designs.[4-6]

As an alternative to this concept, the aircraft could be wrapped around a L/C engine whose size and type is based on sufficient thrust for vertical takeoff (e.g., a Harrier-type engine). In this case, the mission radius and speed are fallouts – for some desired mission radius and speed a serendipitous match is possible.

Based on the missions explored to date, and discussed below, selecting the cruise engine for conventional flight operations leads to the lightest and lowest cost design. This is based on the fact that high-thrust and low-weight DLE's, as well as low-weight deflection devices for the cruise engine, introduce minimal volume and structural inefficiencies to the conventionally arranged aircraft. The aircraft design can thus be optimized for conventional flight, its primary purpose. This approach yields not only an efficient V/STOL article, but, if desired, can also yield a cost-effective companion CTOL version.

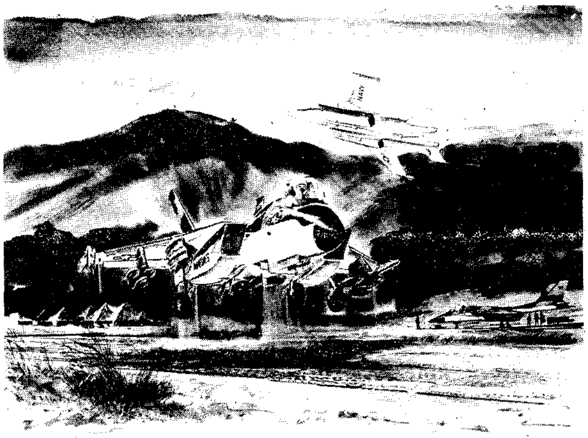

Fig. 1 The two-in-one $L + L/C$ concept saves money.

L/C Engine Location

As illustrated in Fig. 2, the axial location of the *L/C* engine in asymmetric designs has a major impact on the overall aircraft configuration and DLE size. We have selected *L/C* engine location as one parameter to highlight some of the challenging design problems involved in configuring a supersonic V/STOL aircraft. To investigate this parameter, we have adopted the following desiderata. 1) The mass balance should lead to a cg location close to the aerodynamic center, to minimize control surface size and trim drag. 2) The resultant VTOL thrust vector should be close to the cg, to avoid oversizing the zero-speed control mechanisms. 3) All of the potential *L/C* thrust should be used for VTOL, to minimize the DLE dead weight during conventional flight. 4) The resulting cross-sectional area should be low, for efficient supersonic operation. 5) Engine location should not impact pilot visibility over the side, which should be better than normally provided in CTOL design. 6) To minimize reingestion, the main engine inlets, auxiliary inlets, and jet nozzles should be high off the ground, and the jets should not be in close proximity to the inlets. 7) Minimum control power should be necessary at zero speed to provide for safe crew ejection in the event of any engine failure. 8) The *L/C* nozzle should be placed in a base-free area, to minimize the cruise boattail drag. 9) The DLE should provide zero-speed control power, to avoid compromising the *L/C* engine for conventional flight. 10) Sufficient space should be available near the cg for carrying a variety of stores.

The 30,000-lb-class single-*L/C*-engine concept shown in Fig. 3 was configured in accordance with the above factors. Two DLE's are required to supplement the available *L/C* thrust and provide 60% of the total propulsive net lift (see Fig. 2b). One of the unique features of this concept is the use of twin swivel nozzles for each of the engines, with full (0 to 110°) vectoring to reduce engine-out moments (item 7) and reingestion (item 6). One of the important trades relative to the above list was item 3 vs items 4, 8, and 10. Using additional *L/C* thrust for VTOL conditions (item 3) would require an engine located closer to the cg. The result would be: an increase in cross-sectional area (item 4) since the wing is also near the cg; a nozzle installation with high cruise boattail

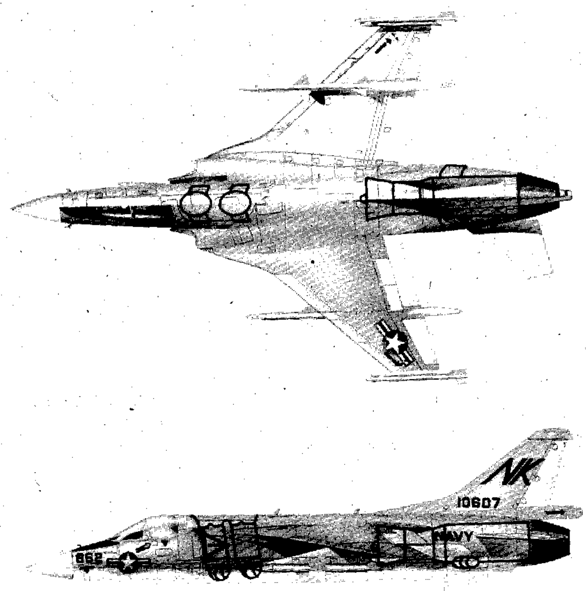

Fig. 3 Single-engine concept.

