V/STOL Status from the Engine Technology Viewpoint

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This paper aims to summarize the technical and operational status of jet V/STOL, taking note of the significant achievements in research and development, prototype demonstration, and service deployment. From this background the available technology can be shown to present definitive options for V/STOL combat aircraft with mission capability beyond that of many contemporary front-line CTOL aircraft. Advanced engineering programs enable projections to be made for future V/STOL aircraft, taking advantage of further improvements in the powerplant thrust/weight ratio. The associated installation and engine airframe interface issues, also the subject of ongoing research and development, can be identified and configurations can be defined which will enable the operational flexibility inherent in V/STOL to be realized. The next generation of V/STOL combat aircraft can be planned to maximize the returns from these advanced engineering programs within the framework of operational procedures established by over a decade of service deployment. The emphasis of this effort is toward cost-effective weapon systems in the circumstance of runway attrition and the criteria for evaluation of V/STOL systems worthy of examination.

Introduction

A VERY considerable background of test data and operational service experience is available on V/STOL fighter systems. As a consequence it is possible to project a clear view of the types of high-performance V/STOL combat aircraft that can be made available to the armed services within the next decade. Inevitably, the powerplant configuration is a major driver in determining the layout of a V/STOL aircraft and the technology issues to be resolved in establishing a definitive system design.

The objectives of this paper are to highlight the extent of the background and the lessons it offers today, to promote the resulting powerplant preferences, and to indicate aircraft systems achievable by 1990 using the existing data bank and established technology programs.

Background Experience

As a pioneer in the field of jet lift propulsion, Rolls-Royce has been fortunate to have been deeply involved in all phases of the evolution of V/STOL fighter aircraft and to have gained first-hand experience ranging from experimental research and development to front-line service in the field and the definition of future system designs.

Service Experience

The most significant V/STOL experience is that obtained in the front-line service operation of all the necessary equipment. Many issues, including those of logistic support, deck operations, ground and other environmental effects, engine life usage, control and flight management, vulnerability to foreign body damage, and the use of jet deflection in flight have been explored in the course of routine operations. The operation of real high-performance V/STOL combat aircraft in the field has yielded firm data that cannot be obtained with equivalent security from parametric studies and incremental technology programs.

It is not necessary to dwell on the service background of the Harrier and AV-8A, which includes 12 years of operation, 380,000 sorties, and more than 60,000 vertical landings. However, the lessons learned are extremely important. Very high sortie rates and fast responses are made possible by the forward basing of the aircraft. The logistic support problems of operating from dispersed sites are solvable and the solutions are practical. Operation from small ships (less than 20,000 tons) is practical and the aircraft can be mixed with CTOL operations on larger carriers. The most effective method of operation is STOVL (short takeoff, vertical landing) which gives high productivity, particularly for shipborne operations.

Development Experience

Although studies continuously develop new configurations for high-speed V/STOL aircraft, it should be recalled that a significant variety of alternative options has already been taken to the prototype flight stage. While the Harrier/Pegasus configuration is the only one of these that has been launched into production and service operation, the considerable development effort on alternative airframes, systems, and powerplants has extended the total V/STOL data base and provided valuable design data. Some details from the wide-ranging V/STOL development programs based on Rolls-Royce engines are listed in Table 1.

In support of these experimental aircraft programs, a number of engines designed for V/STOL operation have been developed. These may be grouped as follows to indicate the range of concepts given serious consideration:

1) Specialized lift engines, thrust/weight ratio up to 20/1: RB108, RB162, and XJ99 (did not fly).

2) Vectored thrust turbofans, including running with duct burning for thrust augmentation: Pegasus, RB193, and BS100 (did not fly).

3) Dual-purpose lift and propulsion swiveling engine: RB145.

4) Afterburning turbofan with jet deflector: RB153 (did not fly).

The projects were supported by tethered and untethered piloted hovering rigs to explore the problems of the different concepts in jet-borne flight and by wind tunnel and rig tests on system components. As a result a large number of problem areas associated with V/STOL propulsion have been identified and understood through extensive research activity. These include ground erosion effects, induced lift loss effects, hot-gas circulation, lift engine control and response

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Table 1 Prototype and demonstrator aircraft using Rolls-Royce V/STOL engines

