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DEVELOPING A V/STOL COMBAT AIRCRAFT.

by

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In order to keep this paper of reasonable length I shall be confining my talk to the high performance military V/STOL aeroplane which achieves the ability to operate from confined spaces by the use of engine thrust for lift.

Aircraft in this class (say 20 to 40,000 lb. all up weight) have been proposed in various forms and several types have been taken to the prototype stage. There has been a high incidence either of engineering difficulties or the operational value of the type has been in doubt. However the Harrier, about which I shall be speaking in some detail, has been developed to a satisfactory operational stage for the Royal Air Force and is due to go into Service in the Spring of 1969.

In its earlier days, the interest in V/STOL was mainly technical, to show that it was possible to achieve such manoeuvres. Now the assessment of V/STOL must be taken on a much broader basis to satisfy operators that V/STOL aircraft can meet all the requirements for the particular class of aeroplane and do this in an economic manner, taking total costs into account. A satisfactory economic picture is the future challenge for designers, whether of military or civil aircraft. The way in which the complete pattern of operations will develop is then the concern of operators. On the military side this is a particularly difficult matter as it involves correctly foreseeing the pattern of future situations in the widest possible framework. For a meeting such as this, it is usual to give attention to the technical side of the subject. But this must be seen in relation to the type of vehicle to which it is applied and the use to which this vehicle is put. Mention is therefore made first of the state of the art in the V/STOL strike aircraft, taking the Harrier as an example. Some of the problems and the new areas of technology involved are then mentioned and finally possibilities for the future examined.

THE HARRIER.

I do not intend to describe this aeroplane in detail, because there are many published sources of information. But I should like to describe the development background, keeping to the V/STOL aspects, because this is illustrative of the amount of work that has gone into this one aeroplane.

The V/STOL aeroplane is completely dependent on its engine and I am very pleased that this Conference has had a paper by my friends at Rolls-Royce on the Pegasus engine. This describes the vectored thrust principle of being able to direct the four jets from the aeroplane in any direction between straight back and 18° forward of the vertical. This particular system of applying engine thrust to lift the aeroplane was chosen because it was regarded as the simplest. As produced by what is now the Bristol Division of Rolls-Royce the arrangement has now proved itself to be completely satisfactory engineering system.

The production Harrier derives from the P.1127 which first hovered tethered over a grid with a test bed engine thrust of 11,300 lb. Fig.1. This thrust was brought up to 14,000 lb. for six prototypes which flew between 1960 and 1964. These aircraft established the technical feasibility of the type and laid the foundation for satisfactory operation, safety limits, and control requirements in all the basic manoeuvres, vertical and short take-off and landing, and transition to wing borne flight.

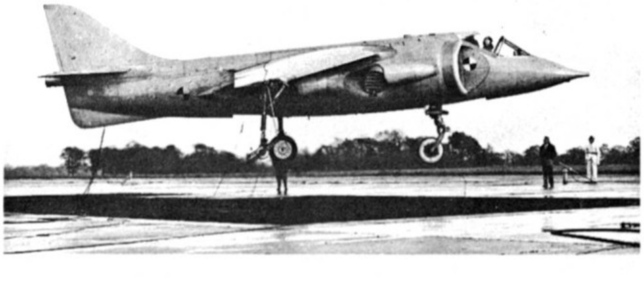


Fig.1

The next stage seen to be necessary was to establish that these capabilities could be applied in operations. A developed version of the P.1127 with a 15,500 lb. engine thrust was produced, known as the Kestrel, Fig. 2. Nine of these aircraft were built and formed an Evaluation Squadron jointly funded by the Federal Republic of Western Germany, U.S. and U.K.

Fig. 2

Fig. 4

The outcome of this evaluation was very favourable and early in 1965 the Royal Air Force ordered a further six development batch aircraft followed by an initial order of 60 production aircraft of a type developed from the Kestrel and now known as the Harrier. Engine thrust was 19,000 lb. The step from the unequipped Kestrel to the Harrier, although small in the technical sense, involved considerable re-engineering as shown by the list of changes , Fig. 3. Almost every drawing of the Kestrel has been reworked to produce the Harrier, Fig. 4.

CHANGES FROM KESTREL TO HARRIER

Engine thrust increased from 15.500 lb to 19.000 lb

Gas turbine starter/A. P. U.

Carriage of armament.

Inertial nav/attack system.

New cockpit layout.

New communication system.

Undercarriage structure strengthened.

Ferry wing tips and flight refuelling.

Fuel jettison.

Increased fatigue life.

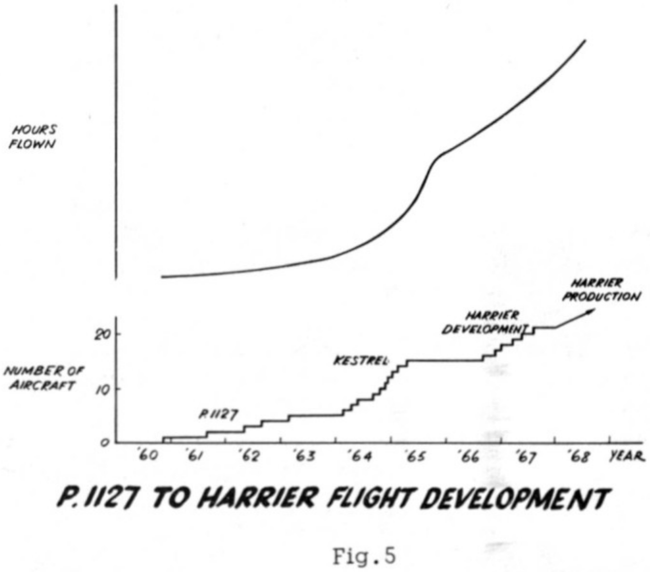
New wing planform and section.

New drawings throughout.

Fig. 3

In respect of its V/STOL aspects the Harrier work has comprised making more accurate measurements, defining the operation procedures and extending the capabilities in many ways. The short take-off and landing procedures have been studied in detail so as to be able to choose nozzle angles and flying techniques for optimum performance. Cross wind operations have also been studied to establish safe limits. External lighting has been optimised for night landings. Controls have been developed and artificial stability has been introduced to reduce the pilots work load, although the aircraft can and does carry out V/STOL operations without it. Thrust vectoring in flight has been evaluated as an operational technique and nozzle trim has also been tried as an alternative to changing the pitch attitude of the aeroplane to control it in the transition.

Altogether 21 aircraft have now been flown on development and evaluation work, 4 production aircraft have been flown. During development flying about 50 pilots have converted to the type and over 10,000 V/STOL manoeuvres have been carried out, Fig. 5.



