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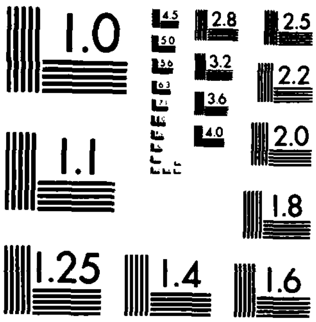
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ADDENDUM TO

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SPECIAL COURSE ON V/STOL AERODYNAMICS

AN ASSESSMENT OF EUROPEAN JET LIFT AIRCRAFT

by

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PREFACE

In the Special Course on V/STOL Aerodynamics (AGARD-R-710) it had been intended to include a review of layout considerations for European jet lift V/STOL aircraft, and Mr R.S.Williams (Senior Project Engineer at British Aerospace, Kingston) commenced this paper. Unfortunately he was unable to participate in the course, but he did complete this paper, which can be regarded as an extra lecture associated with that course.

This survey by a project engineer who has been at the heart of V/STOL since the beginning should be of great interest. In particular, his assessments of weight and cost factors cast light on project assessments from a viewpoint that is not often seen.

CLIFF BORE
August 1984

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AN ASSESSMENT
OF EUROPEAN JET LIFT AIRCRAFT

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ABSTRACT

A review is undertaken of European jet lift V/STOL, past and present, to illustrate the extent to which the powerplant has affected aircraft layout and consequently the aerodynamic design. Direct comparisons of V/STOL with contemporary conventional layouts are made. The successful Harrier's aerodynamic progress is highlighted. Promised engine performance advances are shown to offer more aerodynamic freedoms to V/STOL designs.

1. INTRODUCTION

The jet lift era based on the gas turbine began over thirty years ago, in Europe, with the first flight of the Rolls-Royce 'Flying Bedstead'. Rapid advances in jet engine technology had encouraged the conventional aircraft designer to enter the vertical take-off and landing (VTOL) arena hitherto the province of the rotorcraft. In these early days, one objective appeared paramount. It was to design for a full load VTO capability. With hindsight, this was possibly the basic reason for the lack of success. Not until vectored thrust with its V/STOL capability appeared and was eventually vindicated, did jet-lift aircraft enter production. Today, further engine advances are tempting the project engineer, because he sees the possibility of the aerodynamics being less compromised this time.

Consequently this paper is presented in three parts, matching the three phases of progress. The first part deals with early European projects and prototypes, the lessons they convey and the dominance of the lift engine. The second describes the Harrier, its subsonic and supersonic developments and why vectored thrust succeeded. The last part introduces the concepts involved in the present revival of interest in a UK supersonic V/STOL fighter, with respect to the effect on aerodynamic design.

To demonstrate the influence of the powerplant on aircraft layout, the configurations of European V/STOL designs (some perhaps not so well known) are compared with those of equivalent conventional (CTOL) aircraft, i.e. similar operational roles. In this way it is possible to isolate the allowance for V/STOL, and show how it is handled in the examples, particularly its effect on the aircraft weight 'cake' and, very broadly, the cost implications.

2. NOTATION

Ac	Conventional aircraft variable mass percentage - %TOW
Av	V/STOL aircraft variable mass percentage - %TOW
BLC	Boundary layer control by supercirculation (blowing)
CTOL	Conventional take-off and landing.
ΔP	Powerplant increment (V/STOL - conventional) - %TOW
NASA	National Aeronautics and Space Agency
PCB	Plenum Chamber Burning
SEVT	Single Engined Vectored Thrust
STOVL	Short Take-Off and Vertical Landing
Tc	Conventional aircraft rated thrust (total)
Tv	V/STOL aircraft rated thrust (total)
TOW	Take-off mass
V/STOL	Vertical and short take-off and landing
VTOL	Vertical take-off and landing
V	Net V/STOL allowance - %TOW
VIFF	(Thrust) Vectoring in Forward Flight

3. THE AIRCRAFT WEIGHT CAKE

Aircraft design is as much a science as it is an art. Therefore although this paper is largely qualitative, it starts with some numbers in the form of aircraft cake or pie charts to illustrate the dilemma facing the project designer. This method of comparing aircraft of a similar type treats total mass as a cake and allocates slices proportional in size to the mass of each discipline (Figure 1). Most importantly, each slice contains firstly, a variable mass portion - which, when the aircraft is scaled, varies in proportion to the take-off mass (TOW) - and secondly, a fixed mass portion. For instance, the structural slice includes items such as canopy, equipment support and pressure cabin which are unchanging; whilst primary fuselage and wing structures are variable, remaining proportional to TOW. The powerplant slice is almost wholly variable. Hence the designer has two choices if there is an increase in the size of the powerplant slice (ΔP) when a CTOL design is converted to V/STOL. He can constrain the aircraft size (as shown) by reducing the structure fraction (which to a large extent determines the aerodynamic configuration) and also by reducing the fuel fraction thus directly affecting range or combat radius. Alternatively he can let the aircraft grow so that the constant masses (in each slice) diminish sufficiently as percentage TOW to make room for the ΔP percentage. In this latter case, aerodynamics and performance should be little changed.

The ratio of variable mass to fixed mass is widely different depending upon aircraft scale and role. However, Figure 2 shows the effect on size when values are assigned to the variable mass percentage (A) of both CTOL and V/STOL, and the difference between them is called V, the net V/STOL allowance. For example, if a V/STOL fighter concept is assessed to have a V of 15% then it would be about 60% heavier than its CTOL counterpart. The Harrier, in the comparison shown, has a zero value of V. The powerplant increment, ΔP, is usually the largest component of V, and includes not only the variable mass increase of the powerplant itself but the extra variable masses in the fuel system, aircraft controls etc., directly required to perform the V/STOL functions. Hence the value of ΔP for the chosen examples and its effect on the other increments, especially structure affecting aerodynamics, is noted and summarised at the end of the first two parts.

Relative TOW is certainly not the only criterion by which to judge a design. Simplicity, performance, survivability, operational flexibility, timing and cost are just some of the considerations affecting acceptance. Of these excess cost is seen as the worst enemy. As fighter aircraft life cycle costs have been found - all other things being equal - roughly proportional to total installed thrust (Reference 1) the thrust ratio (Tv/Tc) is presented, again at the end of the first two parts, as an indication of V/STOL costs.

PART I - SPECIALISED JET LIFT ENGINE AIRCRAFT

4. THE BEGINNING OF THE SPECIALISED JET LIFT ENGINE ERA

This part includes only those designs which illustrate the main alternatives available in the early years and is not a complete survey of European effort. A full account of those that flew (European and US) and their behaviour is given in Reference 2. As will be seen, because the small jet lift engine designed for low speed use only was being offered at attractive thrust/weight ratios - twice the normal propulsion (cruise) values (Figure 3) - it featured prominently in nearly all layouts. It put the powerplant fraction for VTOL within reason. The hidden snag was the added complication caused in other departments.

To just demonstrate jet lift vertical flight and control principles requires very little in the way of aerodynamics and the first jet lift vehicle, the Rolls-Royce Flying Bedstead (Figure 4) of 1953 certainly had very little. However it was a clever use of engines and jet pipes which were readily available. The bifurcated jet pipe on one of the engines was a Hawker patent originally used on a Rolls-Royce Nene in the Seahawk fighter. This was also the first occasion that air was bled from the engine compressor and ducted to reaction control valves for all axis control. The tap-like control nozzles could rotate for yaw. Another first occurred in the United States in 1954 when the Bell VTOL test vehicle (Reference 3) utilising light aircraft and helicopter components, provided a separate compressor for reaction control air. It also had tiltable jet lift engines.

The basic principles established by the Bedstead were put to use in the Short SC.1 experimental VTOL aircraft (Figure 4) of 1958. It was powered by the first specialised lift engine, the Rolls-Royce RB.108 which provided up to 10% of its airflow as control bleed and was tiltable over a limited range (35 deg) to aid transition manoeuvres. Every effort was made to achieve the lightest fuselage and wing structure to compensate for the high (34%) powerplant fraction. Low drag and efficient lift were not essential at this stage. Unfortunately, the large root chord delta wing, with the close grouped lift engines placed at its centre of area, suffered large suckdown forces in ground effect and hover, and grid VTOL operations were necessary. All five engines supplied bleed air to the reaction control system for hovering flight. The SC.1 was used primarily for the development of auto-control systems (Reference 4).

5. EARLY V/STOL PROJECTS

While the concept behind a project proposal which does not progress remains unproved, the design very often contains ideas which appear in later prototypes. Here are some examples.

5.1 Lift Engine Fighters

The Kingston fighter airframe team had close associations with Rolls-Royce (Derby) Engines on the Seahawk and Hunter programmes and were well aware of their progress in jet lift engines. It is not surprising therefore that these engines figured in the first Kingston VTOL project, the P.1126 (Figure 5) of 1957. It utilised the "pop-out" lift engine principle of later designs and also incorporated one of the delusions of the time. It was thought that a considerable part of the increase in powerplant fraction could be offset with a lightweight undercarriage, i.e. no heavy oleos, wheels, tyres and brakes. Consequently skid undercarriages, like a helicopter's, were sufficient since STOL was not proposed, and a lack of ground mobility was acceptable (Reference 5). The P.1126 aerodynamics - its counterpart the Fiat G.91 shows the fashion of the day - were not optimised for subsonic flight. The shape owed more to the supersonic SAAB Draken, but provided light weight and low drag storage volume for the retracted lift engines. The suckdown problem of the SC.1 was avoided by using two separate banks of lift engines, and near the ground a positive cushion from the jet fountain at the fuselage centreline is obtained. The following project, the P.1127 (which later became the Harrier and is discussed in Part II) did not use separate lift engines and offered a much simpler approach to the problem.

As the P.1127 was only subsonic and new conventional designs were mainly supersonic, in 1959 a VTOL supersonic alternative, the P.1137 (Figure 6) was also studied. It incorporated the latest RB.153 lightweight lift and propulsion engine proposals in a cruciform layout for thrust modulated and vectored hover control. The basic aerodynamic shape resembled the Northrop F-5A shown, but like most VTOL designs, it suffered higher span and wing loadings in an attempt to offset the greater powerplant mass. The study (Reference 6) concluded that incorporating a supersonic capability would nearly double the take-off mass of V/STOL tactical aircraft, a finding which still holds today.

