ARTICLE NO. 79-1287R

Type A V/STOL Propulsion System Development

E. R. Glasgow* and R. E. Skarshaug†
Lockheed-California Co., Burbank, Calif.

Design and performance considerations associated with the development of a unique Type A V/STOL four-turbofan propulsion system concept are described. This propulsion system uses fixed horizontal nacelles with thrust vectoring nozzles installed for achieving lift, a coaxial fan flow reaction control system for pitch control and trim, and a reaction control system for roll and yaw control and engine-out roll trim. The turbofan engine is specially designed to provide continuous compressor bleed flow for the reaction control system during vertical flight while achieving low specific fuel consumption during conventional flight modes. Critical propulsion system sizing conditions are identified, and the sensitivity of aircraft takeoff gross weight to changes in control criteria requirements, engine cycle parameters, and engine rating schemes are discussed. In addition to having competitive performance characteristics, the propulsion system concept described herein has zero single-point failures, low development cost and risk, and good reliability/maintainability.

Introduction

THE development of a propulsion system for a subsonic V/STOL (vertical/short takeoff and landing) aircraft provides a substantial challenge to the propulsion community since the requirements are more extensive, less compatible, and more stringent than those for a conventional aircraft. The development problems are more extensive and stringent because the propulsion system is required to perform a larger number of functions in a more severe environment. Not only must the propulsion system supply the longitudinal thrust, but it must also supply all or a portion of the forces required for aircraft lift, control, and trim. When operating near the ground, the propulsion system must provide sufficient thrust for VTO (vertical takeoff) and OEI (one engine inoperative) emergency landing in the presence of propulsion induced aerodynamic effects and hot gas reingestion. Also, the propulsion system must be capable of operating in high winds during hover and at relatively high angles of attack during transition. During cruise and loiter, the specific fuel consumption must be low even though the thrust required is less than half that available. Furthermore, these multiple functions must be efficiently performed by a propulsion system which has low development, acquisition, and operational costs; low development risk; good reliability/maintainability; minimum single-point failures; and reasonable infrared signature and radar cross-section characteristics.

Many different types of subsonic V/STOL aircraft have been proposed, including such generically defined concepts as lift/cruise fan, direct jet lift, thrust augmentors (ejectors), tilt wing, tilt rotor, and stopped and/or stowed rotor. Since the propulsion system development problems are very configuration-dependent, a different set of problems exist for each aircraft type. Even for a given aircraft type, the problems can differ considerably because of the widely diverse approaches that are being taken to configuration design. A lift/cruise fan-type aircraft, for example, may achieve lift either by maintaining the propulsion system fixed while using a deflector nozzle to vector the thrust to the desired angle, or by rotating the entire propulsion system with an accompanying change in the thrust vector angle. The OEI lift loss may be minimized by using either multiple engines or oversized engines with power-sharing schemes such as shaft and gas interconnects. Control and trim of such an aircraft during normal vertical operation may be achieved by:

1) Modulating the thrust of shaft-coupled fans with either variable inlet guide vanes or variable pitch blade fans.
2) Deflecting or spoiling the nozzle exhaust flow.
3) Varying the exit thrust of ducted engine fan flow or compressor bleed flow using variable area reaction control nozzles.

OEI roll trim may be achieved by using either power-sharing schemes or a compressor bleed reaction control system.

The purpose of this paper is to present results related to the development of a unique four-turbofan propulsion system concept which was designed as a cooperative effort between the Lockheed-California Co. and the General Electric Co. for a lift/cruise fan-type subsonic V/STOL aircraft. Design and performance data associated with the major components of the propulsion system are described, as well as results from engine cycle optimization studies and engine rating scheme evaluations. The advantages and future tasks for developing such a propulsion system are summarized in the conclusion.

Propulsion System Description

General Arrangement

A general arrangement drawing of the four-turbofan propulsion system installation is shown in Fig. 1. Each of the high bypass ratio turbofan engines is installed in a separate nacelle. The nacelles are paired in a side-by-side arrangement beneath each wing, located adjacent to the fuselage, and aligned horizontally in a fixed position. Lift is achieved by vectoring the engine exhaust flow vertically with deflector nozzles mounted in each of the nacelles. During transition, the thrust vectoring angles are controlled to provide both aircraft lift and forward acceleration. During horizontal flight, the aircraft is operated in a conventional manner with all deflecting nozzles in the stowed position.

Aircraft linear accelerations are independently controlled during vertical flight. Height control is obtained by varying the engine power setting. Longitudinal accelerations are achieved either by changing the pitch attitude of the aircraft

---

Presented as Paper 79-1287 at the AIAA/SAE/ASME 15th Joint Propulsion Conference, Las Vegas, Nev., June 18-20, 1979; submitted Sept. 24, 1979; revision received Jan. 18, 1980.

Index categories: Configuration Design; Airbreathing Propulsion; Engine Performance

*Group Engineer, Propulsion Dept., Flight Sciences Division. Member AIAA.

