C.P. No. 1082

C.P. No. 1082

MINISTRY OF TECHNOLOGY

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

A Discussion of some Jet - Lift V/STOL Aircraft Characteristics and their likely Effect on Operational Applications

by

D. Lean

Aerodynamics Dept., R.A.E., Bedford

LONDON: HER MAJESTY'S STATIONERY OFFICE

1970

PRICE *£1 0s 0d* [*£1*] NET

U.D.C. 629.136-118 : 629.136.5 : 629.13.081 :
629.13.087 : 533.682

C.P. No. 1082*
June 1966

A DISCUSSION OF SOME JET-LIFT V/STOL AIRCRAFT CHARACTERISTICS AND THEIR LIKELY EFFECT ON OPERATIONAL APPLICATIONS

by

D. Lean

SUMMARY

Some of the characteristics of jet-lift V/STOL aircraft are discussed in terms of their effect on the ability of these aircraft to operate from small, semi-prepared sites, without the usual airfield facilities, in both good and bad visibility. Accumulated experience from experimental operations with jet-lift aircraft has been used as a basis for a tentative extrapolation to situations and conditions not yet (in 1964) examined in flight.

An attempt is made to present these particular capabilities in such a way that future statements of requirements for this class of aircraft, and proposals for their tactical deployment may be formulated to take better advantage of such experience as already exists, and of the provisional conclusions that may reasonably be drawn from that experience.

In addition, attention is drawn to what appear to be some outstanding problem areas, and suggestions are made regarding a possible future programme of theoretical, model and full-scale work.

---

* Replaces R.A.E. Technical Report 66150 - A.R.C. 28443.
The author wishes to stress that, in view of the significant progress in the VTOL field, this Paper was originally written five years ago (1964).

CONTENTS

CONTENTS (CONTD.)

ILLUSTRATIONS

ILLUSTRATIONS (CONTD.)

1 INTRODUCTION

The acquisition of a background of operating and operational experience even remotely approaching that of conventional aircraft - or even of helicopters - will be an expensive and time-consuming process for V/STOL aircraft. The development of this class of aircraft could be strongly influenced by the existence of clear and realistic operational requirements, yet, paradoxially, these requirements are difficult to formulate because of this lack of experience of their capabilities and limitations which may, to some extent, be due to the uncertainty as to the precise requirements.

This Paper was written (in 1964) with a view to clarifying some of the fundamental capabilities of V/STOL aircraft, so that current and future statements of requirements may perhaps be formulated to take better advantage of such experience as already exists, and of the lessons that may reasonably be learned from this experience.

This somewhat ambitious objective is, however, restricted to the specific problems of take-off and landing, on the understanding that, outside these phases of flight, the capabilities of V/STOL aircraft may be determined by processes not fundamentally different from those for aircraft using normal techniques. Emphasis is laid on what are understood to be typical operating conditions - small semi-prepared sites, in more-or-less rugged and probably unfamiliar terrain, in good and restricted visibility.

Use is made, naturally, of the results of flight tests and experimental operations, and this data is used as a basis for extrapolation to situations and conditions which, so far, have not been examined in flight. Flight experience is, in fact, already sufficient for certain procedures to be recommended for take-off and landing in preference to others, and the extension of this experience by the use of estimated performance of typical aircraft allows further suggestions to be made for likely procedures in these new situations.

The Paper deals, first, with some of the problems likely to arise in operations from unprepared surfaces, and with ways of alleviating these problems, and of achieving possible performance benefits, by choice of optimum procedures. Then, the airborne manoeuvre of changing from hovering to conventional flight, and back again, is discussed in some detail, from the performance and handling aspects, again with emphasis on the small, restricted site.

Finally, some thought is given to the prospect of operating in restricted visibility, and possible procedures for approach and landing in these conditions are examined.

While an attempt has been made to keep the arguments and discussion as general as possible, in terms of the classes of V/STOL aircraft to which they apply, where it has been necessary to use real or hypothetical aircraft as examples, attention has tended to concentrate on the jet-lift V/STOL aircraft. This is certainly the field in which we have most practical experience, but the capabilities of other systems should not be overlooked. It is hoped that, even though the choice of examples is rather restricted, this Report may at least serve as a guide to the analysis of other systems. It will also become clear that, even in this field in which we claim familiarity, there are many questions as yet unanswered and some benefit may result from the underlining of the importance of such questions.

2 GROUND EFFECTS AND MEANS OF ALLEVIATION, FOR "PURE" VTOL OPERATIONS

Although "VTOL" has come to be associated with operations into and out of a 500 ft "strip", it is proposed to deal, first, with some of the operating problems due to ground effects that arise when true vertical, or "zero-length" performance is required.

2.1 Erosion and debris ingestion

Primary concern in this context is with protection for the aircraft, not the ground, although it should be remembered that in an operational situation, blast or scorch marks on the ground, or dust clouds, may be sufficient to betray the aircraft's presence. Further, it is obviously preferable to attempt to alleviate the problem at its source, rather than to burden the aircraft with protective equipment.

Wire mesh screens over the engine intakes involve a weight and thrust penalty, the latter being dependent on the percentage blockage caused by the mesh. The allowable mesh size should be roughly proportional to engine size (e.g. to the diameter of the first stages of the compressor), so that larger engines would suffer a smaller percentage thrust loss - or might even have no built-in protection at all. The S.C.1. (RB 108 engines) and P.1127 (BS.53 engine) illustrate the two extreme cases, the former having screens of about 0·05 inch hole size while the latter has no such protection. Both aircraft normally operate from prepared surfaces, but the "vectored thrust" feature of the P.1127 has allowed it to demonstrate take-off from grass surfaces which would have created problems for the S.C.1. This point is discussed more fully in a later section.

A further disadvantage of intake screens is that they are liable to blockage by vegetable debris, etc., which, in limited quantities at least, might not harm the engine had it been ingested. This situation has arisen on one occasion with the S.C.1, when the intake was blocked by grass mowings, and resulted in loss of thrust and excessive engine temperatures. In addition, certain combinations of air temperature and humidity produce a risk of icing on these screens, resulting in blockage which could have serious results. The case for dispensing with such screens on an operational aircraft is overwhelming.

This conclusion points to the need to ensure that no debris of a kind that could harm the engines becomes entrained in the intake flow. If this cannot be done by the adoption of the "rolling" take-off and landing techniques described in Section 3, then some form of ground preparation may be necessary.

We are hampered here by (a) lack of definition of what is meant by "unprepared" or "semi-prepared" surfaces and (b) lack of full-scale experience on the disturbance and distribution of debris caused by the operation of vertical lifting jets near such surfaces. The operators naturally await advice on what is likely to be a reasonable requirement, while the setting-up of a research programme involves some guidance as to the sort of surfaces that should be studied.