Aircraft type	Powerplant	Remarks
Short SC-1	4 RB108 lift engines 1 RB108 propulsion engine	Research into VTOL and transitions
Ryan X-13	1 Avon turbojet	Tail sitter
Bell X-14	2 Viper turbojets with thrust deflectors	Research aircraft
P1127	1 Pegasus vectored thrust engine	Harrier prototype
Dassault Balzac	8 RB108 lift engines 1 Orpheus propulsion engine	Mirage IIIV demonstrator
Dassault Mirage IIIV	8 RB162 lift engines 1 TF30 propulsion engine	Operational prototype of VTOL Mach 2 aircraft
EWR VJ 101 C	2 RB145 lift engines 4 RB145 propulsion/lift engines	Swivelling wing tip pods
Dornier Do31	8 RB162 lift engines 2 Pegasus vectored thrust engines	Transport prototype
VFW VAK191 B	2 RB162 lift engines 1 RB193 vectored thrust engine	Strike fighter prototype

requirements, engine ratings for V/STOL, life usage, air intake problems over a wide speed range, stabilizing air bleed systems, afterburning in deflected ducts, vectored nozzle performance, vertical engine operation, tilting engine systems, intake- and nozzle-induced engine vibrations, foreign object ingestion, jet deflection in flight, lightweight engine construction, and the consequences of powerplant failure/malfunction.

This wide development experience has provided many important lessons about V/STOL system design and operation and about V/STOL program management. It has also provided vital V/STOL propulsion test facilities and expertise which is now being applied to the critical problems of future V/STOL systems.

V/STOL Propulsion Options

Rolls-Royce has pursued alternative powerplant options[1] with comparable priority, ranging from the basic lift plus cruise arrangement (in which the functions of powered lift and forward propulsion are separated) to composite engines which function in both lift and propulsion modes (Fig. 1). As a result a good basis exists from which to assess and recommend systems for future development, and it will be evident that this has led to a concentration of effort on the vectored thrust approach using rotating or deflecting nozzles.

The single-engine version of this approach, with a conventional airframe and vectoring side nozzles grouped around the aircraft center of gravity (c.g.), as demonstrated by the Harrier and AV-8A and -8B systems, has been the most successful. This arrangement is relatively easy to package, balance, and control. It is also well suited to subsonic tactical fighter aircraft roles where forward basing and concealment in dispersed sites favor smaller aircraft.

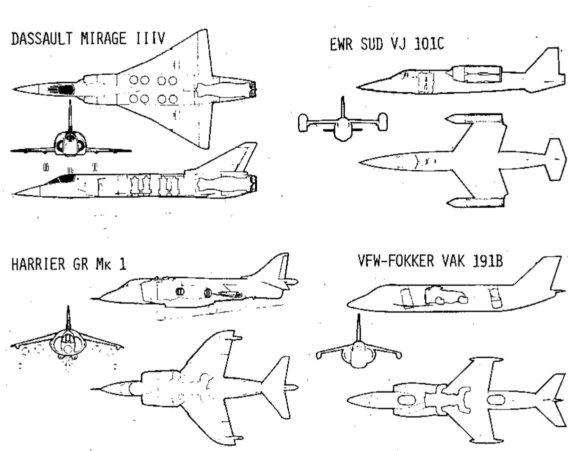


Fig. 1 Alternative V/STOL propulsion concepts.

Problems have arisen in the past when trying to meet more demanding roles and requirements. For example, requirements for a larger and heavier aircraft, good endurance, rapid acceleration to supersonic speeds up to Mach 2.0, ground footprint constraints, and a desire for a twin-engined aircraft and a common engine core system require a major extension of the basic Harrier vectored-thrust concept.

In this situation it is easy to see why alternative systems have been closely scrutinized and, indeed, Rolls-Royce project engineers have been evaluating alternative concepts on a sound comparative basis to see if a change in direction is warranted. The general conclusion is that such a change is not warranted and that for most V/STOL fighter applications, developed and updated versions of the vectoring side nozzle concept with thrust augmentation are to be preferred.

The complexity and cost of alternative systems that have been tested, or studied in depth, are sufficient grounds for this preference, but vectored thrust does have a considerable number of intrinsic advantages that are worth emphasizing.

The engine is positioned in the aircraft in such a way that the gross thrust vector passes close to the center of mass in both jet-borne and wind-borne flight. Trim, balance, and safety problems are minimal compared with many other configurations. High installed thrust in conventional flight, originally attacked as a disadvantage of the Pegasus V/STOL system, is now recognized as a necessity for high-agility combat aircraft. The use of thrust vectoring in forward flight (VIFF) to increase air combat potential is a powerful means by which the engine can be used to improve the agility of the aircraft.

