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COMBINED LIFT AND PROPULSION

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The vital importance of dispersion of military aircraft when on the ground becomes increasingly clear as the years pass.

The war in the Middle East last year demonstrated forcibly that it is of little use to have an Air Force well equipped with modern aircraft if the pre-emptive strike can ground them all by complete immobilisation of their associated long airstrips. This leaves the helpless aircraft to be shot up on the ground at leisure.

Now adequate dispersion and concealment of close support military aircraft is only really possible with V/STOL aircraft. For current military strike aircraft VTO is, however, not the most economic mode of take-off, if the largest weapon load is to be delivered at the maximum radius of action. The benefits of STO are illustrated in Fig 1 where it can be seen that a 300 ft STO run enables the weapon load to be doubled, while maintaining the same radius of action.

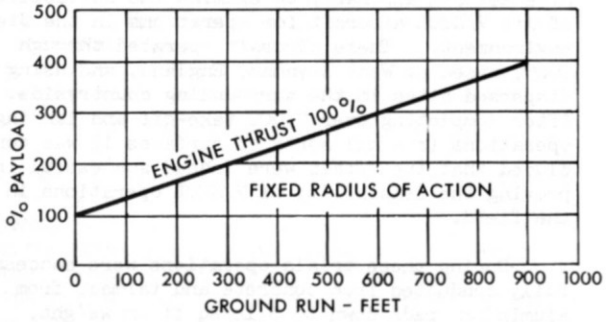


FIG 1 BENEFITS OF STO FOR AIRCRAFT WITH FULLY VARIABLE VECTORED THRUST

All V/STOL aircraft should use STO wherever possible. V/STOL aircraft should therefore be regarded as having a primary short take-off role, with the additional facility for vertical take-off and landing always available, at less than maximum payload or range.

We define aircraft with combined lift and thrust as those in which part or all of the installed thrust can be used either for lift during take-off or landing, or for propulsion in conventional flight. Currently, STO should be regarded as the primary take-off mode of aircraft with combined lift and propulsion engines. For any given aircraft and installed thrust the shortest STO can be obtained if the whole of the installed thrust can be directed in the optimum direction throughout the take-off run. This principle we know as Vectored Thrust.

Let us examine the flexible utilisation of the aircraft with a fully variable vectored thrust engine. Fig 2 illustrates how the vertical and horizontal components of the engine thrust, of say 20% above the normal aircraft weight, can be varied according to the actual all-up weight of the aircraft and the available take-off distance. The pilot can go from the true VTO, through the range of STO to the conventional take-off, and he can take off with ever-increasing all-up weight as the degree of wing lift increases.

In comparison, fixed lift and propulsion engined VTOL aircraft do not have this flexibility. Fig 2 shows how the thrust vector is fixed at around 1.4 W with much reduced options for STO.

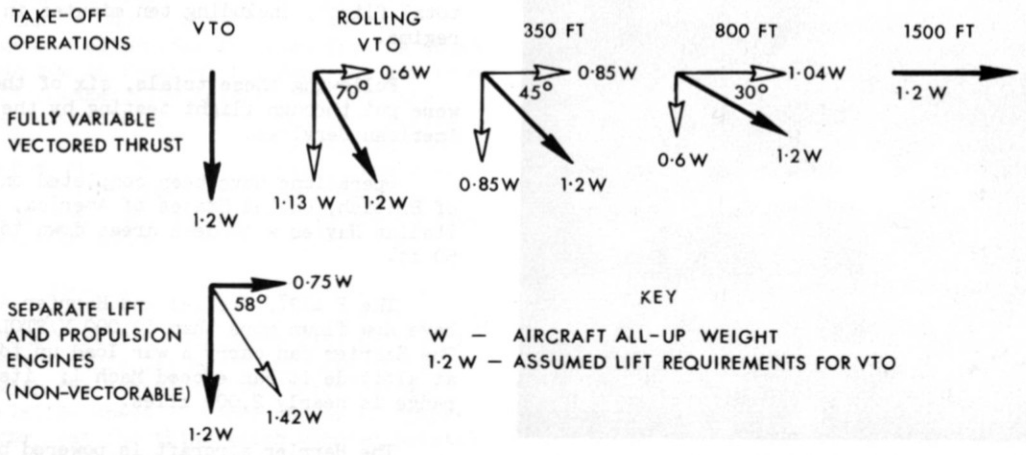


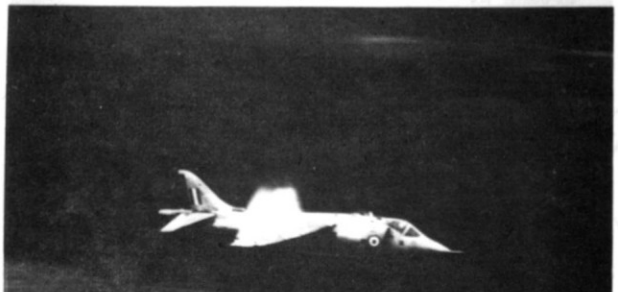
FIG 2 HORIZONTAL AND VERTICAL THRUST COMPONENTS

However, for VTO or STO aircraft the engine or engines to give the required lift for take-off are usually too large for the cruise case. Thus, for best cruise economy, part of the installed thrust must be shut down in cruise. This means that, for best range, we must have more than one engine in the aircraft. For the close support military application, however, a penalty in range may well be acceptable in face of the very great advantage of simplicity. The aircraft with the single vectored thrust engine then gives the overriding benefits of the V/STOL aircraft dispersion facility, without the complications associated with a multi-engine concept.

For 15 years the V/STOL aircraft has been a most fruitful field for the parametric studies which have poured from the technicians, and for the multitude of prototype aircraft which have been put into the air. If we quote from the 1968 Posture Statement of the USA Defense Secretary :-

"During the last seven years, we have invested a total of several hundred million dollars in the development and construction of a wide variety of V/STOL prototype aircraft, using different design approaches. None of them proved to be both technically and operationally feasible. Indeed we found that, technologically, the pacing item was the engine, and that until we had a suitable engine, none of the approaches were likely to produce a successful aircraft".