P.1127 TO HARRIER FLIGHT DEVELOPMENT

Fig. 5

The Harrier has thus become an aircraft which can be operated from an extremely wide variety of ground situations. Unprepared ground has been used in a high proportion of the V/STOL manoeuvres. For ground strength we measure with a cone penetrometer. At 3" to 6" depth a CBR of 8 is required, lower values down to 3 being allowed on the surface. To avoid surface erosion we know that good grass will hold for a vertical landing. If in doubt or if the surface is covered with loose stones we do rolling vertical take-offs or landings, allowing the aeroplane to move forward at a speed of say 30 kts. with the nozzles down. For similar reasons nozzles are always directed back when starting the engine. If ground preparation is necessary the aircraft can be landed on a 30 ft. square if the pilot has some simple marker outside this area to work to; a 50 ft. square can be used without markers. It will often be necessary to cover the surface of the ground beyond this landing pad for a further 15 ft. all round and this can be done with a neoprene cover. The aircraft has shown itself quite satisfactory in operation on surfaces covered with ice and snow and because of its low approach speed it is able to operate in very low weather minima.

All pilots have so far converted to the Harrier without dual control training. Apart from suitable experience in a modern jet fighter, and the usual briefings for a new type, the only additional training has been a few flights dual in a helicopter so as to provide a feel for vertical motion during take-off and landing.

There is however a development programme and production order under way now for two seat Harriers for the Royal Air Force, Fig. 6. The modification to two seats is inherently more difficult for a V/STOL aeroplane because of meeting the cg-jet thrust relationship as well as the cg-aerodynamic centre relationship. A suitable arrangement has however been devised by moving the front cockpit back, so that the new front cockpit is not so far forward, and stretching the rear fuselage while keeping the tailplane in the same position relative to the wing. The aircraft can fly with or without the second pilot and his seat.

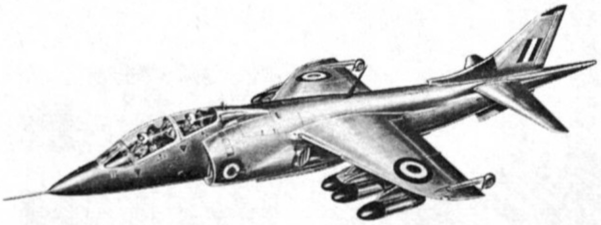


Fig.6

In respect of V/STOL manoeuvres these aircraft should provide quicker training and will allow student pilots to study departures from recommended procedures with an instructor there to look after safety. Operational training can also be given on the electronics systems for navigation and weapon aiming. Development work for these two seaters is intended to cover instrument approaches for one pilot in blind conditions, with the other pilot monitoring, ultimately with the intention of achieving electronic systems which allow for complete blind landings.

The above remarks all relate to those aspects of the Harrier which are connected with V/STOL. In other respects its development has followed that of other similar high performance aircraft. Before going on to discuss some of the work in more technical detail I should like to give you an impression of the aircraft in use, by showing a short film.

I should like now to talk about some of the development problems for the Harrier. I shall of course be keeping to the V/STOL aspects. At the Harrier stage these were not a major part of the total development, because of the P.1127 and Kestrel experience, and to give a complete picture it is necessary in some cases to go back to this earlier work.

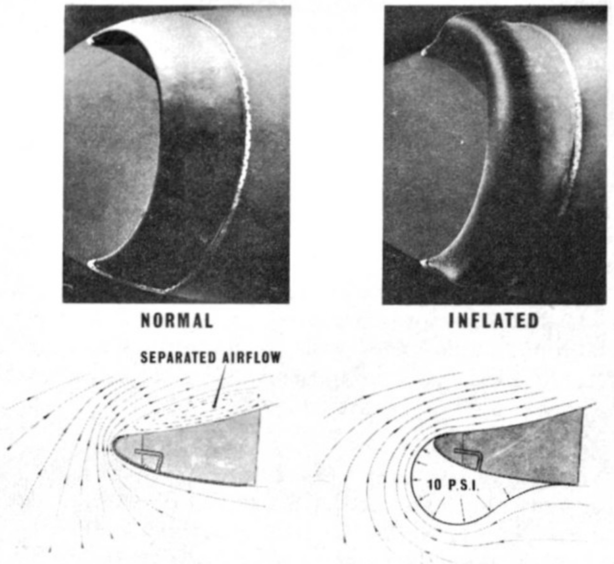
INTAKE.

The engine and intake for a V/STOL aircraft must of course meet all the in flight conditions which apply to a conventional aircraft, satisfactory pressure recovery, stability of flow to give good engine handling, and good spillage drag characteristics.

The conditions of the airflow in the intake is however of particular importance to the V/STOL aircraft at zero and low forward speeds. Any loss of thrust in the static condition has affects only on the take-off run of a conventional aircraft, and probably by a negligible amount for a V/STOL aeroplane there is a direct loss in the weight lifted. The problem is therefore to achieve as high a ratio as possible between the installed thrust of the engine and the test bed thrust as measured with an ideal i.e. bell mouth intake.

The ultimate measure of what is achieved has to be obtained from the aeroplane itself, but development on the aeroplane is expensive and slow and is made particularly difficult in that differences in performance of less than 1% of V.T.O. weight are very difficult to determine.

Most of the work has therefore been done in terms of model and test bed measurements of intake flow conditions together with thrust measurements on the engine test bed with the aircraft intake. A convenient overall measure of the static flow conditions in the intake is the average loss of total head at the engine inlet, measured as a percentage of the outside total head. The percentage thrust loss for the installed engine is then computed, according to the standard performance procedures for the engine, to be about 1.5 times the pressure loss. But this ratio requires a good deal of careful examination because average figures can be misleading.



FLOW PATTERNS UNDER STATIC RUNNING

AIR INTAKE INFLATABLE L.E.

Fig.7

In physical terms the intake requires to have a bell mouth shape for static running, and a sharp inside and faired outside shape to deal with spillage at high forward speed. For the P.1127 this condition was achieved by a physical change to the intake shape provided by a rubber bag on the outside, inflated for take-off and landing, Fig. 7. This system was in fact abandoned because no completely satisfactory means was found to hold the rubber bag down in flight. If deflated at too high a speed the bags might be wrinkled, and if they settled down smoothly at first they might still wrinkle at high E.A.S. There was the risk of puncture with loss of suction inside which would allow the bags to wrinkle more severely and possibly tear away.