Also in 1959, the newly formed group of Bolkow, Heinkel and Messerschmitt were investigating V/STOL designs which could achieve Lockheed F-104 Starfighter like supersonic flight performance (Reference 7). Heinkel's design, the VJ-101A6 (Figure 7) had six propulsion engines all tiltable. The VJ 101B of Messerschmitt, also shown, had two lift engines and four lift/cruise engines with "block and turn" deflection (Reference 8) of the dry thrust. These ideas were almalgamated in the EWR. VJ 101C prototypes described later. This experiment obviously had some drawbacks (e.g. supersonic drag of engine pods) since the VJ 101D project reverted to five lift engines and two block-and-turn lift/cruise engines (based on the RB.153) all in the fuselage. Their final work (to date) on supersonic V/STOL was the variable geometry A.400 (Figure 7) with a Tornado-like task. It had rig tested deflectable reheat (Reference 8) on the propulsion engines, and lift engines which extended to permit greater vectoring in the transitions, and also repeated the VJ 101C triangular arrangement (base first this time) required for thrust modulation hover control. Before work ceased in 1969, the layout was considered to be (Reference 7) "an optimum solution for a high performance VTOL combat aircraft".

Besides the better thrust/weight ratio reason, this spate of multi-engined fighter projects persisted because it was also argued that small engines would be cheaper to develop and produce by virtue of longer production runs. This might have been an engine manufacturer's dream but when all the implications were realised it appeared more like a fighter operator's nightmare, used as he was to ONE or at the most, TWO engines. It was primarily due to the fact that almost any aerodynamic form could be adapted for VTOL with lift engines, that the concept persisted into extended flight trials, and into limited production with the Russian YAK "Forger".

5.2 Supersonic Transports

Interest in jet lift VTOL transport aircraft was aroused in the late 1950's when Dr. A.A. Griffith of Rolls-Royce proposed a series of supersonic layouts (including a $M = 2.5$ fighter) with narrow delta planforms. The lift engines were stowed upright in the deep wing roots and the propulsion engines were mounted in wing tip pods. His transatlantic VTOL airliner (Figure 8) was to carry 88 passengers and cruise at Mach 2.6. The drag and mass estimates (Reference 9) were hopelessly optimistic, since only 51,000 lb of fuel and a take-off mass of 125,000 lb (little more than a BAC One-Eleven) were provided. The wing required a special wedge profile section (as shown) claiming very low wave drag properties (which tests failed to substantiate) and a large internal volume. Here the VTOL feature, i.e. lift engine stowage, was certainly specifying a special aerodynamic characteristic. Fully automatic operations were envisaged since the only crew were positioned at the rear of the layout.

As extreme as Griffith's ideas seemed, they did spur (in 1959) the Advanced Project Group (APG) of Hawker Siddeley Aviation (HSA) to study the implications of adding a VTOL capability to their APG.1000 supersonic airliner (Reference 10). HSA were competing with Bristol for the Concorde contract. This design, the APG.1003 (Figure 9), because it was much larger than Griffith's, could store the upright lift engines in a more aerodynamically acceptable wing profile. It adhered to Griffith's basic principles except that the cruise engines all provided lift and some (the tip engines) provided control power through thrust modulation and vectoring. In this way the total installed thrust to take-off mass ratio was reduced from the Griffith value of 1.92 to 1.51, with a saving in powerplant mass fraction. These high ratios were dictated by anticipated civil airworthiness requirements where it was thought advisable to retain control after any two engine failures in an array of six. Hence multi-engine lift and control provisions were essential (they totalled 128 units). Emergency thrust was available as usual by overspeeding the remaining engines. In a Concorde size of aircraft (the 100 passenger APG 1003 weighed 320,000 lb on take-off), the fuel fraction was considerably reduced, enough to limit range to only half that required. One stop operation on the transatlantic run would defeat the main advantage of supersonic travel - reduced journey time. The powerplant mass fraction, even if engine costs and noise were acceptable, was shown to be too great to make the VTOL supersonic airliner concept viable at any sensible scale. Aerodynamic alternatives could not save it.

5.3 Subsonic Transports

In the late 60's, HSA sought to solve the noise problem of city centre to city centre jet powered VTOL operation using a derivative of the lift engine, the lift fan, of which the Rolls-Royce RB.202 was an example. These airliner projects (Reference 11) used multiple units for safety reasons, mounted alongside the passenger cabin, much like the sponsons on the Chinook helicopter (Figure 10 shows the HS.141). The high bypass ratio propulsion unit was chosen for the subsonic cruise speed. The cost of developing the new lift fan engines at the same time as the airframe posed too large an investment hump for this end of the civil aircraft market to bear.

However the earliest HSA subsonic jet lift transport projects were military where safety was not so critical. One of these was the Hawker Siddeley AW.681 of 1961, to support the P.1154 supersonic fighter (see later), and was offered in two guises. The first (Figure 11) was a STOL version using just four Pegasus lift/cruise engines, from the P.1127 programme. The substantial supply of bleed air was ducted to the wing flaps, ailerons, elevators and rudder to provide supercirculation control (BLC) at the low operating speeds possible. In the second, a conversion to VTOL was achieved by adding multi-unit lift engine pods to the outer wings (Figure 12). Each pod's fore and aft vertically mounted units were thrust modulated for pitch and operated anti-symmetrically for roll. Yaw could be provided by vectoring the outer Pegasus nozzles asymmetrically (Reference 12). A variation on the HS.681 lift pod was used on the twin engined HS.129 (Figure 12). To increase the nozzle vectoring range and also reduce the transition pitching moment and hot gas ingestion in ground effect, the jet lift units were laid horizontally as shown.

The upswept rear fuselage configuration and moderately swept wing with podded engines followed the military transport fashion of the day, exemplified by the Lockheed Starlifter shown. There was little need for adventurous aerodynamics, for the necessary BLC techniques were readily available. After a change of government the P.1154 was cancelled in 1965, and with it the HS.681 support aircraft.

6. EUROPEAN PROTOTYPES

6.1 Fighters

The French Mirage III V VTOL supersonic lift plus cruise engined fighter programme is an excellent example of taking what is readily available and introducing the new features one at a time - a procedure frequently used by Marcel Dassault. Dassault were involved in VTO at a period when NATO was issuing its own multi-national aircraft requirements and the Mirage III V was to compete with the British P.1154 (discussed later) for NBMR-3. Firstly Dassault created a VTOL technology demonstrator, the Balzac V from the Atar-powered CTOL Mirage III E supersonic delta planform fighter (Figure 13). The centre fuselage was enlarged to accommodate the RB.108 lift engines, already tried in the Short SC.1. These eight were placed in pairs each side of the main undercarriage wheel bays and the central intake duct for the lightweight cruise engine, a Bristol Orpheus, as used in the Fiat G.91. The bleed from the RB.108 engines was fed via dual reaction control ducting to paired valves at the fuselage and wing extremities. The Balzac V, intended to explore the VTOL regime only, was constructed quickly and flew in 1962 (Reference 13).

Next, the more powerful III V cruise engine (a Pratt and Whitney TF-106 reheated turbofan) required to propel the prototype's larger fuselage at supersonic speeds, was tested in another modified Mirage III E airframe with enlarged intakes and fuselage, called the Mirage III T. Thus when the first prototype, the Mirage III V 01 arrived in 1965, only the higher thrust RB.162 lift engines were new. Prototype 02 incorporated simpler and lighter intake scoops and doors for the lift engines. During test flying, to avoid suck-down and hot gas reingestion (HGR) into the engine intakes, vertical operation was confined to a grid. A hold-down strop was used during lift engine run-up prior to lift-off. The total installed thrust, a guide to cost, was now over 51,000 lb: nearly four times the CTOL Mirage III E starting value. Reaction control bleed thrust at its maximum could amount to 5,000 lb. The programme (Reference 14) was abandoned prior to the construction of the 03 and 04 pre-production prototypes, which were to use even higher thrust RB.162's and TF-306 cruise engine. Prototype 02, however, did achieve M = 2 in level flight - the only VTOL aircraft to do so. The use of a tried and tested aerodynamic configuration, though wing and span loading had increased, saved Dassault the cost of conventional flight development. Their problems appeared to be mainly VTOL (Reference 2), operational inflexibility and cost. It is interesting to note that later, when they wished to improve on the delta wing's airfield performance, they produced the F.1 model with a moderate aspect ratio swept wing fitted with high lift flaps and a tailplane for longitudinal control as being a cost effective solution.

Parametric studies (as in Reference 8) had shown that a lighter overall VTOL powerplant weight could be achieved with approximately half the thrust devoted to lift only. If the cruise engine's thrust could be made easily deflectable too, this was a bonus. The Germans fielded two projects in this category. The first, the experimental EWR-Sud VJ 101C (Figure 14) eliminated the requirement for reaction control bleed air by placing the engines away from the aircraft c.g. so that thrust modulation and vectoring could be used for hover and transition control. The first prototype X-1, flew in 1963 with RB.145 engines, derived from the RB.108 by adding a zero compressor stage and removing the bleed manifold. The X-2 prototype flew with reheat added to the tip lift/cruise engines. As with the Mirage, vertical operations were restricted to a grid. Although the total installed thrust was then about 20,000 lb, only 14,000 lb was cruise thrust - less than the J-79 of the Starfighter (shown) whose supersonic performance the VJ 101C was trying to emulate. This, together with the relatively high drag of the paired and podded engines at the wing tips, yielded only a moderate supersonic level speed. Anticipating even greater pod drag when the bulkier new technology reheated turbofans were available, EWR reverted to fuselage mounted cruise engines for the VJ 101D production proposal and subsequent A.400 (AVS) described earlier.