A single engine, providing both lift and propulsion, yields a safe, low-cost, and low-risk V/STOL solution having the merit of simplicity. Controls and procedures for V/STOL are simple, reliable, and flexible. STO at increased aircraft weight can be fully exploited by the use of optimized thrust vectoring. Ground surface disturbance can be minimized by deploying nozzles in the aft direction for taxi, deck maneuver, and the initial stage of a rolling vertical takeoff. The vectored thrust concept can fully exploit the potential of a ski-jump launch for increased takeoff weight coupled with short takeoff roll.

As demonstrated on the AV-8B, the vectored nozzle configuration can be integrated into the aircraft high-lift aerodynamic system to provide flap augmentation. Cockpit controls can be kept closely aligned to those of CTOL fighters with one additional control lever only—that for nozzle angle. The vectored-thrust engine configuration is appropriate to the employment of afterburning in the fan exhaust duct for thrust augmentation, giving the thrust boost required to match the requirements of a high-agility fighter with low fuel consumption in the afterburning mode.

These characteristics, most of which have been demonstrated and exploited in the operation of the Harrier and AV-

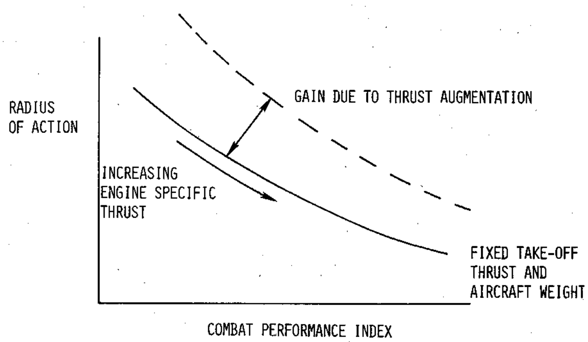


Fig. 2 Relationship between radius of action and combat performance.

8A and carried forward into the AV-8B, can be preserved in the foreseen new generation of supersonic V/STOL combat aircraft.

To this end, Rolls-Royce is currently investigating a range of vectored-thrust propulsion concepts.

Future Development

Perhaps the key advantage of the vectored-thrust approach is that it is the only low-risk way to achieve a high-performance V/STOL fighter within the next decade. In this case, time may not allow the development of completely new systems, in which case it will be necessary to build on existing experience. However, as stressed above, this has proved to be a very successful approach to V/STOL in the past; and, of course, an early high-performance V/STOL fighter could be an invaluable stepping stone to the longer term V/STOL aircraft likely to be required in the 1995-2000 time frame.

With the development and production of the AV-8B now apparently secure, the near and medium term for subsonic V/STOL combat aircraft appears settled. However, the long-term future is not so clear; thus, it may be that if improved combat performance is required some form of thrust augmentation may be desirable, even on subsonic aircraft.

The augmentation would be used in flight and also for takeoff and landing. To increase the thrust for higher combat performance without using augmentation will demand an engine with a higher specific thrust. This engine will have higher fuel consumption, resulting in reduced mission radius and, because of the lower lapse rate of a high-specific-thrust engine, reduced available thrust for takeoff and landing. This is illustrated qualitatively on Fig. 2, where the combat performance index can be defined as a function of engine thrust and wing loading. An increase in the former and a decrease in the latter gives a higher value of the index.

Introduction of thrust augmentation will allow the maintenance of the radius of action by keeping the engine specific thrust down and will provide sufficient thrust for both high in-flight performance and V/STOL. Following this route eventually leads to the provision of sufficient thrust for supersonic flight so that a supersonic V/STOL combat aircraft could evolve with several of the operational and environmental issues already resolved.

The basic method proposed and developed by Rolls-Royce for augmenting the thrust of vectored-thrust engines is to burn fuel in the fan exhaust duct. Known traditionally as plenum chamber burning (PCB), this method of providing augmentation in the bypass stream has been chosen because with the nozzles vertical the thrust center is well forward, easing the aircraft balance problem. In addition, if one augmentation system is chosen to avoid too much complexity, then a bigger thrust boost is available for a given nozzle gas temperature or, for a given thrust boost, the specific fuel consumption (sfc) is lower than for augmentation on the core flow. There is also ample cooling airflow available.

To take full advantage of the vectored-thrust engine, the exhausting of the bypass or core flows through separate nozzle systems offers independent control of the low- and high-power spool speeds by varying the core nozzle area. This permits the engine to be operated with maximum airflow and maximum turbine temperature simultaneously, thereby maximizing thrust; with maximum airflow at reduced thrust conditions, thereby minimizing fuel consumption; and with airflow scheduled to match the air intake supply, thereby reducing intake drag and complexity in high-speed aircraft.