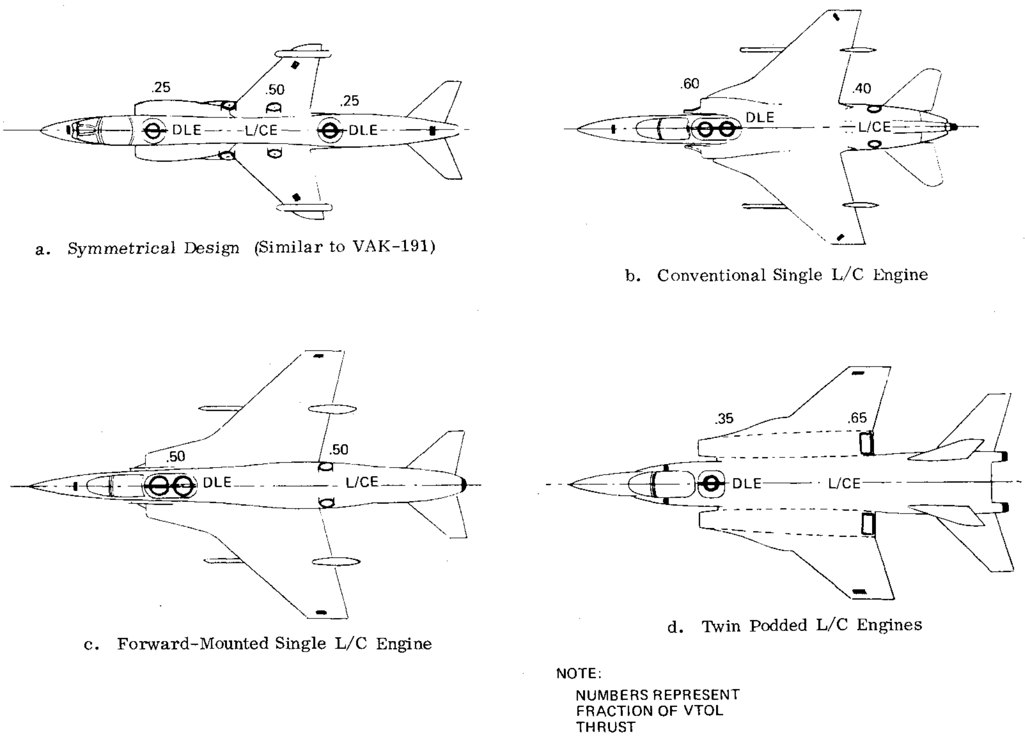

Fig. 2 Typical $L + L/C$ aircraft concepts.

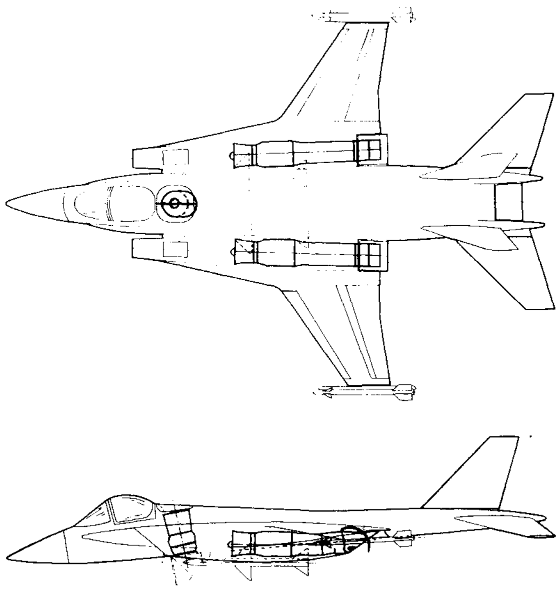

Fig. 4 Twin-engine concept.

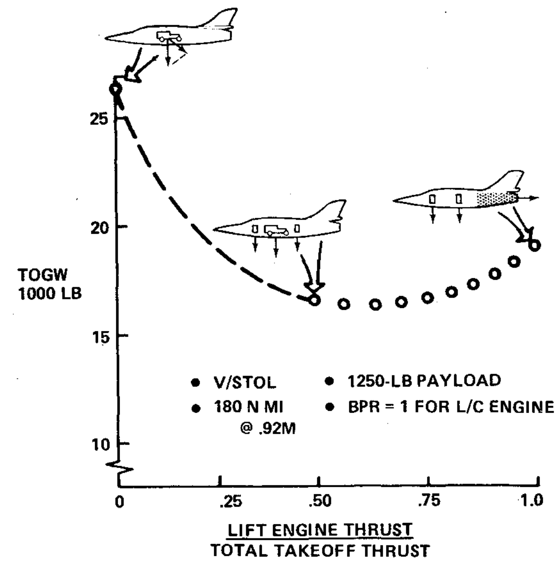

Fig. 5 $L+L/C$ is the lowest cost solution for symmetric designs.

drag (item 8)(see Fig. 2c); and the virtual elimination of effective centerline store stations (item 10).