The second German example, again designed primarily for VTOL, was the VFW-Fokker VAK 191B fighter of 1971 (Figure 15). Being later than the rest it should have benefited from their experience. It was nearly a Harrier layout but with a smaller lift/cruise engine (for better cruise matching) and a lift engine fore and aft. Each of the powerplants supplied bleed air to an independent reaction control system, so there were three self-contained duct arrays. The forward lift engine fed front and rear pitch valves. The bleed from the aft lift engine supplied the yaw and roll valves. The lift/cruise engine was only bled when demand was high and supplied a complete duct and valve system for all axes (Reference 15). The mass of the complication was offset by providing only small wing and tail surfaces which, however, suited the straight-line high-speed, low-level ground attack role. Like the Harrier, the central powerplant with thrust vectoring dictated side intakes (to pass flow around the front lift engine), a bicycle undercarriage with outriggers, and high-set wing and tailplane. This engine being smaller than the Harrier's Pegasus and placed high to keep the drooped nozzle thrust line through the aircraft centre of gravity, there was room below for an internal weapon bay, in a fuselage depth determined by lift engine height. The total thrust of the VAK 191B prototypes was about 2.5 times a conventional contemporary, the Fiat G.91Y also shown. Production versions with bigger wings and more thrust were planned but the requirement lapsed. The G.91 was replaced by the Alphajet in the GAF.

A common feature of these VTOL fighters (and the V/STOL Harrier) was how the higher basic drag of the large fuselages was offset by using only very low drag suppressed windscreen and canopy profiles.

6.2 Transports

The only jet lift VTOL transport to make flight status was the Dornier Do31 experimental prototype (Figure 16) of 1967. Intended as a precursor to a design for NATO military supply duties (like the HS.129), the basic layout was similar to the VTOL version of the HS.681 (see earlier) but differed in detail. For instance the lift engine pods were mounted at the extreme tips of a low aspect ratio unswept wing; the main undercarriage retracted neatly into the rear of the lift-cruise engine pod; and the tailplane was mid-set on the fin. The powerplants were from other programmes; Pegasus 5's from the HS. Kestrel, RB.162's from the Mirage III V. So it was the basic configuration that required testing, and small and large hover rigs were flown before the prototype itself (Reference 16). Here pitch hover control was from valves in the fuselage supplied by Pegasus bleed air (up to 40 lb/sec available). Roll and yaw control were by pod engine thrust modulation and vectoring respectively. Production versions would have had a higher aspect ratio swept wing, like the Kawasaki C-1 shown, and for civil use higher bypass ratio cruise engines and lift fans. However, as with the HS projects, civil developments required city centre access in order to compete with conventional short range transports and this being denied the concept failed, though the Do31 prototype, performed well (except for the extreme noise of its 66,000 lb of thrust).

7. MASS AND COST ASSESSMENTS

The powerplant mass increment ΔP, described in paragraph 2, has been noted for each of the foregoing VTOL designs (except Griffith's and HS.141) and is now presented in Figure 17. The trend line, pointing to better results with less lift only engines, follows the pattern of many parametric assessments of total VTOL powerplant mass as a percentage of take-off weight. However it was the generally high level of ΔP, around 10 to 15%, that provided these early VTOL aircraft with their greatest problem. As shown under design options, the experimental prototypes shed load, fuel and structure to offset (or more than offset) this powerplant mass increment. Aircraft intended for production sought to relinquish some lifting ability and range (cruise efficiency and fuel) but were still prepared, as was the Mirage III V, for a considerable size and mass increase. The V/STOL Harrier, shown for comparison, indicates the least powerplant increment - with no weight devoted to lift-thrust alone.

Attendant on a mass increase is a thrust increase, and the main cost parameter, the ratio of total installed thrust (V/STOL to CTOL), is shown in Figure 18. As expected this ratio is almost directly proportional to the sizing parameter V of Figure 2 (V = the net V/STOL allowance). The curve indicates that production versions of these early VTOL designs could have had life cycle costs between 2.5 and 4 those of times a CTOL aircraft performing similar roles. Note, however, that in military scenarios the added capabilities of V/STOL, i.e. close support, dispersibility etc., are of enormous value in a real conflict.

8. HINDSIGHT ON LIFT-ENGINED PROJECTS

The specialised lift engine enabled a wide variety of aerodynamic configurations to achieve a VTOL capability, albeit from a grid. However the initially attractive basic thrust/weight ratios of these units were diluted by the complicated installation features such as intake doors, exit deflectors and multiple reaction control ducting systems. In fact weight installation factors of well over 2, say for a wing pod installation, were not uncommon. This compared to a value of around 1.5 for a cruise engine in CTOL aircraft. In consequence, the overall mass increment for lift engine based VTOL was greater than expected. Even the presence of the tried and tested 9,000 lb thrust Anglo/American XJ-99, with a much improved thrust to weight ratio, has not encouraged serious lift engined proposals from Europe beyond the A.400 of 1969.

For the performance demanded in the 1960's, CTOL aircraft take-off thrust/weight ratios were quite low. Even the supersonic fighter could manage with less than 0.7. Therefore to provide for a full load VTO and also retain the lift plus lift/cruise concept, much more than double the CTOL thrust was required. Hence the powerplant mass increment and overall cost were too punitive. With hindsight, it can be seen that the requirement of VTO at full load was excessive, and a short take-off ground run to use the wing lift would greatly boost payload - if thrust was fully vectorable.

PART II - THE SINGLE ENGINED VECTORED THRUST SUCCESS STORY

9. THE BEGINNING OF VECTORED THRUST

As noted in Part I the successful fighter aircraft of the 1960's had take-off thrust weight ratios well below unity and consequently if vertical operation was to be achieved, at least double the engine thrust was required. The specialised lift engine solution was to provide more of the same, that is to duplicate the main engine, but this time in small packages disposed around the airframe; no use at all in forward flight! The single engine vectored-thrust (SEVT) concept moves somewhat towards helicopter principles, and uses the jet engine to move more air at a lower speed, i.e. multiply thrust. H. Wibault saw this and also the possibility of directing the entire thrust in the optimum direction for vertical or horizontal flight, and so guaranteeing the shortest possible take-off runs. This simple idea was taken up jointly by Bristol Engines and Hawker Aircraft who then co-operated to provide a practical engineering solution: the Pegasus engine in the Harrier airframe (Figure 19). This story has been told many times (e.g. References 18, 19, 20 and 21), therefore this part concentrates on the aerodynamic possibilities that remain once the basic layout is chosen. A detailed numerical assessment, as in Part I, has not bee applied to the SEVT projects mentioned, but comment is made on a few typical results at the end of this part.

10. HARRIER AND DEVELOPMENTS

10.1 P.1127 Prototypes

The basic configuration of the BE.53 (later Pegasus) powerplant oscillated considerably until (a) the fan and core had a common intake (April 1958) and (b) the rear exhaust was equipped with the patented Hawker Seahawk (P.1040) bifurcated jet pipe (August 1957) (Figure 20). Once this was settled, the dictates of minimum mass determined the airframe shape and size. The need for the jet exhaust to sweep the rear sector about the aircraft centre of gravity (c.g.) pushed the wing and tailplane to a high mounted position. Thus a wing mounted main undercarriage would be tall and too heavy at this stage of limited engine thrust. With such a large amount of central fuselage volume occupied by the powerplant, this precluded (a) a conventional fuselage-mounted undercarriage and (b) sufficient fuel space in the fuselage. To satisfy the first, a bicycle undercarriage (like the B-47 but with main wheels nearer the c.g.) and wing tip mounted outriggers were adopted. A wing with a relatively deep aerofoil section and a large root chord became the major integral fuel tankage (half the total) and met the second objection. A small highly tapered planform was used to satisfy the minimum wing mass target, as with the Short SC.1.

The fuselage length (for minimum mass) was kept short by wedging the pilot's cabin between a very short bifurcated intake (akin to sitting in the front of a Boeing 747 engine nacelle) and by installing the engine through the hole left when the one piece wing was removed. After an abortive scheme to use low pressure compressor air, the actual reaction control system fitted used high pressure air bled from the rear of the core compressor to feed valves at the fuselage nose, tail and wing tips - using just one tapping and set of ducting. So it can be seen that in the early stages of a project, where with a new powerplant and a new airframe, excess thrust is difficult to achieve, almost everything must be sacrificed to proving the concept. Thus while the P.1127 fitted with Pegasus 2 and 3 engines became a very useful V/STOL vehicle and was operationally acceptable, its conventional flight performance had certain shortcomings. Minor modifications were made at the tip of the wing (to help reduce wing buffet and stall) but it was not until the Kestrel and Harrier that the necessary improvements were accomplished.

10.2 Tripartite Kestrel

The order (in 1962) for nine Kestrel aircraft (Figure 21), with Pegasus 5 engines, from the UK, US and German governments provided the opportunity to improve the basic P.1127 layout. A less tapered wing planform with a swept trailing edge was used to give larger outer wing chords to reduce the local lift coefficients and prevent aileron deflection from stalling the section ahead of it, the cause of the earlier severe wing drop and buffetting.

The lack of longitudinal stability was cured in two ways. First an insert in the fuselage ahead of the wing (Figure 22) was made to bring both the overall aircraft c.g. and the engine thrust centre forward (since they must not get separated by much). The engine also needed the forward move because the promised thrust improvements were (and usually are now) from uprated engine speed and turbine temperatures, which increase rear thrust more than front thrust. The c.g. movement was to correct an under-estimate of the lift developed by the intake at full thrust. As an acceptable c.g. range is from 2% to 18% of the wing chord (and the wing alone lifts at 25%), intake/body lift must be substantial. The second longitudinal stability improvement was to give the tailplane anhedral and increase its span (Figure 23). The aircraft configuration is such that it has quite wide and high velocity engine and fan exhaust passing just below the inboard half of the tailplane. Thus the normal changes of downwash in this region are prevented, and this part of the tailplane cannot contribute to stability. Hence the span increase is necessary to place more of the tailplane outside the jet influence. The addition of anhedral made it possible for the outer (effective) part of the tailplane to clear the wing wake earlier and meet stabilising airflow. At high incidence now, the desired strong pitch down occurred.

The Kestrel trials enabled many important operational and logistic assessments to be made, and some Kestrels finished in the service of NASA: indeed, one of them now hangs in the Smithsonian Museum of US Aerospace!

10.3 Harrier

The Harrier (Figure 24) with a Pegasus 6 (later 11) arose as a replacement for the RAF P.1154 (see later) cancelled in 1965, allegedly on grounds of excessive potential cost. Apart from not having a terrain following radar and supersonic level speed capability, the Harrier's equipment and duties were almost identical to those of the P.1154. Cost was to be saved by basing the Harrier directly on the Kestrel, and yet another chance of modifications was now possible. Longitudinal stability was further improved by increasing the wing span outboard of the outriggers (more wing area behind the aircraft c.g.). Also the intake cowl was enlarged to reduce spillage drag and auxiliary inlet doors were introduced to improve static intake efficiency, replacing bulged or inflatable intake lips.