'LIFT'



'THRUST'
FIG 3

It is perhaps because of their basic simplicity of concept that the P 1127 and Kestrel aircraft have progressed steadily over the years, and have led to the Hawker Siddeley Harrier V/STOL close support strike fighter now about to enter into Squadron Service with the RAF. We think the achievement merits a few lines on the aircraft and the Rolls-Royce Bristol Pegasus engine which powers it. In describing these we shall establish a datum for the present status of the V/STOL aircraft with combined lift/thrust engines.

The development history behind the Harrier started some ten years ago when the early Pegasus engines were designed and development commenced backed by joint American/Bristol finances. The P 1127 Prototype aircraft were also taking shape as a Hawker Aircraft Private Venture, and in the Autumn of 1960, just twelve months after the first engine run on the test bed, the first aircraft hover took place. A year later both the take-off and the landing transition had been completed. As the engine thrust was increased development flying progressed, and the concept showed such promise that the United Kingdom, the Federal Republic of Germany and the United States of America agreed to sponsor a tripartite Squadron of nine Kestrel aircraft, to examine the suitability of jet V/STOL aircraft for operations in the field environment. These aircraft operated through 1965, based at West Raynham, England, and using dispersed sites in the surrounding countryside. After completing over 2,000 take-off and landing operations from all sorts of surfaces it was concluded that the trials were indeed successful in proving the feasibility of V/STOL operations in the field.

During these trials operations were successfully conducted from concrete and tarmac, from aluminium pads down to 3 lb/sq ft in weight, from various types of trackway, from polyester fibreglass and from snow-covered air fields.

The extreme simplicity of pilot conversion on this type of V/STOL aircraft is illustrated by the fact that pilots with widely varying experience can complete their conversion in some five hours total flight, including ten minutes in the V/STOL regime.

Following these trials, six of the aircraft were put through flight testing by the three American Services.

Operations have been completed on the ships of British, United States of America, and the Italian Navies with deck areas down to 100 ft x 50 ft.

The P 1127, Kestrel and Harrier Aircraft have now flown more than 10,000 V/STOL sorties. The Harrier can carry a war load up to 5,000 lb; at altitude it can exceed Mach 1; its ferry range is nearly 2,000 miles.

The Harrier aircraft is powered by a single Rolls-Royce Bristol Pegasus 101 engine. (Fig 4). This engine is rated at approximately 19,000 lb

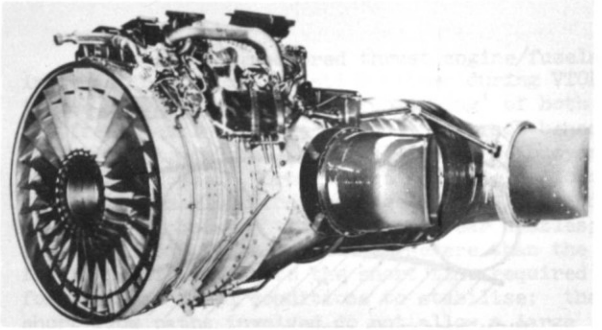


FIG 4 BRISTOL PEGASUS 101 ENGINE FOR HAWKER SIDDELEY HARRIER

of thrust, which is developed by four nozzles ganged together and rotatable to give the combined thrust in any direction desired by the pilot.

The Pegasus is fully Type Tested and has completed high density/high temperature testing to simulate flight at 0.95 Mn, world wide maximum temperature, together with icing and bird ingestion tests. The engine is now in quantity production for the RAF.

The engine is a high by-pass ratio ducted fan. Over 400 lb/second of air passes into the fan and is compressed to approximately 2:1 by three compressor stages. The LP compressor or fan discharges into a plenum chamber from which some two thirds of air passes to the front, or "cold" nozzles. The remainder passes into an 8-stage HP compressor with a single stage of variable geometry stators at the front end. The overall compression ratio of the two compressors is 13:1.

The HP compressor exit diffuser discharges into an annular vapourising type combustion chamber which develops a turbine entry temperature of a little over 1400°K at lift ratings. During V/STOL ratings the engine is delivering up to 10% of the HP compressor mass flow to the aircraft stabilising "puffer" jets. Four stages of turbine follow, two driving the HP compressor and two the fan. Both stages of the HP turbine have cooled stator and rotor blades. Finally the gases are split by the bifurcated jet pipe and discharged through the two rear or "hot" nozzles.

Note the economy of main bearings, which number only four (Fig 5). The LP system is supported by a thrust bearing aft of the fan and a roller bearing in the turbine outlet diffuser. This arrangement eliminates the need for the usual stator blade row in front of the fan, the air from the aircraft intakes flowing straight onto the first stage rotor blades. This feature enables the engine to pass the full icing schedules for gas turbines with no de-icing provision whatever. The fan rotor blades shed ice intermittently by centrifugal force, and no restrictions are necessary for operation under any icing conditions.

The HP system is supported by a thrust bearing in the intermediate casing aft of the fan, and by an intershaft roller bearing running on the LP turbine shaft. This latter is an interesting bearing; with the contrarotating rotor systems it has a relative speed of inner and outer tracks of 17,500 rpm, yet the thing which worried Bristol in the early days of the Pegasus was whether conditions might exist when the rotor speeds might be equal and opposite, when the roller cage would come to rest. The absence of centrifugal force on the rollers would then undoubtedly lead to their slipping with catastrophic results. Fortunately, worries in this direction proved without foundation, as the HP rotational speed is always greater than the fan speed.

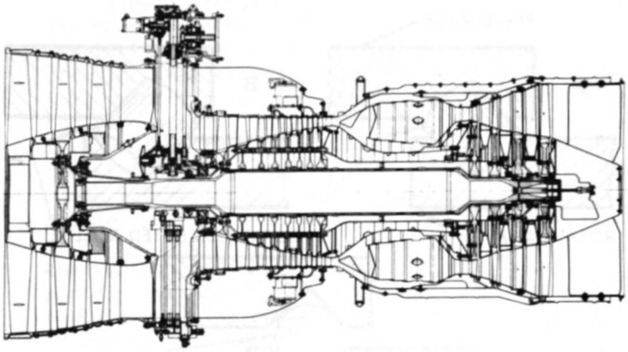


FIG 5 BRISTOL PEGASUS ENGINE

The complete integration between the Pegasus engine and the Harrier aircraft is well illustrated by the contrarotation of the two engine rotor systems. This feature was realised to be of great importance for a V/STOL aircraft and the resulting absence of gyroscopic couples has led to an aircraft remarkably free from unpleasant trim changes during hover and transition phases of flight.