A typical 30,000-lb-class twin-L/C-engine design is shown in Fig. 4. Only one DLE is required to provide 35% of the liftoff thrust. For this type of configuration, items 3, 4, 8, and 10 are not compatible with items 6 and 7. Note that most of the vertical thrust can be supplied by the L/C engine when it is mounted closer to the c.g. (item 3). By pod-mounting the engines in out-board locations and contouring the fuselage, the cross-sectional area is kept low (item 4), the two-dimensional exhaust nozzle is integrated with the wing (item 8), and a wide variety of weapon mixes can be placed on the wing and fuselage (item 10). The forward exhaust gas location, however, causes the intake region to be more susceptible to reingestion (item 6), and the outboard engine location requires additional zero-speed roll control power (item 7).

Discussion of these tradeoffs remains academic without some sort of quantification. In the area of conventional performance, trends can be attained from a data bank of previous aircraft complemented by detailed design studies. Unfortunately, many of the items discussed previously (e.g., reingestion, control-power sizing, and nozzle-interference drag) are not amenable to completely analytical predictive techniques. Experimental studies are thus required. The remainder of this paper is devoted to the results of design and experimental studies in several of these key areas.

$L+L/C$ Sizing Studies

Numerous government and industry studies have been performed to determine the desired thrust split between L and L/C engines. The approach in such a study is to fix the mission requirements, vary the amount of supplemental DLE thrust, and examine the trends in aircraft gross weight. The results of one such study for symmetric $L+L/C$ designs[7] (see Fig. 2a) are reproduced in Fig. 5 for a low-level, high-speed penetration mission. Similar studies[3] have been reported for supersonic asymmetric designs and escort-type missions. The trends in all these studies indicate that a large TOGW penalty is incurred by eliminating the lift engine(s).

In a more recent study, variants of the twin engine concept, (shown in Fig. 4) were used to examine the size of the L/C engine (and associated DLE and control equipment) for the various V/STOVL (short take-off and vertical landing) missions given in Fig. 6. A scaleable, modern, low bypass ratio fighter cycle was used for the L/C engine and a 20:1 uninstalled thrust/weight ratio lift engine cycle for the DLE.

The resulting TOGW trends are presented in Fig. 7. The results confirm previously reported conclusions,[2,7] i.e., the $L+L/C$ concept will provide the lightest, and lowest cost, solution for high-speed V/STOL missions. At one extreme, the pure L/C concept requires an engine so inefficient and over-sized, (for the tactical missions of Fig. 6) that extremely large aircraft are required to provide the needed cruise fuel. At the other extreme, the $L+C$ concept requires an inordinate amount of lift engine, which is a needless penalty for conventional flight.

It may be argued that new technology L/C engines or vectored-thrust designs may be more efficient at low-power settings, and hence reduce the TOGW required to perform future Navy and Marine Corps missions. However, this advanced-cycle engine technology can, at the same time, reduce the V penalty for $L+L/C$ designs by providing control power at zero speed, reducing lift-engine size and weight, and generally reducing aircraft size and cross-sectional area. Therefore, at this time, it appears unlikely that the results of Fig. 7 will change substantially, unless the mission requirements are severely downgraded.

Jet-V/STOL Aerodynamics

Jet-induced effects, as used here, denotes the forces and moments on the aircraft due to propulsion jets prior to full wing-borne flight. It is well known that jet-induced effects can require additional lift thrust and control power of almost the same order of magnitude as the basic thrust. (See Ref. 8 and references listed therein.) Jet-induced effects produce a flow field over the aircraft which is affected by the entrainment of ambient air which, in turn, is affected by jet geometry, free stream conditions, and proximity to the ground. The basic data required to predict the quantity of air entrained comes from theoretical and empirical data on turbulent mixing. At the present time, there is no complete solution that properly accounts for the mixing of arbitrary jet cross sections, crossflow effects, and jet confluence in and out of ground effect.

Detailed studies have been started on a predictive technique[9] which relies on semi-empirical data, simplified models of the jet, and theoretical potential flow methods. The empirical data is used to describe the developments of free jets, out-of-ground effect, and jets impinging on a ground plane. These data lead to: entrainment coefficients for both free and wall jets; the free jet shape in a crossflow and its merger with neighboring jets; and the jet formation along the ground plane which interacts with other jets, leading to the so-called "fountain" effect.

