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V/STOL COMBAT AIRCRAFT PROGRESS FROM THE POWERPLANT VIEWPOINT

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ABSTRACT

After more than 20 years of research and development there is still only one operational jet V/STOL Combat Aircraft in the Western world. Many different and complex systems were designed and tested in the 1950's and 1960's and many lessons were learned. However, the advances in technology since that period of activity are such as to make it possible to design aircraft of greatly increased capability. Consequently a resurgence of interest is evident in new project designs for both sea based and land based use. This paper reviews the evolution of Jet V/STOL, outlines possibilities for future military applications and summarises some of the basic lessons learned.

1. INTRODUCTION

Jet lift V/STOL, in many experimental forms, has been with us since the early 1950's. Its practicability rests on the high and increasing thrust/weight ratio of the gas turbine powerplant. Many jet lift powerplant configurations proved their capability to achieve VTOL but fewer have shown flexibility to exploit both STOL and VTOL.

The rate of advance in jet lift technology appeared high in the 50's and 60's and promised to spawn a multiplicity of combat and transport aircraft types. However, by the early 70's this interest had largely disappeared. Some reasons for this change may well have been:

1. Operational capabilities and roles for these aircraft were not properly established in the early days.

2. The apparent penalty of jet V/STOL seemed too great when CTOL technology was advancing rapidly. (Note aircraft $T/W < 1$ then for combat).

3. Complex propulsion airframe integration problems of jet/lift aircraft deterred many design teams and procurement agencies.

In retrospect it seems the initial high level of interest was the natural 'let's explore', opportunist response to a potentially attractive new concept. As the lessons were learnt this was bound to wane leaving us with a few survivors and many "also rans".

Only two jet lift aircraft, the Harrier/AV8A and the YAK 36 have gone forward to operational service. The latter is believed to be limited to VTOL whereas the former is a highly versatile V/STOL aircraft.

The Harrier has revealed much of the potential of V/STOL during its ten years of service operation and it now stands poised for major improvement with the Sea Harrier entering service and the YAV-8B showing greatly enhanced V/STOL capability with the standard Pegasus engine.

On the other hand the V/STOL transport would play supporting roles in the military field which can already be carried out with severe performance limitations by helicopters. Its main attractions would be higher speed and longer range. It is perhaps significant that the only jet lift transport aircraft so far flown, the D.O. 31, was powered by Pegasus engines as used in the Harrier, plus additional lift engines.

In the civil aviation field, the Jet V/STOL transport, after extensive study, has been dismissed as being too costly a system for the mass travel market and impracticable for City Centre operation on any reasonable scale. The STOL aircraft has achieved some limited success in special situations.

This paper will therefore consider the military Jet V/STOL scene in more detail and attempt to identify some of the lessons learned in:-

(a) the experimental V/STOL activities

(b) the operational V/STOL use of the Harrier/AV8A as seen from the powerplant viewpoint.

To set the scene the paper includes a short historical review.

2. BRIEF REVIEW OF JET LIFT EVOLUTION

Jet lift V/STOL categorises systems in which lift is obtained from the exhaust of turbojet or turbofan engines either directly, or via some form of augmentation system. This can be taken to include systems with all the engine elements combined in single power units, and systems in which the elements are connected but not necessarily close together e.g. remote fans, burners, etc. In general terms it means high specific thrust (or high disc loading) ducted systems based on gas turbine technology, as distinct from open propeller or rotating wing technology. Figure 1 illustrates the magnitude of this distinction. A wide variety of different jet lift systems is possible - indeed diversity has been a feature of the V/STOL scene from its beginnings right up to the present time. Figure 2 classifies the main alternatives.

Jet lift was conceived almost as soon as the jet engine itself had been born. In the U.K. it was considered as early as 1941, and exploratory development was well underway in the U.K. and U.S. by the late '40's.

The 1950's was essentially a period of experimentation. Many lessons had to be learned to achieve controlled jet-borne hover and transitional flight and a number of different rigs and prototype aircraft were built and flown to explore this new flight regime as shown in Figure 3. The earliest of these were powered by existing R.R. jet engines such as the Nene (Flying Bedstead), Avon (Ryan X.13 Vertijet), and Viper (Bell X.14). However the later aircraft were conceived around specialised jet lift powerplants then being developed. These were the RB108 lightweight lift engine (Short SC1) and the R.R. Pegasus vectored thrust turbofan (Hawker P 1127).

During the 1960's effort was directed much more towards practical applications and a number of aircraft with operational potential were built and flown. In Europe there were developments of both the separate lift engine and the vectored thrust lift/cruise approaches notably the EWR/Sud VJ 101 supersonic interceptor, the Dassault Mirage IIIV and Hawker P.1154 Supersonic strike aircraft and the Hawker Harrier and VFW-Fokker VAK 191B subsonic strike aircraft. In the U.S. two types of augmented jet lift powerplant were investigated, namely ejectors (Lockheed XV4A 'Humming Bird') and tip driven lift fans (Ryan XV5A). The continuing development of jet lift propulsion systems was a vital factor during this phase, some highlights being as follows:-

- <u>Lightweight lift engine</u> - thrust/weight ratio improved from about 9 (RB108) to a demonstrated value of 20 (RR/Allison XJ99),

- <u>Vectored thrust turbofan</u> - first generation Pegasus take-off thrust improved from 9000lb. to 21500 lb. for same size and 60% weight increase,

- <u>Augmented vectored thrust turbofan</u> - B.S.100 engine with fan exhaust burning (Plenum Chamber Burning) demonstrated for supersonic P.1154 aircraft at over 30000 lb. thrust with a thrust/weight ratio of 7.

Without doubt, the most far reaching consequence of the 60's was the development of just one jet lift aircraft, the vectored thrust Harrier, to operational status. In addition to being a highly sucessful low level strike aircraft, this has provided:

- Unique experience of the jet lift V/STOL aircraft development task, from concept to deployment,

- An opportunity for the armed services to assess the real capabilities and military worth of jet V/STOL combat aircraft.

The 1970's can be characterised as a period of consolidation. There have been no radical new developments in terms of aircraft or propulsion hardware, apart from the Russian YAK 36 Forger. On the other hand, intensive trials of the Harrier/AV8A by the RAF and the U.S. Marine Corps have provided very convincing proof of the value and practicability of V/STOL combat aircraft in the Close Air Support role from both land and sea bases;

Harrier service experience is shown on Figure 4 starting in 1969 with its introduction into service with the Royal Air Force and followed in 1971 with the U.S. Marine Corps. The aircraft has proved itself in dispersed site operations and has demonstrated a unique capability to fly large numbers of sorties per day. As experience has built up, new operational concepts have been developed and the aircraft has been shown to possess additional capabilities such as vectoring in forward flight (VIFF) which is a major factor in improving the aircraft performance in turning combat.

In addition there has been considerable investment in developments of the Harrier/AV8A aircraft to provide improved payload/range performance, greater fighter agility etc. It now seems likely that improved versions, such as the AV8B, will be deployed in the 1980's.

Another important feature of the 1970's has been the study activity devoted to assessing:

- the long term need for jet lift V/STOL combat aircraft in various supersonic and subsonic roles,

- the requirements such aircraft should aim to meet,

- the capabilities and problems of various jet lift propulsion concepts.

In the U.K. this effort has, in the main, been focussed on supersonic fighter aircraft with advanced lift/cruise powerplants such as the 'plenum chamber burner' augmented vectored thrust turbofan. Developments of this engine type with take off thrust to weight ratios up to 11 have been proposed, and considerable research has been done on the installational problems of very hot exhaust jets and on the supersonic drag of vectored thrust powerplants. Development work on the plenum chamber burner boost system has also been resumed recently.

In the U.S., studies on a wide range of different jet lift combat aircraft have been carried out, particularly by the U.S. Navy who have a strong interest in jet V/STOL.

It should be noted that the smaller Navies now have a big interest in jet V/STOL, and Spain already operates Harriers (Matador).

The overall gestation period for jet V/STOL has been long. In part this must be due to the dilemma which faces military planners. If they conclude that V/STOL is essential for, say, reasons of airfield destruction or denial, then they rule out the CTOL option and hence are vulnerable to the possibility that the V/STOL aircraft may have combat characteristics significantly inferior to those of a CTOL opposing airforce.

As the USA and the UK pause to review their experience with the Harrier/AV8A before deciding whether to proceed further with aircraft such as the AV8B, the important questions being debated are:-

1. Is V/STOL to remain a relatively minor activity associated with close air support?

2. Is supersonic V/STOL a practical concept with little penalty relative to CTOL?

3. Will the major Navies move towards the smaller V/STOL Carrier concept?

3. THE OPERATIONAL NEED FOR V/STOL

The fact that the majority of the Air Forces of the World have not hastened to adopt V/STOL aircraft can be attributed in part to the widely held view that V/STOL capabilities are accompanied by unacceptable penalties in cost and performance.

The implication in much of this thinking is that the comparison must be made between the VTOL load carrying performance of the V/STOL aircraft and that of the CTOL aircraft operating from normal runways. The proper comparisons surely should be on a basis of operational capability from a given field length, the vertical take-off case being an extreme which is not open to the CTOL aircraft.

A flexible V/STOL aircraft such as the Harrier always has a greatly enhanced payload capacity when operated in the STO mode. In comparison with aircraft of similar gross weight, the V/STOL aircraft will generally show a superior performance, particularly for the shorter air field performance considered desirable, if not essential, in a wartime situation. This is illustrated in Figure 5. This would seem to show that it is the CTOL aircraft which has the performance penalty.