†Research and Development Engineer, Propulsion Dept., Flight Sciences Division.

or by vectoring the engine exhaust flow. Lateral acceleration is obtained by changing the roll attitude of the aircraft.

Aircraft angular accelerations and trim during vertical flight are achieved by using reaction control systems, whereby ducted flow is exhausted through variable area nozzles located on either side of the aircraft center of gravity. For pitch control and any trim required to compensate for shifts in the aircraft center of gravity location, a coaxial fan-flow reaction control system is used. For this system, a portion of the fan bypass flow is split within the nacelle and ducted to two variable area thrust deflecting exhaust nozzles located immediately behind the fan and near the wing trailing edge. The remaining bypass flow and the entire engine core flow are exhausted through a thrust vectoring nozzle located near the aircraft center of gravity. For roll and yaw control and engine-out roll trim, an engine compressor bleed reaction control system is employed. For this system, the variable area nozzles are located at the wing tips. Yaw control is obtained by differential vectoring of the wing-tip flow.

The nacelle arrangement was selected to minimize the penalties for obtaining the aircraft control forces during vertical flight conditions. The nacelles are paired in a side-by-side, rather than over/under, arrangement so that simple and efficient deflector nozzles could be used to exhaust the engine flow beneath the nacelles. The nacelles are located adjacent to the fuselage to reduce the moment arm, and thus the amount of engine compressor bleed required for engine-out roll trim. Such a location also helps to reduce the folded width of the aircraft. The fixed horizontal alignment of the nacelles is such that the aircraft moment resulting from the inlet ram momentum force in a crosswind affects only the yawing moment and not the pitch and roll control requirements.

The most significant feature of the four-turbofan propulsion system is that no single-point failure modes exist. An entire propulsion system (including the fan with partial blade containment provisions, engine core, exhaust nozzles, etc.) can fail and yet the aircraft can still maintain a horizontal attitude when forced to land at the maximum takeoff weight, or can perform a normal landing with reduced (level 2) control when operating at the OEI landing weight. The thrust required from each of the three operating engines is approximately the same as that needed for a normal four-engine takeoff. Also, sufficient compressor bleed can be extracted from the three operating engines to provide the required OEI roll control and trim forces without unduly compromising the engine cycle.

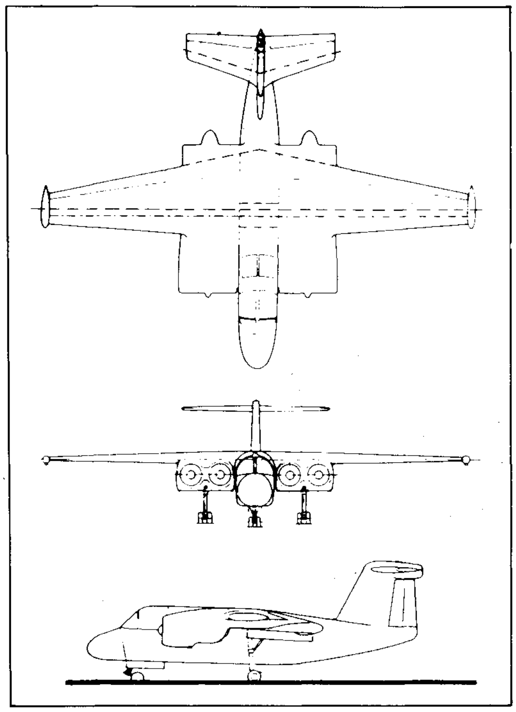

Fig. 1 General arrangement of four-turbofan configuration.

Engines

Four independent, high bleed, confluent-flow, direct-drive turbofan engines were selected for the Type A V/STOL aircraft identified herein. The engines, which are described in greater detail in Ref. 1, are a two-spool design with an overall pressure ratio of approximately 20/1. While the engine is relatively conventional in design, it does represent a technology level consistent with a post-1990 IOC (initial operating capability) time period. The advantages of a direct-drive turbofan engine are:

1) Efficient mechanical and aerodynamic arrangement.
2) Demonstrated long life and good reliability.
3) Directly related military and commercial experience.
4) Low engine development risk.
5) Relatively easy to install.
6) Minimum number of wear-prone mechanical rubbing surfaces.

The low pressure system consists of a single-stage, fixed-pitch fan which is driven by a three-stage uncooled turbine. The fan has a design pressure ratio of approximately 1.7 and is a little more than 3 ft in diameter. The fan requires no inlet guide vanes or variable geometry.