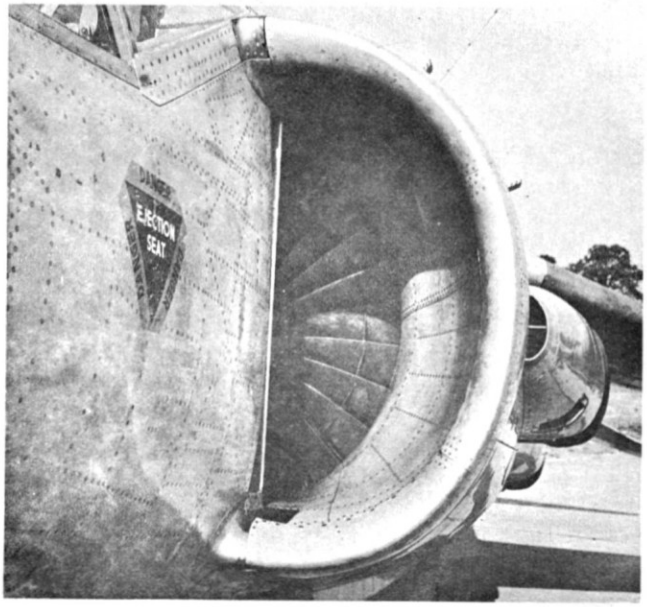


Fig.8

The fixed lip design adopted for the Kestrel, Fig.8, used a highlight-to-throat area ratio which was predicted to give the same static thrust loss as had been measured with the rubber bags. In this it was successful but the flattened external cowl shape which resulted gave a high spillage drag in cruising flight. While this was accepted for the Kestrel it has been corrected in the cowl design for the Harrier (Fig.12).

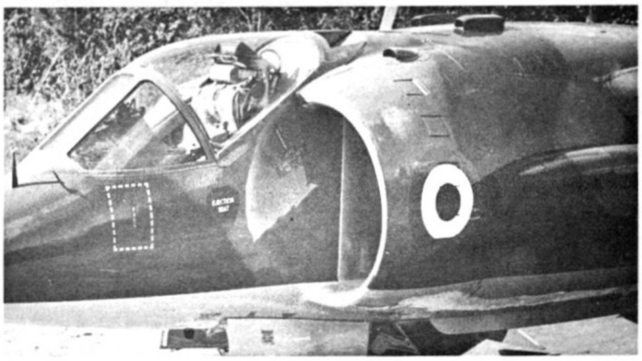


Fig.9

The Kestrel intake was rated at 3% pressure loss static and for the Harrier a better figure was sought. Attention was given to a sliding lip intake but it was possible that the weight of this would have been greater than the thrust recovered. Model test showed that slots with suck in doors providing a secondary air flow were very beneficial, giving about 2% pressure loss (excluding the boundary layer). Figs 9 and 10 show an early Harrier intake. A thrust loss of 3% was therefore expected but when the engine was run with this intake on the test bed the thrust loss was much higher. After considerable investigation it was decided that the average pressure loss was not a very reliable guide to what the thrust loss would be because the engine was responding to the local pattern of the air flow in the intake and not the average. As

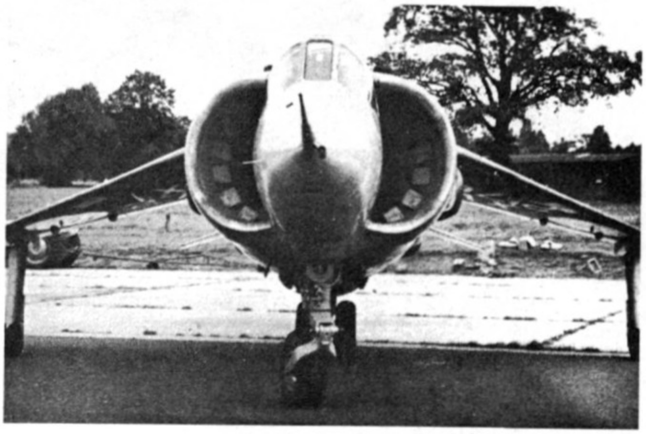


Fig.10

a simple illustration of this, it can now be seen that pressure losses for air going into the high pressure section of the engine would have a more severe effect on thrust than corresponding losses in air which only went through the fan.

Continuing work on the intake for engines using higher air mass flow had shown that if the auxiliary slots were made larger so that they gave a continuous slot on the inside this was very nearly as good as the best moving lip intake. Design decisions had to be based on model tests and a very wide range of detail shapes was tried and pressure contours measured for each, Fig. 11. As a measure of the significance of the apparently small differences in pressure contours, the Pegasus engine was run on the test bed with deliberate interruptions to the air flow to reproduce some of these contours and hence to line up the contour pattern with thrust. From this work the current production Harrier intake has emerged, Figs. 12 and 13.