For land based air forces, the short or zero runway capabilities of a V/STOL aircraft can provide:-

1. Dispersal to small improvised sites not subject to so great a threat as permanent air fields.

2. Mobile forward basing giving rapid-response support for ground forces.

3. Greater flexibility in the use of small satellite air fields.

4. Ability to operate or air-taxi from damaged air fields denied to CTOL aircraft.

It is now being realised gradually that these advantages can be provided with little weight, cost, or performance penalty for both low-level-strike aircraft and high-agility combat aircraft.

The world's Navies are facing a different kind of runway 'denial' threat. The cost of large aircraft carriers with catapults and arrester gear for the launch and recovery of CTOL aircraft is now beyond the financial resources of most nations. Consequently smaller, simpler, aircraft carriers which can operate V/STOL aircraft and helicopters are being adopted by many Navies, and may well become an important part of the U.S. Navy inventory.

An important feature of these smaller V/STOL carriers will be the "ski-jump" ramp which imparts a semi-ballistic initial flight path to the aircraft and which is probably as significant an advance as was the steam catapult.

Some particular advantages which V/STOL provides for Naval aviation are:-

1. Short take-off augmented by the ski-jump.

2. Vertical landing with no requirement for arrester gear.

3. No need for wind over the deck.

4. Ability to operate in conjunction with CTOL aircraft from large carriers and to provide additional capability in the process e.g., increased mission rates.

5. Ability to operate from helicopter platforms on small ships.

The U.S. Navy with its immense experience of large nuclear carriers is poised to decide whether:-

(a) it changes to V/STOL carriers for future procurement, with a mixed force during a transitional period

(b) it operates with a mix of conventional and V/STOL carriers as a long term policy

(c) it retains the conventional carrier for the foreseeable future.

The option to use V/STOL aircraft on any conventional carrier is always available and can provide worthwhile operating advantages.

The smaller navies of the world have little or no option but to procure V/STOL aircraft if they wish to provide or continue with naval aviation. Hence they have pioneered the operational development of naval V/STOL, the Spanish Navy with their Matador version of the Harrier being first in the field, while the Royal Navy has acquired the first purpose built V/STOL carrier in the Western World from which it is now operating the newly developed Sea Harrier. The Russian Navy, with little background of naval aviation, has commissioned Kiev class V/STOL carriers operating the YAK.36.

In pioneering the V/STOL carrier the smaller Navies have, of necessity, had to acquire an existing aircraft design to prove the concept. This is because they require relatively small numbers of aircraft. Having established the concept of the V/STOL carrier force they are likely to want, and to have, a more important voice in the future procurement of new V/STOL designs in spite of the limited numbers in individual navies.

Figure 6 illustrates the length of time for V/STOL to establish itself in the Naval role. While this is frustrating to the Airframe and Engine Designer, it must be remembered that it has required a major re-casting of Naval strategy and the reversal of major political decisions to bring this about.

4. FUTURE OPERATIONAL TRENDS

The concept of V/STOL operations from dispersed or damaged bases carries with it the implication that a wide range of tactical V/STOL aircraft types could be required, ranging from high performance combat aircraft for doing the fighting, to utility transport aircraft for providing support.

Consequently Jet V/STOL has been considered for most aircraft types and missions at various times. However, as a result of the understanding gained from such studies and from the operational development of the Harrier/AV8A weapon system, the future roles and requirements for jet V/STOL military aircraft are gradually being rationalised around two or three distinct types.

For land based operations the main virtue of V/STOL is that it allows combat aircraft to be dispersed to small sites well concealed from the enemy or to be operated from damaged main bases. In this situation, and particularly for the forward bases of close air support operations this implies ground transportation rather than V/STOL support aircraft which would reveal the activity. Since the other air transport needs are likely to be met with conventional aircraft, the air forces of the world are now interested in jet V/STOL primarily for subsonic (or supersonic) fighter aircraft.

At sea the primary issue is operating flexibility and reduced complexity, not concealment. Jet V/STOL is a means of providing flexibility by reason of its simpler take-off and landing characteristics. For this reason it is being actively studied for a range of Naval air roles, particularly in the U.S. Examples are:-

- Fighter/attack
- Airborne early warning patrol
- Anti-submarine warfare
- Fleet defence missileer/targeter
- Cargo/personnel transport.

This probably means two or three distinct classes of jet V/STOL aircraft, e.g., supersonic and subsonic fighter/attack aircraft, and a subsonic multi-mission aircraft for the other roles.

Although the development of V/STOL fighter aircraft is likely to be dominated by developments of the transonic Harrier/AV8A for some time to come, there is little doubt that a Supersonic V/STOL fighter will be required in the longer term future (circa. 2000). In particular this is a Navy requirement where fleet defence missions call for quick response and the ability to engage high speed threats.

Land based air force operations do not have the same imperative requirement for a supersonic capability and could use the subsonic V/STOL aircraft in the attack role while using CTOL aircraft for air defence and air superiority. However, V/STOL aircraft with combined attack and air superiority roles are being proposed; this implies high thrusts and a supersonic capability which could be very advantageous in a situation where CTOL aircraft mainbase runways are rendered unusable.

Finally, it is appropriate to comment on some other factors of an operational nature which may affect the design of jet V/STOL aircraft:-

- V/STOL operation - the most important characteristics of jet lift combat aircraft, highlighted by land and sea operating experience, are their ability to land vertically, and to perform short take-offs with large warloads (Figure 5). This mode of operation, known as STOVL, seems likely to be used for most missions. Important exceptions would be 'air-taxi' movements on damaged air fields, and take-offs from ships with small flight pads. It is emphasised that Jet lift aircraft vary in their STO capabilities; vectored thrust aircraft have excellent STO performance whereas tailsitter (or VATOL) aircraft have no STO abilities.

- VIFF - the use of thrust vectoring in forward flight has given the Harrier/AV8A aircraft a powerful combat manoeuvre enhancement capability which could feature in future aircraft requirements.

- Ground/deck 'footprint' - any constraint on lift jet temperature or velocity to protect surfaces, personnel, or equipment could influence the choice of propulsion system. This has not proved to be a significant constraint on Harrier operation to date.

- Engine failure - insistence on multiple engines and on 'engine failed' vertical landing capability makes the aircraft very large and heavy. The present trend is to disregard such requirements for fighter aircraft at least.

- Reliability and maintainability - the essence of V/STOL, particularly for close air support, is high mission rates and deployment to bases with minimum repair facilities, hence a high level of 'R & M' is essential.

- Operating costs - the use of engines already in the inventory can help to reduce operating costs; this could influence future propulsion design choices in a cost sensitive procurement environment.

- Durability and survivability - these are important issues which are markedly influenced by combat thrust/weight ratio and the use of exhaust burning boost systems. The unboosted Harrier type of configuration has favourable characteristics in this respect because of its low temperature exhausts and long endurance in turning combat and so may prove to be complementary to a supersonic V/STOL fighter rather than being just its predecessor.

5. FUTURE JET V/STOL PROPULSION TRENDS

From the previous section it will be seen that two new basic types of jet V/STOL aircraft are currently envisaged for future military applications viz.

- high performance combat aircraft with Supersonic capability

- utility multi-mission aircraft.

These are quite distinct types with significantly different propulsion requirements. In the case of the combat aircraft the emphasis is on high speeds and manoeuvrability, consequently a compact, high specific thrust, powerplant similar to CTOL fighter practice is required, and typically this means engine by-pass ratios around 1.0 and exhaust burning thrust boost systems. In the case of the multi-mission aircraft the emphasis will be on minimising the installed power needed for V/STOL consequently a low specific thrust powerplant is implied. Since a good high subsonic speed performance must also be maintained the fan cannot be too large and by-pass ratios up to about 10 have formed the basis for a number of project designs.

Fighters

The conventional supersonic combat aircraft which will be added to service inventories in the next two or three decades are likely to have sea level static thrust/weight ratios greater than unity. Hence the ability to rise vertically should not imply a significant fundamental performance compromise or penalty relative to CTOL aircraft, provided that a practical, low weight means of deploying the thrust in a vertical direction can be achieved. The most prominent ways of doing this proposed for fighter aircraft in recent times are shown in Figure 7 and described below:

- Vectored thrust: In this case all the engine thrust, including boosts, can be deflected downward rapidly by vectoring nozzles grouped around the aircraft C.G. Particular merits of this system are that it provides excellent STO acceleration performance, and thrust can be vectored in forward flight. It is also a very simple-to-manage system with 'graceful' transition characteristics.

- Lift plus Lift Cruise: In this case the thrust of one or more conventional propulsion powerplants is deflected downwards by vectoring nozzles aft of the aircraft C.G., while lightweight lift engines ahead of the C.G. provide a balancing lift thrust. In theory this is a good way to power aircraft in which VTO thrust requirements are dominant although it is complex and the STO range/payload performance is less than the maximum achievable.

- Remote Augmented Lift System (RALS): This is similar in layout to Lift plus Lift/Cruise but the lightweight lift engines are replaced by a lift jet supplied with air ducted forward from the main engine via a burner augmentation system. The advantage over Lift plus Lift/Cruise is that only one engine type is needed.

Other systems which have been considered but which have yet to make a big impact are:

- Tailsitters: In this case a largely conventional aircraft is set on its tail against a special vertical 'platform' from which it can operate in a VTOL mode. Though the aircraft is relatively simple and light its dependence on the platform installation and the absence of any STO capability appear to be major limitations.

- Ejectors: Here the objective is lift thrust augmentation by aerodynamic means instead of exhaust burning. A particular merit would be its low velocity and temperature ground footprint. However, practical fighter-type designs have yet to be demonstrated.