Some ad hoc experience is accumulating with the P.1127, aimed at showing that it can operate on a variety of surfaces, including both dry and wet turf, with no ground preparation. More relevant to the problem of preventing erosion is the work of Rolls Royce Ltd[1] which shows that small light-alloy plates on the ground will prevent erosion under typical jet-lift engines, during take-off. Somewhat more sophisticated measures, involving temperature-resistant plastic materials poured onto loose ground and allowed to set hard, were described by the Bell Aircraft Company[2] in 1960.

Some basic work on the conditions governing the start of erosion was started by NASA[3], and covered the whole downwash-velocity field from helicopters to jet-lift in broad outline. This work has been continued in detail but over a limited range of downwash velocities by the Hiller Aircraft Corporation[4], and a comprehensive summary of this, and related studies, is given in Ref.5. One simple conclusion is that the onset of erosion depends on the dynamic pressure of the outward flow close to the ground. Therefore, with increasing thrust over unprotected ground, erosion will begin where the dynamic pressure near the ground (q_s) reaches a maximum and the results given in Ref.3 indicate that this occurs at about 1 to 1.5 nozzle diameters from the centre line. The maximum value of q_s reduces rapidly with nozzle height, for a fixed nozzle dynamic pressure, to about a quarter of the nozzle pressure at a height of six diameters. This indicates that the erosion problem can be greatly alleviated by mounting the nozzles as high as possible on the airframe.*

If ground protection is necessary, the area to be covered is determined by the radius at which the value of q_s decays to a safe level. Appendix A shows that this decay is very rapid and that, for a given thrust, the area needing protection does not vary much with exit velocity. Fig.1 illustrates the effect of temperature on the radial decay of q_s. Fig.2, compares three different jets of the same thrust, and shows that, because the hot, high velocity jet is smaller in diameter than the cooler, low velocity jet, the radius at which a given dynamic pressure is reached is only slightly greater for the former. Even using a fan to give a 20 to 1 reduction in exit dynamic pressure would only halve the radius of the area needing protection.

The above model studies deal with the onset of erosion but give little information on the trajectories of the displaced solid particles. We are mainly concerned with those that might enter the engine intakes or otherwise damage the aircraft. For this reason, while model tests can be useful, particularly where actual lift engines can be used, special care should be taken to get representative intake flow conditions, so that the risks of damage can be properly assessed. It also seems fundamentally necessary to represent properly the transient nature of these effects during an actual take-off. The time spent at full power is only a few seconds, which must alleviate the problem to some extent.

To summarise, if true vertical take-off is required, the amount of protection needed on the ground can be quite small in extent. Light metal plates of about twice the diameter of the nozzle will prevent serious erosion of normal pastureland, etc. Landing on to such plates is neither practicable nor necessary, with this type of surface, since the engines are normally shut

---

*It should be noted that results are given in Ref.3 for jets with potential cores only about one diameter long. It is more usual for jets to have potential cores more than four diameter long and it is therefore possible that the values given for q_s in Ref.3 may not be quantitatively applicable to full-scale jets.

down immediately on touch-down. Both the S.C.1 and P.1127 have demonstrated this.

The exit area loading of the lifting system has relatively little effect on the surface flow, except immediately under the aircraft. The larger mass flow of the lower velocity cool jet could even be more damaging to nearby personnel and equipment, even though its dynamic pressure may be somewhat lower.

2.2 Recirculation

Allowance has always to be made, in performance estimates, for the loss of engine thrust due to a rise in intake temperature during take-off. These estimates are generally based on model tests, but the effect of model scale is uncertain, and representation of the transient nature of the flow is very difficult. Even then, the effect of transient intake-temperature changes on engine thrust is not obvious, and special bench tests may be needed. There is a general lack of model/full-scale comparison data in this field, partly because of instrumentation difficulties (the intake-temperature distribution is generally uneven, and changing rapidly) and partly because the take-off performance is affected not only by this loss of thrust but also by aerodynamic effects (ground suction), which makes the measurement of the individual effects very difficult.

It is worth considering, in general terms, the conditions likely to be conducive to significant recirculation effects, so that means of alleviation may be found. It is clear that convective effects, plus the powerful sink effect of the engine intakes, are mainly responsible for the temperature rise. It can be assumed that the intake will be located clear of the exit flow field, although this may require some design ingenuity when two or more hot jets impinge on the ground under the aircraft, since this condition can give rise to a powerful upward flow of hot gas in their plane of symmetry.

Convective recirculation will be encouraged by the rapid decrease in flow velocity parallel to the ground and the associated turbulent mixing and formation of eddies of hot gas. The closer to the aircraft that this process takes place, the more likely will recirculation become. Benefit could be obtained from any means used to increase the outward flow velocity. Thus, use might be made of deflectors, which, while restricting the free spread of the hot gas, might serve to maintain its velocity over a restricted sector, so that the convective flow could only occur well clear of the aircraft.

Similarly, the effect of slight inclination of the jet axis, relative to the normal, is also beneficial, although if true VTO is to be achieved, two or more nozzles are required, so that the horizontal components of thrust thus generated can be made to cancel out. Fig.3, based on data from Ref.6, shows that, at a given distance from the point of impact, a 20 degree inclination gives a 50% increase in local flow velocity.

The effect of wind is to cause a major distortion of the low velocity flow field. The above data also shows that the flow will penetrate up-wind only to the point where, if there were no wind, its velocity would have been twice that of the wind. Thus, for the examples illustrated in Fig.2, the hot jet flow would extend up-wind to about 50-60 ft, and the cooler fan flow to 40-50 ft in a 20 knot wind. These conditions may lead to excessive recirculation, if the heated air has risen to the level of the intake by the time it has been blown back to the aircraft, but it can be alleviated by a slight inclination of the jet axis in a down-wind direction, since the bulk of the flow will then be in that direction.

The above results are based on very limited data, and much more needs to be done, especially at full scale. It should be noted that, due to boundary layer conditions, the effect of wind, with the aircraft stationary, may be quite different from that due to forward motion of the aircraft itself. Full-scale tests on the S.C.1 [7] show that at forward speeds of 25 knots and above, the recirculation ceased, due to the containment of the forward part of the hot gas cloud under the wings, as the aircraft moved forward, even though the forward separation of the hot flow from the ground may have occurred relatively closer to the aircraft than if it had been at rest.

2.3 Heating effects

Because of the rapid fall in gas temperature with increasing distance from the jet, heating effects in general are not a serious problem. Those parts of the structure which are foreseen to be exposed to high temperatures can be designed accordingly. The lay-out of the S.C.1, with centrally mounted jets and main undercarriage units quite close together and near the jets (because of the small size of the aircraft) is probably as severe a case as will be met. The P.1127 has the main gear inboard of the hot flow, which is thus mainly away from the main wheels, etc., and although the outriggers are in the flow, they are a fair distance away.