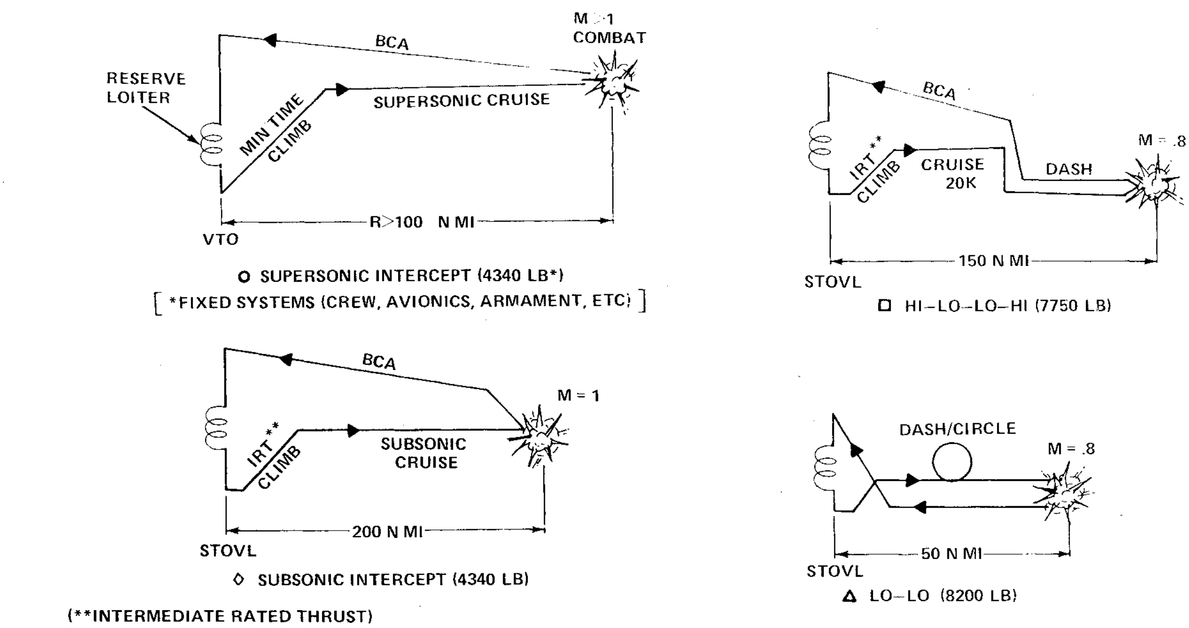

Fig. 6 High-speed tactical mission profiles.

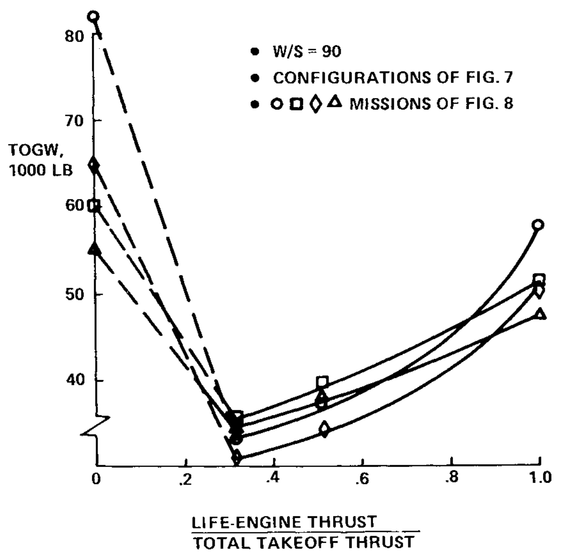

Fig. 7 $L+L/C$ is also the lowest cost solution for asymmetric designs.

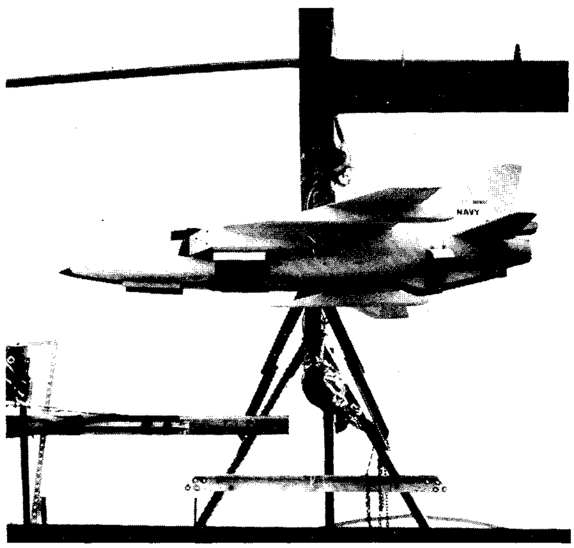

Fig. 8 Grumman's hover rig is a useful design tool.

