An All Turbofan VTOL or STOL Intercity Transport

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Turbofan powered VTOL or STOL intercity transports with the safety, reliability, speed, and passenger appeal of today's fanjets and meeting future noise limitations are now possible. Advances in turbofan engine technology and aircraft design which make them possible are described. Turbofan lift engine designs based on established technology now offer new compactness, light weight, low fuel consumption, and low noise. Predicted noise levels make possible a 100 passenger VTOL or STOL transport meeting a community noise limitation of 95 PNdb. A unique aircraft design uses deflected thrust from the cruise engines for VTOL or STOL attitude control and reduces the optimum number of lift engines to 4. Fully redundant lift and control are provided, and the same basic aircraft can be manufactured in VTOL or STOL versions by changing the size of the lift engines. Estimates indicate that the design is cost competitive with other concepts.

Introduction

TODAY, the urgent need to relieve air traffic congestion at major airports is generating an airline demand for short range transports which can operate independently of long range traffic patterns. If we are to also satisfy passenger and community desires, the new transports must be capable of delivering the passenger increasingly closer to city centers as ground traffic congestion continues to increase, and it must do this with less noise and high standards of safety, reliability and passenger appeal. Today's levels of reliability and passenger appeal are made possible by turbofan propulsion more than by any other single factor. Fortunately, advances in turbofan engine technology now make possible the design of an all turbofan powered VTOL or STOL aircraft which can deliver the passenger to airports moving closer and closer to city centers and at the same time reduce noise and meet today's standards of safety, reliability, and passenger appeal. Such a design can be created by the use of new high bypass turbofan lift engines and new aircraft design concepts. This will be our subject.

A New Generation of Lift Engines

The development work which has established high thrust to weight ratio turbojet lift engines is now being combined with established high bypass fan technology to create a new generation of turbofan lift engines specifically designed for commercial applications. These new engine designs bring to the commercial transport the highly desirable characteristics of turbofan power with a new low noise level. Fortunately, fundamental requirements for low noise and low specific fuel consumption are both served by increasing bypass ratio. It remained only to bring together the advances made in thrust to weight ratio of turbojet lift engines and reductions made in fan specific weight to give high bypass turbofan lift engines which retain excellent thrust to weight ratio while reducing both noise and fuel consumption.

Designs have been created by two major engine manufacturers, which are based on established technology and which have low noise, low specific fuel consumption, high thrust to weight ratio, and low engine volume. A brief summary of these developments is appropriate at this point.

Lift Engine Technology

The first generation of lift engine development concentrated principally on increasing the thrust to weight ratio of the turbojet.[1,2] The high degree of success obtained is illustrated by Fig. 1, which shows that thrust to weight was increased from 8 to 20, an improvement of 150%.

Second generation lift engine work is introducing the high bypass turbofan lift engines. This work has combined the light weight technology of the turbojet lift engine with the advanced high bypass fan technology coming from the new generation of high bypass cruise engines. The effect of the high bypass fan on weight and fuel consumption is a small reduction in engine thrust to weight ratio, and a marked reduction in specific fuel consumption.[3] These trends are shown on Fig. 2. The influence of these trends on total proplusion weight is illustrated by Fig. 3 which plots the ratio of lift engine thrust to the weight of the lift engines plus their fuel. This ratio, which we shall call effective thrust to weight ratio, is plotted against bypass ratio for various hover times. Equivalent hover time is defined as the length of time that

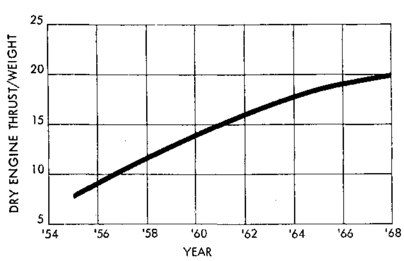

Fig. 1 Turbojet lift engine *T/W* trend.

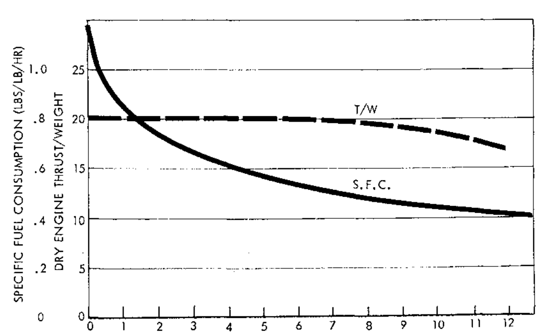

Fig. 2 Effects of bypass ratio.