Measurements on the S.C.1 [7] show that the surface temperatures reached even on elements exposed to the direct flow, are generally less than the estimated local gas temperature, and are less for metallic than for non-metallic (poorly conducting) materials. The time of exposure to the flow is also obviously important, and during a rapid take-off cycle the temperature rise may be only 60% of that of the local flow, relative to ambient conditions.

A note of caution needs to be sounded, however. Items like the undercarriage may act as deflectors, and result in hot "streaks" of gas reaching unprotected parts of the structure, or, worse still, finding access into equipment bays, etc. Similar effects may arise from interaction of adjacent nozzles, due to a strong upward flow in the plane of symmetry. Even with 4 closely-spaced nozzles, as on the S.C.1, evidence was found of hot gas flow upwards between the 4 engines, and a baffle had to be inserted to prevent this flow from entering the intake bay.

Provided that a careful model survey is done, there appears to be no serious problem in designing for the sort of temperatures likely to be reached on jet VTOL aircraft.

As far as the ground is concerned, high temperatures on natural surfaces will tend to make erosion more likely. Moisture acts as a binding agent on loose surfaces, and turf relies on the protection of the binding and reinforcing properties of the grass root structure as well as the surface vegetation. In time, therefore, most unprepared surfaces will erode, and it will be necessary to avoid repeated operations from one spot. Quite thin metal plates protect such surfaces from blast effects, although some drying-out must occur underneath. On heavy metal decks, however, the heating is restricted to a relatively small area, and the temperature rise, even directly under the jet, may be quite small[7].

2.4 Suction losses

It is now well known that the lift due to a jet emerging from near the centre of area of a wing near the ground is less than that available away from the ground. This loss is reduced if, instead of using a concentrated central jet, the nozzles are moved out, towards the periphery of the planform - leading ultimately to a ground cushion vehicle, with considerable augmentation of lift force.

Estimates of lift loss based on model tests are very difficult to confirm at full scale, because the effect is inevitably combined with thrust losses due to recirculation and intake temperature changes. The very scanty full scale data so far available (e.g. Refs.7, 8) does, however, suggest that there may be a favourable scale effect, by comparison with the model results of Ref.9. More work is needed to clarify this situation.

Obviously, every attempt should be made in the design stage to reduce this loss as much as possible, for example, by separating the lifting units so that a region of positive pressure can be created between them, to offset suction losses elsewhere, or by raising the height of the nozzles relative to the ground.

Little can be done to alleviate this loss for layouts for which it occurs, either by choice of procedures or the use of simple equipment "in the field". Of course, if a permanent base can be constructed, the loss can be eliminated completely, but this involves a major constructional effort (see, for example, the base illustrated in Ref.7). However, quite effective reduction in losses can be achieved by the use, for take-off only, of a semi-portable platform of the type developed for the S.C.1 (Fig.9 of Ref.7). Such a platform can get rid of almost all erosion, recirculation, heating and suction losses, but its use on dispersed sites could raise a formidable logistic problem.

3 USE OF "ROLLING" TAKE-OFF AND LANDING PROCEDURES

As currently envisaged, most VTOL operations will probably take place from sites on which there is at least the space available for ground runs of a few hundred feet, although the surface itself may not be suitable. There are two main advantages (and some problems as well) in using this space for both take-off and landing. Firstly, ground erosion and recirculation effects can be very much alleviated by forward motion, although other ground effects (heating, suction) may not respond so favourably. Secondly, even the limited space likely to be available might permit the use of airspeeds at take-off such as to produce significant and worthwhile increases in payload for no increase in installed thrust. These benefits are discussed more fully in the sections following.

3.1 Benefits of "rolling" take-off

For this procedure to be practicable at all, it is, of course, necessary that the surface be compatible with the undercarriage and tyre characteristics. Unfortunately, the emphasis on weight-saving in VTOL aircraft design may dictate against the use of large low-pressure tyres and a massive undercarriage. To some extent, therefore, a requirement for a reasonably smooth hard surface will ease the erosion problem which itself is one of the reasons for using a rolling take-off. Put another way, if the surface of the site is such that a rolling take-off is impracticable, then erosion problems are likely to be more serious anyway. Some further guidance from the operators of these aircraft seems essential, in this respect.

Erosion is a time-dependent phenomenon, and any procedure which reduces the time for which a particular point on the ground is subject to blast effects must be beneficial. For example, an RB.108 engine can be run continuously without any ill effects if it is moving forwards, at 10 knots whereas, if it were at rest, it would erode good quality turf in a matter of seconds[1]. Similarly a recirculation flow pattern must take a finite time to reach the height of the intake, and if the aircraft has some forward speed the hot flow can pass below the level of the intake.

Rolling take-offs with the S.C.1 and the P.1127 aircraft confirm these benefits on concrete, tarmac, and dry and wet grass surfaces. It should be noted, however, that the P.1127 configuration offers the great advantage that the start-up procedure can be done with the thrust line horizontal, and the take-off itself can be begun in the same condition. With the S.C.1 layout however the starting of the lift engines is necessarily done with the aircraft stationary, so that some local protection of grass, etc. surfaces would be required. With that layout, however, the propulsion engine can provide the horizontal acceleration, so that the lift engines need not be opened up to full power till the aircraft is moving forward fast enough to avoid erosion and recirculation.

Heating effects are not necessarily alleviated and may, in fact, be worsened by the adoption of a rolling take-off procedure. The effect of the relative wind is to distort the isothermals of the jet flow in a downwind direction, thus bringing different parts of the aircraft within the hot flow region, or exposing them to a hotter flow than when at rest. Such an increase in temperature has been observed on the S.C.1[7].

The lift losses discussed in Section 2.4 may be increased, rather than alleviated, by increase in forward speed, because of the mutual interference between the jet exhaust, fuselage-wing combination and free-stream flow. This loss in lift[10] is a function of velocity ratio (free stream/jet exit) and of the wing area surrounding the jet nozzles, and is present in and out of ground effect. As speed increases, the normal lift due to incidence begins to cancel the interference loss. Very little comparative data between model and full-scale are available yet, but rough measurements on the S.C.1[7] do at least show the loss on that aircraft to be greater at forward speeds up to 40 knots, compared with the vertical take-off case.

The effect of this interference loss is that a higher speed, and/or higher wing incidence must be used for a given lift increase, and this in general involves the use of a speed higher than that needed for the alleviation of erosion and recirculation and also some rotation of the aircraft at the unstick point, if the maximum performance benefit is to be achieved.

This performance benefit is likely to be the most important factor governing the use of the "rolling" take-off procedure, the elimination of erosion and recirculation losses requiring relatively low forward speeds. The advantage is that a "rolling" take-off is possible at a weight greater than that at which a vertical take-off could be made with the same installed vertical thrust.