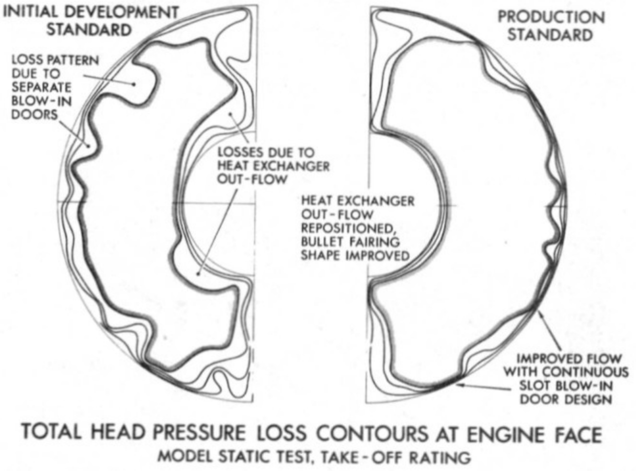


Fig. 11

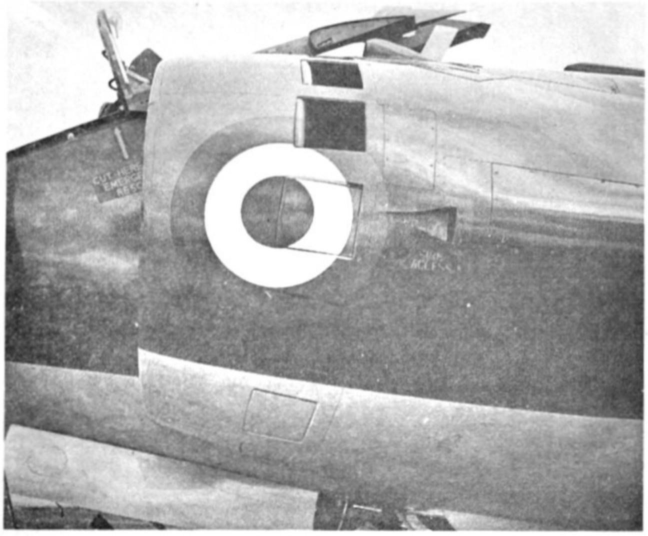


Fig. 12

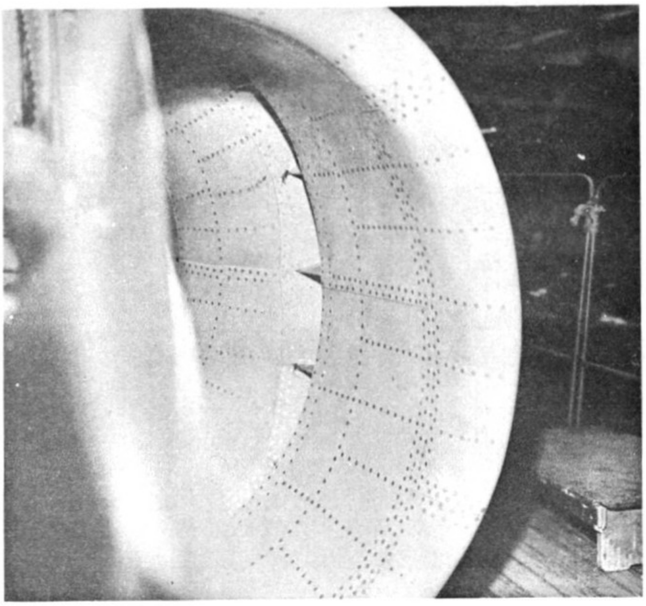


Fig. 13

Fig. 14 shows that this efficiency can also be maintained without appreciable reduction for at least another 25 lbs/sec. of air flow. The thrust loss due to this intake has now been measured on the test bed. There is not a great deal more to be expected by improvements in the intake, and other factors have a greater effect on the V.T.O. weight achieved.

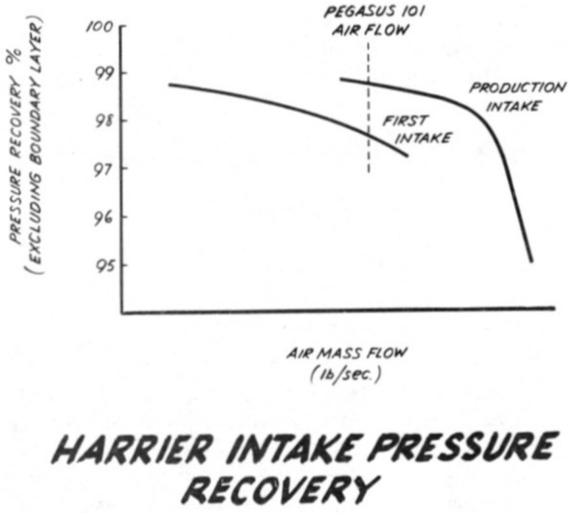


Fig. 14

RECIRCULATION

Recirculation occurs when hot air which has been through the engine mixes with other air and finds its way into the intake. The engine can be affected by the average temperature, the temperature variations across the intake, or by the effect of local temperature variations on sensors which control engine running.

The effect on the aeroplane is at least loss of thrust and at worse loss of control of the engine e.g. by surging. Asymmetry of thrust can be a problem when there is more than one engine.

The mechanism of the recirculation can be envisaged as arising either from immediate recirculation (local) or from the hot air spreading out to some distance, rising by convection, and then returning to the aeroplane (far field).

In principle a single jet impinging on the ground and free to spread outwards would not give local recirculation. With multiple jets however interference occurs of the jets spreading along the ground and these will be reflected upwards at the aeroplane and may be pulled into the flow entering the intake. Fig. 15. shows how a suspension of titanium dioxide in light oil is distributed on the boundary surfaces of a half model by the jet and intake flows.

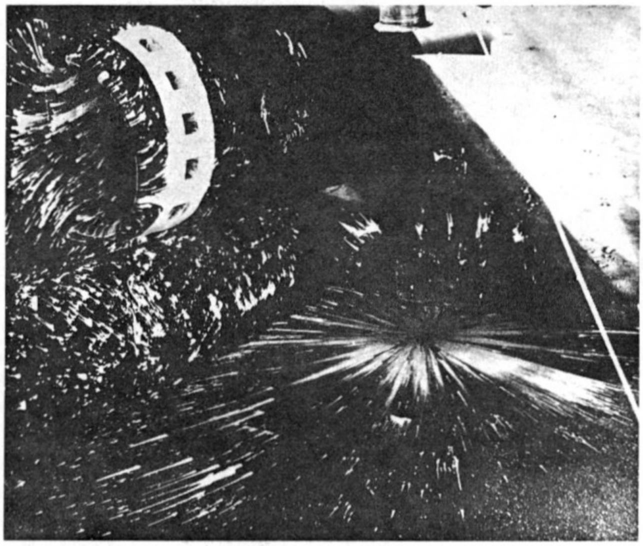
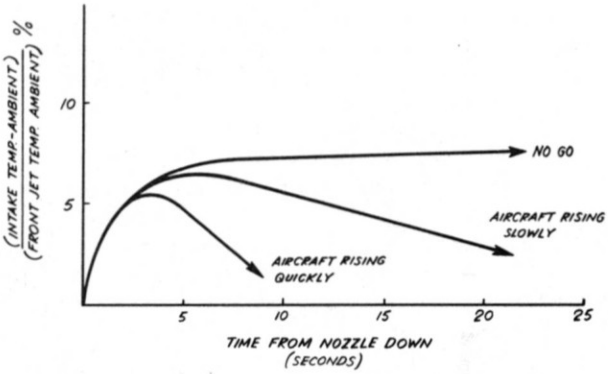


Fig.15

The far field effect is rather more variable, depending on a number of factors. The attitude of the aeroplane i.e. the angle at which the jets strike the ground can be of significance during landing when the aircraft is very close to the ground. Fortunately however loss of thrust at this moment is not significant. The wind can be adverse, which means relatively light, because zero wind and a very strong wind are both favourable. Time is also a significant element.

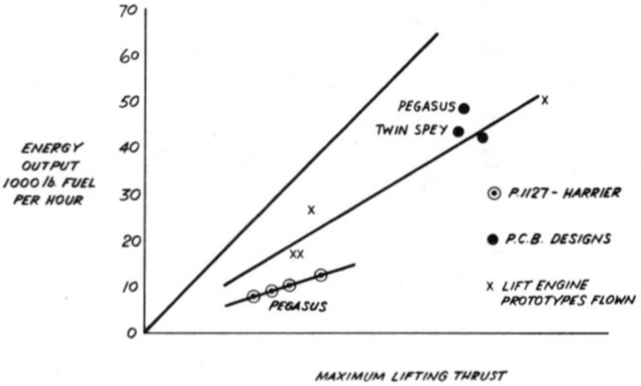
The sum of all these effects for the Harrier is shown in Fig. 16, which also brings in the effect of time. The absolute temperature rise due to recirculation is quite small for the Harrier because the fan air from the front nozzles is relatively cool, no fuel having been burnt in it. In the normal lift off, which would occur after 3 secs. from pushing the throttle forward, the temperature rises only about 4°C, representing about a 2% loss in thrust.