- Rotating engine Lift/Cruise: In this case the propulsion engines would be rotatable in pods to provide vertical thrust. This approach was used on the VJ101C experimental fighter and modern versions have been proposed. Some demonstrator activity has been announced in the U.S.

The boost system evolved over the past 20 years in conjunction with vectored thrust, known as Plenum Chamber Burning or 'P.C.B.', uses Ramjet design technology to achieve combustion in the cool air of the fan exhaust ducts. This is illustrated in Figure 8. Since the amount of take-off thrust is generally fixed by the take-off weight of a V/STOL aircraft, the main reasons for adopting a boost system are to:-

1. Increase the thrust per lb. of airflow and hence reduce aircraft cross sectional area and drag

2. Improve the thrust lapse rate with forward speed to increase top speed and combat agility

3. Improve powerplant thrust/weight ratio

4. Reduce the basic engine size for a given maximum thrust and hence improve throttled back economic cruise fuel consumption.

The RALS system may be regarded as a remotely located form of P.C.B.

Quantitative comparisons of the more prominent system options have been made. Figures 9, 10 and 11 show an assessment of Vectored Thrust and Lift plus Lift/Cruise aircraft gross weights (Ref. 1). Figure 9 illustrates the merits of the Lift plus Lift/Cruise approach in a pure strike aeroplane where range/payload and hence an efficiently packaged take-off thrust capability is the dominant requirement. In this case the vectored thrust solution provides propulsion thrust in excess of that required for the mission, though as Harrier has demonstrated this can give the aircraft a useful and desirable self-defence combat capability. However for a supersonic or highly manoeuvrable aircraft where combat thrust is the dominant requirement the boosted vectored thrust solution is very close to being optimum as Figures 10 and 11 show. Very recent comparisons of advanced Augmented Vectored Thrust, Lift plus Lift/Cruise, and RALS solutions sized for a sea based, deck launched, supersonic interception mission have shown that the vectored thrust solution is competitive with the other alternatives and is superior in its STO overload performance as Figures 12 and 13 from Ref.2 show.

Utility Aircraft

Unlike a fighter, a utility aircraft has no requirement for in-flight thrusts that are even comparable with aircraft weight. These aircraft are efficient high lift/drag ratio designs optimised for load carrying and endurance. Consequently the power required to provide a V/STOL capability can be as much as four times what is required for the conventional aircraft, and in cruise the powerplant may be throttled back to less that 10% of its maximum output. In this situation V/STOL is not a relatively simple adaptation of the equivalent CTOL system. Instead it is a major departure from established practice, requiring an aircraft with quite specialised airframe and propulsion characteristics that fits into the spectrum somewhere between traditional fixed wing and rotary wing solutions. It is important to ask, therefore, if the adaptation can best be made from conventional aircraft or from the helicopter. This question is not discussed here but the authors believe it is right that both routes should be studied.

Either way the objective is an elegant system with the following type of capability:-

- vertical and short take-off
- reduced weight vertical landings with one engine stopped
- payloads (including personnel) up to 10000 lb.
- range up to 1000 miles
- speeds up to M = 0.8
- operable from small and large air capable ships

Preliminary studies of fixed wing jet V/STOL aircraft for this role have been carried out in the last few years in response to the U.S. Navy Type 'A' V/STOL requirement issued in 1977. Most of the systems investigated were adaptations of the high by-pass ratio lift fan powerplant concept though a few designs with lower by-pass ratios and ejector augmentation were considered.

The fan systems proposed were generally similar and Figure 14 shows the main recurrent features.

It will be seen that they are complex and mechanically demanding. The requirement to drive all the fans for an emergency vertical landing with one engine stopped is a particularly stringent constraint and although various ingenious power-sharing transmission schemes have been proposed there remains considerable doubt about the ability to engineer a suitably light, high-power capacity system of drives, gearboxes, clutches and cooling equipment with the reliability, survivability, and cost characteristics required for an operational V/STOL aeroplane. It is emphasised that the shaft horsepowers involved are nearly an order of magnitude greater than for helicopters of the same gross weight.

It remains to be seen how the utility jet V/STOL scene will evolve in the future. This will depend very much on the pressure to begin developing such an aircraft within the next few years. However, the authors believe that it is still at a comparatively early stage in its evolution and that the future will bring simpler more practical systems than have appeared previously.

One such system is described in Ref.3. In this case, conventional direct drive, fixed geometry, uncoupled turbo-fans are grouped close to the aircraft centre of gravity. A vectored thrust system is used to provide vertical lift and reaction jets are used for jet borne flight control, including balance in roll in the event of any one engine being inoperative. Thus all the jet borne flight requirements including the difficult emergency landing cases are met without recourse to mechanical complexity and by using proven jet lift aircraft techniques.

Another possible approach is shown in Figure 15. In this case two Pegasus engines are used to provide a vectorable thrust and also to power a wing trailing edge ejector augmentor system which can be deflected downwards for lift thrust, or aft for propulsive thrust. This approach has been demonstrated with partial deflection of the augmentor system by the D.H. Canada/R.R. Spey Buffalo STOL aircraft (Ref.4), and it therefore provides a low risk approach to evolving a jet lift powerplant suitable for a 40000 lb. aircraft. Particular advantages of this system would be:

- excellent STOL performance due to enhanced lift performance of wing
- cruise performance enhanced due to the reduced drag of open cruise augmentor wing
- commonality with the Harrier/AV8A V/STOL fighter/attack aircraft powerplant
- can be kept in balance in the event of an engine failure during V/STOL manoeuvre

As described, this system would not be able to achieve a one-engine inoperative vertical landing.

6. JET V/STOL DESIGN LESSONS

The diverse experimentation with many forms of Jet V/STOL should not be repeated in the process of acquiring the V/STOL aircraft now required both on grounds of cost and further delay. The technologies required are largely demonstrated to a point where few practical options remain and the need is for a limited number of pre-production demonstration aircraft.

The lessons learned from our previous experience should be applied to the choice of such aircraft. In this section some of the more important of these lessons are discussed.

In retrospect the most fundamental lesson to be learned from all the Jet V/STOL activity to date is that the airframe and its powerplant system must be designed together as an entity. This is because the interactions of the airframe and the powerplant are very complex and significant for V/STOL aircraft, and there is a possibility of disastrous performance penalties if such interactions are ignored. Close relationships between the airframe and engine teams are clearly necessary and these are, perhaps, most easily achieved during the research and experimental phases of a project when the performance targets are often flexible; they are certainly vastly more difficult in the later 'committed project' stages, unless the interaction problems have been broadly overcome in a Demonstrator phase. All this requires good management. In particular it requires acceptance that the conventional demarcations between engine and airframe should not apply and that flexibility and innovation are to be encouraged in seeking solutions. The success of the Pegasus/Harrier was largely due to the adoption of this approach.

Some more specific lessons which can be distilled from the experimental and operational V/STOL aircraft experience of the last three decades can be summarised as follows:-

Overall configuration lessons:

1. The amount of extra equipment and complexity required to provide a V/STOL capability should be kept to a minimum.

2. Maximum use should be made of the propulsion powerplant to provide jet lift.

3. All components of the lift thrust should be capable of being vectored aft to maximise STOL performance.

4. The total thrust vector should pass close to the aircraft centre of mass at all times during transitional flight to minimise the control forces required.

5. The inlet momentum drag level and its moment about the aircraft mass centre are important performance parameters.

6. The thrust deflection system should be capable of very rapid operation, i.e. full deflection in less than one second, in order to:

   (a) minimise STO ground run

   (b) minimise damage due to jet blast and heating

   (c) make possible in-flight thrust vectoring for combat maneouvres

7. Jet entrained airflows over the airframe in free-air hover will produce a downwards force, or lift loss, which should be minimised by careful powerplant configuration design and detailed control of the flows over the airframe.

8. Ground proximity effects need to be recognised as a major factor in the design of the airframe and powerplant and its operation. These are:

   (a) hot gas reingestion, which can cause substantial thrust loss and even engine surge if the levels are excessive.

   (b) airframe heating, arising from the circulation of hot exhaust gas around the aircraft during VTOL manoeuvres.

   (c) Lift force variations, notably suck-down effects which mean that lift thrust has to exceed weight by a substantial margin e.g. 20%.

   (d) ground erosion, which can throw up debris damaging to the powerplant if ingested.

   Figures 16 to 20 illustrate these effects.

9. The ability to deflect the lift thrust vector at high speeds as well as at low speeds can enhance combat manoeuvrability. The use of these techniques on the Harrier AV8A has proved very valuable and probably helped to stimulate the strenuous efforts made to achieve similar characteristics on conventional combat aircraft. (e.g. HIMAT and post-stall control).

10. Location of the engine near the aircraft C.G. tends to lead to high levels of inlet and exhaust duct curvature in a single engined aircraft. This can be a source of flow distortion and adverse performance effects.

Basic engine design lessons:

1. The engine fuel system demands special attention because it is a key part of the primary flight control system for V/STOL flight.

2. The engine sensitivity to throttle movements is of particular importance for the same reason as in Item 1.

3. Except where differential throttling is employed, engines must be designed to allow large air bleed flows (10 15%) to be extracted safely for jet borne flight reaction control purposes.

4. The engine rating system must be tailored to the overall thrust requirements, including the provision of very high lift thrusts for short periods of jet borne flight while supplying reaction control bleed and making use of water injection if required.

5. Provision must be made for overriding the lift rating limits in an emergency; also some form of standby reversionary control to cope with primary system failures is of particular importance for a single engined aircraft. In the case of digital systems a high degree of in-built fault tolerance will be required.

6. It is essential to maximise take-off thrust to weight ratio and to provide for continuous thrust growth to match aircraft weight changes.