These jet data are combined with exisitng wing-body potential theoretical methods in which the aircraft configuration is divided into a large number of panels, each of which contains a singularity (source/vortex) distribution. The usual boundary conditions (zero normal velocity and the Kutta condition) provide a set of linear equations iteratively solved to determine the singularity strength. In an extension of this method the aircraft, jets, and ground plane are all divided into panels. The normal inflow velocity for the jets and ground plane comes from mass entrainment data. After the singularity strength for all panels is determined, the local pressure is calculated for all aircraft panels, and hence the forces and moments.

To supplement the analytical predictive techniques, we tested the concepts shown in Figs. 3 and 4 at the British Aircraft Corporation (BAC) 5.5-m V/STOL tunnel, in Preston, England and at Grumman. The objective of these tests was to obtain a complete propulsion force and moment profile for use in a manned simulation of VTOL control procedures.

In addition, Grumman's hover rig (Fig. 8) permits investigating the effects of a wide range of variables on suck-down forces, at low cost. The model duplicates the type of measurement system used at BAC[10] in which only aircraft forces are on the balance. A 1973 test using this rig proved that strakes added between the nozzles of a six-jet configuration are effective in trapping the fountain and providing a considerable upward force (Fig. 9). The results of other important nozzle variables are given in Ref. 11.

Out-of-Ground Effects

The twin L/C design concept model shown in Fig. 10 was tested at BAC for the following variables: 1) angle of attack; 2) thrust level; 3) forward speed; 4) tail deflection; 5) height above ground; 6) nozzle deflection angles; 7) nacelle spacing; and 8) ground suppression devices.

A significant discovery resulting from these tests was that the major loss in lift at forward speed was due to the use of a simple deflector door for the lift engine (see Fig. 11).

Photographs of the water vapor used for flow visualization confirmed that the lateral spreading of the lift-engine jet must be contained to avoid lift losses during transition. This phenomenon was also confirmed with the rectangular L/C nozzles. The large amount of usable data which was obtained,

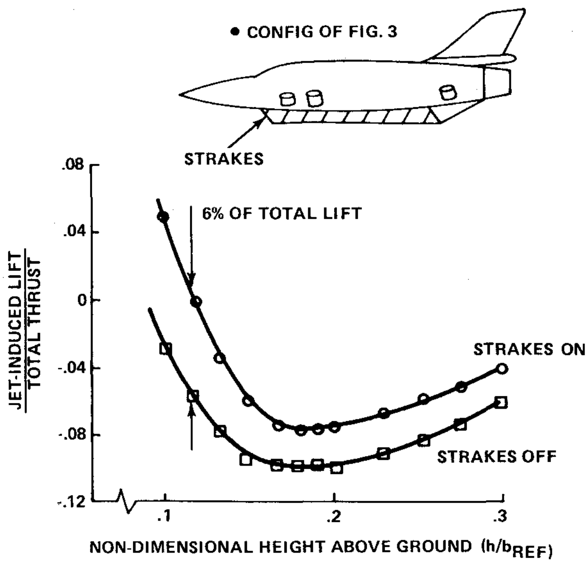

Fig. 9 Capturing "The Fountain" reduces lift loss.

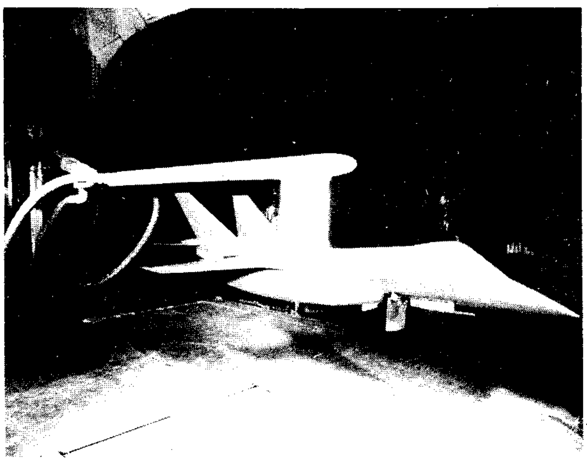

Fig. 10 Tri-jet, twin *L/C* engine test model at BAC.