The large span between the bearings combined with the flexible casings resulting from the large engine diameter, has led to problems in meeting the 8g requirement. The combined deflections of casing and rotors when the pilot pulls 8g cause a reduction of rotor blade tip clearance at the rear of the HP compressor of over 0.030". Lack of full appreciation of this problem led to an engine failure in the air in the early days of the P 1127; titanium rotor blades **rubbed** on the adjacent titanium stator blade platforms and a severe titanium fire resulted. Material changes and increased clearances were required to effect a cure. This is the sort of problem which arises as a new flight concept progresses towards an operational aircraft.

Perhaps the most novel feature of the Pegasus compared with other gas turbine engines is the rotating nozzles which permit full thrust vectoring. The races on which the nozzles rotate were conceived as crossed roller races; these were of the crowded type, with no cage, in order to keep the weight to a minimum. Each roller ran with its axis at 90° to its neighbours. The races were quite satisfactory and gave low operating torques. However, the length of the roller in such an assembly must necessarily be equal to or slightly less than the diameter; unfortunately there are three ways in which these "square" rollers can be fitted into the square holes presented by the two races. (Fig 6). The rollers can be fitted in the two correct ways shown at A and B and in the incorrect way as shown at C, with the axis of the offending roller circumferentially disposed. It was almost inevitable that sooner or

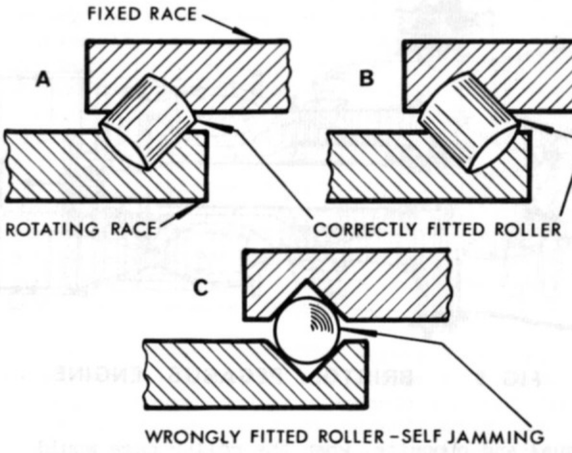


FIG 6 CROSSED ROLLER RACE ASSEMBLY FOR ROTATING NOZZLES

later a roller would be fitted in this incorrect attitude, and it could then become partly crossed and provide a splendid jamming mechanism. This of course could put an aircraft in extreme hazard in STOL or in the take-off or landing transition. It was apparent that a ball could only be fitted one way in a circular hole, and the Pegasus was rapidly modified to fit ball races for the rotating nozzles. (Fig 7).

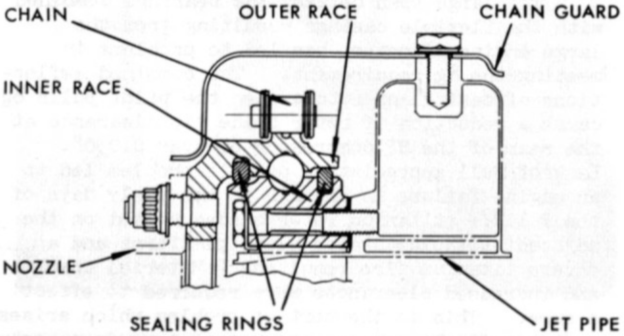


FIG 7 REAR NOZZLE RACE

This did not end the problem however, as the first ball assemblies on test gave high torques to operate the nozzles when the engine was running. This was found to be due to all the balls rotating in the same direction, giving rubbing forces at the point at which each ball touched its neighbour (Fig 8). This difficulty was solved by reducing the size of each alternate ball slightly. These small balls were now free to rotate in the opposite direction to the large load carrying balls; the torques required to operate the revised ball assemblies fell to the original values of the roller races.

Periodic lubrication of the roller races is necessary, but apart from this they give trouble-free service. The nozzles themselves, which carry very large vectored loads of the order of 20,000 lb when in high-speed low level flight, have proved a major problem, since it was essential to keep their weight to a minimum. Early prototype Pegasus P1127 aircraft flew with laminated glass fibre front, or "cold" nozzles, but these were discontinued owing to the extreme difficulties of maintaining the quality of such a complex structure in this material. Nozzles of welded sheet metal construction were adopted and these have proved satisfactory. It has been found possible to obtain lower thrust loss coefficients with only two vanes in the nozzles, compared with the original five vane type. This of course has led to considerable simplification of construction and the reduction in weight of each nozzle to about 40 lb.

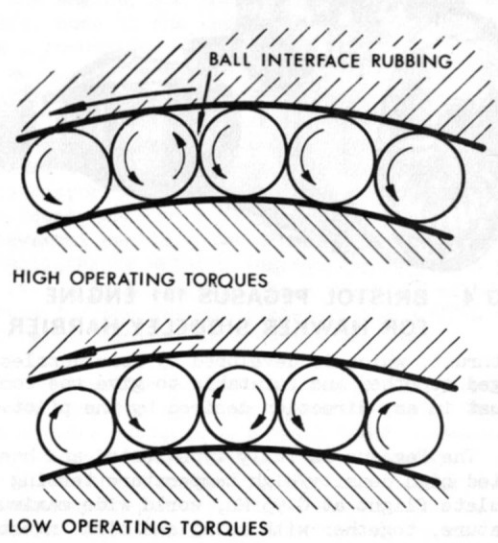


FIG 8 BALL RACES FOR VECTORED THRUST NOZZLES

V/STOL aircraft that depend on jet lift necessarily create an environment containing quantities of hot engine exhaust gas. If any of the hot gas should enter the engine air intake the associated temperature rise of the intake airflow causes a reduction in the available vertical thrust and in the extreme can cause compressor surge due to maldistribution (i.e. hot streaks).