INTAKE TEMPERATURE RISE IN VTO

Fig.16

This problem will become of much greater significance when the front jets are hot. Recirculation needs to be brought down to a relatively lower figure when fuel is burnt in the front jets (Plenum Chamber Burning) which is being studied for future developments. The intensity of the heat flow and the scale of the aeroplane can vary widely as shown in Fig. 17. This shows the Pegasus to have been a relatively cool engine and with P PCB. it becomes similar in respect of heat output to systems using lift engines.



ENERGY OUTPUT AT V.T.O.

Fig.17

A good deal of model work has been done to build up practical ways of minimising recirculation. The longitudinal strakes under the Harrier are there to minimise lift loss in ground effect, but they also have an effect on recirculation in causing the reflected jet air to keep going forward, instead of diverting laterally towards the intake. Nose wheel doors have been used in other designs to give a similar effect. A similar result can be obtained by the almost completely opposite device of a transverse obstruction to the hot gases. This can deflect them off the body in a downward direction and so away from the intake. There is very little theory available as guidance and model testing at the design stage, both static and in a very low speed wind tunnel, is the main source of information at the design stage.

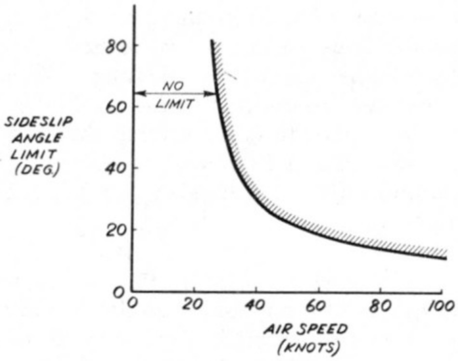
It should be remembered that recirculation of hot gases can also come from other aircraft. In land operations there is no operational need for aircraft to take-off at the same time and close together. The effect has however been studied on carrier decks with the Harrier and helicopters near to each other. In fact no difficulty was found, possibly because it is rare that there is no wind over the deck. The effect of hot funnel gases could be detected, by a reduction in engine thrust but these gases are very localised and a good rule, for conventional aircraft, is to stay tay out of them.

V/STOL CONTROLS.

The classic way of providing control at zero forward speed, for the aircraft with a small number of engines is by reaction controls which take compressed air from the main engine. In the case of the Harrier the bleed is taken from the secondary cooling air which surrounds the combustion chambers. The engine is rated so that the average demand can be taken without any reduction in thrust. With higher flows the gross thrust is reduced and the limiting flow will be reached only in the unlikely case of simultaneous use of a high proportion of the control in all three axes. The time average of air used during hover can be as low as 6 lb/sec. and this will increase to 9 lb/sec. in take-off and landing.

The amount of control is often defined in terms of the angular acceleration it produces and as far as one single figure can go in defining the character of a control system, this is probably a suitable figure to choose. Many other factors are however involved in the description of a satisfactory control system, and in fact maximum angular acceleration as such does not appear when the detail design requirements for the control systems are considered.

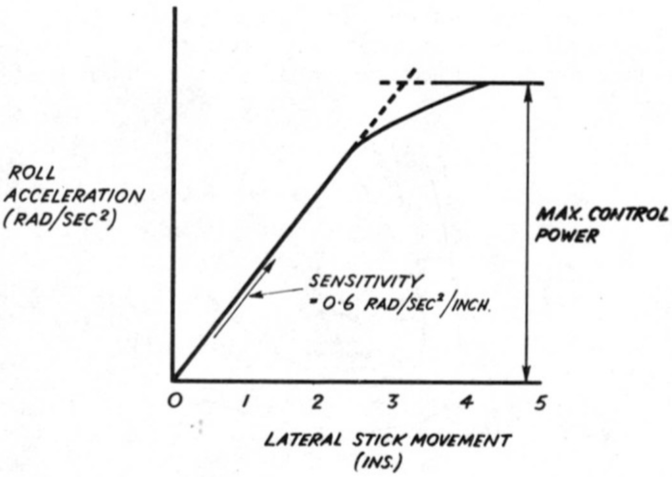
Considering first the roll axis, the maximum control required may be determined by mechanical considerations such as asymmetric stores, which might occur due to failure of a weapon release system. Another consideration arose in early 1127 days, because the outriggers were clear of the ground when the aircraft was on the main wheels and partly jetborne. The negative pendulum effect due to the height of the cg above the ground then required maximum control to pick up a wing. This condition however no longer applies to the Harrier. The amount of control power to deal with effects such as these is very easily determined. Other demands for maximum power control are much more bound up with the aerodynamics of the complete aeroplane and the way in which it is operated. Up to about 50 kts. the Harrier is insensitive to side slip angles but from this speed to the airborne speed there is a relationship, determined by maximum control power, between the permitted sideslip angle and speed. Assuming straight and level flight this is as shown in Fig. 18. For a landing this represents a cross wind of the order of 20 kts. for a straight sideslipping approach. The control requirement can however be reduced by yawing the aircraft in to wind. Since sideslip has to be kept within bounds, although only in respect of coarse angles, a vane is provided to give the pilot an indication of sideslip angle. The vane itself can be seen outside the aeroplane or it can put a signal into the head-up display. Attention may need to be given to this if turns are made during the transition although for practical purposes it is best either to make turns before or after the transition. All these factors have a very considerable bearing on the amount of control power required.



HARRIER V/STOL SIDESLIP LIMITS

Fig.18

The gearing between the stick and the rolling moment is also of particular importance when in manual control. This is related to what a pilot finds satisfactory for a comfortable control response when he is operating normally i.e. within the maximum control power. Fig. 19 shows a typical Harrier control curve in which the maximum control power is reached before maximum stick travel, to provide the sensitivity of control which pilots find subjectively to be the best for their aircraft.



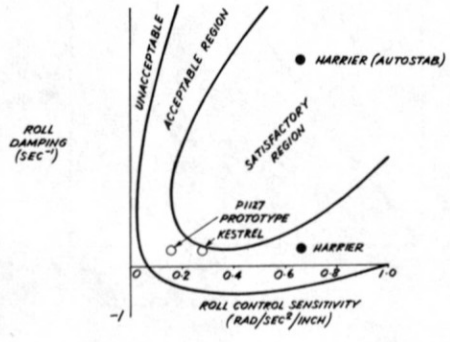
HARRIER ROLL CONTROL

Fig.19

The pitch control required is clearly first of all a function of cg movement. Since in general flight conditions it is possible to moce the cg more in a forward direction than aft, this condition may define the required nose up pitching control power. Changes in pitching moment as the aircraft comes close to the ground in a vertical landing may also have to be studied as the reflected jets can impinge on the aircraft in various places. This effect can go in either direction, nose down if the reflected jet predominantly impinges on the tail, and nose up if the undersurface of the fuselage forward of the jets is large in area. In the transition, the downward flow induced by the jets can induce a downwash over the tailplane so giving a nose up moment. In the case of the Harrier this determines the datum setting and the gearing between the reaction control and the aerodynamic control such that the required trim is shared and satisfactory stick movements together with a reasonably low pitch bleed demand is obtained.