We are now in a position where predictions of 1990 augmented vectored-thrust V/STOL aircraft performance can be made with some confidence. Although more work is required, Rolls-Royce believes that the technology exists to proceed with an aircraft development program. As an illustration of what is thought to be possible, the following information gives some of the indicative improvements achievable with the new PCB-augmented engines.

Table 2 In-flight performance capability (thrust augmentation by PCB)

Sustained turn rate	
Mach 0.6, 10,000 ft	5.9 *g*
Mach 1.2, 20,000 ft	6.2 *g*
Acceleration from Mach 0.8 to 1.6 at 36,000 ft	70 s
Specific excess power, P_s, at Mach 0.9, 10,000 ft	1160 ft/s
Maximum Mach number	1.9

Subsonic Application

In this case the dry vectored-thrust engine is replaced by a reduced-scale engine with PCB augmentation, assuming existing engine technology standards and the same payload/range: 50% smaller engine with PCB, 22% lower takeoff gross weight, and double the specific excess power (P_s) at Mach 0.8 and sea level.

Supersonic Application

PCB augmentation can provide performance broadly in the Mach 1.6-2.0 range. The following numbers indicate the improvements being targeted for a 1990 augmented vectored-thrust (AVT) engine compared with an existing AVT engine of the same airflow, assuming the same takeoff weight, fuel, and warload: 37% increase in loiter time; 46% increase in P_s at Mach 0.9, sea level; 50% increase in sustained turn rate at Mach 1.2 at 20,000 ft; and 16% increase in maximum speed.

The actual in-flight performance that can be achieved with a 1990s technology standard, new vectored-thrust engine with thrust augmentation by PCB, is shown in Table 2. The figures relate to an aircraft designed for a VTOL deck-launched intercept mission with a supersonic dash at Mach 1.6, out to a radius of action of 150 n.mi.

Technology Base

To support the preceding proposition, it is necessary to elaborate on the status of the propulsion technology base needed.

From the background of rig experiments, development experience on several V/STOL aircraft projects, and operational experience on the Harrier/AV-8A referred to in previous sections, a large number of propulsion system technology issues have been identified and a large data base has been accumulated. The main items are as follows:

1) PCB design—Achievement of satisfactory combustion performance, stability, handling, and system integrity over a large flight envelope.

2) Exhaust installation—Achievement of satisfactory exhaust duct, augmentation, and variable nozzle designs which are compatible with the engine and which integrate with

the airframe to give satisfactory aerodynamic and structural behavior in the presence of high-temperature exhaust jets.

3) Environment—Achievement of satisfactory efflux behavior in jet-borne flight as it affects operating site heating and erosion, hot-gas reingestion, and installed lift force.

4) Engine—Optimization of engine design to achieve the right advanced component technology mix, ratings system, thrust response and control, and the supply of large reaction control system bleed flows.

5) Intake—Achievement of acceptable flow distortion to the engine in short inlet ducts at all flight conditions.

PCB Design

When it was first considered, the concept of PCB posed a number of new problems which, while novel, could be studied using existing combustion rigs and techniques. The main issues were the low temperatures of the fan air at the inlet to the combustor, particularly at high altitudes, and the maintenance of adequate cooling flow on the duct walls around the bends through the exhaust system. To study these features both two- and three-dimensional rig tests were carried out at reduced and full scales and on an early Mark of Pegasus engine. These tests were extremely successful and, as a direct result, it was possible to launch the Rolls-Royce BS100 vectored-thrust engine with PCB for the British Aerospace P1154 supersonic fighter aircraft which was being developed for the Royal Air Force and the Royal Navy.

Work to improve solutions to the above problems is continuing and to a large extent is a continuation of the work started in support of the P1154. The stage has been reached where the temperature rise, combustion efficiency, operating envelope, and hardware life for a PCB system are sufficient for an advanced high-performance V/STOL combat aircraft (see Fig. 3 and Table 3). Also a substantial amount of test hardware exists which is suitable for further PCB studies or for the development of advanced nozzle hardware or for environmental investigations.

The reliability of the PCB system must be the same as that of any other major engine component, since the ability to perform a safe vertical landing will depend on the PCB operating just as much as a compressor or turbine. The conditions for combustion are good for a vertical landing at low altitude and relatively high engine power and the chances of a failure during the landing are remote. A further safeguard to avoid failure on one side of the PCB system is a cross connector between the two combustors that provides an instantaneous relight when the fuel is restored after a deliberate interruption.