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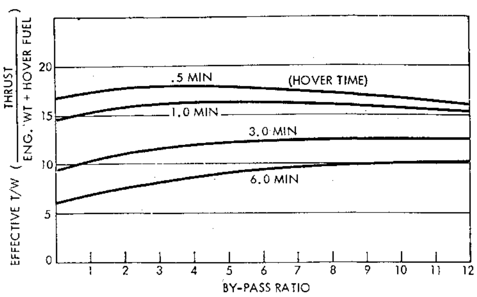


Fig. 3 Effective T/W trend.

the lift engines would run at full throttle to consume the same amount of fuel as that consumed during total lift engine use, including start up, takeoff, transition to cruise, restart, transition to landing and landing. Note that the improvement in specific fuel consumption with increasing bypass ratio gives the high bypass lift engine an effective thrust to weight ratio that is increasingly better than the turbojet as hover time exceeds one half a minute.

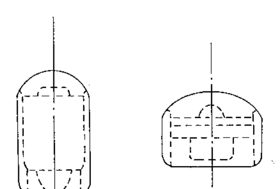
Lift engine size could have become a problem as bypass ratio was increased, but ingenious designs for high bypass lift engines have drastically reduced the ratio of the length of the engine to its diameter. The result is illustrated by Fig. 4 which shows that a typical lift engine pod for bypass 12-lift engines has a little less frontal area and a little more wetted area than an equivalent turbojet lift engine pod. The net result is a somewhat smaller drag for the high bypass lift engine pod.

Lift Engine Noise

The design of high bypass engines to drastically reduce noise output is based on two fundamental factors, the first is a reduction in fan tip speed and the second is a bypass and fan pressure ratio combination which allows the fan to absorb most of the gas generator energy, thereby de-energizing the exhaust velocities and temperatures as illustrated by Fig. 5.

The effect on noise of de-energizing the exhaust is shown on Fig. 6 by the curves marked jetstream and untreated turbine. It should be noticed that the untreated fan is the only noise source above 92 PNdb. It is estimated that noise treatment of the fan will bring the total noise down to 95 PNdb for a total thrust of 80,000 lb. These data have been supplied by Rolls Royce and is based on actual isolated engine component noise measurements.[3]

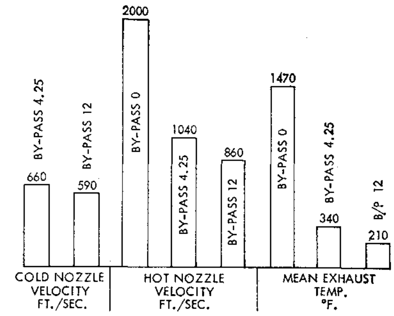
It should be borne in mind that the community noise problem not only depends on the level of aircraft noise at the source, but also on the distance from the aircraft to noise sensitive areas and on the attenuation of noise with distance, which is dependent on the frequency spectrum of the noise. Figure 7 illustrates the rapid attenuation of high bypass lift engine noise with distance. When the rapid attenuation with distance is combined with the steep angles of climb and the increased angles of glide-slope characteristic of STOL and VTOL performance, the area on the ground subject to noise in the region of 95 PNdb barely exceeds the confines of the airport. This area is approximately 0.7 square miles compared to 30 square miles which is typical for today's turbofan transports.[4]



	TURBOJET	BY-PASS 12 TURBOFAN
POD TOTAL THRUST	40,000 LBS.	40,000 LBS
FRONTAL AREA	19.9 FT^2	15.9 FT^2
WETTED AREA	549 FT^2	583 FT^2
ISOLATED DRAG (.8 Mn, 20,000 FT.)	733 LBS	695 LBS

Fig. 4 Lift engine size comparison.

Fig. 5 Effect of bypass ratio on exhaust.



Aircraft Thrust to Weight Ratio

Maximum safety of flight for a VTOL transport demands complete redundancy of lift and attitude control; or in other words, design for safe flight with any thrust producing or attitude controlling component failed. The requirement for redundant lift in conjunction with the power for hover attitude control are determinents for the total thrust required by a lift engine VTOL. It has been found that when these two needs are filled there is sufficient thrust in excess of the weight of the aircraft for an adequate rate of vertical climb for both normal and engine out operation. However, for an efficient VTOL transport, it is essential that the excess thrust installed to provide for engine-out operation and hover control be kept at a minimum.