Detailed estimates of this gain require a specification of the aircraft and the take-off procedure that is not appropriate to this qualitative survey, but some generalisations are possible. If the aircraft has separate lift and propulsion engines, or if it should not be possible to alter the nozzle position of the vectored thrust engine during the take-off, then the ground roll and unstick must be assumed to be made with the resultant thrust deflected to some fixed angle from the vertical. It is shown in Appendix B that, for a minimum ground roll distance, this fixed angle is simply $\cos^{-1} T/W$, and the resulting distance is a function of thrust/weight ratio and the conventional unstick speed, i.e. the unstick speed that would be used if the thrust line was along the axis of the aircraft. Fig.4(a) shows these distances for 3 values of the conventional unstick speed - 100, 150 and 200 knots. In order to retain the margin of 0.05g vertical acceleration which is recommended in Ref.11, the thrust actually used is less than the maximum available by an amount which would result in this acceleration increment being produced if thrust were increased without change in angle. Thus, the curves reach zero at a thrust/weight ratio of 1.05, instead of 1.00.

These simple estimates show that if, for example, a ground roll of 300 ft could be used - which may be appropriate to operations from a 500 ft "strip" - then the thrust/weight ratio could be reduced from the figure of 1.05 needed for a vertical take-off to 1.01 if the conventional unstick speed is 150 knots, or to 0.89 if the speed were only 100 knots. These reductions in thrust/weight ratio can be regarded as increases in take-off weight at constant thrust, if the conventional unstick speeds are kept constant by corresponding increases in wing lift coefficient.

These gains in permissible all-up weight represent very useful increases in payload or range, and well illustrate the value even of this somewhat cautious use of the rolling take-off technique. However, it is important to note that it does not make full use of the capabilities of one class of VTOL aircraft - the thrust-vectoring type that can use <u>all</u> its thrust for horizontal acceleration during the ground roll, and avoid ground effects at the same time. In the limiting case, the distances could be reduced still further as shown in Fig.4(b) by assuming rotation of the thrust-vector to the vertical at unstick. This is an extreme case because the aircraft could not accelerate after take-off, and in practice, some lesser rotation (typically to 20°-30° from the vertical on the P.1127) is used at unstick. In the estimates shown in Fig.4(b), the thrust/weight ratio actually used is 0.05 less than the maximum available, in order to provide the same margin of vertical acceleration as in the previous case. The analysis of this procedure is also given in Appendix B.

Compared with the previous example, the use of a 300 ft ground roll with this extreme technique would allow the required thrust/weight ratio to be reduced from 1.05 to 0.89 if the conventional unstick speed is 150 knots, or to 0.78 if that speed is 100 knots. Even for a conventional unstick speed as high as 200 knots, a thrust/weight ratio of 0.95 would suffice with this technique.

It is important to remember that the above discussion relates only to the ground roll performance, and takes no account of obstacle clearance requirements.

3.2 Lift margins during unstick and initial climb

The typical VTOL operating site is usually defined as being 500 ft in extent, surrounded by 50 ft obstacles. Adoption of the rolling take-off procedure therefore raises the question of safety margins during the airborne phase up to the point of clearing the obstacle. Because of the forward speed of the aircraft, only a limited time is available and a minimum vertical acceleration capability is thus defined. By contrast, true vertical take-off from such a restricted site is theoretically possible with a near-zero vertical acceleration, although in practice a margin of 0.05g is usually recommended.

Probably the best-known proposal for rationalisation of these margins is that of Ref.12. Strictly applicable only to direct-lift systems, this paper proposes that, if the climb-out manoeuvre requires the use of a vertical acceleration of ng, then the total available acceleration, Ng, should be given by:-

$$N - n \geq (0.1 + 0.35\,n)\,F$$

where F is an "alleviation factor" dependent on the proportion of total lift produced by direct engine thrust, i.e. not subject to limitation due to stalling or other high-incidence effects. Modifying slightly the form given in Ref.12, we define F as

$$F = \sqrt{1 - \left(\frac{P}{1.05}\right)^2}$$

where P is the proportion of total lift produced by direct thrust. When the direct thrust is sufficient for vertical take-off, i.e. when P has the value 1.05, F becomes zero and no additional lift margin is required.

For the purposes of the calculations in the next Section, however, it will be sufficient to assume that (N - n) should not be less than 0.05. The best climb-out performance is then obtained by using a vertical acceleration 0.05g less than the maximum available. This maximum includes the wing lift contribution, and occurs when the resultant thrust is deflected so that the horizontal component is just sufficient to maintain speed at the unstick value. At the low speeds considered here, the drag is low enough for the loss in vertical component to have a negligible effect on the vertical acceleration.

This procedure can be readily adopted on aircraft using vectored-thrust engines (e.g. P.1127), but may not be achieved exactly when separate lift and propulsion engines are used, (the latter remaining at full power), unless the aircraft is rotated to an extreme nose-up attitude in order to bring the resultant thrust vector to the required angle. However, the ability to rotate the lift engines in the accelerate sense means that the fuselage can be rotated to a nose-up attitude without losing the horizontal component of thrust. This enables some contribution from propulsive thrust to be added to the vertical lift.

It is sometimes argued that, because of the greater total installed thrust resulting from the use of separate lift and propulsion engines, a greater performance margin is available, compared with a thrust-vectoring layout. In fact, the difference is not really apparent in this initial climb-out phase, since this climb performance depends mainly on the vertical lift available. To the extent that the resultant thrust of the composite-engined aircraft cannot be rotated readily down to the optimum direction it can be said that some reserve of vertical thrust is available by rotation of the aircraft beyond its normally-used attitude.

Quite apart from the ground effect problem with separate lift engines, the take-off performance can suffer, relative to a thrust-vectoring layout, because the acceleration in the ground roll is lower. In addition, this acceleration will be maintained to some extent, (depending on the attitude chosen) after unstick, with a corresponding reduction in the time available to clear the 50 ft obstacle.

The real benefit (to the pilot) of the separate-lift-engines layout comes after clearing the obstacle, in that, for the same take-off performance, this aircraft, having a greater total installed thrust, will generally have a better acceleration or climb capability in the transition to wing-borne flight.

This brief discussion makes it clear that it would be imprudent to pronounce in favour of one layout rather than the other on the basis of take-off margins alone.

3.3 Take-off performance from restricted sites

The effect of these lift margins on the overall take-off performance is illustrated in Fig.5, for the vectored-thrust layout. The manoeuvre is made up of 2 parts (a) a ground roll using full thrust in the horizontal direction, and (b) a climb with the thrust approximately vertical, except for a small horizontal component sufficient to maintain speed.