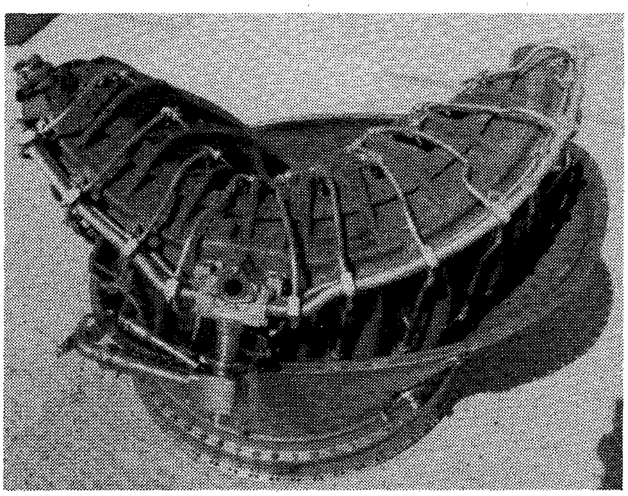


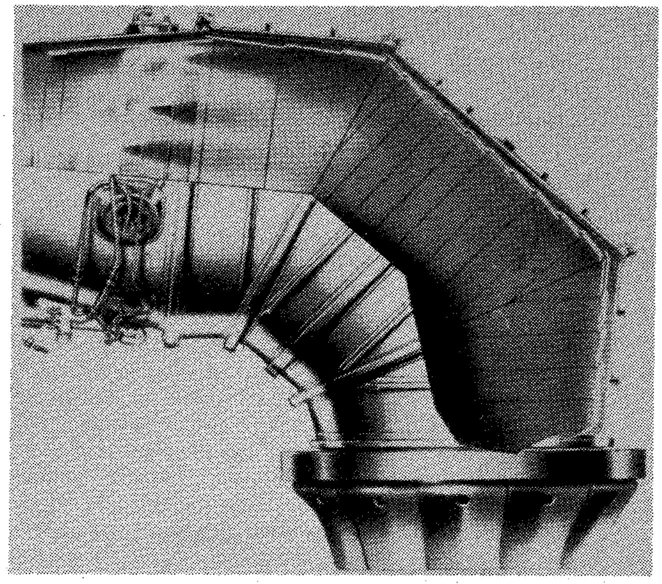
Fig. 3 PCB combustor.

Table 3 Test experience with PCB combustor

Very stable combustion, even with massive water ingestion
Maximum temperature rise (ΔT) of 1100°C (2012°F)
Peak efficiency of 90% at $\Delta T = 800$°C (1470°F)
Colander pressure loss of 3%
Thrust boost of 35% (relative to basic engine)
Successful 25 h endurance run

Exhaust Installation

The work on thrust-vectoring exhaust systems has ranged from model to full-scale testing on systems designed for both lift and lift/cruise engines. The gas temperatures for which the nozzles were designed ranged from that corresponding to fan delivery up to full reheat. The list of exhaust systems tested and the particular tests carried out is a long one, but two of the more spectacular tests were the deflection of the reheated exhaust flow of the RB153 turbofan engine, shown in Fig. 4, and PCB exhaust tests on a Pegasus engine, shown in Fig. 5. The engine configuration cannot be divorced from



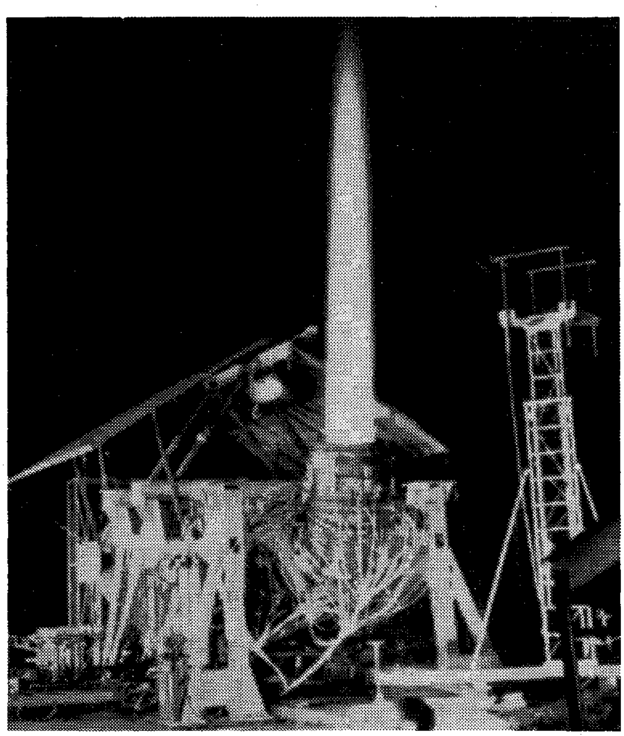


Fig. 4 Deflector nozzle on test with reheat.