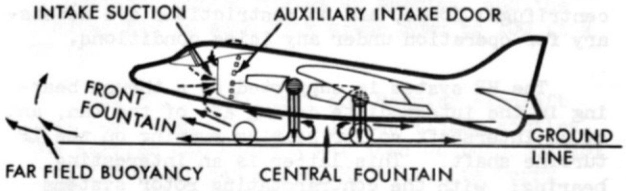


FIG 9 NEAR AND FAR FIELD HOT GAS INGESTION IN VTO

For a single, vectored thrust engine/fuselage installation the re-ingestion arises during VTOL in the near field, due to 'fountaining' of both the front nozzle effluxes as they interact beneath the aircraft, and in the far field due to buoyancy effects (Fig 9). Normally the near field 'fountain' extends along the fuselage centre-line and transversely between the front and rear nozzles; the near field fountain is more severe than the far field effect due to the short time required for the near field conditions to stabilise; the short flow paths involved do not allow a large temperature reduction in the gases by mixing with the surrounding air. In headwind conditions, however, the buoyancy effect can also present a problem owing to the 'rolling up' of the jet flow along the ground.

On the Harrier installation however, the relatively cool air from the front nozzles completely shields the intake from ingress of hot gases from the hot rear nozzle efflux. Model tests have shown that the degree of ingestion is quite insensitive to jet pipe temperature. The ingestion which occurs is therefore a function of the modest temperature rise in the fan, and is correspondingly less severe than on many V/STOL aircraft. Ingestion effects are critically affected by the nozzle angle; a 10° aft movement of the nozzles from the vertical approximately halves the ingestion effect.

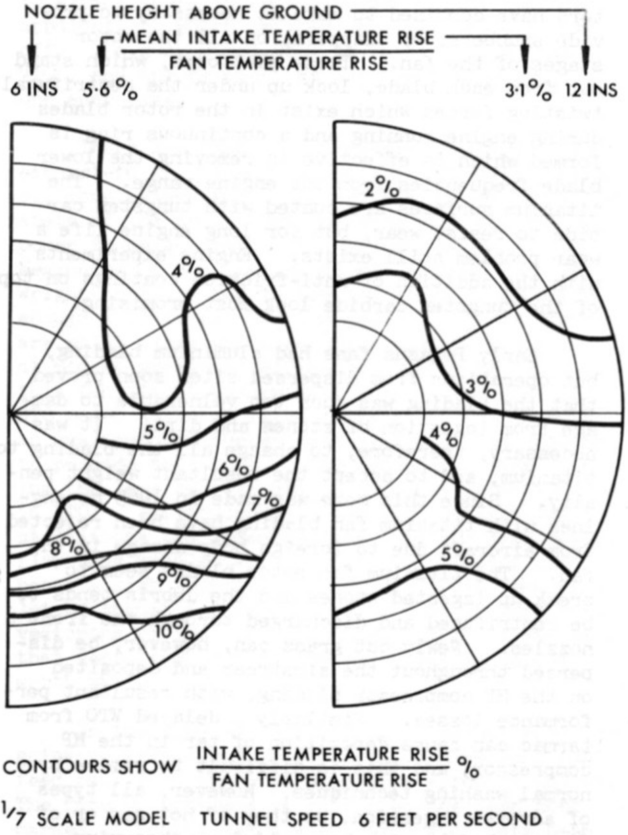


FIG 10 FAN TEMPERATURE DISTORTION CONTOURS AFTER ONE SECOND - VTO CONFIGURATION

Time is fundamental to the formation of hot gas masses around a VTO aircraft, and on the Harrier it is found that about 5 seconds after rotating the nozzles to the vertical is the critical point if the aircraft has not by then commenced to ascend. The mean engine intake temperature will by then have risen some 5% of the fan temperature rise, due to the contamination of the clean intake air by the fountain from the front nozzles. This will cause an engine thrust loss of 2½% or about 400 lb. Assuming however that the vertical climb has commenced, the situation rapidly improves. Fig 10 shows comparative results on a 1/7 scale model, with its nozzles 6" and 12" above the ground, both at 1 second from commencement of the test (equivalent to about 5 seconds at full scale). It can be seen that the increase in height has halved the mean intake temperature rise due to hot air ingestion.

Assuming the aircraft is headed into the wind during VTO this has a most beneficial effect on the near field ingestion problem. Ingestion of the far field cloud can however be aggravated, as it tends to be rolled-up by the wind and blown back into the aircraft intake. For VTO in still air the far field presents no problems. Nor is its effect noticeable in the rolling VTO (nozzles at 80°) or in the STO probably because the times involved are so small. Indeed one of the maxims of VTO should be "get up and get out of it".

Note that hot gas ingestion presents no particular problems in vertical landing, though sink rates may increase at the last moment. On the Dornier Do 31 aircraft, jet borne by eight Rolls-Royce RB 162 and two Rolls-Royce Bristol Pegasus engines, (Fig 11) the standard landing procedure is to ease back the Pegasus throttles until the aircraft descends low enough for the engines to feel the effects of hot gas ingestion. The throttles are then left alone until the aircraft touches down. No undue sink rates result and the procedure is simple and satisfactory.

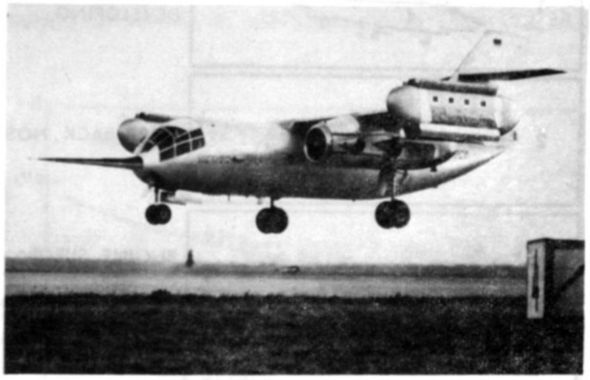


FIG 11 DORNIER Do 31 IN HOVER POSITION

Fig 10 also shows the engine intake temperature rise distribution due to near field ingestion. As would be expected the hot air is concentrated at the bottom of the intake. This maldistribution of hot gas can, if it becomes severe, extend up-wards to cause a sufficiently adverse HP compressor intake distortion to produce surge. On V/STOL engines large overfuelling surge margins are necessary to provide a margin against the dangers of hot gas ingestion.