The ground roll distance to the unstick speed, V, is given by:-

$$D_1 = V^2/2 \frac{T}{W} g ,$$

ignoring drag and friction. If the conventional unstick speed is V_{min}, the aerodynamic lift/weight ratio at unstick is simply V^2/V^2_{min} and with the thrust acting vertically, the nett vertical acceleration is thus

$$\ddot{h} = \left(\frac{T}{W} + \frac{V^2}{V^2_{min}} - 1\right) g$$

and the airborne distance to the 50 ft obstacle, at constant speed V, is

$$D_2 = V\sqrt{100/\ddot{h}} ,$$

while the total distance is simply $(D_1 + D_2)$.

Three sets of curves in Fig.5 refer to conventional unstick speeds of 100, 150 and 200 knots, each covering a range of thrust/weight ratios from 0.85 to 1.05. (The higher ratio is sufficient for a vertical take-off, nevertheless, a rolling take-off procedure may be necessary in order to alleviate ground effects.)

The effect of including the 0.05g margin can be found simply by subtracting this amount from the available thrust/weight ratio. For example, the curve for, say T/W = 0.95 with the 5% margin would be very nearly the same as the one drawn for T/W = 0.90 and no margin. However, when the wing lift contribution is significant, then some or all of this 5% reserve could be obtained by increase in incidence beyond the normal value, and little or no increase in engine thrust need be allowed. When the unstick speed is more than about one-third of the conventional unstick speed, this 5% lift margin could be produced by a wing-lift increase of less than 50%. At lower speeds, some of the margin would clearly have to come from an increase in engine thrust.

These results illustrate the fact that operations from the assumed 500 ft site require thrust/weight margins very close to unity, particularly when the wing-lift contribution is small (high conventional unstick speed). In fact, with the assumed technique, only the low wing-loading cases produce distances less than 500 ft to the 50 ft obstacle for thrust/weight ratios less than 1.0. This result is rather similar to that illustrated in Fig.4, which refers to the ground roll only, without consideration of the obstacle clearance problem. The improvements in take-off weight that can be achieved by use of a rolling take-off are small when the minimum conventional flight speed is high. Nevertheless, they may well represent significant gains in payload and/or range.

3.4 Some differences between take-off behaviour of vectored-thrust and composite power-plant aircraft

The take-off procedure assumed above for the vectored thrust power plant layout involves a change in thrust vector angle at the unstick point. The operating mechanism must have very high integrity, because the horizontal acceleration will be very high (almost 1g) and with the limited space available, a failure to operate must be expected, in general, to produce an over-run. In fact, assuming a 500 ft strip and an average braking deceleration of g/3, any failure above 50-55 knots would result in an accident of this sort. The need for integrity is emphasised by the fact that a full-power check of the operation of the vectoring mechanism is not possible before take-off. Fortunately, with the thrust/weight ratios needed for operation from a 500 ft strip, there is no need to delay the vectoring operation to higher speeds than the above, as illustrated in Fig.5.

The composite power-plant layout results in a similar problem, in that the lift engines cannot be checked at full power before take-off (unless special ground facilities are provided). However, the best performance requires the lift engines to be run at full power as soon as the forward speed is sufficient to alleviate ground effects (erosion and recirculation) and this speed may be as low as 20 knots. Lift engine failure at these speeds could be dealt with by normal braking, within the confines of the 500 ft strip.

Unstick and climb-out over the 50 ft obstacle will, in critical conditions, generally require some rotation of the aircraft in order to generate the needed aerodynamic lift, irrespective of the power-plant configuration. During the climb, particularly, a further change in attitude may be needed to maintain this aerodynamic lift, if there is a significant upward acceleration resulting in a steepening of the flight path.

These attitude changes will result in corresponding changes in the angle of the resultant thrust vector to the vertical, unless the pilot makes similar changes in the angle relative to the aircraft. The need for precision in making these changes is greatest when the maximum performance is sought, and the thrust vector has to be in its optimum direction. As explained above, it is not usually possible to achieve this optimum vector angle with the composite power-plant. To this extent, precision in attitude control may be less important, and the pilot's problem may be eased by the ability to increase the vertical thrust component by rotation beyond the normal attitude. But this advantage has to be weighed against the fact that, for a given take-off performance, the total installed thrust is necessarily greater with the composite power-plant than with the combined (vectoring) layout.

3.5 "Rolling" landing procedures and performance

The reasons for using the "rolling" landing procedure are so similar to those for the take-off case that it is worth interrupting the discussion of the take-off sequence to deal with this part of the landing now. Considering, for the moment, only that part of the landing from the 50 ft obstacle down to rest, the use of some forward speed may be expected to show advantages very similar to those for take-off, namely, alleviation of ground effects, and the use of some aerodynamic lift.

If we assume, as before, a braking deceleration of g/3, then using just half of the available 500 ft strip fixes a limit of about 45 knots for the maximum touch-down speed. At this speed, normal undercarriage design limits would probably require the flight path just before touch-down to be no steeper than about 6 degrees (1 in 10) and consequently the descent from the 50 ft obstacle will generally involve some reduction in rate of descent, i.e. a normal flare.

The excess lift required for this flare can come partly from the available aerodynamic lift, but the associated forward velocity makes it necessary to descend more rapidly, to avoid overshooting the landing area, and thus the required excess lift is greater than it would be if a slow, near-vertical landing were made.

A rough approximation to the distance involved can be made using some simplifying assumptions. We will suppose that the rate of descent is to be reduced to zero before touchdown. The flare is initiated by instantaneously rotating the thrust vector, T, to the vertical and increasing the wing lift coefficient to the value corresponding to level flight at the minimum conventional flight speed, V_{min}.

The nett vertical acceleration is then, approximately,

$$\ddot{h} = \left(\frac{T}{W} + \frac{V^2}{V_{min}^2} - 1\right) g$$

and if the descent angle is γ, the descent velocity, $V \sin \gamma$, will be reduced to zero if the flare is started at a height, h, where, roughly,

$$h = V^2 \sin^2 \gamma / 2 \left(\frac{T}{W} + \frac{V^2}{V_{min}^2} - 1\right) g \quad .$$

If this height is less than 50 ft, the total distance from 50 ft to rest, assuming that γ is small so that the above acceleration is roughly normal to the flight path and results in a flare which is a circular arc, and assuming $g/3$ deceleration in the ground roll, is approximately,

$$D = \frac{50}{\tan \gamma} + \frac{h}{\sin \gamma} + \frac{3V^2}{2g} \quad .$$

If the height is greater than 50 ft, the distance from 50 ft, still assuming a circular flight path in the flare, becomes

$$D' = \sqrt{100h/(1 - \cos \gamma) - 2500} + \frac{3V^2}{2g} \quad .$$

The above analysis is obviously too elementary for the estimation of absolute distances, nevertheless, the results plotted in Fig.6 are good enough to show obvious trends. Here, a range of thrust/weight ratios has been used, for 2 values of the minimum conventional approach speed and 2 glide angles. Clearly, for short-landing operations in the present context, thrust/weight ratios not far short of unity have to be available, even with no margin for correction of errors. In fact, for a true vertical landing, Ref.11 proposes that a total thrust/weight ratio of at least 1.15 should be available, and the application of the proposals of Ref.12 (in a form similar to that discussed in Section 3.2, above) also requires the availability of a vertical acceleration margins between 0.05 and 0.15g over and above those actually used, depending on the sharpness of the flare.