7. Careful account must be taken of engine life-time thrust degradation in designing a V/STOL powerplant and its rating system in order to maintain its VTOL capability.

8. A philosophy of ruggedness, simplicity and flexibility should be adopted. As far as possible, dependence on automatic control systems and failure detection devices which can mislead should be minimised.

9. It is important to maintain a consistent thrust centre location during major powerplant thrust growth development for both single and multiple engined solutions.

7. CONCLUSIONS

1. Jet V/STOL is now establised and successful in the land based and marine close air support role.

2. Seabased operating experience with jet V/STOL in its subsonic form is now being acquired by several Navies.

3. To fully exploit the jet V/STOL concept the inventory needs to be extended to include supersonic combat aircraft.

4. A subsonic jet V/STOL utility aircraft is a desirable addition to the inventory though some of its duties could probably be performed by rotating wing aircraft.

5. The V/STOL capability for new designs should be achieved by the simplest and cheapest route otherwise the overall objectives of the system are unlikely to be met.

6. The mission requirements for new jet V/STOL aircraft are now identified and the technology is available.

7. As a pre-requisite to production limited demonstrator aircraft programmes should be undertaken.

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2. W.J. Lewis. A comparison of propulsion systems for V/STOL supersonic combat aircraft. SAE Aerospace Meeting, October 1980.

3. E.R. Glasgow R.E. Skarshang. Type A V/STOL propulsion system development. AIAA 79-1287, June 1979.

4. D.G. Whittley The Augmentor Wing: Powered Lift. STOL A Proven Concept INTERAVIA No.2 1974

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POWERED LIFT SYSTEMS

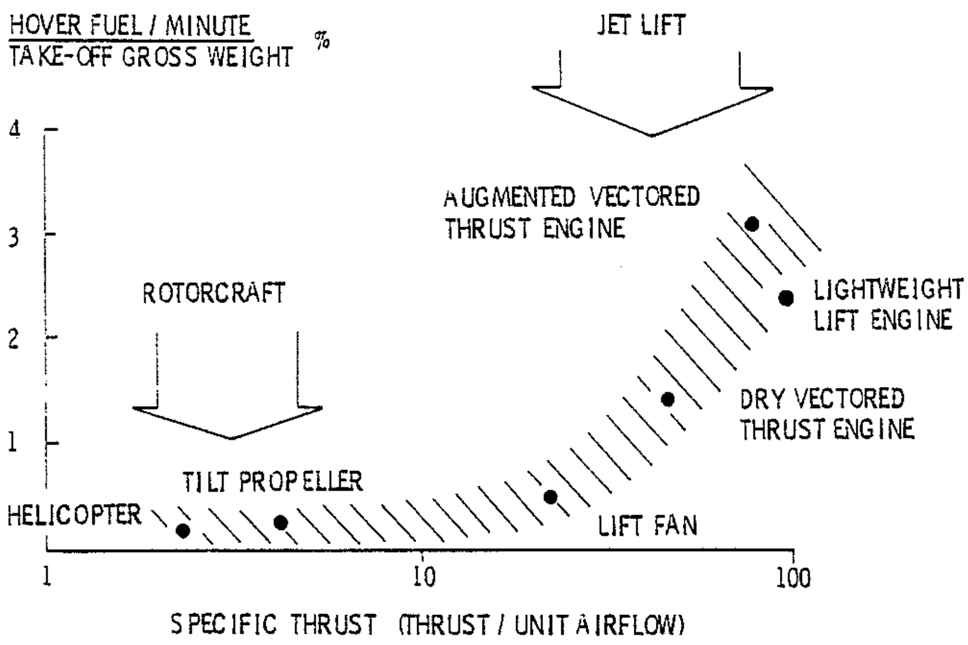
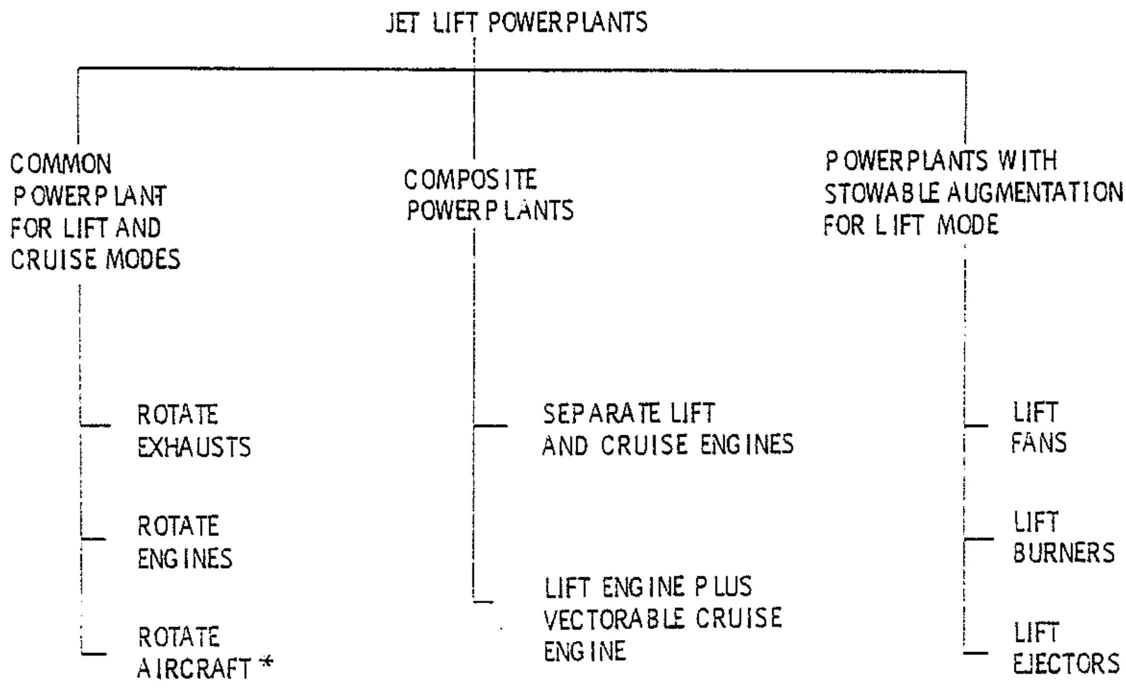


Figure 1

ALTERNATIVE JET LIFT SYSTEMS



* VERTICAL ATTITUDE TAKE-OFF AND LANDING

Figure 2

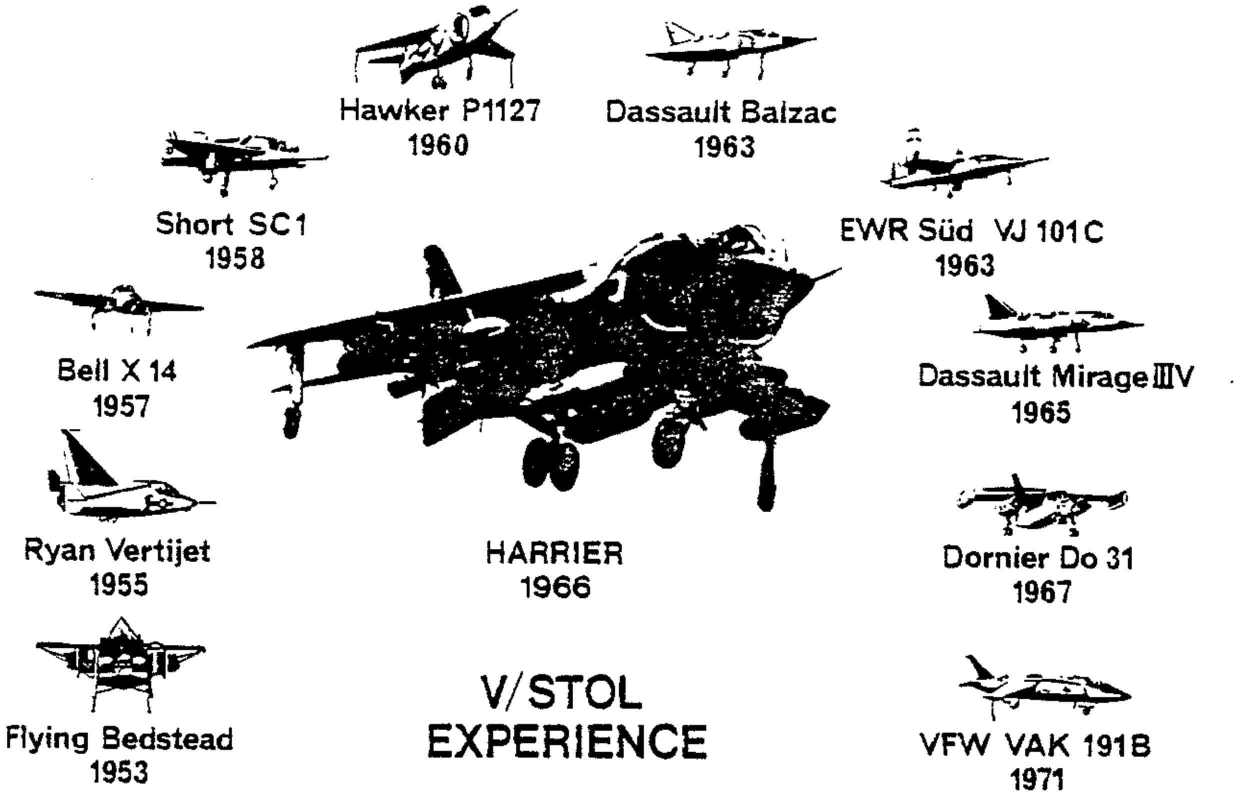
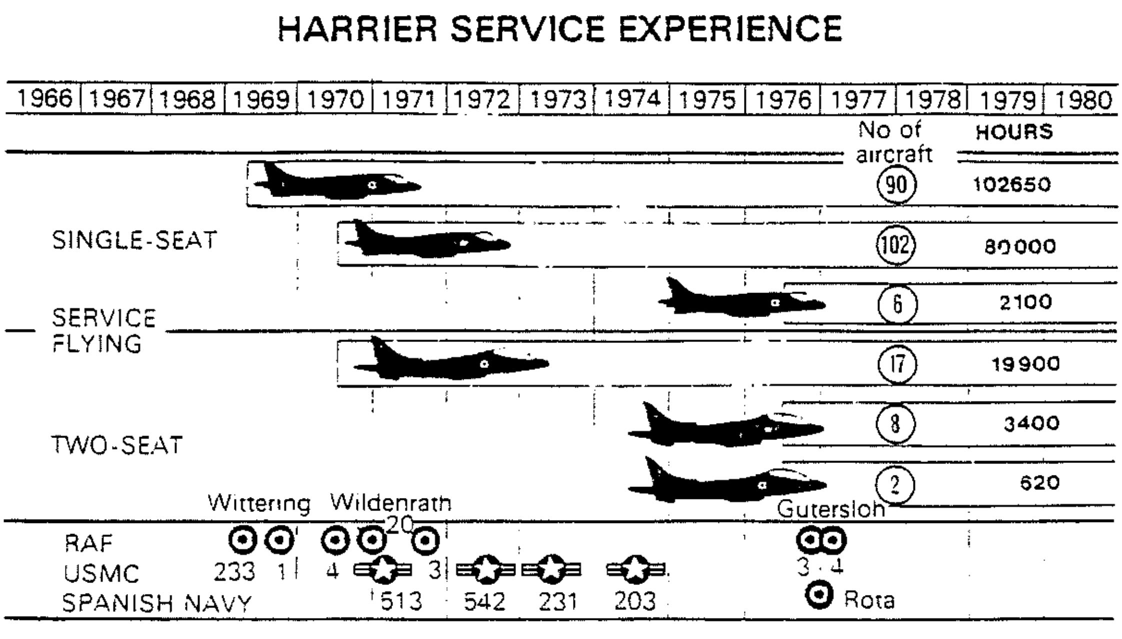