First, consider the excess thrust required for engine-out operation. If the lift engines are installed at a location some distance from the aircraft c.g., such as in wing pods, the failure of one lift engine causes an unbalanced moment too large for the hover control system to trim out while retaining sufficient power to meet the hover maneuver requirement. The only recourse, in effect, is the shut down of a lift engine on the opposite side of the aircraft from the failed engine. To minimize this engine-out penalty, a large number of lift engines is required so that the double loss resulting from an engine failure does not constitute too large a percentage of the total lift. It has been found, typically, that in the case of wing pod located lift engines the most cost effective number of lift engines is 8. On the other hand, if the lift engines are located close enough to the aircraft c.g., it has been found that the unbalanced moment created by a lift engine failure is small enough so that the hover control system can trim out the unbalanced moment and still meet the hover maneuver requirement. In this case a second engine need not be shut down, and the optimum number of lift engines is reduced to four. The location of the weight of the lift engines close to the aircraft c.g., reduces the aircraft moments of inertia, reducing

PEAK PERCEIVED NOISE LEVELS DURING VTOL @ 500 FT GROUND DISTANCE FROM THE TAKE-OFF POINT 80,000 LB LIFT

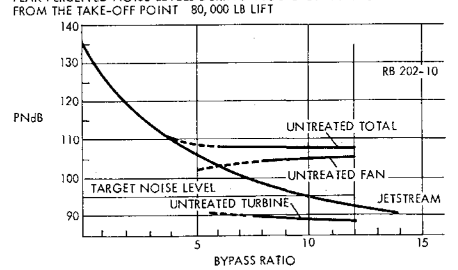


Fig. 6 Predicted noise levels.

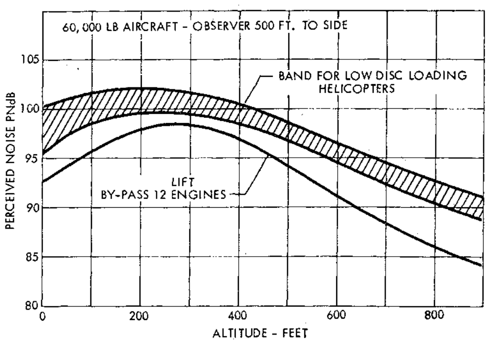


Fig. 7 Effect of distance on noise.

the hover control power, which in turn reduces the gross weight. The combination of reduced gross weight and reduced number of engines provides a considerable cost reduction.

Next, consider the case of excess thrust required for hover control. Three principal sources are available for control power on a lift engine aircraft, bleed air thrust, lift engine thrust, and cruise engine thrust. The required control moments vary directly as the aircraft moments of inertia, which in turn vary approximately as the square of the aircraft gross weight.[5] For this reason, aircraft exceeding 60,000 lb gross weight require high control power and there is not enough thrust available from the bleed air to provide the required hover control. With the lift engines close to the c.g., the demand on their thrust for hover control would become excessive because of the short moment arm; therefore, the cruise engines are the most logical source for hover control moments. By diverting their full thrust either up or down, their effectiveness is more than doubled compared to thrust modulation in one direction only, and they provide flexible, efficient hover control without the response lag problem which throttle modulation would present. Figure 8 illustrates a cruise engine installation incorporating this principle. In changing from horizontal to vertical flight, the tailpipe clamshells close while the louvers in the top and bottom of the pod open to divert the thrust from horizontal to vertical. The louvers can then be actuated to give differential exhaust areas between top and bottom as upward or downward thrust is demanded for roll or pitch hover control. By deflecting these same louvers sideways, yaw control can be provided.

Aircraft Design

Figure 9 illustrates the design of a 100 passenger intercity transport incorporating the foregoing principles to minimize aircraft thrust to weight ratio and number of lift engines. Four turbofan cruise engines having a bypass ratio of approximately 2.5 are sized to provide 0.8 Mach cruise at 25,000 ft. The 2.5 bypass ratio was chosen because it gives a good match between cruise and hover control thrust requirements and

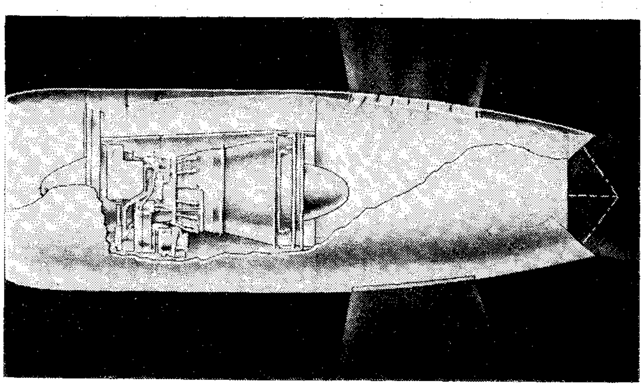


Fig. 8 Cruise engine thrust diversion system.