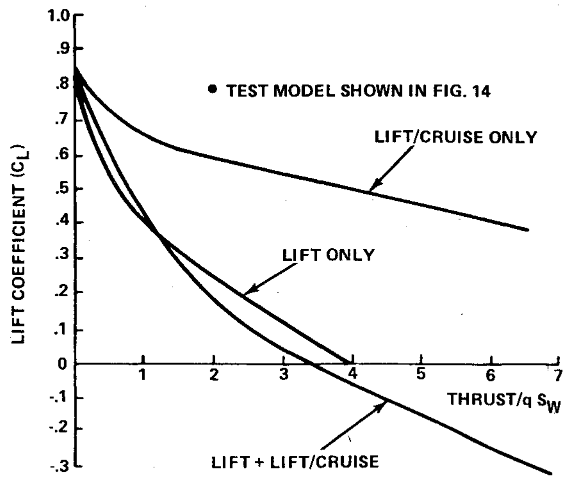

Fig. 11 Typical lift-loss test results out-of-ground.

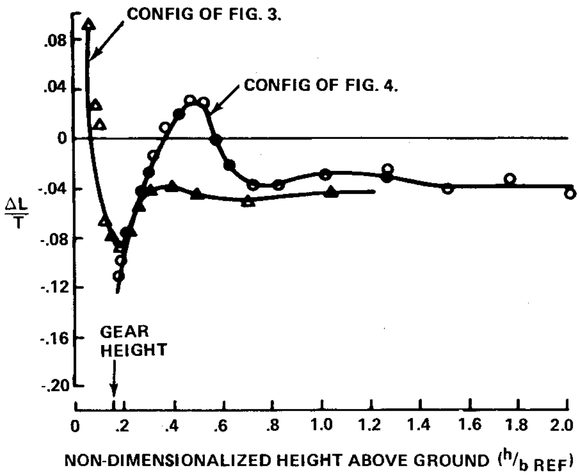

Fig. 12 Jet-induced losses are highly configuration oriented.

the method of testing to obtain a component buildup of jet-induced effects (e.g., Fig. 11), and the trends in test data, have led us to conclude that this type of testing is absolutely necessary if costly full-scale modifications are to be avoided during development.

In-Ground Effects

With a sufficient thrust margin to overcome aircraft weight-plus-lift losses during VTOL, any additional lift loss requires more engine thrust (or less usable payload). Figure 12 shows that these jet-induced effects are highly configuration dependent, and suggests that alternate development approaches should be tried. For example, test results of the single-L/C-engine concept with six jet exhausts, presented in Figs. 9 and 12, indicate a decreasing jet-induced lift with height above ground beyond static gear height. But sufficient thrust margin must be available for the lowest point on the lift-loss curve. Decreasing gear length (and weight) to effect less loss at gear height would be ineffective. On the other hand, the twin-engine concept studied (with three engine exhausts) shows an increasing lift with height-above-ground beyond static gear height (Fig. 12). Near the static position, the steepness of the curve (and the eventual positive lift) indicates that, for this configuration, small increases in gear length (and weight) could be effectively traded for increased engine size. Obviously, these entrainment effects must be coupled with reingestion effects to obtain a full accounting of the in-ground jet-induced effects as they vary with the height above ground. Only then can one make the rational configuration tradeoffs previously discussed.

Hot-Gas Effects

In spite of the attractiveness of the $L+L/C$ concept, many concerns have been expressed regarding reingestion, erosion, hot spots and ground handling of these high-disc-loading propulsion systems. One of the focal points of our technology development efforts is aimed at addressing these concerns through model test and, eventually, the development of scaling relationships and hot-gas prediction techniques. Figure 13 shows a test model that we used at the VFW-Fokker hot-gas facility in Bremen, Germany, to determine the effects of high-temperature exhaust systems on the ground, fuselage, and engine intakes.

This model contains separate ducting to simulate engine intake and exhaust flow simultaneously. The important variables tested were: 1) height above ground, 2) temperature level, 3) aircraft attitude, 4) thrust split, 5) ground suppression mats, 6) nozzle deflection angle, 7) wind speed and direction, 8) inlet location and auxiliary inlet size. Excellent flow visualization techniques were used to determine the ground flow pattern (see Fig. 13) and calibrate the nozzle angles from 110° to 45° (relative to the ground plane). The simulated compressor face was heavily instrumented to monitor the temperature patterns and levels.

The test results in Fig. 14 show the dramatic effect of nozzle deflection angle on the lift/cruise inlet temperature rise. This type of information is invaluable in eventually formulating aircraft operating procedures.