Figure 3



Total service flying—over 200 000 hours

Figure 4

AIRFIELD PERFORMANCE COMPARISON

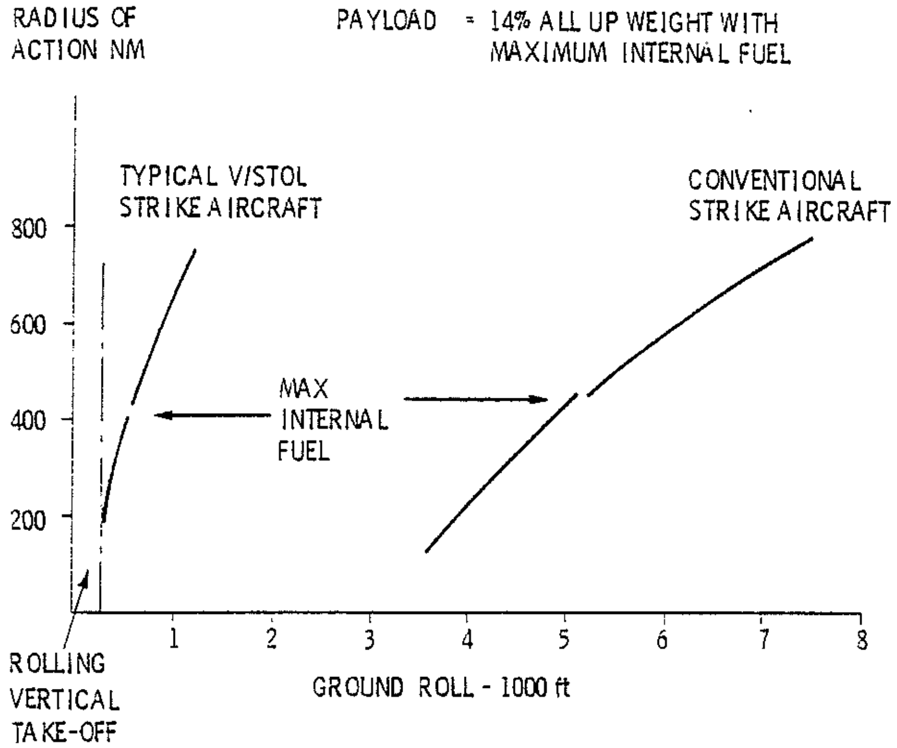
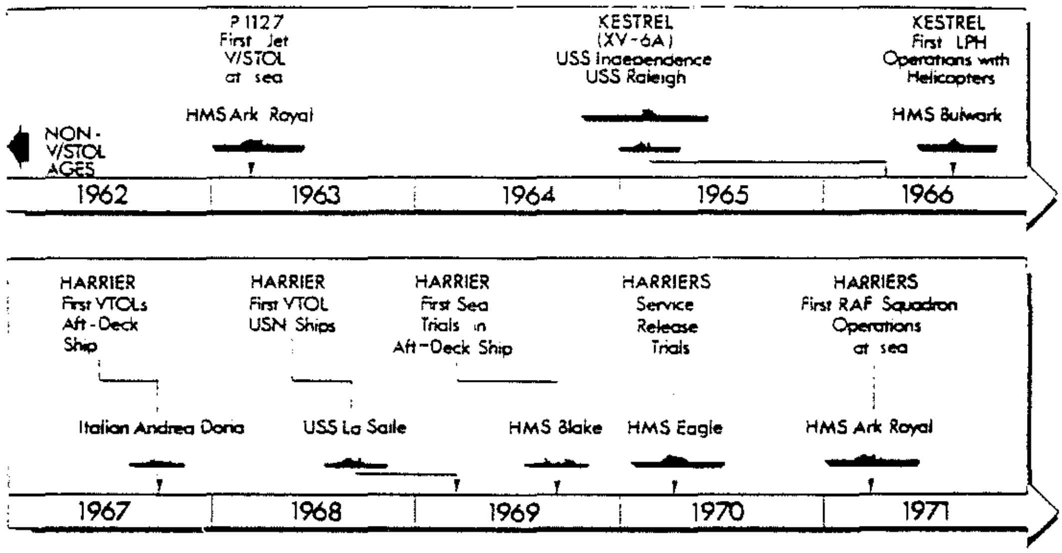


Figure 5

V/STOL Maritime Milestones



V/STOL Maritime Milestones
(Cont'd)

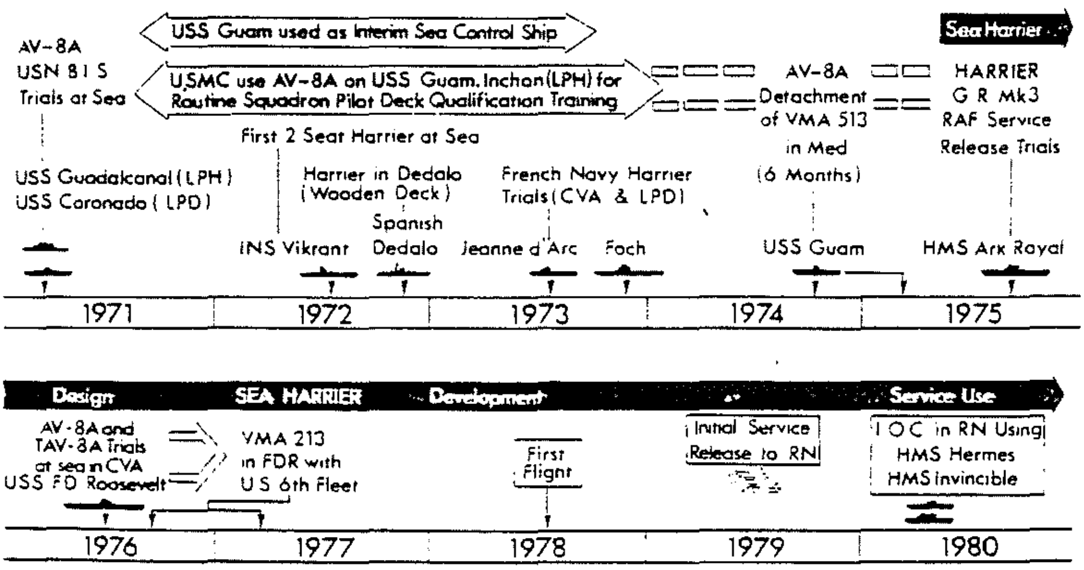
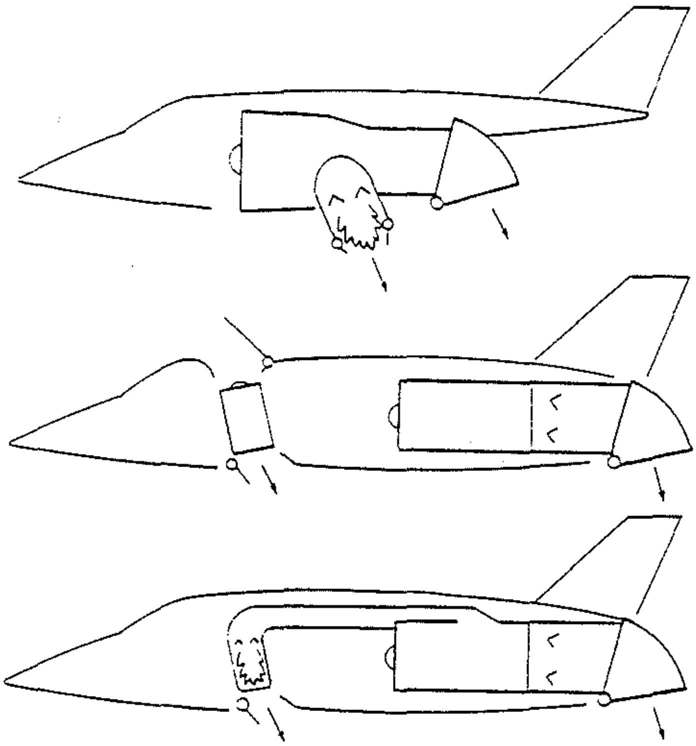