In yaw the means of defining the maximum control is less clear. Aerodynamic forces are not very powerful until the flying speed is reached and natural aerodynamic stability takes over. There is however a measurable unstable effect due to the momentum drag at the intake. This is proportional to speed and engine mass flow whereas the aerodynamic stability is proportional to the square of this speed. The speed at which the aerodynamic stability takes over is very much a function of the layout of the aeroplane. For the Harrier it is in the region of 60 kts. and as with many such effects the aeroplane is in the condition for only a very short time when used operationally.

When using reaction controls in normal operations the other forces on the aircraft are usually small and may be slightly stable or unstable. Provided the general consensus of pilot opinion is satisfactory. It does not pay to be too concerned about weak adverse forces in transition conditions. There is much to be said for retaining a manual control ability for the aircraft as complete dependence on automatic controls can lead to quite elaborate and heavy systems. In adding some degree of automatic control to a satisfactory manual arrangement it has been found best to add both damping and a degree of stiffness. Again the amount of this is a subjective matter for the pilot. Fig. 20 shows the amount of damping which has been added in by a single channel autostabiliser for the Harrier, plotted against some boundaries recommended from NASA tests.



HOVERING HANDLING CRITERIA IN ROLL (NASA AMES SIMULATOR)

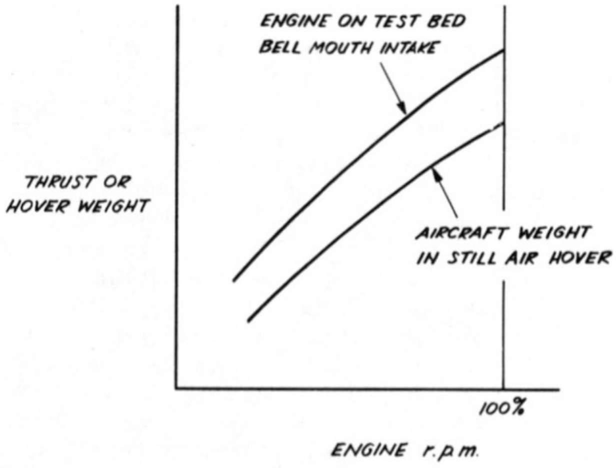
Fig. 20

V/STOL PERFORMANCE.

The prediction of V/STOL performance involves a good deal of interpretation because a large number of effects are involved. While theory indicates what these effects might be, the magnitude can often only be determined experimentally. These remarks apply of course in the practical case when the design aim is to obtain the last few percent of performance. Subsequently it is often necessary to devise new flight procedures to establish what has been achieved.

To take an apparently simple quantity, the measurement of vertical take-off weight can be quite troublesome, particularly if small changes in design are being compared. If the aeroplane lifts off, a weight has been established less than the V.T.O. weight, but without an indication of what the true V.T.O. weight is; if it does not lift the reverse applies. A protracted raising of r.p.m. to lift off at less than maximum r.p.m. is not appropriate either as it gives unrepresentively high ground effect losses.

The study of V.T.O. weight is therefore usually started by measurement of the free air hover conditions in which the engine r.p.m. and aircraft weight are recorded simultaneously, the essential condition of this manoeuvre being that it can be maintained for a relatively long time. While the zero, vertical and horizontal velocities are set up. A graph such as Fig. 21. can be obtained in which the weight lifted is typically about 90% of the test bed thrust at the same r.p.m., (after correcting for atmospheric conditions) and this may be taken to cover losses from intake,



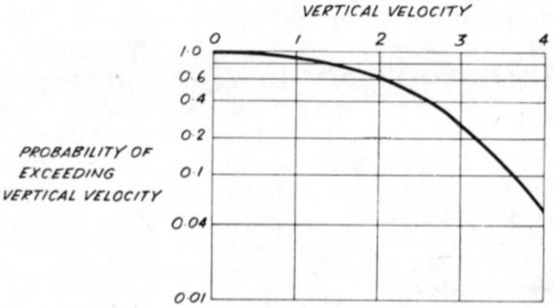
MEASUREMENT OF HOVERING PERFORMANCE

Fig. 21

induced downwash, splay angle of the nozzles, minimum use of reaction controls and other engine installation features such as power offtakes. Results should be obtainable to about 1% accuracy.

In the vertical take-off from the ground there are other effects to be considered, notably recirculation of hot gases and the effect of the reflection of the jets. It may not be enough that the aircraft lifts off. The variation of lift loss with height must be such that the aircraft keeps going. It must also be able to accept a reasonable range of conditions in the transition so that no hesitation is shown in accelerating to flying speed. Small variations in the nozzle angle for V.T.O. have been explored for the Harrier. Over the practical range there is a small effect on the lift off weight (1 or 2% at most) but the choice of angle is also determined by secondary conditions such as the attitude of the aeroplane and the time build up of recirculation. At the preferred figure 76° relative to engine axis) the jets are 5° back from the vertical.

The vertical landing can be done at a similar weight because the free air hover condition, which starts the landing, will then show about 5% of lift in hand and this is used for the control of vertical velocity. New pilots usually put the aeroplane down too lightly which means extra engine time fuel and pilot effort. A steady rate of descent of about 4 ft. per sec. is quite appropriate for the Harrier but in fact 95 per cent of the landings are at a lower vertical velocity, Fig. 22.

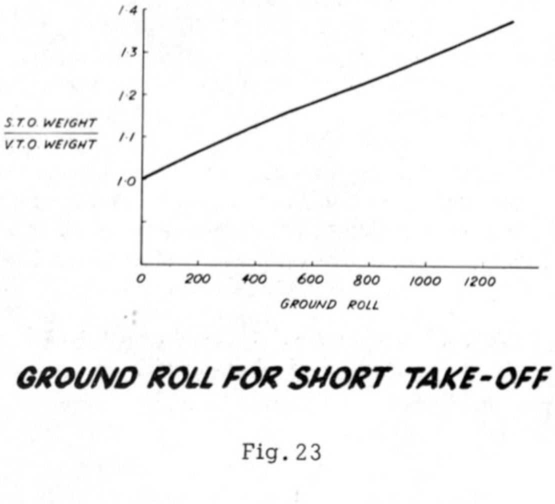


VERTICAL VELOCITY IN VERTICAL LANDING

Fig. 22

With forward speed a number of effects need to be disentangled. A forward speed of about 20 kts. can give an increase in lift of 5%. This is considerably greater than the computed lift from the wings and can be put down to a reduced loss from ground effects and perhaps some improvement in intake efficiency. This speed will be obtained in less than 100 ft. of ground run and this of course leads to the question of what total field length should be provided. Assuming that there is no barrier of any considerable height at the end of the field, the standard procedure of supposing that the aircraft must be at 50 ft. height at the end of the field is a condition which comes to mind, but this is an unrepresentative condition for this type of manoeuvre. The reason for this is that the aeroplane has only a short time in flight before it reaches the end of the field and during this time it must accelerate itself up to the nominal barrier height. This upward acceleration requires extra lift. A safer manoeuvre is to use the extra field length to achieve a greater forward speed which gives greater lift in hand, although the end of the field is crossed at a lower height. There is perhaps nothing new in a pilot preferring speed to height at the end of a take-off but in fact detail calculations for this class of aeroplane show results which are very much more on the side of extra forward speed.