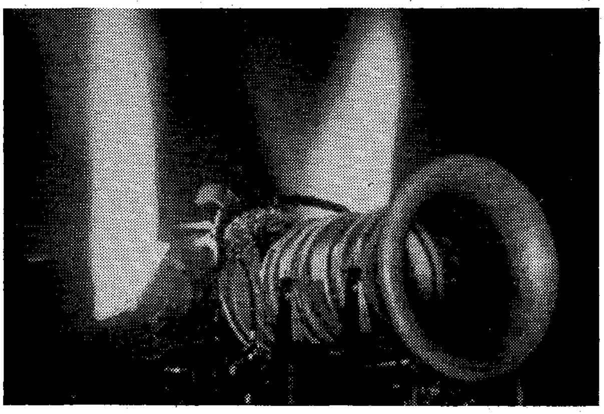


Fig. 5 PCB-augmented vectored-thrust engine test.

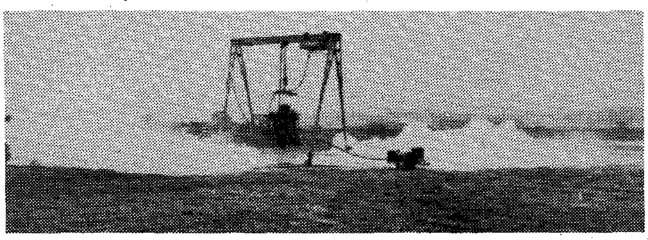


Fig. 6 Ground erosion test rig.

the requirements of the aircraft designer but it would appear that for a single-engine aircraft a vectored-thrust engine with three nozzles, rather than the four of the Pegasus, offers some installational advantages and a reduction in drag. Tests to investigate this have been made. Of course, the nozzle configuration must be tailored to meet the variable geometry and flow expansion requirement, as well as ground clearance requirements in the vectored-down setting, to integrate with the fuselage for low supersonic drag, and to avoid excessive fuselage structure heating. Design and experimental studies on alternative nozzle and heat shield shapes have provided data in this area and coordinated programs of nozzle/airframe integration studies, including supersonic wind-tunnel tests, are now being conducted by Rolls-Royce. The problem of airframe structural heating appears to be more readily solvable with some of the new insulators and heat-resistant materials now under development.

Work thus far carried out indicates that the introduction of the PCB into the front nozzle exhaust system does not increase the internal performance losses relative to those already experienced on today's Pegasus engine. The pressure loss of the combustor tends to be offset by a reduction in the bend losses because the flow Mach numbers are reduced to allow efficient combustion.

Environment

Ground erosion has been studied with a rig consisting of a gantry in which an engine could be mounted (Fig. 6). The height of the engine above the test surface or ground, the angle of the engine to the vertical, and its thrust setting were all variable. In addition, the gantry was sufficiently mobile to enable it to be moved from one test surface to another. Initially, testing was carried out using a RB108 turbojet lift engine and this was followed by tests with a reheated Avon engine to permit independent control of exhaust jet temperature and pressure. The average test duration was about 3 min and the sequence of tests was designed to determine the optimum concrete mix to constructing pads for repeated operations, to measure the erosion of unprepared surfaces and pastureland, and to investigate some of the preferred methods of rapid VTOL site preparation, e.g., lightweight aluminum planking.

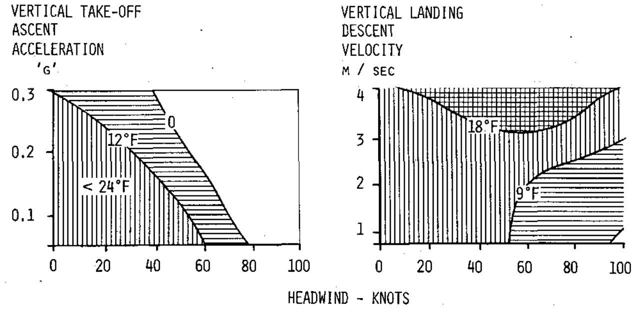


Fig. 7 Reingestion control of residual inlet temperature rise with 2800°F lift jets.