Secondary conclusions from the above analysis, illustrated in Fig.6 are (a) that the approach angle, over the 50 ft obstacle has very little effect on the total distance, because the steeper angle requires the flare to be started higher, and (b) that the actual thrust/weight ratio has less influence on the distance when the minimum conventional flight speed is lower.

The broad conclusion is that, while the "rolling landing" procedure may be beneficial from the point of view of alleviating ground effects, no great performance benefits can be expected if really short landing distances are required.

4 THE TAKE-OFF TRANSITION

4.1 Procedures with vectored thrust and composite power-plants

In this phase of flight the aircraft accelerates from a near-hover condition to one in which it can be entirely wing-borne, and in conventional flight.

Using the vectored thrust arrangement, the forward motion is initiated by a small rotation of the thrust vector in the accelerate sense. Unless the thrust is increased at the same time, a small loss in lift must result - though not necessarily a loss in height, if the aircraft is still climbing after lift-off. As forward speed increases, wing-lift becomes effective, and a further rotation of the thrust vector can be made. In theory, a continuous, progressive rotation could be made, but in practice (on the P.1127, for example) the thrust vector is rotated in a series of discrete steps, while maintaining the desired height or climb path.

For the pilot, this procedure has raised no particular problems in the absence of obstacles near the intended flight path. Obviously, the thrust vector angle must be very precisely controlled, but the pilots have achieved this precision without difficulty because of their high sensitivity to normal acceleration cues ("seat-of-the-pants" effect). Excessive rotation of the thrust vector is immediately sensed as a reduction in vertical acceleration, and corrected by stopping the rotation, and/or increasing wing incidence, once some forward speed is attained.

The procedure can be illustrated by the following simple analysis of the manoeuvre, for the vectored thrust configuration. It is assumed that the incidence is held constant throughout at the value appropriate to flight at the minimum conventional flight speed, V_{min}, and that the constant thrust, T, is deflected to an angle, θ, from the vertical so as to maintain zero nett acceleration normal to the flight path which is a straight climb at an angle, γ, to the horizontal. For simplicity, lift interference losses are ignored, and a constant aerodynamic lift/drag ratio (L/D) is assumed. Instantaneously, the aircraft, of weight W, is at a speed V, and a distance x from the start.

Then, for balance of normal forces, we have

$$\frac{T}{W} \cos (\theta + \gamma) + \frac{V^2}{V_{min}^2} - \cos \gamma = 0$$

and the acceleration along the flight path, $\ddot{x}$, is given by

$$\frac{\ddot{x}}{g} - \frac{T}{W} \sin (\theta + \gamma) + \sin \gamma + \frac{V^2}{V_{min}^2} \left(\frac{1}{L/D}\right) = 0$$

These equations lead to the results shown in Fig.7, for the case of a horizontal transition (γ = 0), for two thrust/weight ratios, 1.05 and 1.00. The start has been taken as a speed of 5 knots, because the aircraft hovering (V = 0) with thrust exactly equal to weight cannot, in fact, start the transition without losing some height. The transition ends at $V = V_{min} = 150$ kt, in this example. A nominal L/D ratio of 4 has been used, although, because the drag includes a momentum drag component, the ratio cannot, strictly, remain constant in this case. For illustrative purposes, this error can be ignored.

The variation of thrust vector angle with time is of particular interest. The rate of rotation is quite small in the early stages, but builds up to over 10°/sec. In practice, the pilot cannot achieve this ideal; the actual angle will tend to be less than the maximum possible and the surplus vertical thrust component will be compensated by use of less wing-lift. For example, as is shown in Fig.7, with the P.1127 the vector angle has usually reached only about 45 degrees when conventional flying speed is reached, and, except at the start, the maximum rate of rotation of the thrust vector seldom exceeds 2°/sec.

Thus, in practice, the performance - in terms of distance and time elapsed - will be below the theoretical limit. However, the same trends will be apparent, namely that the higher available thrust/weight ratio has a more beneficial effect on the time taken (and therefore on fuel used) than on the distance. It is also clear that restriction of the rate of rotation of the thrust vector (3°/sec on the P.1127) will extend the distance by reducing the acceleration that can be achieved in the later stages of the transition, where it is the most beneficial. However, safety dictates some such restriction, and this particular performance penalty is of no great importance.

The composite power-plant configuration presents the pilot with a somewhat less demanding task. By using the separate propulsion engine, the transition can be started without tilting the lift engines, if desired, although better acceleration will result if this can be done without loss of height.

The pilot is free to choose any attitude (or incidence) he finds best, because the propulsive thrust component available is independent of the lift carried on the wings. The most economical transitions are made with all engines at maximum thrust, at approximately zero incidence, so as to gain normal flying speed as quickly as possible. If appreciable wing lift is allowed to appear too early, the lift engine thrust may have to be reduced, if the engines cannot be tilted far enough, and then the acceleration will suffer.

4.2 Performance aspects

The comparison between the theoretically possible and the normally achieved transition performance illustrated in Fig.7 is not, of course, an attempt to correlate theory with practice. Rather, it illustrates the obvious dependence of this performance on the assumptions as to the way in which the gross thrust vector is controlled by the pilot, and as to the flight path he wishes to follow. With so many variables, parametric studies would be laborious and of little value.

There is, however, the problem of defining, in the specification stage, the performance required in terms of the height and location of obstacles in the vicinity of the take-off area, particularly those beyond the traditional 50 ft screen.

The best mission performance - payload and range - will result if the aircraft can be allowed to accelerate in level flight after clearing the 50 ft screen. If, on the other hand, it must continue to climb, and particularly if a significant manoeuvre capability is required, then more fuel will be used and, for manoeuvring, an extra margin of total lift/weight ratio will be required, resulting in a mission performance penalty if the take-off weight has to be further restricted.

4.3 Lift margins for manoeuvring during transition

The manoeuvrability margin defined in Ref.12 and already mentioned in Section 3.2 is strictly applicable only to the initial climb to the 50 ft screen, where the normal acceleration to be used can be specified, and where conditions are more-or-less unchanging. The problem from that stage onwards is that the accelerations to be used in avoiding obstacles, etc., are not known, and, further, the relative proportions of aerodynamic and engine lift are changing continuously. Thus, the probability, and the consequences of exceeding a limiting wing incidence during such manoeuvres will vary from start to finish of the transition. At the start, the thrust vector provides the major part of the manoeuvring force; at the end, the wing takes over this function.