It was on the Harrier that the evasive properties of rapid retardation, lift jump and pitch-up from thrust vectoring in forward flight (VIFF) was developed. This was just one of the virtues of the Harrier which attracted the US Marines and it entered their service almost unchanged as the AV-8A.

When a two seat version was required, the extra side area forward was compensated for by moving the fin aft and increasing its size (Figure 25). An alternative would have been to insert a section in the rear fuselage and move the tail unit rearwards as a whole, like the AV-8B later did (also shown) and compensate more fully for the forward mass at the same time. The extended boom on the two seat Harrier carries ballast and provides an increased arm for the rear reaction control, to counter the larger pitch inertia. The Sea Harrier also had modifications forward, a raised cockpit and multi-purpose radar, which required a fin size increase and rear ballast.

10.4 AV-8B

In the late 60's, Hawker Siddeley Aviation at Kingston began the first of a series of studies to decide upon the most suitable successor to the Harrier under the project headings P.1184 (subsonic) and P.1185 (supersonic) and using an uprated Pegasus. These studies continued into the 1970's when comparisons were also made with conventional designs. The ultimate decider was cost again as Figure 25 shows. Supersonic V/STOL was still outside the RAF budget restraints and it seemed that subsonic V/STOL was the only affordable solution. By this time McDonnell Douglas had a subsonic design based on the AV-8A which incorporated most of the P.1184 improvements and some of their own. The greatest change from the Harrier was a larger area, higher aspect ratio (4), thicker, supercritical sectioned wing (Figure 27) with additional pylon stations. This wing was constructed mainly of carbon fibre to minimise any mass increase which would require more landing thrust from the UK engine and hence increase development expenditure, especially abroad. Kingston revived the P.1184 ideas with Harrier proposals using an already developed "Big Wing" in competition with the AV-8B. However, it became commercially prudent for Kingston (BAe by then) to back the AV-8B because of the wider market, and the RAF ordered it as their next V/STOL aircraft calling it the Harrier GR.Mk.5.

Hence after 24 years of subsonic SEVT, the practical layout is still basically as it started, like the P.1127, and it is likely to see service at least until the year 2000, a total of 40 years: an indication of its appropriateness perhaps?

11. SUPERSONIC VECTORED THRUST PROJECTS

The P.1150 (Figure 28) of 1960 was the first attempt at a supersonic version of the basic P.1127 layout. The main changes were, as expected, thinner flying surfaces and a larger sleeker body, partly to accommodate the fuel displaced from the wing. The powerplant, basically a developed Pegasus, had drooped nozzles to permit (a) removal downwards and leave sufficient fuselage structural depth beneath the wing, (b) less turning loss in the ducts, and most importantly (c) greater clearance between the jet exhausts and the rear fuselage/tailplane. The fan air had its thrust greatly augmented by plenum chamber burning (PCB) for take-off and landing and especially for increased supersonic thrust.

11.1 P.1154 RAF

Since the P.1150 was unable to fully satisfy the NATO requirement NBMR-3, a new design, which became the P.1154 (Figure 29) was proposed. Being heavier it required a new bigger engine; the BS.100 with a revised cycle, better matched to supersonic flight and the increased reaction control bleed requirements. The P.1154, along with another SEVT design, the Fokker/Republic Alliance, was submitted to NATO in 1962 and declared joint winner with the Mirage III V. Only the RAF and RN were interested in the P.1154 ultimately.

After 18 months of attempting to satisfy the different requirements of Navy and Air Force with one design, the RAF decided to go it alone with the RAF P.1154. Its main role was to perform lay-down attacks behind enemy lines, flying at high speed and low level to evade ground defences. For ride comfort the wing loading and sweep should be high, consequently only a small wing was necessary. Hard manoeuvring to engage enemy fighters was not thought worthwhile then. In fact for this specialised role, a supersonic capability was hard to justify. It was the M = 0.92 dash speed that dictated the supersonic shape in order to delay the drag rise. A halt was called in 1965, when the prototype RAF P.1154 was about one third built, and the Harrier substituted.

11.2 P.1154 RN

The wing planform to best suit the naval role of the 1960's should have had a large aspect ratio and moderate leading edge sweep, and this is mostly where the compromise difficulties with the RAF version arose. The RN needed an interceptor which could perform continuous air patrol (CAP) for several hours at least 100 nautical miles from the ship. In order to see the enemy bombers early enough, a large radar was required together with a second crew member to operate it. A rapid climb and supersonic level speed were needed to accomplish the interception. All these capabilities required a much larger fuel fraction than the RAF version.

Catapult take-off was the standard method of carrier launching then and to fit into the launch cycle, the RN P.1154 was fitted with a nosewheel tow bar and holdback. The deck behind the catapult was not free for short take-off. So that the mainwheels could avoid the catapult shuttle hook proud of the deck, they were moved from the RAF versions fuselage (bicycle) position to rear spar mountings on the wing, thus eliminating the outriggers.

By now the airframe mass of a specialised RN version had outrun available engine landing thrust though several upratings (later development stages) of the BS.100 and even twin Speys were considered. Vertical landing was no longer possible and a low speed aproach (85 knots) arrester hook was fitted. It was obvious that the V/STOL design was being asked to fit into a RN carrier philosophy which did not suit it, and compete with designs in which "the airfield" was built into the ship and not the aircraft. The RN ordered the Spey-Phantom, a conventional design, for their new big carriers.

Twenty years later, these same big carriers have been scrapped to save money and, because the V/STOL concept survived, a ship-borne fixed wing combat force still exists in the Royal Navy in the form of the Sea Harrier and its payload boosting capability, SKI-JUMP.

11.3 The Last 20 Years

Subsequent to the cancellation of the RAF P.1154 after three years of effort, and while the subsonic Harrier was entering RAF service, BAe Kingston continued to pursue solutions to the problems of supersonic V/STOL or short take-off and vertical landing (STOVL) as it was called later. Alternative configuration investigations including multi-engined projects (P.1179 series) and intake hot gas reingestion (HGR) tests all tended to confirm the correctness of SEVT for this purpose. The P.1154-looking P.1185 was the next firm proposal to the RAF (1970). A navalised "P.1185" called the AV-16S (Figure 30) was proposed in a joint study wih McDonnell Douglas for the US Navy (1974), but this eventually lost out to the subsonic AV-8B. Nevertheless, Kingston project studies and model testing have been continuing to take advantage of the advances in conventional powerplant technology which also yield benefits to the STOVL designs. In the last five years (1979-1984) renewed official interest from the RAF and RN has sponsored some of the more detailed model testing and also the fullscale Shoeburyness trials. Of the current SEVT proposals the McDonnell Douglas Model 279-3 can be seen (apart from having a forward tail) to have retained the main features of the original P.1150/P.1154. It still has a high set moderately swept wing, a four nozzle powerplant with side intakes and a bicycle undercarriage and outriggers.

12. HINDSIGHT OVER VECTORED THRUST

12.1 The Harrier Success

The Harrier succeeded because the powerplant and airframe concept was both simple and flexible. The configuration was (and still is) unique, among others which have failed. Its extreme compactness led it to appear to the operator in both size and complication not much more than a V/STOL Skyhawk (A-4). It purposely did not attempt to provide a full load VTO capability and its STO performance was unmatchable (until the larger wing AV-8B). Vertical landing, that is "stop and then land" (Reference 24), was the asset which made the Harrier as at home on ships as on land. Because the engine and its exhaust nozzles are at the aircraft c.g., full-range thrust vectoring in flight with manageable trim changes was possible and found to be a truly vital combat element.

12.2 Mass and Cost Assessments

The P.1127 flew with a 11000 lb thrust Pegasus 2 engine of 5.2 thrust/weight ratio (Figure 31) and basing the calculation of ΔP (relative to the Skyhawk) on the grid VTO mass, a value of 12.6% is obtained. This powerplant increment reduced to 7% (as in Figure 1) when based on the normal STO mass of the Harrier with a much improved thrust/weight ratio (7.0) Pegasus 11 which developed 21500 lb at take-off using a short lift rating and water injection. Fuel and structure mass savings resulted in a net V/STOL allowance (V) of zero. The enchanced STO performance of the AV-8B increased STO mass considerably without a thrust increase, and although the value of ΔP remained at 7%, this time it is relative to the A-7 Corsair II as its nearest conventional counterpart; then the value V goes negative to - 12%, since AV-8B structure and system percentages are much less than A-7.

On the simplified cost basis assumed in Part I, the Harrier cost factor (relative to the Skyhawk) is 2.25, and for the AV-8B has reduced to 1.43, relative to the A-7.

The current (1984) fighters use take-off thrust to weight ratios around unity to give the conventional designs STO and enhanced manoeuvrability. Consequently the extra powerplant thrust required to convert conventional designs to STOVL (V/STOL) has already lessened considerably since the early designs (Part I). As SEVT uses the minimum thrust to weight ratios of any present STOVL concept, it appears likely to produce the lowest value of ΔP and cost (thrust) factor. It remains to be seen whether this stays so when the new designs of Part III progress further.

PART III - PRESENT DAY PROJECTS

13. NEW CONCEPTS

The higher thrust to weight ratio engine for the 1990's (Figure 31) will allow the powerplant slice (%) to be reduced and though this will affect conventional and STOVL aircraft alike, it means more of the aircraft cake is available for experiments with different aerodynamic and structural configurations. The opportunity also exists for more radical (and higher mass fraction) powerplant concepts. Another alternative is to use the lower powerplant mass in established concepts to reduce the overall size of aircraft to perform a given task and so save life cycle costs. All these approaches are being tried in Europe.

The future European conventional fighter whilst retaining thrust to weight ratios of unity or above, is proposing to use these savings in engine mass (and structural mass with composites) to provide even better manoeuvrability via lower wing loadings, and better mission performance with more extensive avionics.