The core engine design consists of a high pressure compressor driven by a two-stage cooled turbine. The compressor is designed to provide a maximum interstage bleed quantity of approximately 22% of the core engine airflow during all vertical and transitional flight maneuvers. Bleed air is extracted at a point in the compressor which provides flow at approximately 100 psia (during takeoff), with a corresponding temperature of approximately 600°F. These pressure and temperature levels, which are consistent with current aircraft installations, were selected so that a significant advancement

POINT NUMBER	GROSS THRUST PERCENT	RCS THRUST PERCENT	AEO OR OEI
1	100	18	AEO
2	100	30	AEO
3	100	47	OEI
4	100	83	AEO
5	100	93	OEI
6	100	94	OEI
7	96	94	OEI
8	89	87	OEI
9	76	71	AEO
10	30	31	AEO OEI

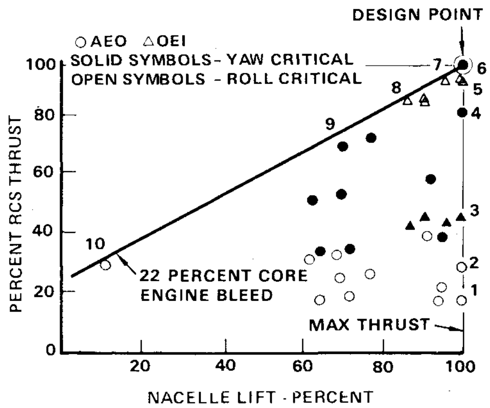

Fig. 2 High bleed engine sizing.

in ducting technology would not be required in developing the wing-tip reaction control system. During cruise the bleed is shut off and the engine is rematched to a conventional cycle. This is accomplished by using variable stators in the compressor, which is a technology that exists today, especially at the relatively low design pressure ratios under consideration.

The engine size and maximum bleed capability is defined by the lift and level 2 control requirements at the engine-out, maximum landing weight condition. This is illustrated in Fig. 2 where the nacelle lift, which is the total aircraft lift divided by the number of operating nacelles, is plotted vs RCS (reaction control system) bleed thrust requirement per engine. The right-hand side of the figure identifies the maximum thrust the engine must meet for several VTO and both AEO (all engines operable) and OEI landing cases, each for a critical aircraft control situation. The total aircraft lift required for the OEI case is exactly 75% of that required for the VTO case.

Part power control requirements can also be very demanding. Figure 2 shows the RCS bleed thrust variation with reduction in engine thrust or lift at a constant 22% bleed flow rate. The percent bleed flow requirements for various aircraft control conditions at different aircraft weights are also presented in the figure. Although the bleed requirements at reduced power are significant, they are not sizing since all the points fall below the engine bleed capability line.

Vertical flight control requirements and ground effects have a significant influence on both engine and aircraft sizing, as illustrated in Fig. 3. Providing control capability in a 35 knot crosswind during VTO results in an increase in engine size of approximately 4% and an increase in TOGW (takeoff gross weight) of 5%. If a 5% reingestion loss is included in addition to a loss in lift because of the suck-down forces, these effects change the required thrust-to-weight ratio and result in a 10% increase in aircraft TOGW. Similar effects on TOGW occur during OEI landing conditions. The goal is obviously to establish equal thrust-to-weight requirements for both the VTO case and the OEI vertical landing case in order to minimize the required engine size.

Nacelle

Each of the four nacelles have a zero length, slotted lip inlet; partitioned duct; and three exhaust nozzles. Figure 4 presents a schematic of the nacelle configuration showing the forces which act on the nacelle during the following three VTO control conditions: maximum pitch up, equilibrum, and maximum pitch down. During equilibrium, the portion of the fan flow ducted to the forward and aft nozzles accounts for 24% and 14% of the total engine lift, respectively. The core/fan flow exhausting from the center nozzle provides 50% of the total engine lift, and the compressor bleed flow exhausting from the wing-tip nozzles provides the remaining 12%. To achieve an aircraft maximum pitch maneuver, the control forces are varied ±12% relative to the equilibrium conditions. Strong and well-controlled fountains form underneath the nacelle between the nozzles when operating near the ground and tend to augment the pitch maneuver (i.e., the fountain formed between the forward and center nozzle is stronger than that between the center and aft nozzles during pitch up and weaker during pitch down). The nacelle has been designed to always exhaust relatively cool fan flow through the forward nozzle during VTOL operation, regardless of the pitch control requirement, so as to help shield the inlets from the relatively hot flow exhausting through the center nozzle. Mixing a portion of the fan flow with the core exhaust helps to reduce the center nozzle jet impingment temperatures and infrared signatures.

Twin zero length, slotted lip inlets designed for high performance during both cruise and low speed operation are mounted in close proximity to the fuselage. The shorter inlet length, as compared to a conventional inlet, reduces the inlet weight, decreases the moment arm associated with the inlet ram force during crosswind and improves pilot visibility in the side/aft directions. For this inlet concept, which is illustrated in Fig. 5, the fan face is located at the inlet throat, thus eliminating the diffuser section, with the increased throat area being obtained by decreasing the internal lip contraction ratio. Blow-in doors open when a pressure differential exists across the doors at static and low speed operation conditions (high mass flow ratios). With the doors open, the flow passing through the resultant slot will enter the inlet upstream of the inlet throat, effectively increasing the inlet aerodynamic contraction ratio and decreasing the peak surface Mach number in the highlight region compared to that which would be obtained for a conventional inlet with the same geometric contraction ratio.