The Pegasus overfuelling surge margin of around 100% at lift ratings has in general proved adequate for the requirements of an operational V/STOL aircraft. On two occasions in the whole history of the Harrier and Kestrel aircraft, however, extreme head up attitudes have been assumed when very close to the ground during slow landing operations, and power increases were called up at the same moment with hot air and gas being directed forward by the resultant forward nozzle angle. The sequence of Fig 12 taken from a film shows one of these incidents, which occurred during the Evaluation Squadron assessment of the Kestrel in 1965. The aircraft experienced nose down trim approaching a near vertical landing. To correct this the control stick was pulled back with over-correction to a 20° nose up attitude. At this moment, with hot gasses and air trapped between the aircraft itself and the ground and directed forwards, a power increase was called up to check the rate of descent.

Engine surge occurred, though the power losses were so momentary as to have no adverse effect on the landing. Indeed in this case the pilot concerned knew nothing of the surge until it was reported to him later! It is important to note that with an adequate surge margin such an incident can only take place with the aircraft almost touching the ground.

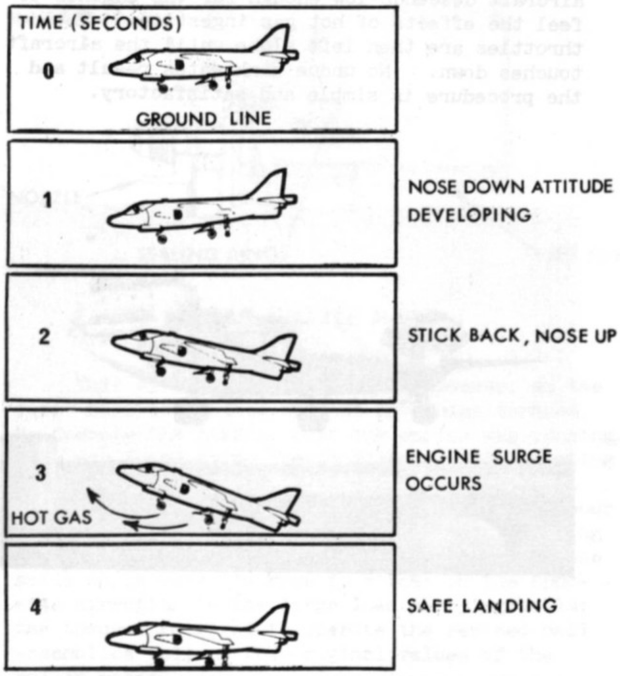


FIG 12 ENGINE SURGE DUE TO HOT GAS INGESTION AT END OF VERTICAL LANDING

The Harrier intake has been the subject of very considerable development as a result of extensive model and flight testing. Because of the importance of weight saving, the intake was kept short and variable geometry was excluded, except for the provision of auxiliary intake doors aft of the intake lip, which open under engine suction conditions. Boundary layer bleed doors are also provided on the fuselage walls, which open under intake spillage conditions in conventional flight.

Referring back to Fig 3 it is clear that the bifurcated intake provides conditions which are ideal for second engine order (2 EO) excitation effects in the fan. The junctions of the intake lips with the fuselage walls also produce areas of high pressure loss, giving a 4 EO excitation effect. In conventional flight the aircraft incidence produces higher losses at the bottom than at the top of the intake. This effect can lead to 3 EO excitation. In conventional flight when the engine is throttled back at high aircraft forward speed, considerable intake spillage occurs with consequent diffusion and danger of breakaway on the fuselage walls. It is a tribute to those who have worked on the development of this short and difficult intake that the distribution has been made acceptable to the engine

On the Pegasus engine it is the division of the major proportion of the fan delivery air into two parts for discharge through the front nozzles that provides powerful 2 EO excitation. This is felt in the latter stages of the fan and also at the front end of the HP compressor. These factors have combined to make it necessary to provide snubbers, or clappers, on all the rotor stages of the fan. These platforms, which stand out from each blade, lock up under the centrifugal twisting forces which exist in the rotor blades during engine running and a continuous ring is formed which is effective in removing the lower blade frequencies from the engine range. The titanium surfaces are coated with tungsten carbide to resist wear, but for long engine life a wear problem still exists. Engine experiments with the addition of anti-friction coatings on top of the tungsten carbide look most promising.

Early Pegasus fans had aluminium blading, but operations from dispersed sites soon proved that the blading was much too vulnerable to damage from ingestion of stones and dirt. It was necessary, therefore, to change all the blading to titanium, and to accept the resultant weight penalty. Since this move was made in 1965 no engines with titanium fan blading have been rejected from aircraft due to foreign body damage in the fan. The titanium fan rotor blades seem to break up ingested stones and the debris tends to be centrifuged and discharged through the front nozzles. Newly cut grass can, however, be dispersed throughout the airstream and deposited on the HP compressor blading, with resultant performance losses. Similarly a delayed VTO from tarmac can cause deposition of tar in the HP compressor, and this is difficult to remove by normal washing techniques. However, all types of adverse ingestion, be they of hot gas or of foreign bodies, can be avoided by observing quite simple take-off and landing techniques.

Before turning from the Harrier to other combined Lift and Thrust installations it is opportune to note the very great dividends obtained on a V/STOL aircraft by increases in the engine thrust. For a vertical take-off every pound of additional engine thrust enables the same weight of extra fuel or weapon load to be carried, and the benefits in STO are commensurate. The Harrier is far from the end of the line in the field of the simple subsonic V/STOL aircraft.

If we look at the years of experience which lie behind the Harrier and its engine, they can be summarised by saying that operations V/STOL military aircraft must be rugged and above all they must be simple. Only then can the true benefits of V/STOL be fully exploited.

Up to this stage the paper has dealt with some of the thinking that led to the Pegasus for the Harrier and has shown that this is a good solution, and there is still a lot of stretch potential.