13.1 Present European STOVL Efforts

Mention has already been made of the new UK interest in supersonic fighters with vectored thrust with plenum chamber burning (PCB). British Aerospace has projects which use the promised new engine technology to either:-

(a) reduce the vectored thrust powerplants mass fraction (slice) and hence increase the structural fraction for more adventurous and capable aerodynamic configurations, or

(b) retain the vectored thrust powerplant fraction and because of the smaller engine, in an airframe of reduced size and lower first and life cycle cost. This assumes that lesser performance goals are adequate.

To these projects must be added the new concept investigations of Rolls-Royce mainly (Reference 22) into:-

(a) augmented ejector lift, which unlike the XFV-12A experiment, divorce the control function from the lift provisions.

(b) remotely augmented lift system (RALS), a variant of vectored thrust which places the PCB nozzle(s) well forward of the main engine which is then moved rearwards to its more usual position.

(c) tandem (hybrid) fans which incorporate the variable cycle principle to provide efficient jet lift as well as propulsive force.

13.2 Aerodynamic Possibilities

The latter three concepts have the drawback of requiring a large volume for the powerplant. However they permit some degree of freedom in vertical jet positioning and usually arrange for the high energy propulsion only jet to exhaust at the rear of the design, clear of local structure. The resulting fuselage is long and relatively slender, aerodynamically. Consequently the lifting surfaces have an extensive mounting base and can take a large variety of forms.

The low volume vectored thrust concept, especially in the two poster and tilt nacelle variations, relies on the hot engine exhaust issuing from the aircraft central region in both lift and propulsion modes. Thus slightly radical layouts, like Boeing's (Reference 23) with twin booms, must be adopted or otherwise structural protection employed, as with the P.1154 and the McDonnell 279-3 project (Reference 22). A design which provides freedom from jet interference on surrounding surfaces could have a light structure but a restricted lifting surface geometry and low aerodynamic efficiency in some phases of flight. It really depends upon the design's main roles as to which compromise is adopted.

To summarise, the new STOVL designs aim to match the conventional aircraft's flight performance and hence its aerodynamics, with the expectation that, because take-off thrust to weight ratios are now similar, the V/STOL increments are small and acceptable, bearing in mind the other virtues.

CONCLUSIONS

14. LESSONS FROM EUROPEAN JET LIFT EXPERIENCE

14.1 Lessons from Part I

It was a mistake to design for a full load vertical take-off with the state of jet engine technology existing in the 1960's. (The ballistic rocket succeeded by virtue of its highly energetic exhaust and low powerplant mass). To compete successfully with CTOL designs in this era required short take-off combined with vertical landing only (STOVL). It was then that the mainly powerplant based mass increment (as defined in this paper) could be small enough to be offset by acceptable aerodynamic and fuel load compromises.

14.2 Lessons from Part II

Having decided on STOVL, keep it simple as the vectored thrust Harrier did. To be operational acceptable to the users the jet lift aircraft must appear only marginally more complicated than the design it replaces. To the US marines, the AV-8A Harrier was another A-4 Skyhawk but with deflecting nozzles this time.

14.3 Lessons from Part III

The lessons of Part I and II are in danger of being forgotten in the search for new concepts for the 1990's. The advantages stemming from a smaller powerplant (and structural) fraction possible with the new technologies could be squandered by invoking more complicated jet lift concepts and aerodynamic layouts than are really warranted. If such engineering advances are used to minimise the size of STOVL projects based on tried principles, the cost of future V/STOL may well become as acceptable as the operational virtues are now.

15. ACKNOWLEDGEMENTS

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16. REFERENCES

1. Williams, R.S. — Simplified Aircraft Costs. Future Projects, HSA Limited, Kingston. SPDN 7 (Issue 2), 1977.
2. Anderson, S.B. — Historical Overview of V/STOL Aircraft Technology. Ames Research Centre. AGARD-CP-313, Paper 9, 1981.
3. Bridgman, L. — Jane's All the World's Aircraft - London. 1955-56.
4. Foody, J.J. — Control of VTOL Aircraft. Eighth Anglo-American Aeronautical Conference, London, 1961.
5. HSA Limited — Review of V/STOL Strike Fighter Projects 1956-1967. Project Office, Kingston (unpublished). 1968.
6. Williams, R.S. — Hawker P.1137. An Investigation into Supersonic v Subsonic Capability for the Tactical V/STOL Aircraft. POR 113. Project Office, Kingston. 1959.
7. Biehl, W. — Propulsion System of the VJ 101C VTOL Aircraft - Philosophy and Practical Experience. Munich AGARD-CP-135, Paper 28. 1973.
8. Taylor, R.P. Lander, J.A. — Recent Technology Advances in Thrust Vectoring Systems. General Electric Company. AGARD-CP-135, Paper 9. 1973.
9. Griffith, A.A. — A Narrow Delta Jet Lift Supersonic Transport Cruising at 1500 Knots. Rolls-Royce Limited, Derby. 1959.
10. HSA Limited — Feasibility Study on Supersonic Transports. Appendix 10 and Supplement, VTOL Considerations. Advanced Project Group, Kingston. APG 1000/2305. 1960.

11. Brown, D.G. The Case for V/STOL Aircraft in Short Haul Transportation. HSA Limited, Hatfield. SAE Paper 700333. 1970.

12. HSA Limited AW.681. STOL Military Transport to OR.351. Advanced Project Group, Kingston. APG 1014/0110. 1961.

13. Interavia Forerunner to a Mach 2 VTOL Fighter. September 1963.

14. SAE Journal Article on Mirage IIIV. Pages 60 to 65. November 1964.

15. Weiland, K. The Development and Flight Testing of the Propulsion System of the VAK 191B V/STOL Strike and Reconnaissance Aircraft. VFW-Fokker. Bremen AGARD-CP-135, Paper 32. 1973.

16. Lotz, M.; Bartels, P. Problems of V/STOL Aircraft Connected with the Propulsion System as Experienced on the Do.31 Experimental Transport Aircraft. Dornier. Friedrickshafen. AGARD-CP-135, Paper 30. 1973.

17. Lewis, W.J.; Simpkin, P. Multi-mission STOVL with Vectored Thrust Engines. Rolls-Royce Limited, Filton, Derby. AGARD-CP-313, Paper 18. 1981.

18. Aircraft Engineering Reprint Hawker Siddeley Harrier GR.Mk.1. December 1969.

19. Fozard, J.W. Sea Harrier - The First of the New Wave. R.Ae.S. main lecture reprint - November 1976.

20. Rolls-Royce; British Aerospace Vectored Thrust Jet V/STOL - An Evaluation of the Harrier AV-8A and the Pegasus Engine. Publication TS.3080. Rolls-Royce Limited, Aero Division, Bristol. December 1978.

21. Hooper, R.S. Preliminary Design Aspects of Military Aircraft - Designer's View of Powerplant Problems. HSA Kingston, AGARD-CP-62, Paper 8. September 1969.

22. Lewis, W.J. Preparing for Supersonic V/STOL. The Roll-Royce Magazine, Number 18, Page 12. September 1983.

23. Smith, H.W.; Burnham, R. The Outside has to be Bigger than the Inside. University of Kansas: Boeing Company. AIAA Paper 80-0726. 1980.

24. Farley, J.F. Why Vertical Landing? BAe Kingston/Dunsfold. BAe-KRS-N-301. February 1984.

17. LIST OF FIGURES

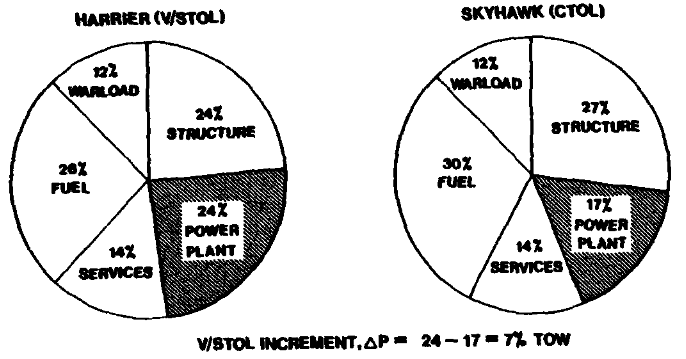


Figure 1 Comparison of Mass Breakdown

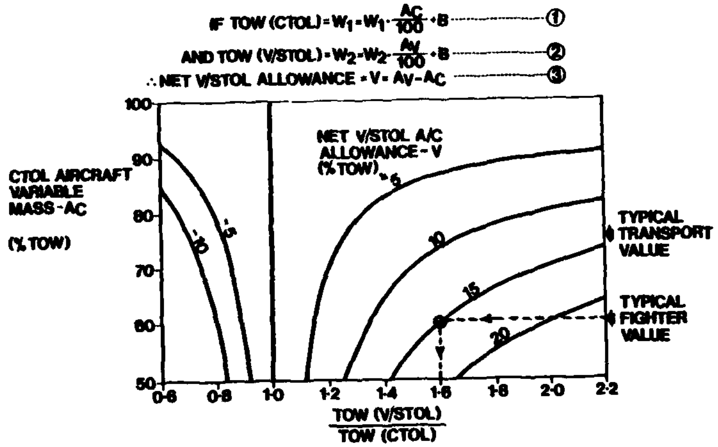


Figure 2 Sizing Parameters

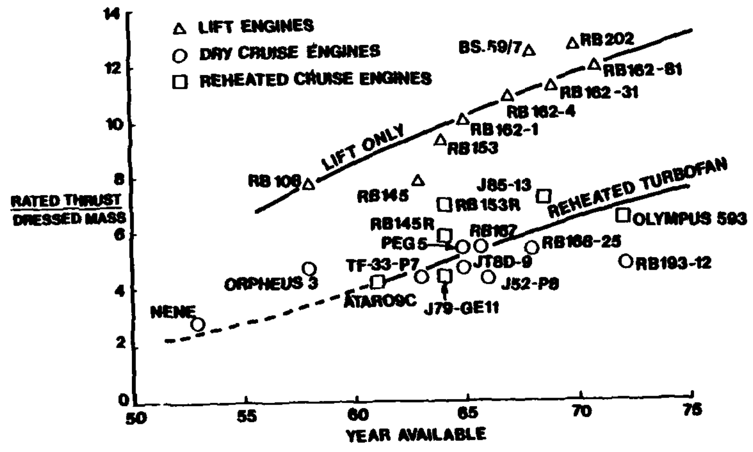
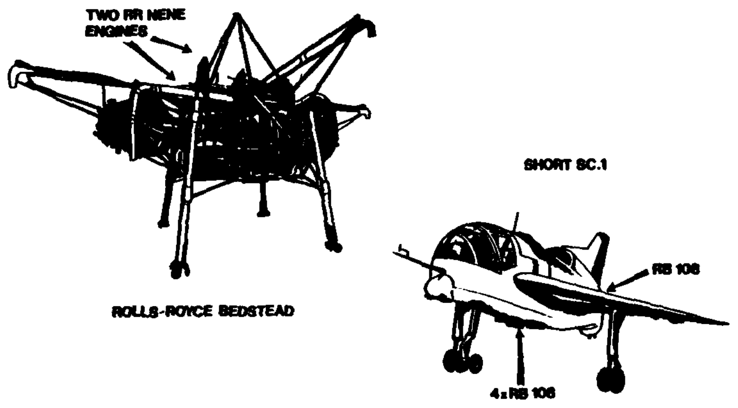