Figure 6

V/STOL COMBAT AIRCRAFT JET LIFT SYSTEMS



VECTORED THRUST

LIFT / CRUISE ENGINE THRUST DEFLECTED DOWN FOR V/STOL

LIFT + LIFT / CRUISE

PROPULSION ENGINE THRUST DEFLECTED AND AUGMENTED BY PARTIALLY VECTORABLE LIFT ENGINES FOR V/STOL

REMOTE AUGMENTED LIFT SYSTEM

PROPULSION ENGINE THRUST DEFLECTED AND AUGMENTED BY REMOTE FAN EXHAUST BURNER WITH PARTIAL DEFLECTION FOR V/STOL

Figure 7

ENGINE CONFIGURATION WITH PCB

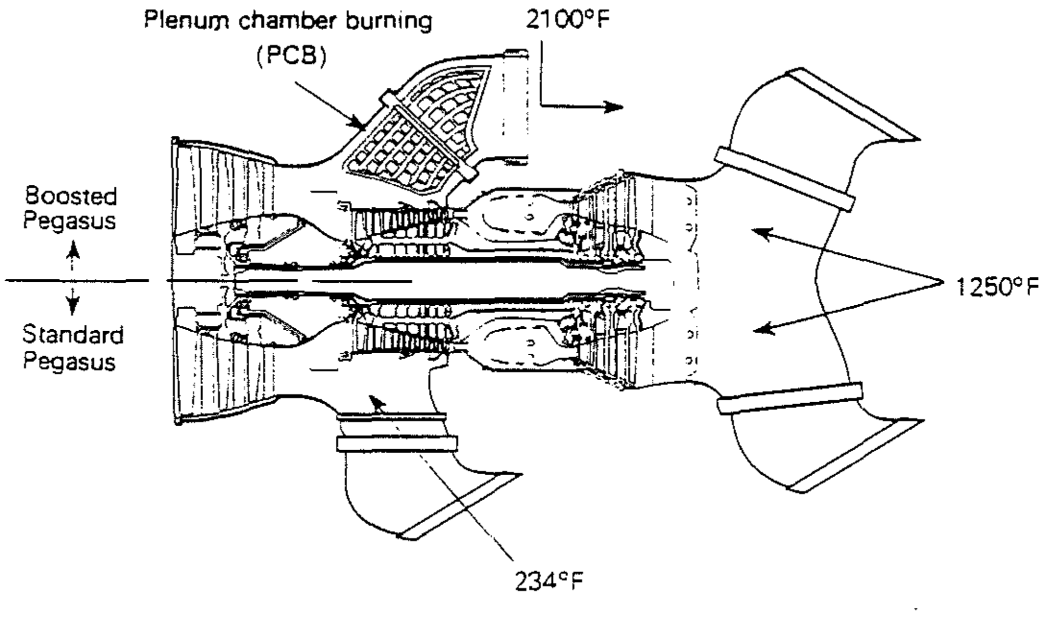


Figure 8

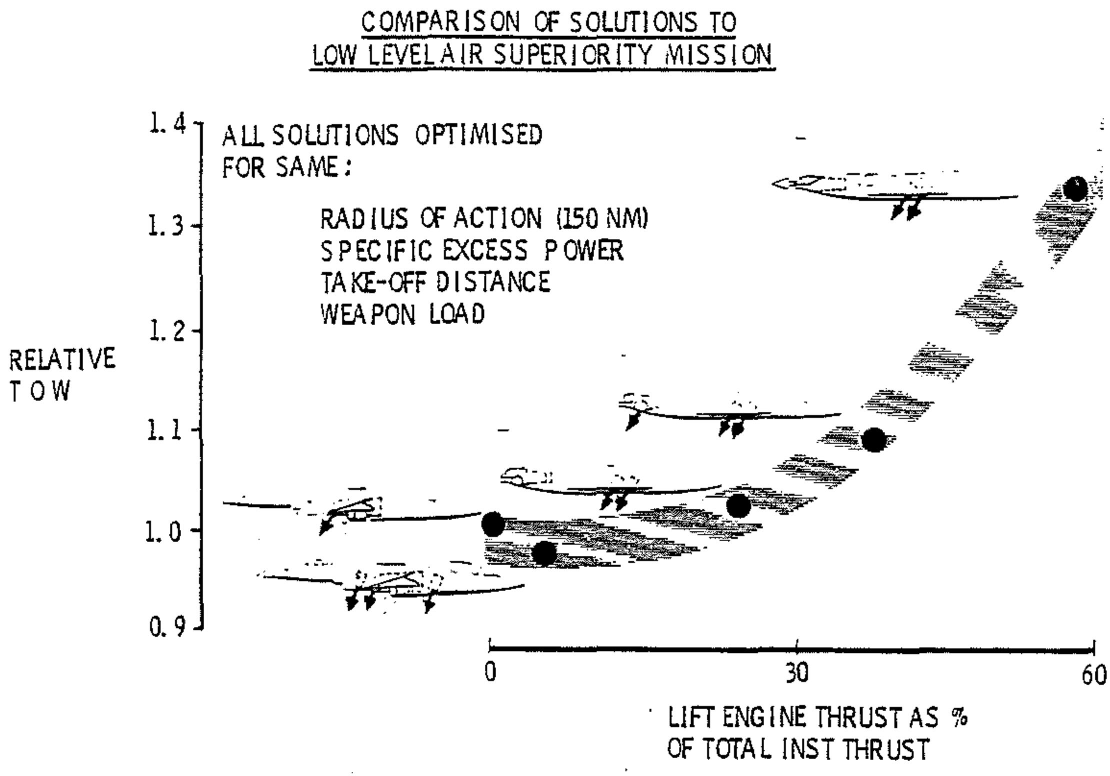


Figure 9

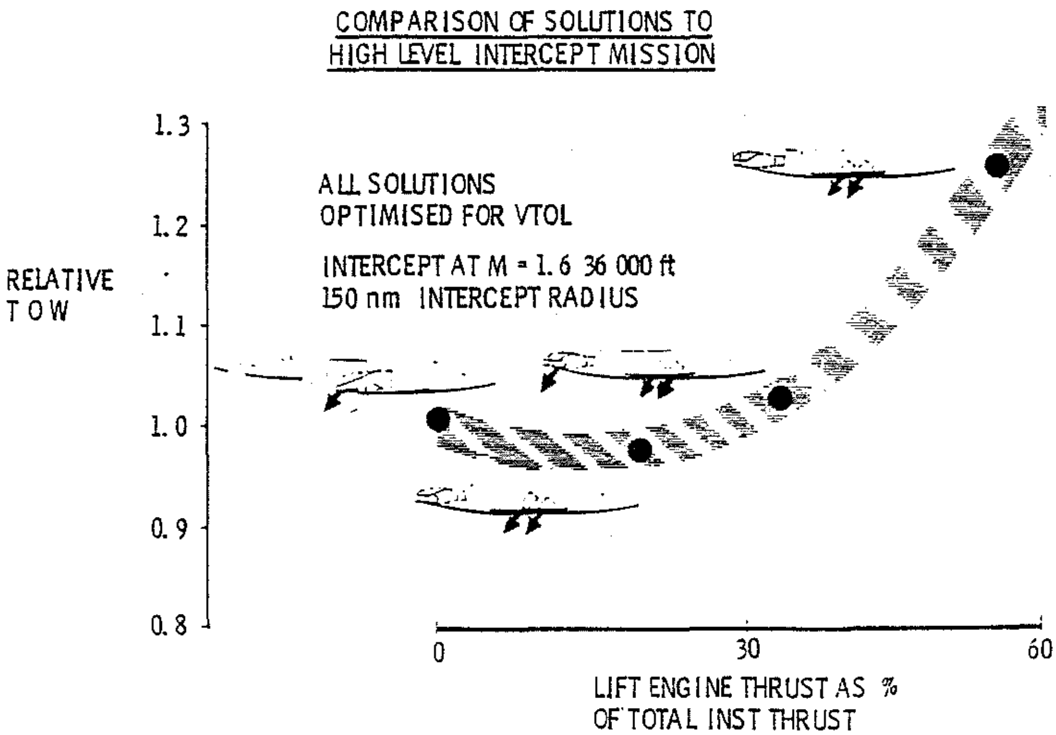


Figure 10

COMPARISON OF SOLUTIONS TO LOW LEVEL CLOSE AIR SUPPORT MISSION

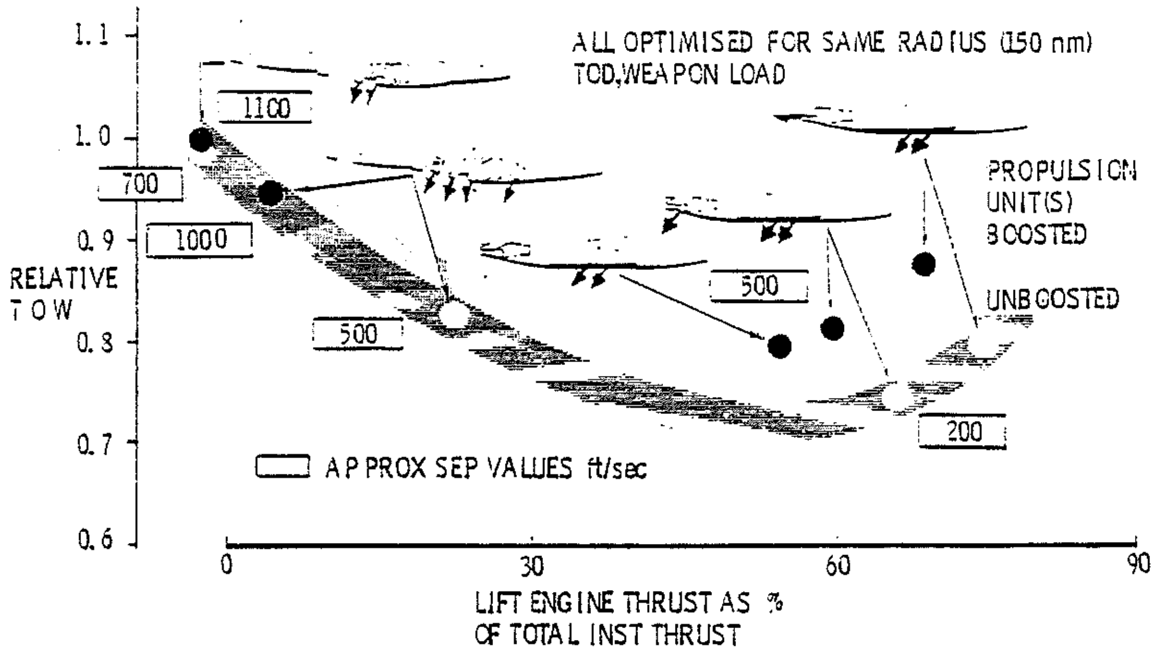


Figure 11

COMPARISON OF ALTERNATIVE V/STOL COMBAT AIRCRAFT SIZED FOR SHIP LAUNCHED INTERCEPT MISSION

	VECTORED THRUST	LIFT PLUS LIFT / CRUISE	RALS
TAKE-OFF WEIGHT lb	27 000	30 500	32 600
WING AREA ft^2	340	380	385
SUSTAINED TURN M = 1.2, 20 000 ft	6.2 g	5.6 g	6.3 g
ACCELERATION TIME M = 0.8 1.6, 36 000 ft	70 secs	83 secs	55 secs
MAXIMUM MACH NUMBER	1.9	1.92	1.95
RELATIVE COST	1.0	1.20	1.10