Zero length, slotted lip inlets were first installed on the C-141, as described in Ref. 2. Even though the physical contraction ratio for the C-141 inlet is only 1.12, the aircraft is still able to operate in crosswinds and quarter tailwinds as high as 50 mph. Good static and low speed inlet performance has also been reported in Ref. 3 for a translating lip axisymmetric inlet designed for a high subsonic transport aircraft. The NASA Lewis Research Center is currently sponsoring an experimental model program[4] to investigate the low speed inlet performance and fan blade stress characteristics associated with a zero length, slotted lip inlet

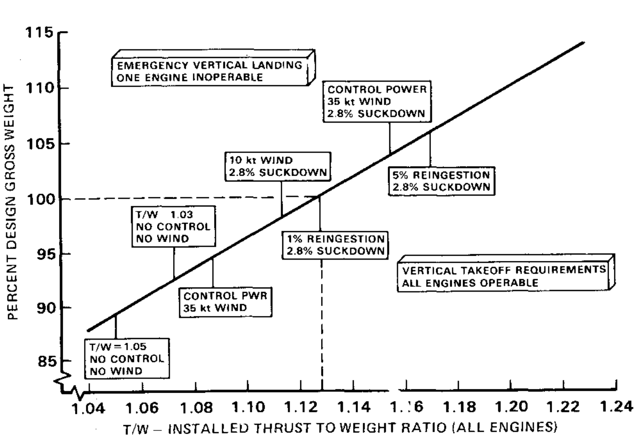

Fig. 3 Gross weight sensitivity to hover control criteria.

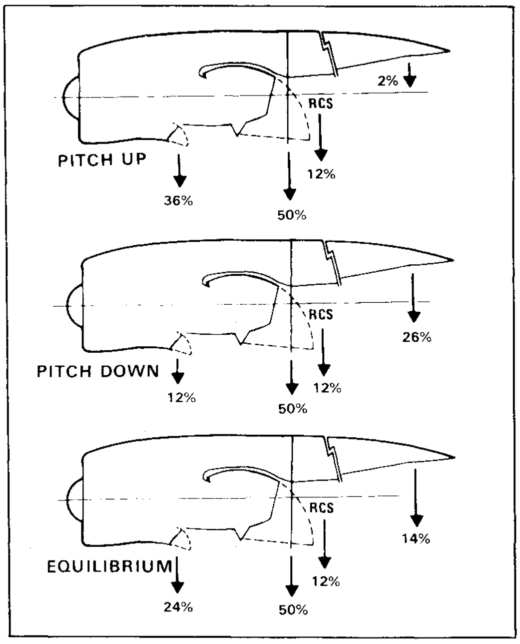

Fig. 4 Propulsion system force vectors for pitch control and trim.

designed for a fixed nacelle lift/cruise fan subsonic V/STOL aircraft. The model, which is shown in Fig. 6, will mate with an existing NASA 20 in. diameter fan simulator and will consist of a single cowl lip with two alternate slats, as well as provisions for varying the distance of the slot from the cowl lip (slot width). Two inlet spacers will also be supplied to vary the distance of the cowl lip from the fan face. All testing will be conducted in the NASA Lewis Research Center 9 by 15 ft low speed wind tunnel.

The design of the partitioned nacelle duct and exhaust nozzles involved trade-offs between the following requirements and constraints:

1) The distance between the forward and aft nozzles should be as large as possible so that the amount of flow transfer and associated duct oversize required to provide pitch control and trim can be minimized.

2) The aft nozzle should be located near the wing trailing edge and have a relatively high aspect ratio so that supercirculation lift can be obtained on the wing, thus enhancing the STOL characteristics of the aircraft.

3) The forward nozzle, and also the center nozzle, if required, should be located far enough ahead of the aircraft center of gravity so that the maximum flow through the forward nozzle is equal to or less than 50% of the engine bypass flow. This maximum flow limit was established based upon considerations of fan flow distortion and flow turning efficiencies.

4) The nacelle should not impair pilot visibility.

5) Scheduling of the forward and aft nozzle areas should be such that the total fan area and associated fan thrust will remain constant.

6) The nacelle should be partitioned so that the flow perturbations required for pitch control and trim are isolated from the core exhaust so that no back pressure fluctuations will exist to affect the engine operating point.

Of the three nozzles, only the forward and aft nozzles have variable areas, and only the forward and center nozzles have thrust vectoring capability. During transition, the fixed-area center nozzle provides the horizontal thrust component while the forward and aft nozzles maintain positive pitch control. At the end of transition, the forward nozzle quickly converts from the vertical to horizontal mode and the aft nozzle area is closed off. The position of the forward nozzle area control flap can then be set so that the desired proportion of the fan bypass flow is diverted to the fixed-area center nozzle.