Figure 3 Early Engine Thrust/Weight Ratios



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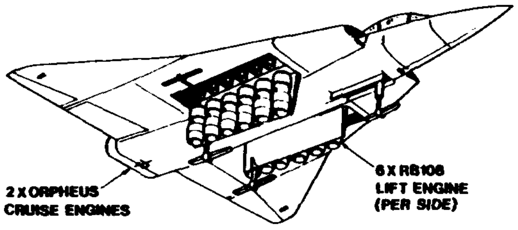
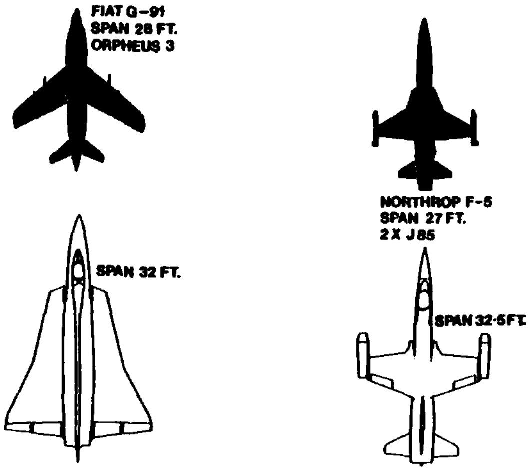


Figure 5 P.1126 Subsonic VTOL Fighter



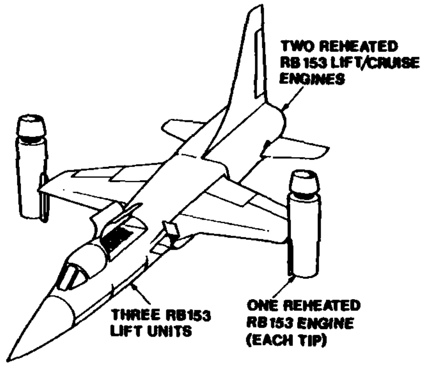
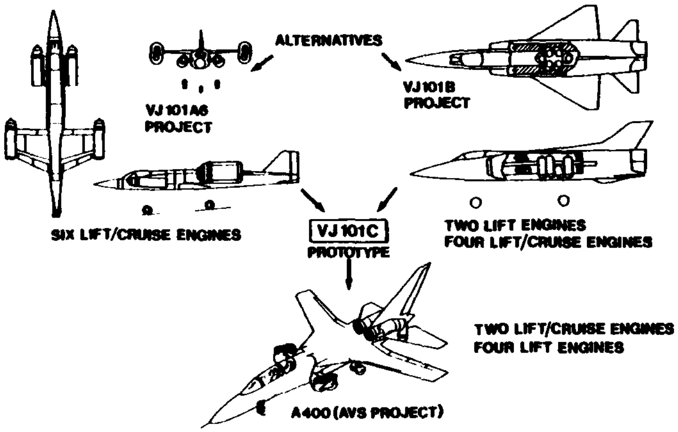


Figure 6 P.1137 Supersonic VTOL Fighter



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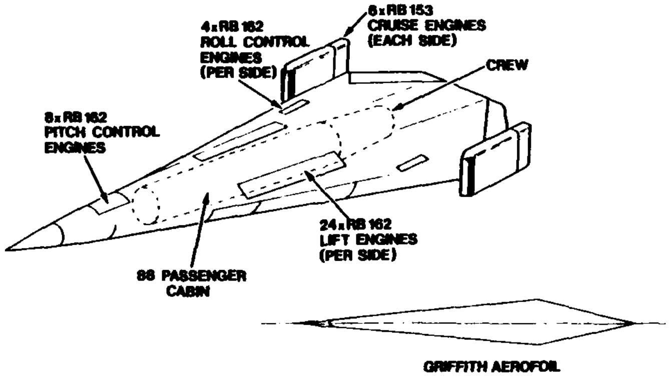
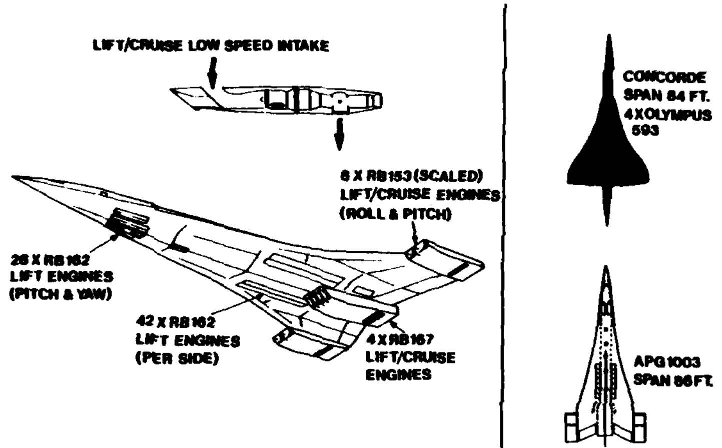


Figure 8 Griffith Supersonic Airliner



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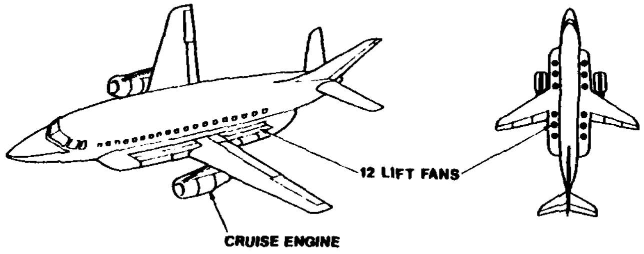

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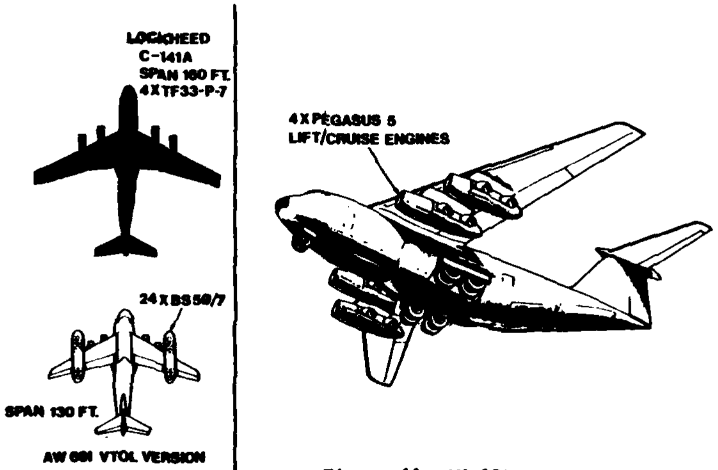

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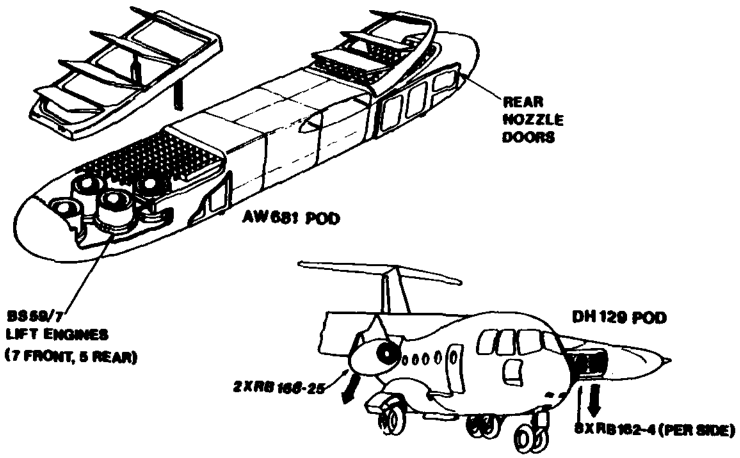

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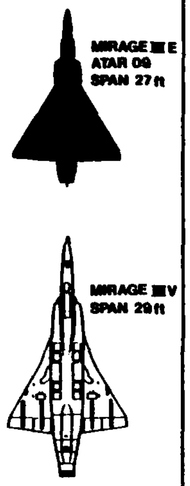


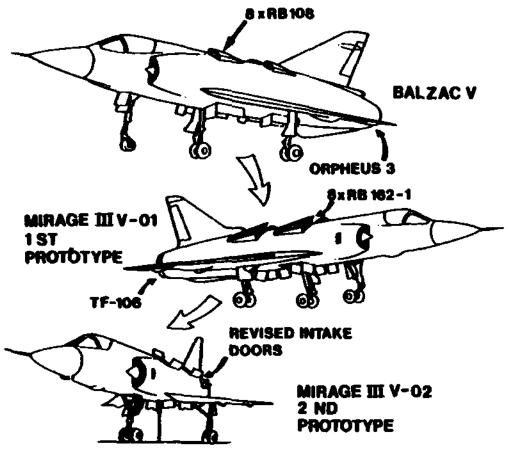


Figure 13 Mirage III V

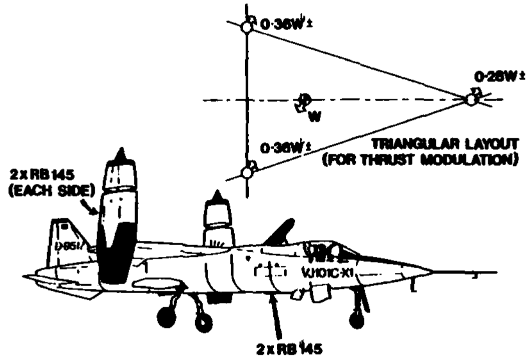
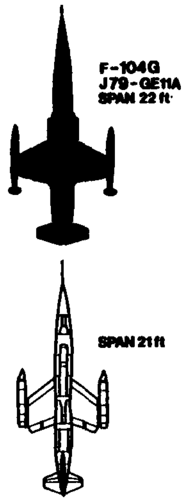