Let us now examine the basis of our assumptions a little to make sure that we understand the basis on which todays conclusions are founded and how some of this basis may change in the future.

So we go right back to fundamentals and note that there are a considerable number of ways of using the power produced by an engine in order to get the aircraft off the ground, and a lot of varied aircraft roles, military, civil, long range, short range and so on, so that it is not reasonable to expect there to be a fundamental law for all applications which defines the best mode of take-off. In many cases STOL is better value than VTOL, and the Harrier, as has been explained, is one such case.

There are complex inter-relationships between parameters on the engine and aircraft which change our conclusions about the optimum according to the state of the art. For instance with the low power to weight ratio of a piston engine at the beginning of the century it was obvious that the Wright brothers had to use the wings to generate enough lift to get off the ground. Where there are still wings which generate significant lift at modest speeds an effective compromise is to use this facility together with some direct lift in an STO mode, although it is quite practical to have an unwinged helicopter or a system of jet engines to provide this lift. The higher the wing loading the less benefit can be obtained from the wing in STO. Particularly in the case of lift fan installations the momentum drag from the high mass flow fans coupled with a high wing loading and hence a high transition speed will mean needing a lot of thrust for transition. This in turn makes vectoring of the lift fans important, and may mean that vectoring of the propulsion engine is not worth while.

In the same way the thrust to weight ratio is going to affect our conclusions because this can feed back into the most desirable aircraft layout. The rate of progress in this area has been most marked of recent years when components have been evolved to carry out a higher duty, particularly more compression per stage in the compressor, more expansion per stage in the turbine, and less volume for the combustion. How far this process can be continued is always a hazardous guess, but we can certainly see our way to some further steps without a major breakthrough in materials or construction techniques.

We can see from Fig 13 that we have now got propulsion jet engines as light as the first lift jet engines. The achievement over the last 10 years has been to double the thrust to weight ratio.

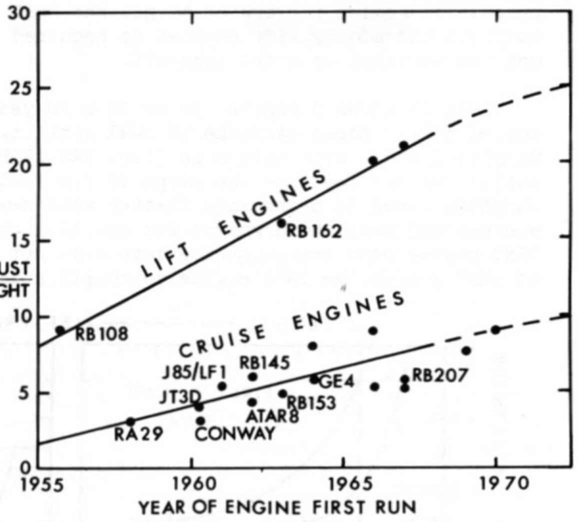


FIG 13

If this was the only important parameter we could perhaps hope for this trend to continue. But having got reasonably light engines, the importance of weight decreases in relation to other parameters such as fuel consumption, volume, noise and so on. The lowest weight solution can be achieved by a small number of components loaded very heavily and working hard, which is the opposite solution to getting the best fuel consumption and lowest noise.

Increasing pressure ratio has been a traditionally rewarding way of getting better fuel consumption but we have had the bulk of the improvement that we can hope for in that direction, although increases do still pay off. (See Fig 14).

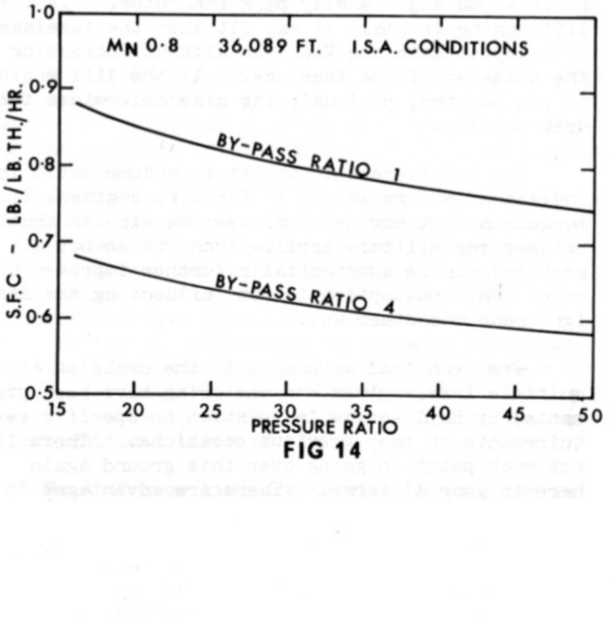


FIG 14

The most important area to exploit in the next 10 years is likely to be improved component efficiencies at the same weight rather than further weight savings, but it will be our customers who make the choice.

A very major contribution to the usefulness of the aircraft over longer ranges is the fuel consumption during the mission, and it is here that the major argument comes for having the powerplant of a V/STOL strike aircraft complicated by sizing the propulsion engine for cruise to get the best consumption and adding lift engines as required to get the vertical or short take-off.

Fig 15 shows 3 engine cycles in a 10 year period and compares each one at full size (i.e. Harrier layout) with half size (i.e. VAK 191B layout). We can see that the slope of the fuel consumption curve is being made flatter with newer engines and that the argument for adopting the lift engine plus cruise engine layout is not nearly so strong with the 1974 engine consumption loop.