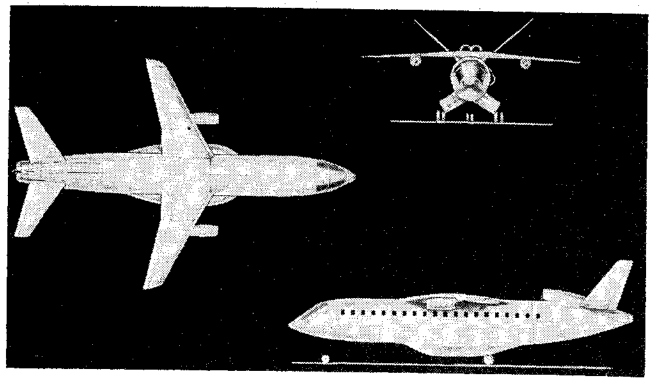


Fig. 9 General arrangement.

helps reduce turning losses in the thrust diverter, compared to higher bypass ratios. During hover the two cruise engines on the wing devote their entire thrust to provide redundant roll control. The two installed in the tail provide redundant pitch and yaw control. Yaw control comes from the tail engines by sideways deflection of the previously mentioned louvers in the top and bottom of their pods. A V tail is chosen in order to avoid problems of exhaust impingement on tail surfaces while retaining a long moment arm for pitch control thrust and providing side by side engine installation to minimize engine out coupling between the roll and pitch axes.

It will be noted that the lift engines are installed in pods which also house the main landing gear. The engines are canted at 30° in the front view, and their thrust is deflected to the vertical by a rotatable hoop of turning cascades over the exhaust exit. Rotation of these cascades toward the front or rear provides a horizontal thrust component forward or aft for aircraft horizontal acceleration or deceleration. The canted position of the engines is selected for four reasons: 1) it allows part of the engines to be tucked into the fuselage to decrease the lift engine pod size; 2) it locates the center of lift closer to the centerline of the aircraft to minimize engine-out assymmetry; 3) it reduces interference drag between the pod and the wing, and 4) it reduces pitch-up moment caused by the turning momentum of the lift engine intake air during transition. The doors which close the intakes of the lift engines open to form a bellmouth entrance having an area greater than the gross engine intake area to keep entrance losses low. The exhaust area formed between the aircraft and the ground exceeds the gross lift engine exhaust area to avoid back pressure.

The design payload is 100 passengers over a design range of 500 naut miles at a cruise speed of 0.8 Mach at 25,000 ft, with vertical takeoff and landing on a sea level 90°F day.

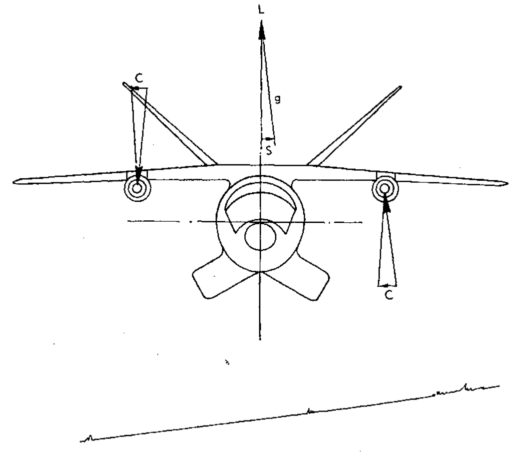


Fig. 10 Hover control forces.

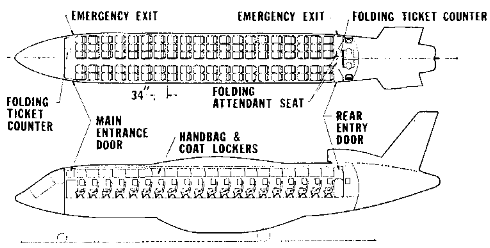


Fig. 11 Interior arrangement.