Since the discharge coefficient (ratio of actual flow area to minimum physical area) for a vented-type deflector nozzle can be as low as 0.8, the physical throat area of the center nozzle must be oversized by as much as 20% to exhaust the required flow during vertical operation. During horizontal flight the total engine flow area for optimum cruise efficiency is less than that for vertical operation, and the discharge coefficient is generally within 1% of unity. Since the physical throat area of the center nozzle is fixed, the proportion of fan bypass flow to be exhausted through the center nozzle must be increased for horizontal cruise flight. This is accomplished by closing the aft nozzle area and reproportioning the fan bypass flow between the forward and center nozzles.

A parametric deflector nozzle/nacelle test program was conducted to provide a technical data base for designing vented-type nozzles for V/STOL aircraft. Both isolated nozzles and a nacelle with two deflector nozzles in tandem were tested. The configuration variables included nozzle hood deflection angle, throat area variation, aspect ratio, hood radius ratio, throat area flap angle, and nozzle type (i.e., double-flap deflector nozzle and circular hood deflector nozzles with rectangular and "D" shaped cross-sections). The data for the different nozzle types were correlated in terms of loss coefficient, deflector angle, and throat area ratio. These correlations, which are described in Ref. 5, enable nozzle thrust coefficients to be computed as functions of nozzle entrance Mach numbers and nozzle pressure ratios for a given nozzle type and thrust vector angle. A typical thrust coefficient map is shown in Fig. 7. The nacelle test results demonstrated that significant pitching moment variations can be obtained by changing the forward and aft nozzle throat areas while maintaining a relatively constant lifting force. Although the flow vector angle for each nozzle changed slightly with throat area for a fixed deflector hood position, no horizontal thrust component resulted for the nacelle since the components for the two tandem nozzles tended to be equal in magnitude but opposite in direction.

Wing-Tip RCS

A schematic of the reaction control system used to provide roll and yaw control and engine-out roll trim is shown in Fig. 8. The system is configured with two sets of ducts and nozzles, where each engine supplies air continuously to each duct during normal vertical operation. The ducts are sized for the OEI condition where the bleed flow from the three operating engines is diverted to the wing tip nearest the inoperative engine. In the event of a duct rupture or nozzle failure, sufficient capability exists within the operating duct/nozzle system to provide emergency roll and yaw control with all four engines operating. Thus, the wing-tip reaction control system has no single point failure mode.

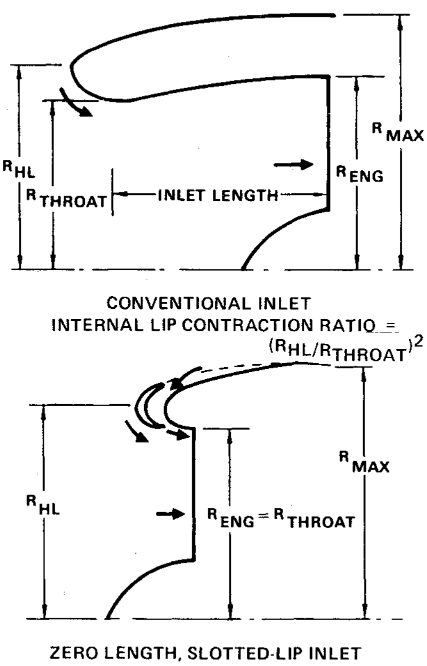

Fig. 5 Zero length, slotted lip inlet concept.

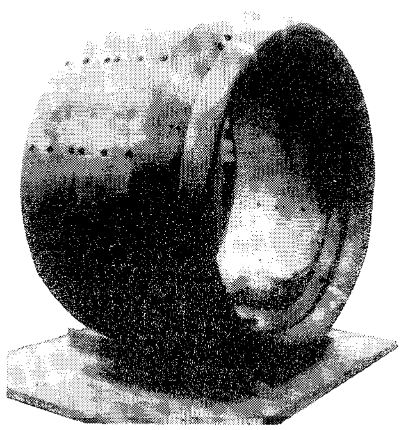

Fig. 6 Zero length, slotted lip inlet model.

Figure 9 presents the vertical forces affecting the roll and yaw attitude of the aircraft during hover. The upper figure shows the aircraft in normal vertical takeoff flight, all four engines running where approximately 21% of the bleed flow must be transferred between wing-tip nozzles to satisfy the most critical roll control condition. For a nozzle maximum yaw angle of 25 deg, only 85% of the wing-tip thrust is needed to satisfy the most critical yaw control condition. Rather than reduce the engine compressor bleed to only that required for control, the excess bleed is used for lift with an associated reduction in nozzle yaw angle. This continuous compressor bleed approach has been selected over a demand bleed approach so that the bleed flow used for control will not affect the engine power required for lift, and so that bleed thrust will be immediately available for roll trim if an engine fails. The lower portion of Fig. 9 shows the propulsion system thrust vectors acting on the aircraft during an engine-out landing, where essentially all of the available bleed is needed for providing maximum emergency roll and yaw control and roll trim to balance the lift lost from the outboard engine.