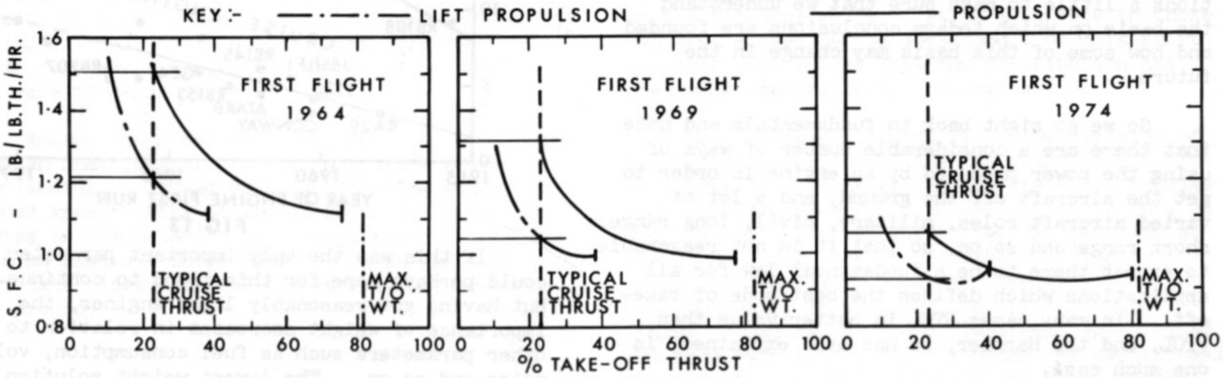
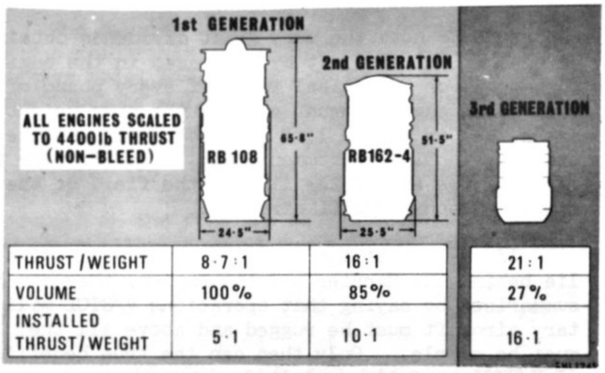


FIG 15 COMPARISON OF SPECIFIC FUEL CONSUMPTION USING PROPULSION AND LIFT / THRUST PROPULSION V.T.O.L. SYSTEMS
Mn 0·9 SEA LEVEL I.S.A. CONDITIONS

The weight of fuel saved in the mission has to be offset against the weight of the lift engine installations but as the lift engines are of better thrust/weight ratio than the propulsion engine this is not usually a problem. If the lift engine is large in size it is difficult to tuck it out of the way and this is one of the problems of a high speed machine which is launched by a helicopter rotor - you can't easily park the rotor. If the lift engine is small it may fit into the fuselage of a layout like the VAK 191B without increasing the diameter of the fuselage. If the lift engine is pod mounted, obviously its size determines the drag penalty.

The achievement in thrust to volume ratio is indicated in Figs 16 and 17 for lift engines. If the market in lift engines improves one expects that volumes for military applications (noise not a problem) can be substantially further improved because fuel consumption is not influencing the design trend the other way.

The technical arguments in the decision of multiple lift engines and vectoring have been presented by Rolls-Royce in relation to specific requirements on many previous occasions. There is not much point in going over this ground again here in general terms. There are advantages in both layouts which must be examined for each particular aircraft role.



	1st GENERATION	2nd GENERATION	3rd GENERATION
THRUST / WEIGHT	8·7 : 1	16 : 1	21 : 1
VOLUME	100%	85%	27%
INSTALLED THRUST / WEIGHT	5·1	10·1	16·1

FIG 16 VTOL ENGINE COMPARISON

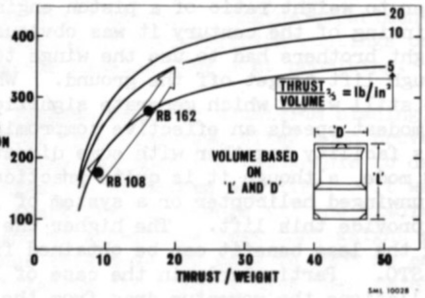


FIG 17 STRIKE-RANGE IMPROVEMENT

Some of the important effects are :-

1. Top speed of the aircraft or energy for manoeuverability (acceleration or climb rate) if high, will mean that reheat on the whole engine air flow is needed. A limitation of the 4 nozzle engine of the Pegasus or RB 193 type is that burning on all 4 nozzles is going to be complicated, as well as the drag from protruding nozzles becoming significant at high speeds, unless careful attention is paid to area ruling of the aircraft. But the 4 nozzle system almost entirely eliminates base drag. A conventional reheat layout looks more

attractive installationally and for the design of the control system. There is of course an overlap where a 4 nozzle engine with burning on the front nozzles is a good solution, and you will recall that this was well advanced in development before the cancellation of the P 1154 and known as PCB.

PCB has the attraction that by burning in the cold air stream, the available temperature rise is large because the fan pressure ratio is small and no prior combustion has taken place. If the bypass ratio is large then most of the engine air flow is available at the cold nozzles and the thrust boost is quite considerable. See Fig 18.

P C B ARRANGEMENT

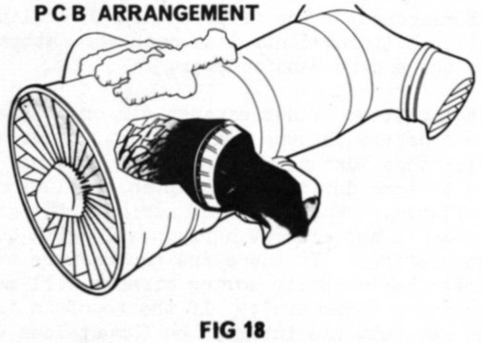


FIG 18

It is of course quite practical to vector reheat in the manner adopted on the VJ 101C aircraft, (Fig 19), that is by rotating the engine complete with reheat pipe. Although this is mechanically complicated it looks simple compared to Tilt Wings with Propellers and Cross Shafting. This layout is more suitable in the context in which it was proposed i.e. an interceptor where you want to get up and away very quickly but is in danger of re-ingesting the reheated exhaust gases unless the take-off is done very quickly or not quite vertically.

FIG 19 VJ.101C AIRCRAFT

Swivelling reheat has also been shown to be practical in a test on an RB 153 engine carried out by MAN. (Fig 20).

Although this can be fully vectored through 90°, it is not a very easy installation problem to get the thrust line in the right place for all conditions.

There does seem to be keener interest today in military minds towards higher speeds and energies which, conventionally, means using reheat.