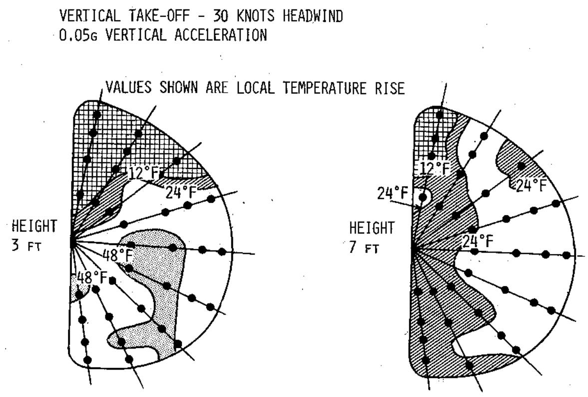


Fig. 8 Measured inlet temperature distribution.

The problem of obtaining a low or zero intake temperature rise due to hot-gas reingestion with high-temperature lift jets has been studied experimentally with subscale models, and a data base now exists which allows assessment of the preferred exhaust system configurations. These data allow confident predictions that operations will be possible with mean intake temperatures that are only slightly or no higher than those experienced on the Harrier today (15-20°F maximum) despite lift jet temperatures up to 2800°F (Fig. 7). This is achieved on an engine with PCB by converging the front jets toward each other to suppress the high-temperature upwash between them that would occur without convergence.[2]

A number of different rigs have been used at Rolls-Royce for subscale hot-gas reingestion testing. These rigs have had varying degrees of complexity and sophistication to allow for vertical motion of the model aircraft, wind speed and direction, nozzle vectoring, and aircraft altitude. The latest rig is capable of providing data on the instantaneous temperature distribution in the air intake during fully representative takeoff and landing maneuvers. Figure 8 shows the measured intake temperature distribution, corrected to full-scale conditions, for a typical example from the large number of configurations tested. In addition, sufficient hardware already exists to permit full-scale reingestion tests with an installed PCB engine system at varying heights above the ground.

Engine

The basic thrust requirements of a V/STOL aircraft may be completely different from those for CTOL, depending on the mission and in-flight performance requirements. A further complication may be the need to provide large amounts of engine bleed flow for aircraft stabilization during jet-borne maneuvers. Conventional engine ratings will not be appropriate and special short-duration ratings will have to be evolved (as in the case of the Rolls-Royce Pegasus engine) which will provide the necessary thrust profile while maintaining the required engine life. Since the aircraft

Table 4 Pegasus thrust ratings

Parameter	Thrust, lb	Turbine entry temperature limit, °F	
Short lift, wet	21,500	2385	15 s
Short lift, dry	20,500	2285	15 s
Normal lift	19,500	2240	2.5 min
Maximum thrust	16,750	2060	15 min
Maximum continuous	13,500	1855	Unlimited

requirements and the choice of propulsion system will dictate the thrust-sizing conditions, each case will have to be assessed separately. Table 4 shows the Pegasus engine ratings as they have evolved. It also shows the thrust increase available with water injection. While this technique offers a worthwhile increase in thrust, generally the thrust/weight ratio of the system is less than that of the basic engine when the weight of the water is included. Thus, water injection should be viewed as a last resort rather than part of the initial design.

Nearly all of the V/STOL aircraft built to date use the engine compressor bleed air to provide control forces during jet-borne flight. The best position from which to take this bleed air has been determined to be the combustion-chamber outer casing. This location allows the engineer to construct a large manifold; also, the low-flow Mach number permits up to 15% of the core flow to be bled from the engine without disastrous effects on the combustor outlet temperature distribution.

The bleed flow requirements may be reduced in pitch by independent control of the front and rear nozzle thrusts, varying both by PCB temperature and low- and high-power speed independently by means of varying the core nozzle area.

Aircraft height during jet-borne flight is controlled entirely by engine thrust and, because there is no stored energy as in a helicopter rotor, response to the pilot's demand must be rapid and precise.

Although the Pegasus engine has been developed to allow manual control during VTOL, the response from lift engines needs to be just as rapid even if autostabilization systems are used. Future propulsion systems employing thrust augmentation during VTOL will impose greater demands on the control system since additional parameters will be controlled. Additionally, there may be a need to develop fast-acting nozzle area control systems to avoid significant engine mismatching.