Figure 14 EWR VJ 101C Supersonic Fighter



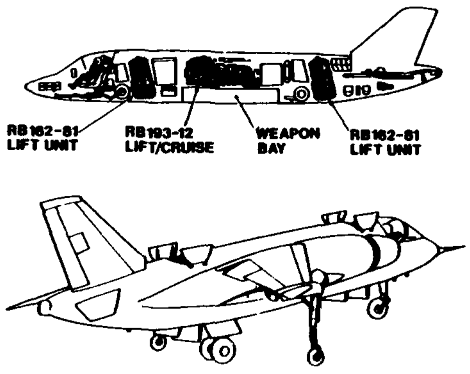


Figure 15 VAK 191B Subsonic Fighter

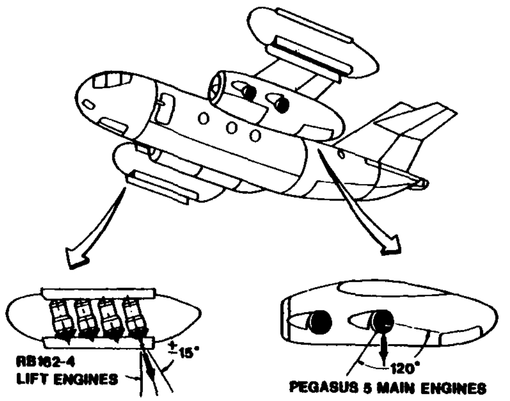
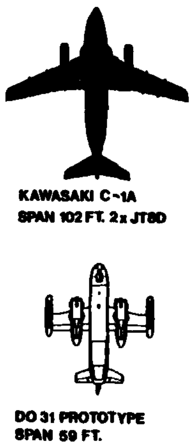