Since the RCS bleed ducts will be located in areas which potentially could be subjected to combustible fuel vapors, the maximum bleed air temperature was limited to approximately 600°F so that the system could be operated safely. This temperature limit was established based upon prior aircraft design experience, as shown in Table 1, and on the test results of Ref. 6. During this test, JP-4 fuel in the form of a liquid spray, drops, and a combustible fuel/air mixture was brought in contact with a 3 in., high temperature, simulated compressor air bleed line. Although no flame appeared during any of the tests, it was assumed that the first appearance of smoke constituted ignition. The lowest surface temperature at which smoke appeared was 760°F. Subsequently, an air leak was created permitting air to impinge directly upon a spray of JP-4 fuel. Smoke did not appear until the air temperature was increased to 825°F. These tests were then repeated using MIL-0-5606 hydraulic oil with smoke appearing at a duct surface temperature of 687°F, and impinging air leaks on an oil spray with smoke appearing at 763°F. To preclude the possibility of combustible vapor ignition, the maximum duct surface temperature and bleed air temperature was limited to values at least 87°F below the minimum temperatures which caused smoke to appear in the Ref. 6 tests.

Engine Cycle Optimization

Cycle optimization studies were conducted on the four-turbofan bleed engine configuration to establish the optimum

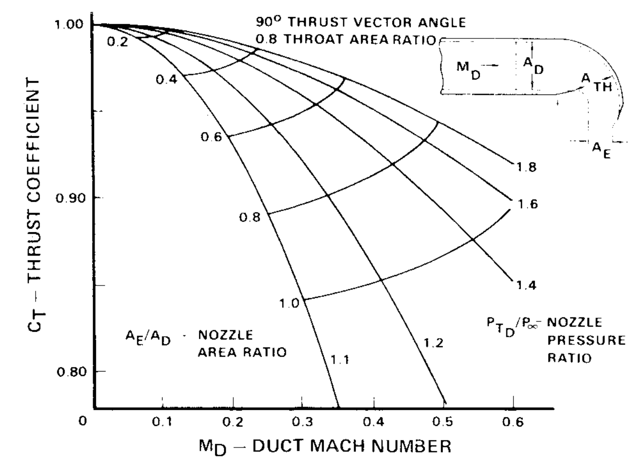

Fig. 7 Thrust coefficient map for circular hood deflector nozzle, aspect ratio 2.0.

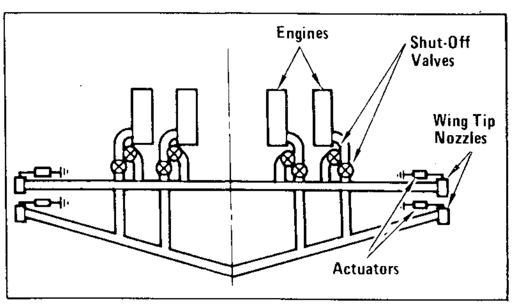

Fig. 8 Schematic of wing-tip reaction control system.

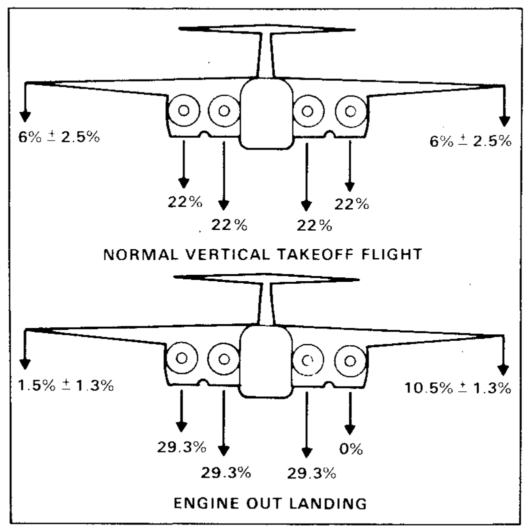

Fig. 9 Propulsion system force vectors for roll/yaw control and roll trim.

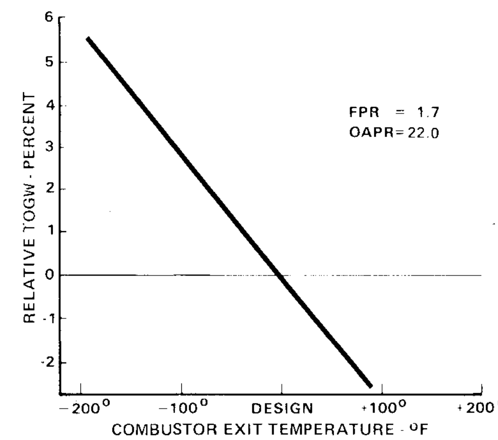

Fig. 10 Effect of combustor exit temperature on ASW TOGW.

Table 1 Duct system comparisons

Description	P-3	S-3	L-1011	F-104	V/STOL
Purpose	Anti-ice	Cabin pressure	De-ice	Boundary layer control	Reaction control
Pressure, psi	280	165	50	125	100
Temperature, °F	470	760	550	730	600

design for the Type A aircraft. The basic engine performance data were developed by General Electric. The cycle parameters and associated range of values which were investigated are FPR (fan pressure ratio) of (1.30-1.75), OAPR (overall pressure ratio) of (20-32), and CET (combustor exit temperature) of design CET $\pm 200°F$).