Figure 12

ALTERNATIVE V/STOL COMBAT AIRCRAFT - COMPARISON OF FIGHTER ESCORT RANGE (STO OVERLOAD) PERFORMANCE

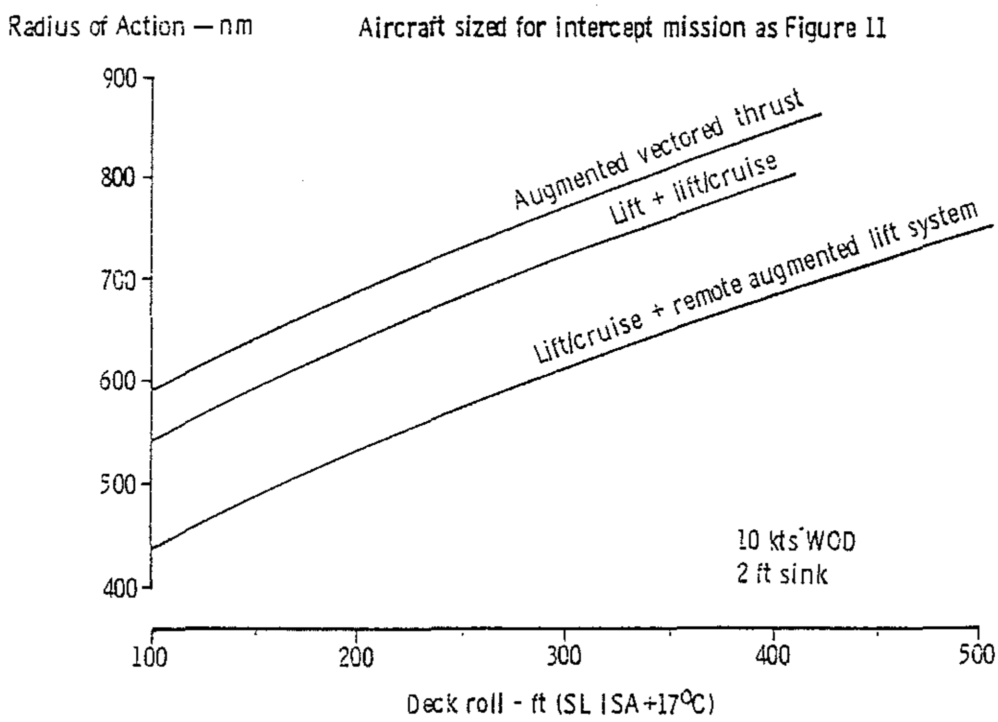


Figure 13

V/STOL UTILITY AIRCRAFT - TYPICAL FIRST GENERATION PROPULSION SYSTEM FEATURES PROPOSED

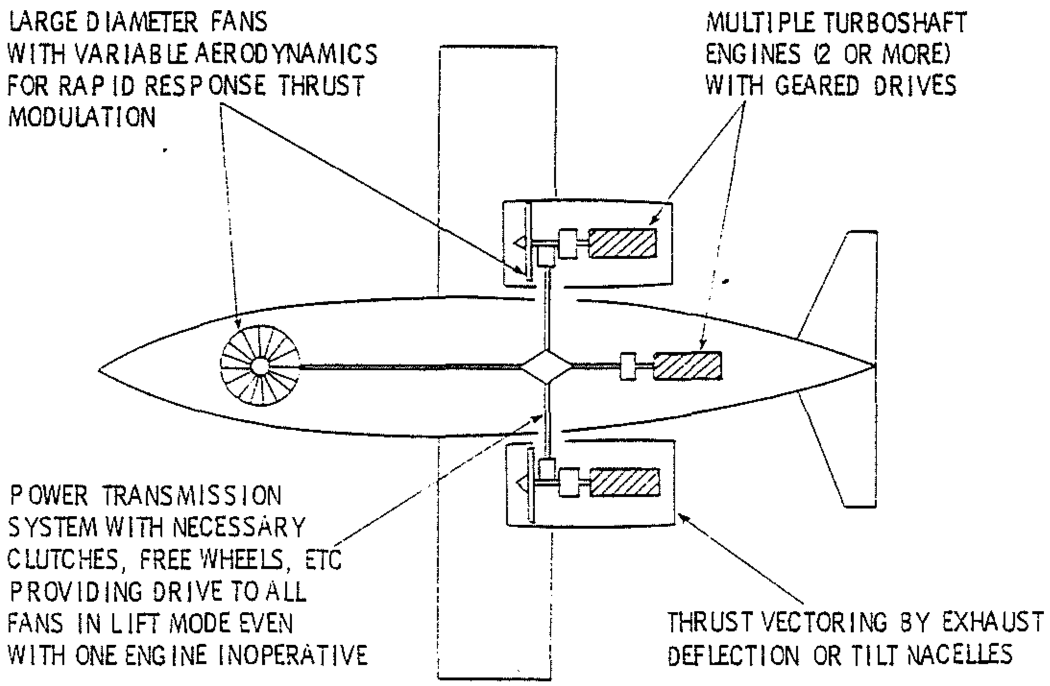


Figure 14

NOTIONAL 40 000 lb V/STOL UTILITY AIRCRAFT

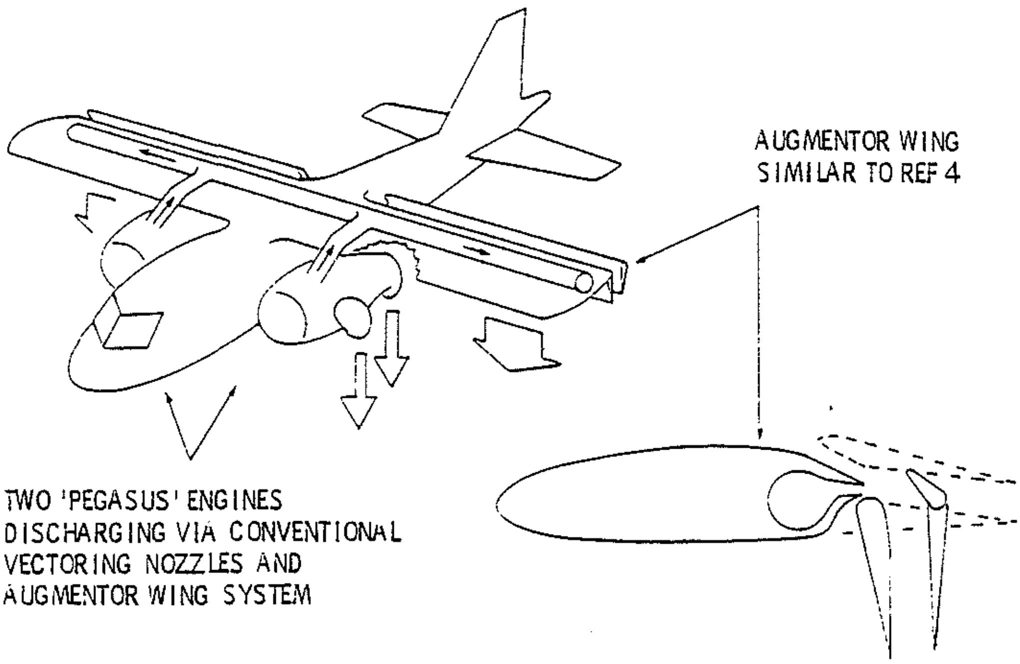


Figure 15

JET INTERACTIONS NEAR THE GROUND

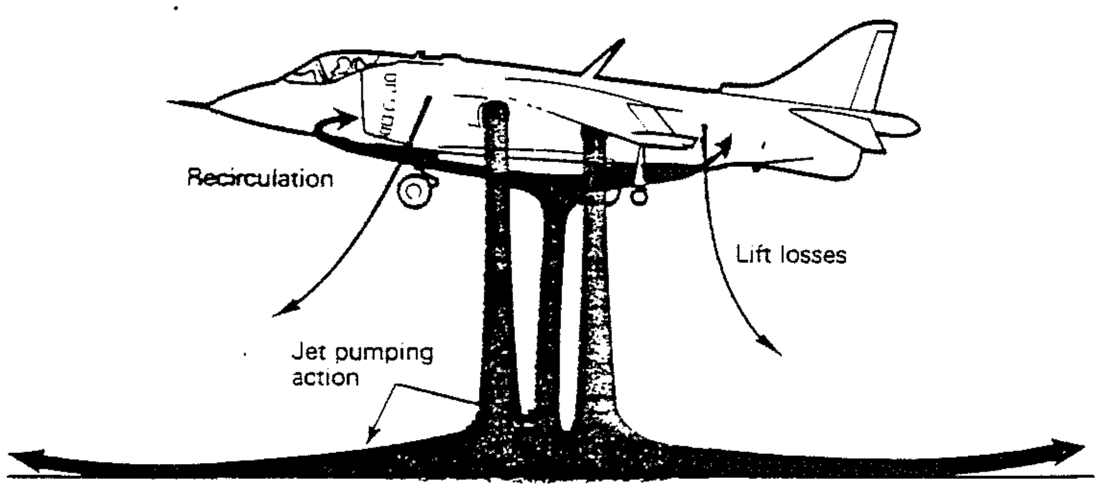


Figure 16

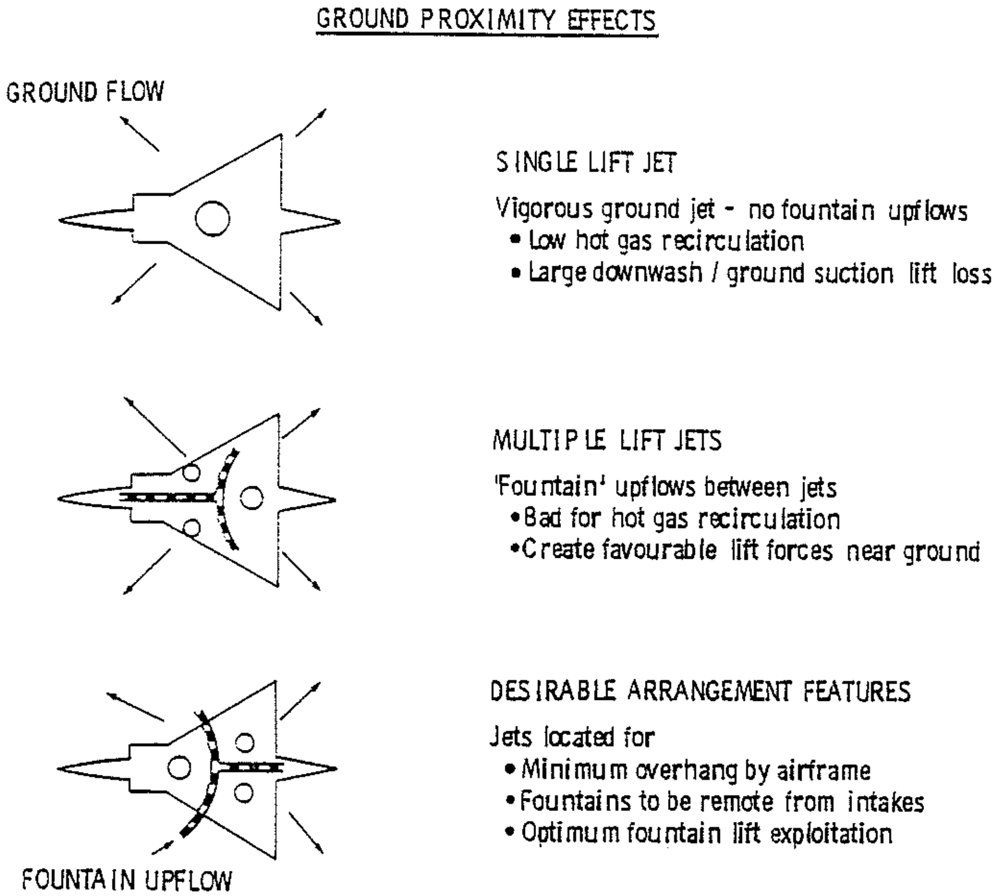


Figure 17

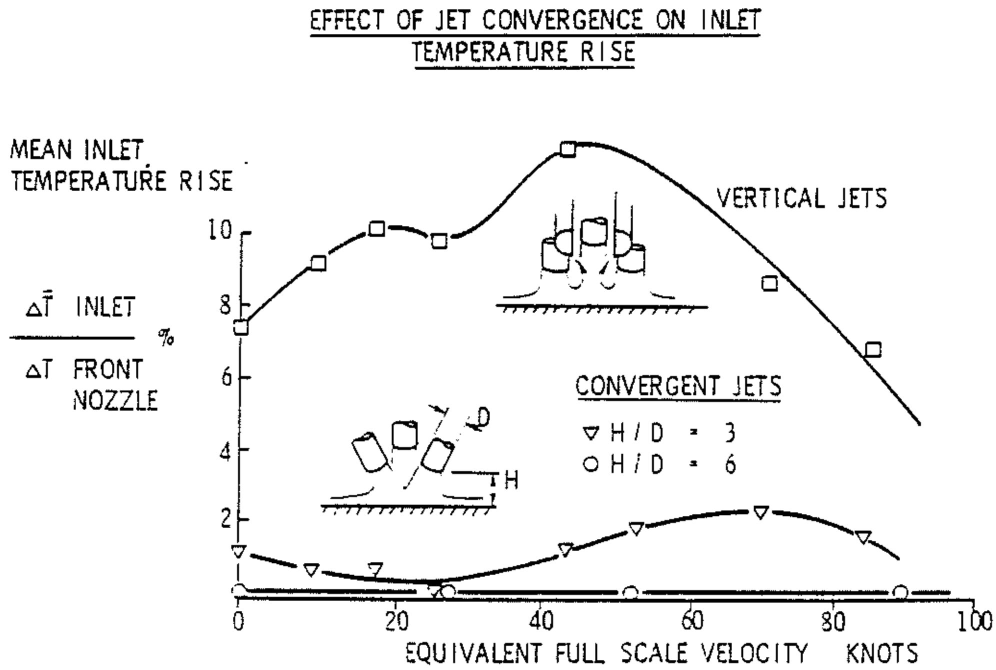