A vectored thrust aircraft following the procedure assumed in Fig.7 for maximum performance has, of course, no lift margin in hand for manoeuvring. In practice, the P.1127 results show that, from about half-way (in time) through the transition, the thrust vector is more nearly vertical than is theoretically necessary. Consequently, less than maximum wing lift is being used, and a useful lift margin becomes available as the speed increases.

A similar situation usually exists with the composite power-plant layout, because the resultant thrust vector (lift and propulsion) cannot, in general, be rotated to the theoretical ideal angle, and consequently the wing lift has to be kept below maximum. This class of aircraft in general has the advantage (for the pilot) of offering a greater lift margin than the corresponding vectored thrust aircraft, since it is possible to use the whole of the wing lift for manoeuvring, with the vertical thrust component balancing the weight.

To summarise, there is a need for (a) a clearer definition of the likely location of obstacles which may affect the choice of transition path, and (b) statistical data on the average normal accelerations used during such transitions. Then, if ng is the required usable acceleration, the total, Ng, that should be available might be defined[12] as

$$N - n \geq (0.1 + 0.35\, n)\, F$$

and the alleviation factor, F, modified to agree with the recommendations of Ref.11 for vertical take-off lift margin, as in Section 3.2, is given by replacing the lift/weight ratio, P, by (T cos θ)/W, so that:-

$$F = \sqrt{1 - \left(\frac{T \cos \theta}{1.05\, W}\right)^2} \quad .$$

It is suggested that the total acceleration available, Ng, should be defined as that produced by maximum thrust and maximum incidence only, but not including that increment which might be produced by rotation of the thrust vector (relative to the aircraft datum) back towards the vertical.

Finally, it should be noted that, so far, wing/jet lift interference losses have only been briefly mentioned. In fact, these losses can be serious, and it is known that on one aircraft, at least, the total lift (wing + jets) at one stage of the take-off transition is normally less than the weight, despite the use of full engine power and 12 degrees wing incidence. Only by acquiring an appreciable vertical velocity early in the transition can an actual loss of height be avoided on this aircraft.

Tunnel data on this effect is now available (e.g. Ref.10) but there is a marked lack of flight data for correlation. Clearly it is important to establish the amount of this loss if there is to be any precision in determination of these lift margins. Flight tests for this purpose are, in fact, in hand on P.1127 and S.C.1.

4.4 Consequences of engine failure

There is obvious interest in attempts to compare the relative safety, for pilot and aircraft, of the vectored-thrust and composite power-plant configurations with each other and with corresponding conventional aircraft. There are, however, so many imponderable factors affecting safety that only very cautious generalisations can be made. These factors include:-

(a) The probability of engine failure during the take-off.

(b) The proportion of lift and propulsive thrust lost when an engine fails.

(c) The speed, height and flight path direction at the instant of failure.

(d) The effect on trim and control power.

(e) The type of terrain over which the transition is made (i.e. its suitability for a forced landing).

(f) Pilot's actions.

In these general terms, the composite engine layout need be considered no further if the number of engines is such that it can maintain height when one has failed (or with 2 "failed" if a second engine has to be shut down to restore trim) and if the transient effects of the failure are controllable either by the pilot or by some automatic system. The recommendations of Ref.11

are intended to cover these handling problems, and any multi-lift-engined aircraft meeting these recommendations should be able to survive. If height can not be maintained, at zero speed, then an emergency landing will result unless the forward speed can be increased before hitting the ground. There is thus an area on a speed-height diagram - the "dead man's curve" - outside which an engine failure can be tolerated. The lower boundary to this curve describes conditions from which a landing could be made without excessive vertical velocity - if the terrain were suitable. Fig.8, is a typical "dead man's curve" for the S.C.1, with one engine failed.

By comparison, the single vectored-thrust engine aircraft is less safe. Engine failure almost inevitably means loss of the aircraft (as it does on a single engined conventional aircraft), and at low speeds the pilot is endangered as well, because loss of engine power will also deprive the aircraft of its main, if not only, source of control power. The risk would, however, be less than that for the composite power-plant configuration if the latter aircraft could not be trimmed following engine failure - with a single engine, the failure should at least be symmetrical and give the pilot a reasonable chance to escape.

The vectored thrust engine VTO aircraft cannot strictly be compared with a conventional single engine aircraft, even though the engines may have the same probability of failure. The environments of the two types of operation are likely to be very different, the one taking-off from a small semi-prepared site with rough terrain outside it, the other from a long level runway with prepared over-run areas and no obstacles under or near the take-off path.

Accepting that the aircraft will be lost or damaged (unless the failure occurs early in the take-off) in either case the pilot is concerned with the time for which he, himself, is exposed to danger. With the conventional aircraft, the risk period probably extends from the time of passing the critical ("refusal") speed up to the point at which he has sufficient height (and, therefore, time) to make the decision, complete the vital actions and clear the aircraft before it hits the ground. In this series of events the time taken to make the decision is probably the most important and certainly the most indefinite item. Experience has shown that, even with a "zero-zero" ejection seat, the pilot tends to stay with the aircraft in circumstances where reason dictates that he should leave, when the emergency occurs close to the ground.

Despite the fact that the vectored thrust VTO aircraft can gain height rapidly after lift off, the risk period, during which there is insufficient time for the pilot to be sure of escape, is probably longer than that for a conventional aircraft. It is not possible to state an exact height from which the pilot would survive if the aircraft dropped freely with him still strapped in his seat, but it is probably less than 50 ft. From that height, it would be necessary to subject the pilot to a <u>mean</u> deceleration of 10g if the seat is to be arrested in 5 ft by structural deformation. A safer assumption would be 25 ft for this critical height, at zero ground speed, and an even lower height if there is appreciable forward velocity because of the extra energy to be absorbed by the structure on impact. Therefore, if failure occurs above 25 ft (and this is a lower height than we can assume for a take-off and level accelerating transition) the pilot must clear the aircraft before it touches the ground.

It is easy to show that, at low forward speed, wing lift has very little effect on the time of fall. Fig.9 shows this time of fall as a function of forward speed and initial height, on the assumption that the vertical (downwards) acceleration is simply $(1 - V^2/V^2_{min})g$. Until at least half minimum flight speed is reached, there is no significant improvement, and increase in height from 50 to 100 ft does not add more than 1 second to the time, at low forward speeds.

If we assume that the pilot needs at least 3 seconds to clear the aircraft, having made the decision, it appears that the speed must be at least 60% of conventional flight speed if failure occurs at 100 ft, or 80% at 50 ft. To reach these speeds takes, typically, 20-25 seconds for a vectored thrust aircraft, to which must be added the time taken to climb from the assumed critical height (25 ft) to the height at which the transition is made - say, a further 5-10 seconds. The total is therefore about 30 seconds, irrespective of the height - the greater height is safer, but it takes longer to get there.