Figure 10 presents the change in aircraft TOGW as a function of combustor exit temperature for an ASW (antisubmarine warfare) mission. This parameter has a significant effect on the aircraft gross weight showing a 3% change to TOGW for every 100 deg change in temperature. The favorable decrease in TOGW with increasing combustor exit temperature results from a significant reduction in core engine size and, therefore, overall engine weight, and from a slight reduction in specific fuel consumption. However, in addition to performance considerations, the selection of a design combustor exit temperature must take into account such factors as projected state-of-the-art, development costs and schedules, maintenance and reliability requirements, and life cycle costs.

The aircraft TOGW is fairly sensitive to changes in overall pressure ratio, as shown in Fig. 11. Study data indicate that relatively low cycle pressure ratios are desirable; however, as the pressure ratio is reduced (at a constant combustor exit temperature), the low pressure turbine inlet temperature increases. Since the low pressure turbine is uncooled, the limit on minimum engine pressure ratio is encountered (at approximately 20/1 for the high bleed engine) prior to reaching an optimum level.

Increasing the fan pressure ratio up to the limit for a single-stage, fixed-geometry, nongeared fan results in a fairly significant reduction in TOGW, as shown in Fig. 12. Although the specific fuel consumption increases slightly with increasing fan pressure ratio, the engine weight, fan duct and exhaust system losses, and jet-induced aerodynamic effects all decrease. Also, the fan diameter and airflow decrease with increasing fan pressure ratio, which results in small/lightweight inlet and exhaust systems, reduced engine-out roll trim moments and associated compressor bleed requirements, and reduced moments associated with the inlet streamtube. Furthermore, having small fan diameters and low airflows provides such secondary benefits as reduced aircraft width with the wings folded, improved pilot visibility, reduced radar cross-section, minimum volume of vulnerable components, and less frequent bird ingestion.

Engine Rating Scheme

The high bleed engine is designed such that the maximum RCS bleed thrust per engine is provided continuously for all vertical and transitional flight modes. This bleed thrust provides level 1 roll and yaw control during normal vertical flight and level 2 roll and yaw control and roll trim during an engine-out landing. A study was conducted to determine the desirability of designing the engine RCS bleed thrust to provide only the level 1 roll control during normal vertical flight, with yaw control achieved by differential thrust vectoring of the main engine nozzles. This approach would reduce the design RCS bleed requirement to approximately one-third of that required by the original design, with a corresponding reduction in design turbine inlet temperature of 200°F. The OEI landing case would still require 22% compressor bleed, and this capability would be provided by overboosting the design turbine temperature with some corresponding reduction in high pressure turbine blade life.

By employing this alternate rating scheme, the engine can be designed to use a reduced level of turbine cooling flow during normal AEO vertical flight. Reducing the cooling flow requirements results in a smaller core engine size and corresponding lower engine weight and cruise/loiter specific fuel consumption.

This alternate rating scheme can best be understood by reviewing the RCS bleed thrust envelope shown in Fig. 13. RCS thrust is presented as a function of total nacelle thrust and percent bleed (relative to core engine airflow). The figure also shows lines of constant turbine inlet temperature, high pressure rotor speed, and fan speed. The VTO point and both AEO and OEI vertical landing points are shown in the plot.

The change in rating level from VTO and OEI can be achieved as rapidly as the bleed control valves can be actuated. This is because the engine requires only a small increase in core rotor speed and a small decrease in fan speed to achieve the OEI maximum bleed rating. There is no requirement to increase the engine fuel flow rate significantly since appropriate increases in combustor fuel/air ratio and increasing turbine inlet temperatures are achieved as a result

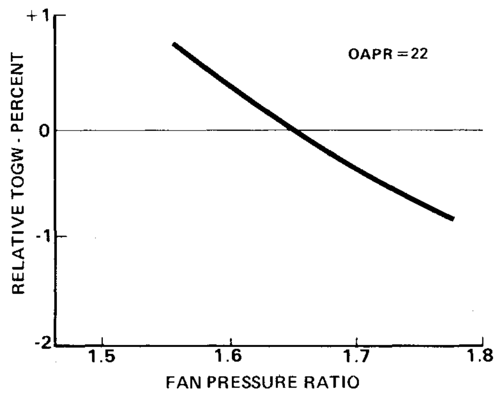

Fig. 12 Effect of fan pressure ratio on ASW TOGW.