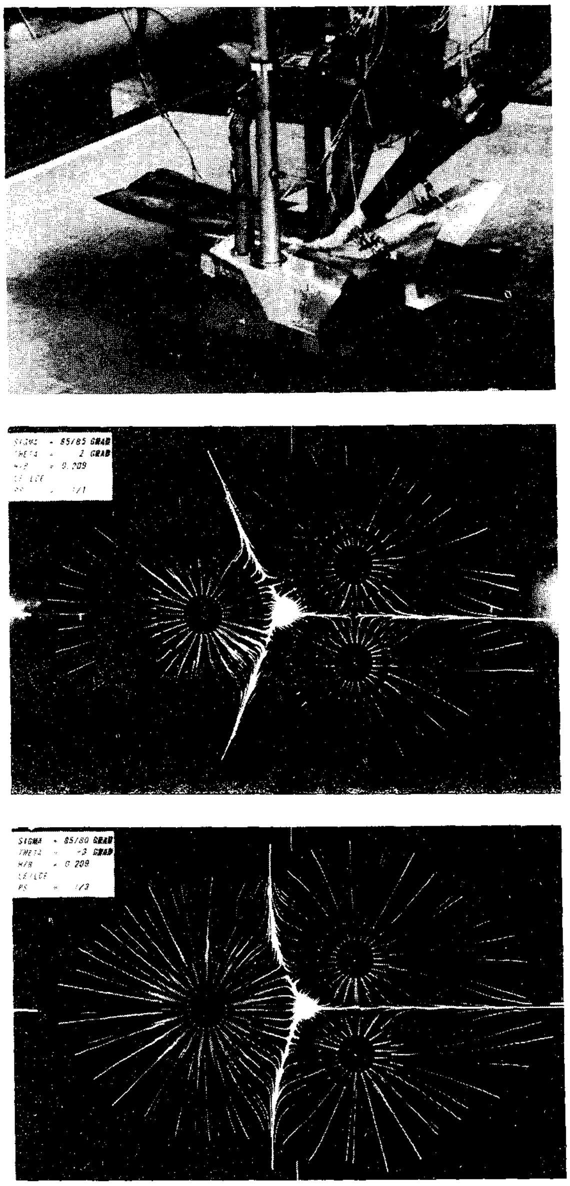

Fig. 13 Hot-gas test model and unique flow visualization at VFW-Fokker.

In a multi-jet configuration, trapping the fountain not only decreases lift losses (Fig. 9) but also causes hot gases to impinge on the airplane lower surfaces. The direct impingement of the fountain (or upwash) on the aircraft may occur at a wide range of locations between the forward and rear engines, and depends on nozzle angles, wind velocities, height above ground, and aircraft attitude.

Fountain heating was investigated using test data and heat-transfer analysis. Some of the results are shown in Fig. 15. Fountain gas temperatures were approximately 800°F, for a 3000°F L/C engine exhaust and a 1900°F DLE exhaust. The fountain gas temperature, however, decays rapidly and is negligible six seconds after takeoff with a net vertical thrust-to-weight (T/W) of 1.05, and nine seconds with a net T/W of 1.02 (See Fig. 15). Aluminum skin temperatures remain within acceptable limits in both cases. But if the airplane remains on the ground for an appreciable time (15 to 20 seconds) with jets vertical and at maximum power, then the skin temperatures can become excessive ($T/W = 1.0$ in Fig. 15).

Other notable results of the tests and subsequent analysis were: 1) Scaling laws can be evolved to predict the effect of temperature level and jet Mach number. Thus, model data can be used to more reliably predict full-scale temperature levels.

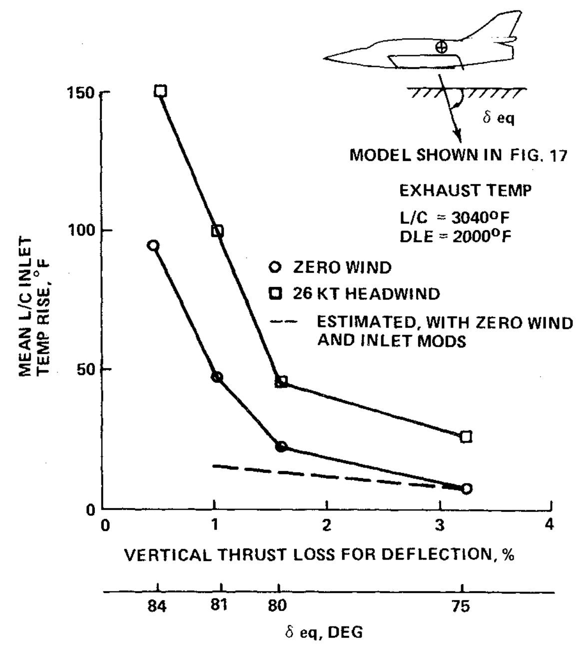

Fig. 14 Nozzle orientation has significant effect on inlet temperature rise.