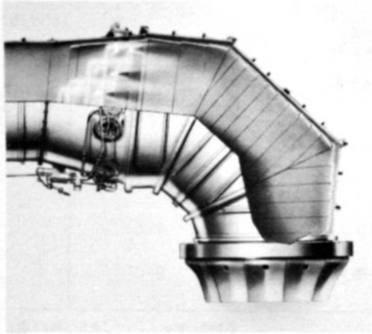


FIG 20 BENT REHEAT

But reheat has changed in relation to the engine. If you look at an early example it was a convenient way of producing extra thrust just by burning a bit of extra fuel in the pipe. The specific cost and specific weight of the power plants were improved by reheat. With the advent of the newer lighter and cheaper engines which need big diameter pipes because of the desire to take advantage of the better fuel consumption of fan engines, this is no longer so marked. If the thrust/weight ratio of a reheat system is no better than that of a lift engine, why not use a lift engine as a booster for the short period of combat rating usually needed in say a strike aircraft? The engineering for swivelling to get variable vectoring is similar to that of the VJ 101C and for retracting the engines is similar to that of the XJ 99 in the US/FRG. (Fig 21).

Such a layout has twin engine "get-you-home" capability which a single engine with reheat certainly has not.

2. The mission range is a major factor in determining the break even point for reducing the engine fuel consumption and the installational drag, against the complexity of the more sophisticated layouts.

Opinions differ widely about the range requirements of strike aircraft and until this situation hardens it is logical to continue with a simpler machine and gain experience of the other operational aspects as the RAF are doing with the Harrier.

But looking further ahead a military aircraft with longer range is going to be a continuing desire and this will maintain the impetus on reducing the penalties of the more sophisticated layouts.

3. In the case of civil transports we have seen a sharpening of interest in VTOL recently because of the problems of increasing air traffic density at major airports and the desire to get nearer to the city centre to city centre role. Certainly for city or near city operations noise has become a major factor in determining the powerplant design and this alone must mean moving more air more slowly, particularly since V/STOL aircraft must expect to come in under the general traffic pattern of conventional aircraft.

Fans of some kind are an elegant solution and

IN SERVICE DATE	THRUST / WEIGHT			THRUST / COST		
	NON REHEAT ENGINE	REHEAT SYSTEM	BOOSTER	NON REHEAT ENGINE	REHEAT SYSTEM	BOOSTER
1960	4·4	4·8	-	1	1	-
1967	4·6	8·0	7·0	1	2	1
1975	8·0	8·0	12·0	1	1½	1⅓

FIG 21 TYPICAL STRIKE FIGHTER – M_N 2·0 CAPABILITY

we can expect a lot of progress in fan layouts. A great virtue of the small fans is that they can give a higher degree of safety. Any solution which relies on one big rotor or a small number of fans in the wings depends upon absolute integrity of these rotating systems. Even if these are engineered to be as reliable as the aircraft structure, this philosophy is going to take a long time to be accepted. The multiple small fan can not only be allowed to fail without endangering the aircraft, it can also be tested and demonstrated much more easily on the ground by conventional techniques. There will be need to vector the thrust to some extent and this can quite readily be achieved with the swivelling engines or swivelling outlets. (Fig 22).

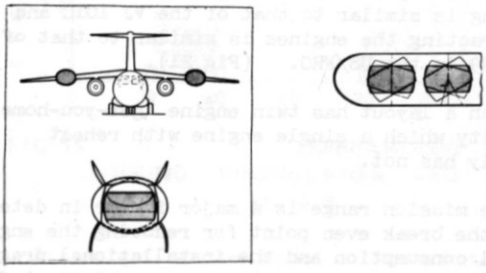


FIG 22 SWIVELLING LIFT FAN INSTALLATION

The layout of the Do 31 aircraft which was displayed at this year's Hanover show, is one which responds well to fan installations in the pods in order to reduce noise. This aircraft has shown that the control system works well. The fuselage mounted engine of the Harrier and VAK 191B have the disadvantage of requiring bleed of HP compressor air to operate the puff pipes for stabilisation. HP bleed is more severe the smaller the cruise engine because the absolute amount of bleed is the same, and the low compression lift engines produce less useful air, leaving relatively more work for the propulsion engine. In the case of the VAK 191B, the penalty is nearly 15% in de-rating and rematching compared to an engine with no bleed. High rates of bleed introduce combustion and mechanical problems. The problems are not insurmountable but may well mean making substantial compromises to the design, such as adding an extra turbine stage to drive the fan under full bleed conditions. HP bleed is therefore thoroughly undesirable from the engine manufacturer's point of view, and only continues to be used because no-one can think of anything better. The alternatives which give a better return of thrust usually fail to meet the need for a high rate of response. The differential throttling type of stabilising control is much more attractive to the engine manufacturer.

4. Re-ingestion of hot exhaust air or of stones and other debris thrown up by the jet outlets is a problem that must be reckoned with, but has been studied in some detail and acceptable solutions are available. When a jet of air hits the ground vertically it spreads out horizontally with quite high velocities. If there are two or more outlets these horizontally moving streams will meet and produce a "fountain". If the fountain is hot and can get into the intake, the thrust loss due to the increase in intake temperature can be very severe. The problem can be avoided by a rolling take-off, by having some cold nozzles such as from a 4 nozzle engine, or the outlets of fans, or by special jets of cold air to control the fountains or by attending to the geometry of the intake and the surrounding structure. The so called "far-field" problems caused by the hot exhaust air rising by virtue of its buoyancy can usually be avoided by getting the aircraft up high enough, quick enough, but effects such as this buoyant air rolling back towards the aircraft on a windy day are something the pilot must be aware of. As civil requirements result in low noise high bypass ratios, re-ingestion is not likely to give us much trouble in civil applications.

There now is wider acceptance that civil VTOL is both viable and practical because it offers the best chance of reducing the true journey time by a substantial amount e.g. 2 hours on the London/Paris run, and will cost less than at first appears because of the reduced terminal costs which the passenger at present pays directly or indirectly.

In conclusion we must not expect what is the optimum today to remain so for tomorrow and we must be prepared to take advantage of new possibilities. VTOL is with us now and by understanding what is practical it can soon become an everyday occurrence for both Military and Civil applications.