Figure 16 Dornier Do31. Experimental Transport



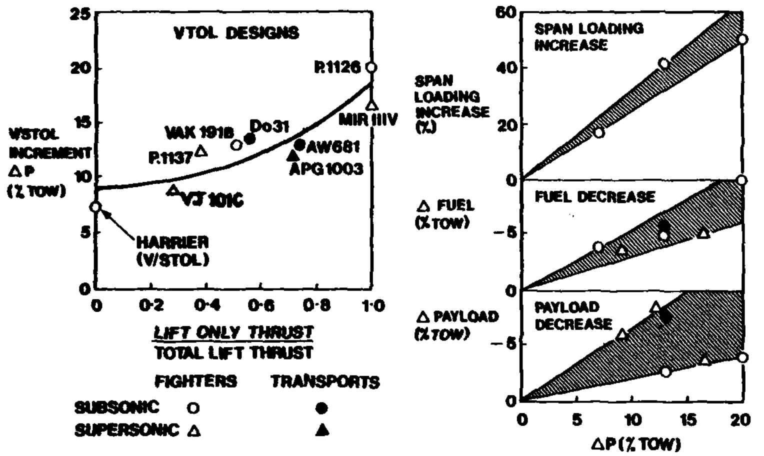


Figure 17 Early V/STOL Design Options

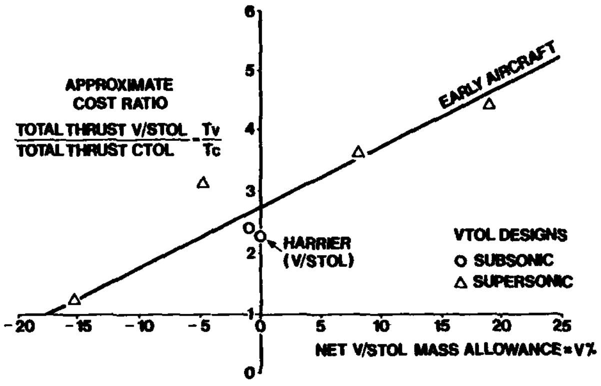


Figure 18 Early V/STOL Costs

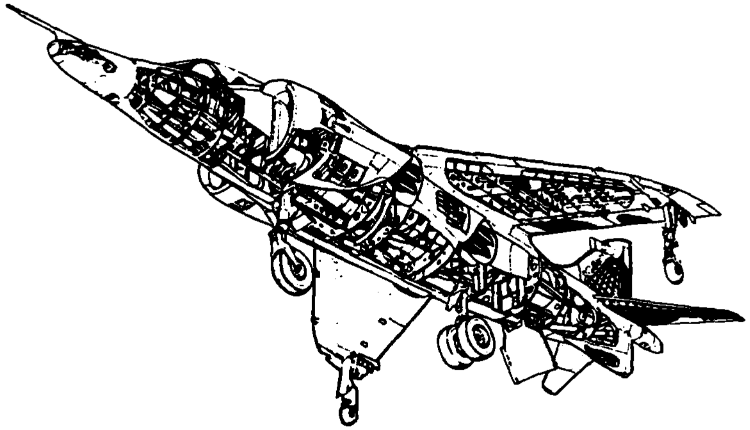


Figure 19 Harrier Cut-away

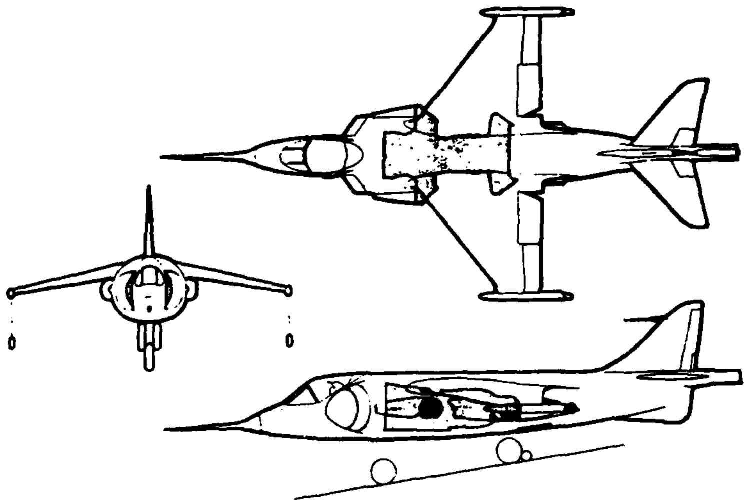


Figure 20 P.1127 Prototype

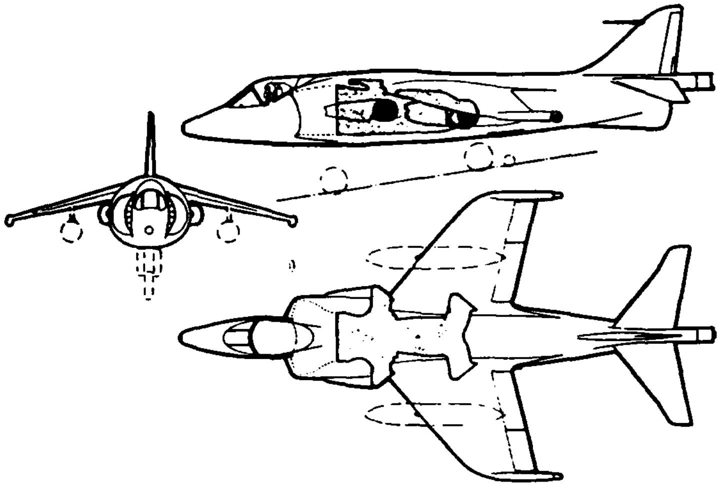


Figure 21 Kestrel - Tripartite Squadron

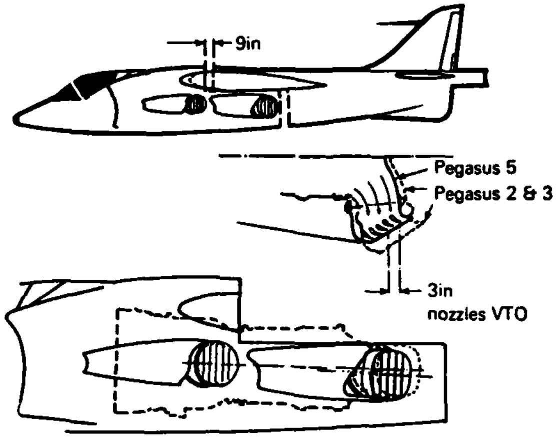


Figure 22 Fuselage Insert

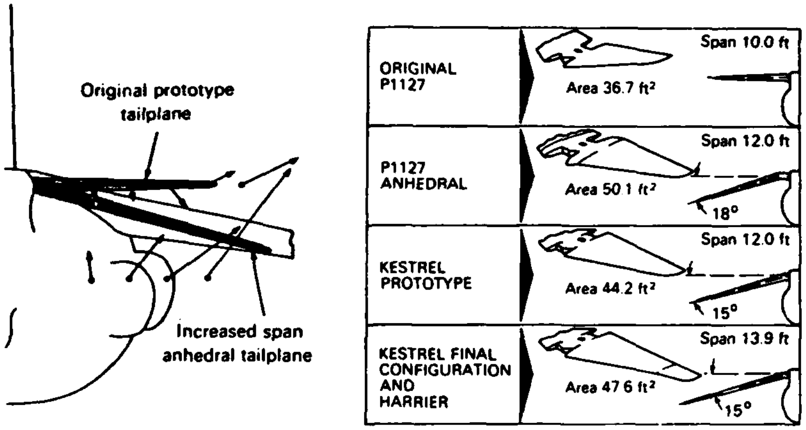


Figure 23 Tailplane Development

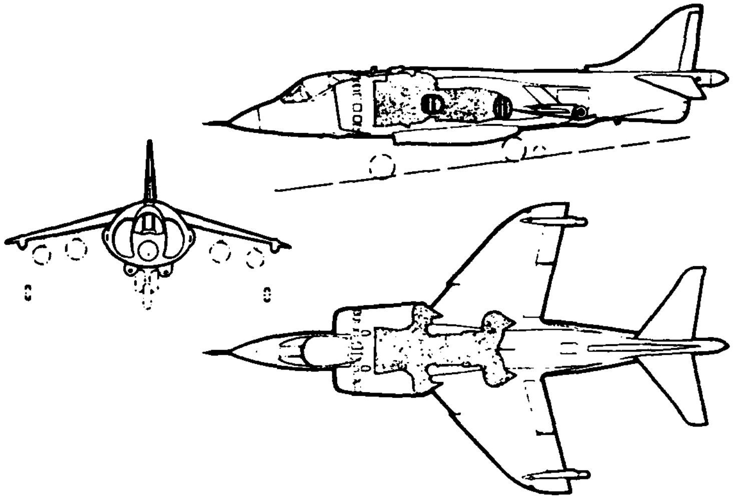


Figure 24 Harrier GR.Mk.1

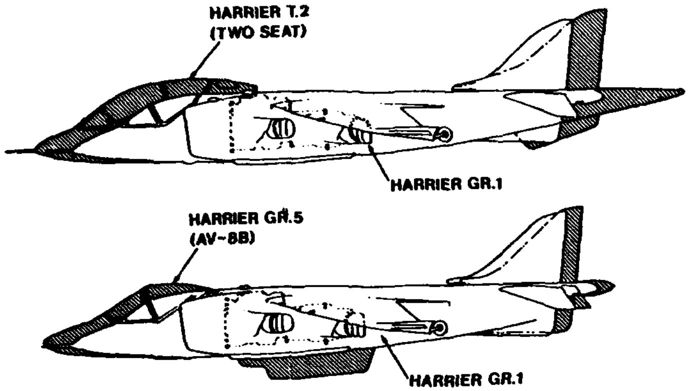


Figure 25 Alternative Fuselage Stretch Methods

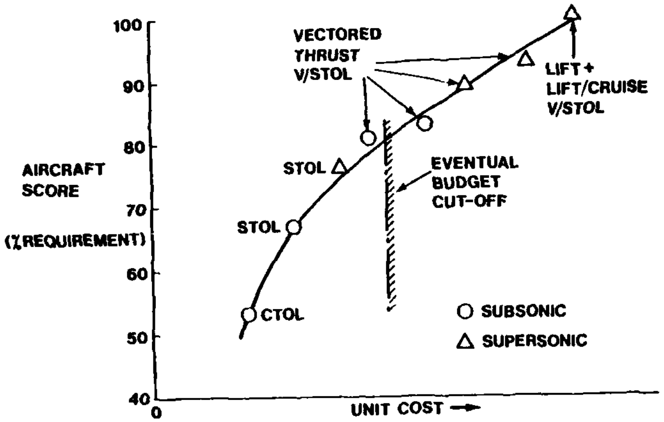


Figure 26 Fighter Project Cost Comparison

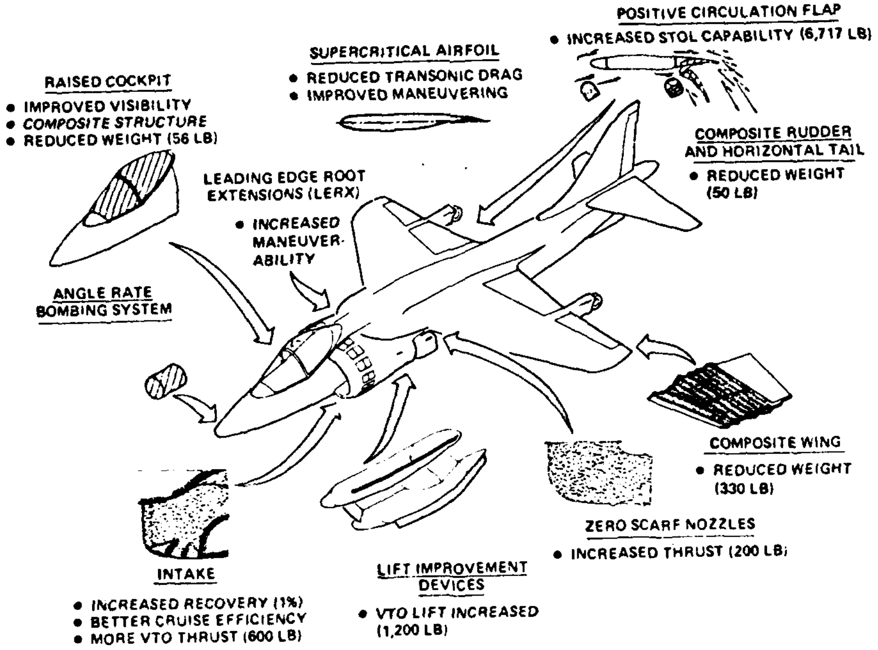


Figure 27 AV-8B Harrier II

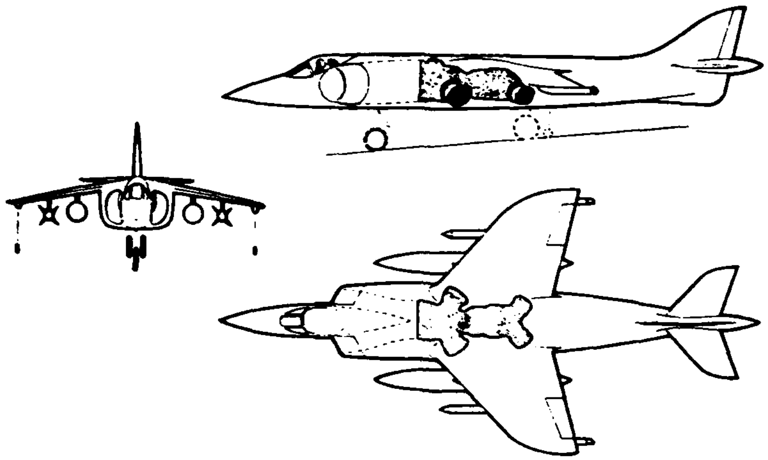


Figure 28 P.1150 Project

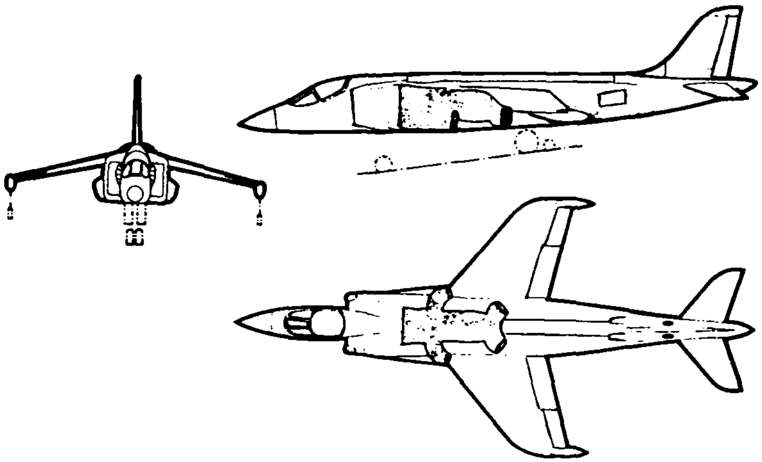
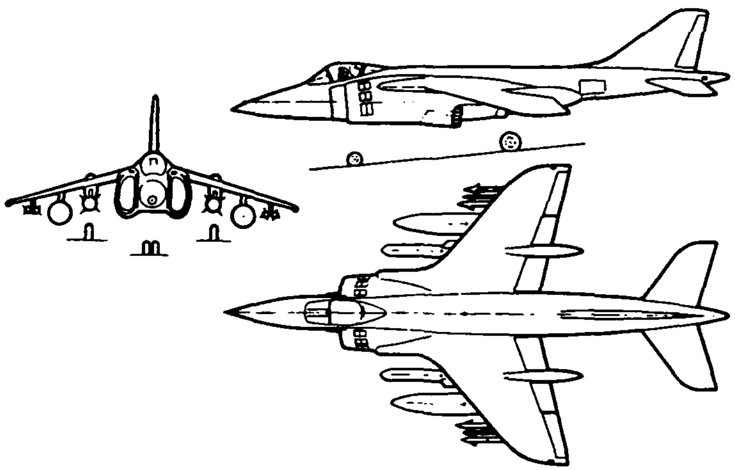


Figure 29 P.1154(RAF) Prototype



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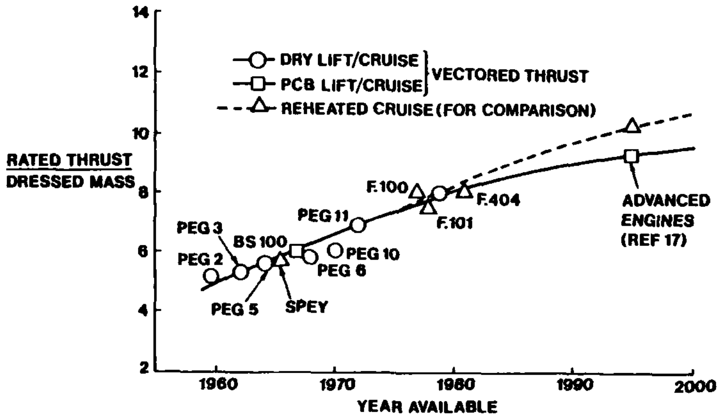

Figure 31 Vectored Thrust Engine Progress

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14. Abstract

In the Special Course on V/STOL Aerodynamics presented on 14—18 May 1984 at the von Kármán Institute, Belgium, and on 4—8 June 1984 at the NASA Ames Research Center, published in AGARD Report No.710 it had been intended to include a review of layout considerations for European jet lift V/STOL aircraft. Unfortunately, the author of this review, Mr R.S.Williams (British Aerospace, Kingston upon Thames, UK) was unable to participate in the course. His paper was completed, however, and is published in this Addendum. It can be regarded as an extra lecture associated with the Special Course.

Mr Williams is a senior project engineer who has been at the heart of V/STOL since its inception. His paper gives a view of the subject, therefore, which is based upon an unusually lengthy experience, and sheds light on assessments of weight and cost factors which are of particular interest.

This publication has been prepared for the Fluid Dynamics Panel of AGARD.

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Advisory Group for Aerospace Research and Development, NATO
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