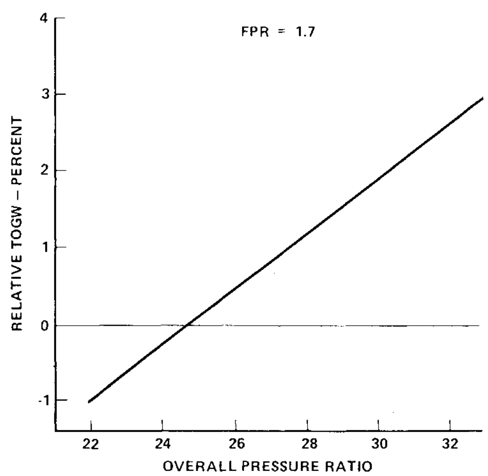

Fig. 11 Effect of overall pressure ratio on ASW TOGW.

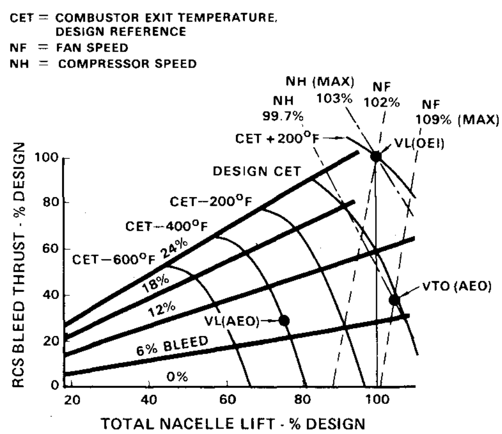

Fig. 13 RCS bleed thrust envelope.

of the reduction of compressor airflow during the high bleed, OEI operation.

In the event of an engine failure during a normal AEO vertical landing, the maximum RCS thrust available (approximately 75% of that available at VTO power) for roll trim at the part-power lifting thrust can be achieved instantaneously. Both the fan and core engine rotor speed will have to increase, however, to produce the rated OEI lift and RCS thrust. This transient will be approximately 0.2-0.3 s.

The propulsion system for each rating scheme under consideration was sized to provide the required thrust for critical OEI landing and VTO flight conditions. The alternate scheme had favorable engine performance and weight advantages resulting from the reduced VTO bleed level; these advantages were offset, however, by propulsion system sizing penalties incurred to provide yaw control with the center nozzles. These nozzles had to be used since insufficient bleed was available during normal operations to obtain yaw control from the wing-tip nozzles. The resultant VTO takeoff gross weight was only 1% lower for the alternate scheme than for the basic scheme. Therefore, the basic continuous bleed engine rating scheme with RCS wing-tip vectoring for both roll and yaw control was selected for the aircraft because of the small difference in TOGW between the two schemes. Also, wing-tip thrust vectoring has many operational advantages, such as, stable ground effects, improved roll control during normal VTOL (vertical takeoff and landing) operations, and OEI RCS bleed thrust availability without any change in engine rotor speed.

Conclusion

A unique Type A V/STOL four-turbofan propulsion system has been developed which uses fixed horizontal nacelles with thrust vectoring nozzles installed for achieving lift, a coaxial fan flow reaction control system for pitch control and trim, and an engine compressor bleed reaction control system for roll and yaw control and engine-out roll trim. The system is unique in that no single-point failure mode exists; no cross-shafting for large horsepower transmission between engines is required for engine-out roll trim; no high technology variable pitch blade fans or variable inlet guide vanes are required for roll control; and no complex, remotely located fans or tilt nacelles are needed for pitch control and trim. The airframe/engine interface is also very straightforward in that only single-engine operation is required for development testing, engine airflow requirements are compatible with existing test facilities, and the division of responsibility between the airframe company and engine manufacturer is similar to that associated with conventional aircraft.

Although the technologies exist for developing the propulsion system described herein, further development work is needed to:

1) Demonstrate the operation of a high bleed compressor.

2) Evaluate the distortion effects of the forward nozzle on fan blade stresses and performance.

3) Determine the nacelle/nozzle performance losses using large-scale "realistic" hardware.

4) Determine installed zero length, slotted lip inlet performance under crosswind conditions.

5) Demonstrate safe operation of high temperature, high pressure RCS bleed ducts.

With proper funding, this development work can be successfully accomplished with very little technical risk.

References

[1] Adamson, A.P., Lander, J.A., and Genever-Watling, D.C., "Engine/Airframe Matching Considerations for Subsonic V/STOL Aircraft," AIAA Paper 78-922, July 1978.

[2] Saylor, James M. and Smith, R.E. Jr., "Internal and External Aerodynamics of the C-141A Nacelle," AIAA Paper 65-604, June 1965.

[3] Henne, P.A., "Low-Speed Test of Translating Lip Axisymmetric Inlet for Subsonic Transport," NASA CR 2467, Sept. 1974.

[4] Lockheed-California Co., "Design and Fabrication of an Inlet Model," NASA Lewis Research Center Contract NAS3-21461, May 1978.

[5] Miller, L.D., "Isolated Deflector Nozzle Static Tests for V/STOL Aircraft," *Proceedings of the Workshop on V/STOL Aerodynamics,* Naval Postgraduate School, May 1979.

[6] Lockheed-California Co., "Evaluation of Fire Hazards in High Temperature Compressor Air Bleed Lines," Lockheed Rept. 11481, June 1956.