As speed builds up the weight increases as the contribution from wing lift becomes more definite. Taking results from earlier P1127 aircraft, a typical relationship between ground roll and weight is shown in Fig. 23. The technique is to start with nozzles down at about 30° with the thrust raised to what the brakes will hold. Brakes are then released and the throttle advanced. At a forward speed selected on the basis of the weight the nozzles are put down to a predetermined position, also determinable with weight. As shown this curve is remarkably near to a straight line. It might have been expected that it would begin with a lower slope, and if the weight went up high enough, to tail off at a lower slope. Certain effects are however known to be operating which invalidate simple theories. The lift improvement at low speed has already been mentioned and perhaps the reduction in ground effect losses goes on as the speed increases. Again air intake efficiency may improve with forward speed. The jet angle is varying so that there is less vertical component from the jets at higher weights, but equally there is probably less air flow obstruction due to the jets and so the wing lifting efficiency may improve. At the higher speeds aircraft rotation to increase wing lift can be carried out more quickly. It has been necessary to do a large number of take-offs to get some statistical measure of effects such as these. Perhaps I could recommend at a meeting such as this that there is a need for a lot more theoretical study of wing lift combined with jet lift near the ground.



GROUND ROLL FOR SHORT TAKE-OFF

Fig. 23

FUTURE DEVELOPMENTS

I should like to close this paper with some observations about future developments for the V/STOL military aircraft.

Before useful statements can be made about what form future aeroplanes might take it is first necessary to consider what the operational requirements may be for future developments of this class of aeroplane.

One principal duty for the aeroplane is combat support for ground forces, or strike sorties behind areas of combat. For both of these functions the flight is likely to be carried out at a subsonic speed at low altitudes so as to avoid radar detection and interception. However because in the future there will be fewer types of aircraft in each air force, reconnaissance and some air superiority capability are usually thought necessary and these requirements can lead to the need for the type also to be supersonic. The size of such an aeroplane is broadly determined by the load to be carried and the radius of action required, together with other requirements such as manoeuvrability and the general level to which the aeroplane is equipped. Size is quite vital to the cost of the aeroplane and therefore is important in any particular design, but I want to discuss rather the design principles for this class of aeroplane, in particular the application of V/STOL.

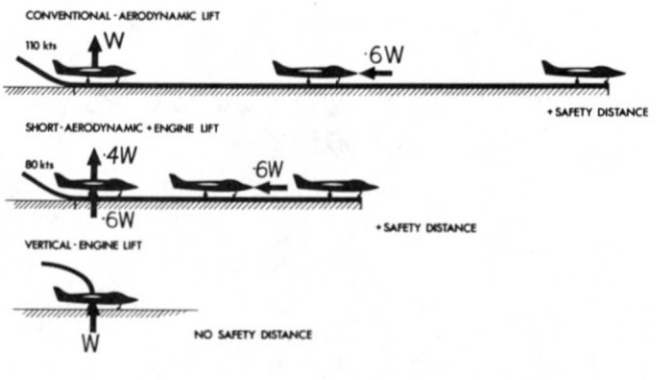
Coming to the question of field length, there is no doubt that serious consideration has been given on a world wide scale to getting away from aerodromes. The V/STOL aeroplane of course offers the ultimate flexibility but while the technical feasibility of the supersonic V/STOL aeroplane can be accepted the decision is lacking yet for it to appear as a production aeroplane, doubtless because of concern so far over the economics of the type.

The best so far achieved for supersonic production aircraft in respect of air field requirements is to improve on the conventional aeroplane by the use of high lift wings together with high thrust for take-off, and reverse thrust for landing. The landing in fact is the most critical manoeuvre for a STOL aeroplane and the best figures so far declared are approach speeds in the region of 100 kts. with a roll of about 1,500 ft. From an operational point of view, interest lies in the question as to what overall field length should be provided for safe operation of an aeroplane such as this. Clearly this could vary with the military situation, and risks could be taken for small numbers of operations. But a major air force operating in combat conditions would be carrying out enough sorties for the statistical level of the risk to make itself felt. Appropriate safety allowances would have to be made. For variations in the accuracy of the approach of the aeroplane, effects of weather and perhaps night operations. Such limited studies that exist on the effect of these variables suggest that the field length would need to be at least twice the ground roll. This gives a field length certainly very much less than military airfields as we now know them, but not so much less than the airfields for communication flying.

The V/STOL aeroplane, when used for short take-off and landing, is inherently capable of doing better than this, and can with lighter loads give progressively shorter runs down to the zero distance of the vertical mode. Achievement of this capability has of course to be kept in mind at the design stage which in practical terms means providing enough wing area so that significant amounts of extra weight can be lifted at moderate forward speed. It is however not necessary to provide more wing area than will probably be necessary in any case for a combat aircraft to give it adequate manoeuvring capability.

It is of interest to note that the conventional aeroplane has to do some thrust vectoring if it is to stop in a short distance when landing. If the thrust can be turned through 180° to stop the aeroplane it is of interest to consider what could be achieved if it was first turned through 90° and used to support some of the weight in the landing approach. The weight of the equipment to do this, additional to what is already provided in the aeroplane, is likely to be similar to the weight of typical high lift devices.

This argument is illustrated in Fig. 24 which shows at the top the landing conditions when using high lift only and below that the conditions if lift is used to carry part of the weight. If all other factors were equal the ground run would be reduced in the second case in proportion to the reduction of lift on the wings. In fact lift coefficients may not be so high for the aeroplanes using engine lift but for this aeroplane to lose all the benefit it would require the conventional aeroplane to have a lift coefficient 2.5 times as great (for the figures shown) and this is far more than will occur in practice. This simple analysis demonstrates that engine lift can be an extremely powerful high lift device and this is borne out in practice by the fact that the Harrier when operated in STOL modes can demonstrate ground rolling distances much shorter than STOL aircraft which do not use engine lift.