Using the graphite fiber composite construction technology projected for 1980–1985, the VTOL version of the design would have a gross weight of 80,000 lb and the 1500 ft runway STOL version would use smaller lift engines and would have a gross weight of 74,000 lb. Using conventional aluminum construction, the VTOL version would have a gross weight of 107,000 lb and the STOL version a gross weight of 100,000 lb.

Propulsion Exhaust

The cruise engines during vertical takeoff will be nominally operated at considerably reduced power with half of their exhaust up and half of their exhaust down. This will be accomplished by scheduling both top and bottom exhaust opening to be more than half open for "stick Neutral," giving the engine more than its normal exhaust area. This will automatically cause the engine fuel control to reduce power to maintain constant rpm. Because of this nominally low power level, the dividing of the exhaust between the upward and downward openings, and the high position of the engines, the downward mass flow from the cruise engines and the velocity at the ground will be small compared to the lift engine exhaust. Based on a considerable background of general test data,[7–10] the relative mass flows of the cruise and lift engines, the ratio of their diameters and separation distances, and their relative heights above the ground are such that there should be no exhaust fountain reingestion problems. Additionally, the bottom exits of the wing cruise engines are tilted outboard and the top exits inboard. Also, the bottom exits of the tail cruise engines are tilted aft and the top exits forward. This tilting will accomplish two purposes, one is to help assure the elimination of reingestion fountains, the other is to improve hover control. This latter function is illustrated by Fig. 10 which shows that as the aircraft tilts, the force of gravity (g) opposing the lift (L) creates a side force (S) which tends to give the aircraft side motion. It has been found in simulator studies that if an opposing side force (C) is applied simultaneously with the roll moment required to level the aircraft, handling qualities are improved, allowing a reduction in the control power required.

Aircraft Interior

Referring to Fig. 11, the aircraft interior arrangement provides a flight deck designed for a 2 man crew with a wrap around 2 piece curved windshield to provide helicopter type visibility, and a cabin which seats 100 passengers, 5 abreast. Forward and aft side entrances are provided. Two toilets are located in the aft end and folding ticket counters are provided forward and aft. Enclosed overhead compartments are provided for coats and hand luggage. Two generous baggage areas are provided in the belly, one forward and one aft of the lift engines. As illustrated by Fig. 12, these areas open wide with the doors forming a roof and the baggage racks are lowered to provide self stow and reclaim baggage areas through which the passengers would be routed as they board and exit. Ground time is a critical cost factor for an intercity VTOL transport and it is felt that self service on-board baggage is essential. To make such a system acceptable to the passengers, covered moving belt walkways and escalators will probably be required from the aircraft into the terminal building.

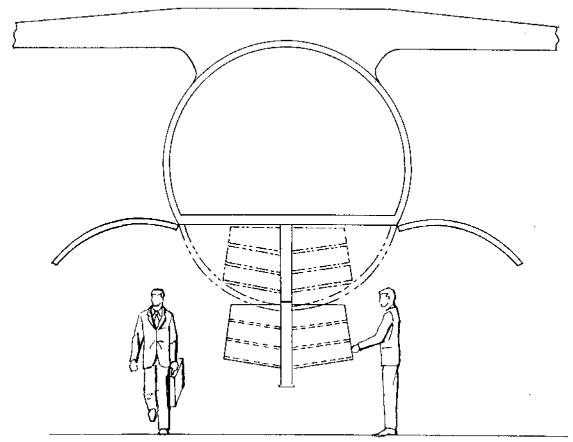


Fig. 12 Self-service on board baggage.

Conclusions

High bypass turbofan lift engine technology and V/STOL aircraft design have progressed to make feasible an operationally practical high speed all turbofan VTOL or STOL transport which could have esthetic passenger appeal and cater to the well established passenger preference for turbofan propulsion. It would be vibration free and the passenger would not be subjected to any radical configuration or attitude changes in any phase of flight. The simplicity of conventional, self-contained turbofan engines would provide high reliability and the safety of fully redundant lift and control would be available throughout the flight envelope without power interconnection. The aircraft could meet anticipated future community noise requirements. Such an aircraft would lend itself to evolutionary rather than revolutionary development since a first generation STOL version would provide operational experience with the basic airframe, its subsystems, and the reaction controls for the second generation VTOL.

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