Figure 18

TYPICAL VARIATION OF LIFT LOSS WITH HEIGHT – CLUSTERED AND WIDELY SPACED JETS

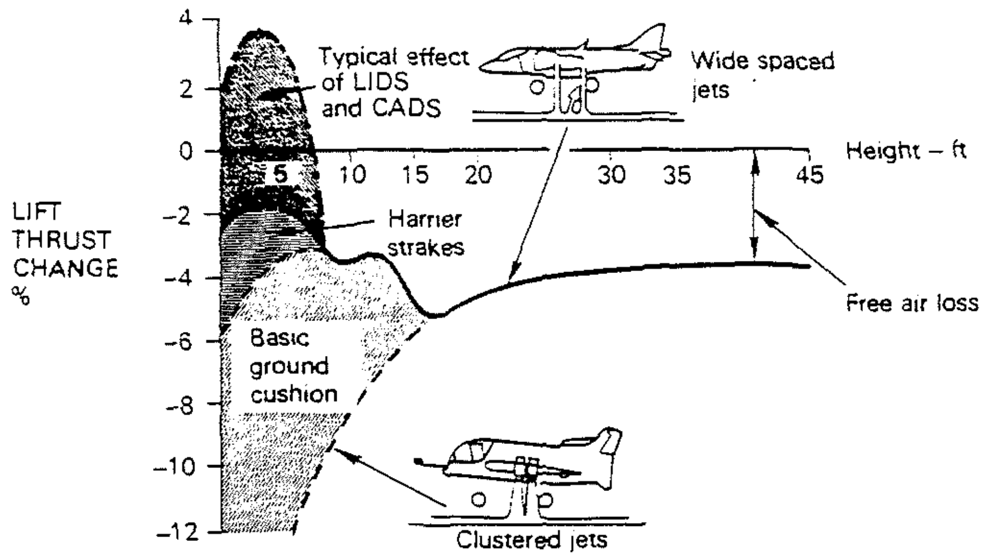


Figure 19

GROUND EROSION

- All downwards directed lift jets will cause ground erosion.
- Practical lift jets have very short residence times (no erosion) on unprepared surfaces.
- Erosion rates highly dependent on surface texture – grassland erodes in less than 1 second.
- Vectored thrust minimises ground exposure to jet blast.
- Harrier operates satisfactorily from grass, tarmac, wooden deck ships, etc.

Figure 20