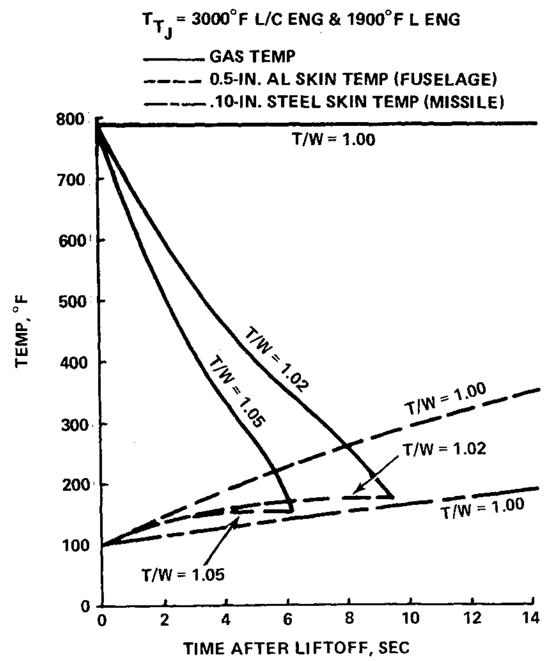

Fig. 15 Hot-gas impingement on fuselage is tolerable.

2) Operation with L/C engine exhausts as high as 3000°F poses no insurmountable fuselage- or ground-temperature problems, with proper VTOL procedures and suitably coated ground mats. 3) Relatively cool regions exist above the aircraft. These should be used to locate auxiliary inlets. 4) Rectangular nozzles yield very directional flow on the ground. This feature can be used to direct the fountain in such a way as to minimize aircraft thermal problems. 5) Worst-case conditions do not necessarily occur at gear height or in a crosswind.

Control System Development

Force and moment data from the low-speed and VTOL wind tunnel tests were used to model aircraft characteristics from in-ground effect, through out-of ground effect, and into totally wing-borne flight. This modeling was required to investigate the low-speed handling and flying qualities that are

Table 1 V/STOL Cooper-Harper handling quantities simulator results[a]

Controller	No augment	Rate cmd system	Attitude cmd system	Rate cmd attitude hold
Conventional stick & rudder pedals	8.5	2.6	3.3	4.3
2-axis side-stick controller	7.5	2.6	3.0	1.5
3-axis side-stick controller	9	3.7	4.7	5

[a]Based on single-L/C-engine concept.

peculiar to V/STOL aircraft. Specifically, the objectives of these tests were to: 1) Obtain pilot performance and opinion on various control system designs (rate command, attitude command, and rate command/attitude hold). 2) Assess the advantages of various pilot controllers for low-speed approach and landing (conventional stick, and two- and three-axis side-arm controllers). 3) Determine pilot workload during transition and hover. 4) Determine proper pilot and control system response to engine failures during low-speed approach. 5) Assess various landing techniques and landing aid requirements.

The program was based on the use of a 6-degree-of-freedom (6-DOF) computer simulation which drives a 3-DOF (pitch, roll, and heave) piloted moving-base simulator and a 4-DOF (range, altitude, azimuth and lateral translation) rear screen projection visual display. The pilots were exposed to various cockpit controller and control system configurations, and required to perform specific VTOL tasks. The evaluation used Cooper-Harper ratings, rms values of aircraft rotational acceleration, and recordings of aircraft dynamics and flight path.

Using the single-L/C-engine concept (Fig. 3), it was found that the two-axis side-arm controller was preferred (low Cooper-Harper rating shown in Table 1).

The pilots felt that the side-arm controllers provided more precise control at low speeds, but that a three-axis controller provided inadvertant cross coupling of roll and yaw control at periods of high pilot work load. Also, the absence of stability augmentation is unacceptable (high Cooper-Harper rating in Table 1), and the rate command/attitude hold system was perferred for pitch and roll.

During simulated engine failures, the sequence of events was so critical that the pilots preferred an automated system to vary the thrust and nozzle position of the remaining engines. One solution explored was a thumbwheel switch on the stick which would rotate nozzles to a preselected position.

In developing the control system and thrust management system for jet-borne operations, maximum use should be made of components (computers, actuators, etc.) which are required for conventional flight. In this way, the effect of V on overall weapon system reliability and maintainability can be minimized. For example, in the twin-engine concept discussed herein, estimated abort and loss rates of the V/STOL version operating in a conventional mode were only slightly higher than those of its companion CTOL version (approximately 3%). Operating in the V mode, the loss rate is only .04% higher than when operating in a conventional mode.

Concluding Remarks

Our design and experimental studies have convinced us that most of the required lift-plus-lift/cruise technology is at hand and that the $L+L/C$ approach is an attractive and viable solution for fighter-attack V/STOL. However, there is still work to be done in the areas of: 1) Improving propulsion-prediction techniques 2) Control-system optimization and demonstration 3) Aircraft/site interface optimization 4) Optimizating takeoff and landing procedures.

We believe that V/STOL will be a necessary element of the future Navy, not only for economic reasons but to provide increased effectiveness against the growing Soviet naval threat.

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