Intake

Regardless of the V/STOL propulsion concept, the air intake tends to be shorter than that of a CTOL aircraft. This is particularly true for lift engines and lift/cruise engine installations and occurs because of the need to keep the thrust line acting through the aircraft c.g. during jet-borne operations. These short air intakes may present the engine with nonuniform entry flow for a number of reasons:

1) Lip flow separations when operating at high incidence, e.g., lift engines at light-up during a landing transition for which there is insufficient duct length for the low total pressure flow regions to mix.

2) Flow separations in the duct due to high curvature in regions of adverse pressure gradients, something particularly likely when the curvature occurs near the intake entry plane.

3) Nonuniform static pressure due to duct curvature close to the engine entry plane which, even if the total pressure were uniform, implies varying velocities and incidence angles around the fan face.

As a consequence, the V/STOL engine is likely to have to tolerate worse entry flow pressure nonuniformities than its CTOL equivalent, and allowance for this has to be made in the early design stages. Additionally, the engine will have to tolerate nonuniform temperature distributions due to hot-gas reingestion and any loss of surge margin will be additional to the loss caused by pressure distortions.

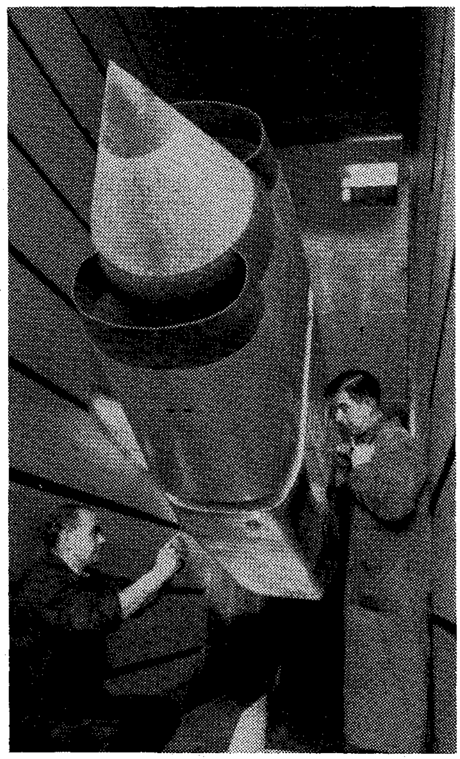


Fig. 9 Wind tunnel for V/STOL engine installed tests.

Extensive static tests have been carried out on both model and full-scale engines to measure these effects for a Pegasus installation and to determine their sensitivity to alternative duct configurations. In addition, tests have been carried out in a special rig (Fig. 9), constructed so that full-scale installations can be tested at low forward speeds with the engine in-situ and operating. This permitted the engines to be "flown" through the complete takeoff and landing transition profiles. As well as intake/engine compatibility, other installation problems, e.g., zone ventilation and structural cooling, were studied.

Conclusions

The existing service, development, and research experience in high-speed V/STOL propulsion provides an extensive background for decisions on the next generation of runway-independent combat aircraft. The necessary technology exists to accomplish a high-agility tactical fighter, with performance in advance of contemporary aircraft and with the basing flexibility afforded by V/STOL.

Any study of future V/STOL options necessarily focuses attention on cost of ownership issues, usually resulting in the conclusion that for equivalent mission performance and technology level the V/STOL machine will be more expensive than CTOL. Some studies have indicated a differential of the order of 15%. This result is relevant only when the necessary runways for CTOL can be guaranteed to be invulnerable to critical damage and when optimum runway locations are available for the chosen scenario.

It is perhaps worth noting that an examination of helicopter power requirements and unit costs indicates that, in general, rotary wing aircraft are several times more expensive than fixed-wing aircraft, both in basic price and in fuel burned per seat mile. This does not, however, have any relevance to the demand for helicopters when runway facilities for fixed-wing aircraft do not exist.

Similarly, in a runway attrition situation, V/STOL combat aircraft can easily be shown to be more cost effective than

CTOL equipment, which has to be based at an invulnerable distance from the combat zone.

The case for V/STOL is therefore wholly dependent on the evaluation of the threat and the airfield defense capability and, in the naval context, on the cost and availability of large ships. These issues are outside the field of expertise of the engine designer, but circumstances can be foreseen when a V/STOL force may be mandatory for the retention of air capability.

The powerplant technology to respond convincingly to this challenge exists and continuing advanced engineering programs progressively enhance the performance and cost-effectiveness prospects for V/STOL combat aircraft.

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