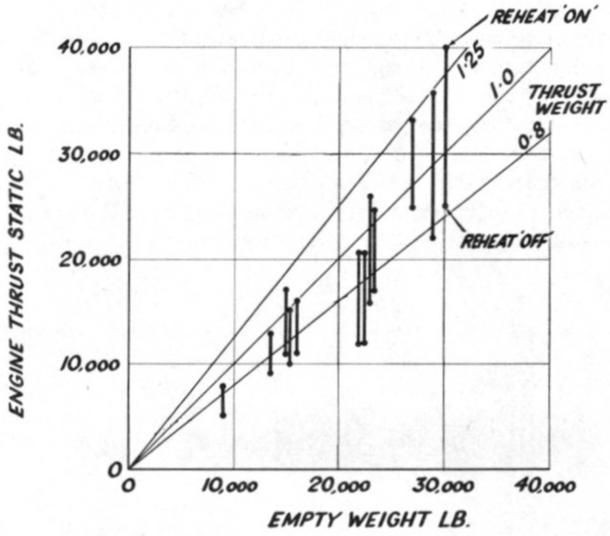


LANDING MANOEUVRES

Fig. 24

If engine thrust is used, in the way discussed, only to achieve STOL it does not give the full operational flexibility of the V/STOL aeroplane. It is therefore of interest to consider how much extra thrust this class of aeroplane may need, beyond what is required for in flight use, to provide the vertical mode of operation. Strictly this can only be answered within the context of stating how much load is to be carried in the vertical mode. As a minimum, the achievement of a vertical landing would seem to offer a high proportion of operational advantage, leaving the take-off with full load to be performed in the S.T.O. mode. Obviously since the landing must include a certain amount of remaining fuel and stores, there will also be a limited V T.O. facility.

An examination of some supersonic aeroplanes shows that in fact the engine test bed thrust is typically equal to the empty weight, Fig. 25. It therefore does not require an excessive increase in thrust to achieve the condition of a vertical landing for this class of aeroplane.



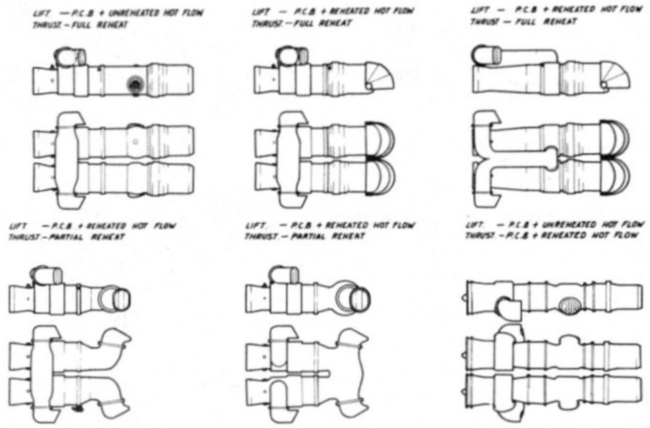
ENGINE THRUST/EMPTY WEIGHT COMPARISON

Fig. 25

To summarise these general lines of argument it would seem that we should examine further the economical use of engine lift without demanding that it should lift too great a load in the vertical case and we could also expect that this aeroplane would have an STO capability with maximum load equal to that offered by any other design.

I should now like to come to some of the engineering considerations which influence the ways in which the V/STOL aeroplane can develop.

Firstly there is the question of the engine arrangement. Experience on ways of diverting engine thrust is now very considerable. In addition to the classic four nozzle arrangement of the Harrier the experience on thrust reversal offers other ways of diverting the jets and these have been studied with rotatable cascades. Many possible arrangements of nozzles can therefore now be devised and some considered in current studies are shown in Fig. 26. These are shown in twin engine installations but in each case a corresponding single engine installation can be envisaged if that is the preferred design choice. While development is always required to fit additional nozzles such as these to a given engine, the arrangements shown are all generally within the present state of the art, and hence reliable predictions can be made about their performance, weight and cost.



ENGINE CONFIGURATIONS

Fig. 26

The size of the powerplant is quite vital to a V/STOL aeroplane and it must be kept within limits because of weight, size of installation and intakes, and cost. Keeping to the V/STOL requirement within bounds, and using some forward run for taking off with sizeable loads, has already been discussed as one design decision which can help in this matter. I should however like to draw attention to three matters within the engine itself which all help to ease the problem of the powerplant.

In the engine layout as shown Plenum Chamber Burning is used. This is an analogous to reheat for the conventional engine installation and is necessary to achieve supersonic speed. Equally it increases the thrust of the engine at take-off by perhaps 25% and this leads to a smaller basic engine for a given weight lifted.

Secondly the new technology engines are developing in the direction of smaller size and weight for a given thrust level. This must be of benefit to a type of aircraft requiring high installed thrust. Thirdly these engines are being designed so that they hold their consumption down to relatively low levels of thrust. This in fact must effect the balance of the argument in connection with lift engines because certain of the arguments in their favour depend upon the expectation that a single lifting engine is inefficient at cruising thrust.

If advantage is taken of all the points I have mentioned it can be expected that a future supersonic aircraft of the type I have been discussing could achieve the operational flexibility of V/STOL within the size and cost of aeroplane very comparable with conventional STOL designs. Just what form this aeroplane should take depends on a discussion with the users, but one possible layout is indicated in Fig. 27. This could be taken as an exercise to produce a supersonic version of the Harrier taking advantage of the matters I have already discussed. It does however provide one illustration of the fact that the engineering points I have mentioned can be brought together in an appropriate aircraft layout.

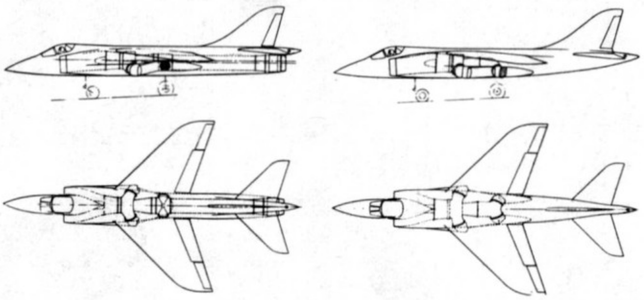


Fig. 27

FINAL REMARKS.

This paper has been restricted only to the V/STOL characteristics of military aircraft such as the Harrier, some of the technology involved, and some thoughts for the future. It has not been possible to give more than general impressions, but to conclude I should like to leave three items in mind for further thought.

1. V/STOL aircraft are now going into Service and further experience will be building up on how this class of aeroplane can be best used to deploy air power away from aerodromes.

2. The technology to join together the V/STOL characteristics with all the other features of an operational aeroplane is well established, at least for the single engine vectored thrust aeroplane. The problems mentioned however, taken across the field of all possible layouts of V/STOL aeroplanes, represent an expanding area of new technology should be of considerable interest to this Conference.

3. The development of the vectored thrust layout to more advanced aeroplanes represents an interesting and immediate design challenge. The provision of a V/STOL capability, while providing the maximum possible flexibility of ground operating conditions, may be no more of a problem for the military combat aircraft of the future than the provision of short take-off and landing by conventional means.