No worthwhile simple calculations can be done for the conventional aircraft, but the risk period for the pilot will generally be appreciably shorter than that for the VTO aircraft.

For safety's sake, therefore, the best procedure is to gain flying speed as quickly as possible. It is shown in Ref.13 that total energy, defined in terms of the "energy height", h_e, where:-

$$h_e = h + V^2/2g$$

is gained most quickly if the aircraft accelerates along the ground for as long as possible consistent with an unstick and climb over the 50 ft obstacle at constant speed, i.e. without further acceleration. Equating total energy to safety, it is clear that increase in speed is more effective than increase in height.

5 THE LANDING TRANSITION - GENERAL

5.1 Factors affecting deceleration distance

An infinite variety of transition paths is possible, but for simplicity in demonstrating the effect of variations in important parameters, a straight path will be assumed. The resultant thrust vector is held at a constant angle relative to the aircraft datum, and the thrust itself is adjusted to maintain zero acceleration normal to the flight path. If allowance is made for idling thrust of the propulsion engine, the analysis can be applied equally to a composite engined or vectored thrust layout.

With the symbols defined in Fig.10, the balance of forces normal to the flight path gives

$$L - \left(\frac{\Delta L}{T}\right) T + T \cos(\alpha + \theta) - W \cos\gamma = 0$$

i.e.

$$T = \frac{W \cos\gamma - C_L \frac{1}{2}\rho V^2 S}{\cos(\alpha + \theta) - \left(\frac{\Delta L}{T}\right)} .$$

Then, if $\ddot{x}$ is the acceleration along the flight path, we have,

$$\frac{W}{g}\ddot{x} - W \sin\gamma + D + T \sin(\alpha + \theta) = 0$$

where

$$D = C_D \tfrac{1}{2}\rho V^2 S + M_e V$$

and the engine mass flow, M_e, is a function of T, while the lift-loss ratio, $(\Delta L/T)$ is a function of airspeed, V. This is almost certainly an over-simplification of the lift-loss effect, since it varies, in general, with the deflection angle, θ, but will be good enough for present purposes.

Combining the above equations, we can write the acceleration as

$$\ddot{x} = A + BV + CV^2$$

where the coefficients A, B and C are given by

$$A = g\left(\sin\gamma - \frac{\cos\gamma\,\sin(\alpha+\theta)}{\cos(\alpha+\theta) - \left(\frac{\Delta L}{T}\right)}\right)$$

$$B = \frac{-g\,M_e}{W}$$

and

$$C = \tfrac{1}{2}\rho\,\frac{S\,g}{W}\left(\frac{C_L\sin(\alpha+\theta)}{\cos(\alpha+\theta) - \left(\frac{\Delta L}{T}\right)} - C_D\right)$$

Then, by plotting $V/\ddot{x}$ against V and integrating graphically, the distance, x, required to decelerate can be obtained directly, since

$$x = \int \frac{V}{\ddot{x}}\,dV \quad .$$

In the presence of a headwind, the speed, V, in the above integration is, of course, the ground speed, but the acceleration, $\ddot{x}$, has to be calculated for the airspeed corresponding to each particular ground speed.

At low speeds, the constant term, A, is clearly the most important in determining the deceleration, and it remains significant at all speeds in the range considered. Its importance relative to the remaining terms becomes less at higher airspeeds, in a manner depending on the engine mass flow (which determines the momentum drag contribution) and on the wing loading and wing incidence (which determine the aerodynamic drag and lift, the latter, in turn, affecting the amount of engine thrust required). With the usual approximations for small angles the acceleration at zero speed is given very closely by $g(\gamma - \alpha - \theta)$, with the angles in radians. This quantity must, of course, be negative.

Some insight into the contributions of these various parameters may be gained from Fig.11, which shows the variation of the resultant deceleration with airspeed for various wing incidences, for two classes of jet-lift aircraft - one highly-loaded vectored thrust aircraft roughly resembling the P.1154, the other lightly-loaded with separate lift and propulsion engines (S.C.1).

The results refer, for illustration, to a glide slope of 10 degrees; for any other glide slope, the foregoing analysis shows that, to a close approximation, the deceleration would be changed by a constant increment equal to $g \sin (\gamma - 10)$ ft/sec^2. It will be noted in Fig.11 that the thrust deflection angles chosen for the two aircraft differ slightly. This difference has been chosen so that both aircraft have roughly zero acceleration at zero speed and zero incidence, despite the effect of the idling thrust of the propulsion engine on the S.C.1.

On both aircraft, at low speeds, there is the expected increase in deceleration due to increasing incidence, but the effect falls off at the higher speeds. The reason is that the accompanying increase in wing lift requires a reduction in engine thrust in order to maintain the glide path. At some speed a situation is reached where an increase in incidence results in a reduction in deceleration, showing that the increase in wing lift is such that the necessary reduction in engine thrust more than counteracts the increase in drag and the more favourable inclination of the thrust vector.

This effect is naturally most marked on the lightly-loaded S.C.1 aircraft, and the calculated stopping distances, shown in Fig.12(b) illustrate the anomaly. Because of this, and the insensitivity of the total stopping distance to the incidence used at the start, it is common practice on the S.C.1 (as noted, also, in Ref.14) to hold the incidence (or attitude) more-or-less constant at whatever value the pilot finds most comfortable, say 5-10 degrees, during the early part of the transition. At low speeds, of course, when the pilot is, in any case, more aware of the need for changes in deceleration, incidence or attitude changes are very effective for making the final corrections to the stopping point.

Nevertheless, this is not necessarily a general conclusion, and the results illustrated in Figs.11 and 12 for the highly-loaded aircraft show that incidence can be quite effective overall in controlling the deceleration. Fig.11, for example, shows that the speed at which the anomaly occurs is not much below the minimum steady conventional flight speed on either aircraft, and in the case of the highly-loaded aircraft the anomaly rapidly disappears as speed is reduced. The calculated stopping distances for this aircraft are also shown in Fig.12.

Increase in glide slope, of course, increases the stopping distance, as shown in Fig.13. The stopping-performance of the vectored thrust strike aircraft is apparently much better than that of the S.C.1, since at a given speed (below V_{min}) it requires a larger engine thrust to maintain the flight path, due to the higher wing loading, and thus a larger decelerating component is available also. However, allowing for the difference in speed at which the deceleration must be started - say, 200 knots for the strike aircraft, 140 knots for the S.C.1. - the difference is not large in this particular case.

The effect of a change in glide slope can be largely eliminated if a corresponding change can be made in the thrust deflection angle, as shown in Fig.14. The reason is simply that the expression for the deceleration, above, is dominated by the constant term, A, which, in turn, depends largely on the difference between these two angles. This is particularly the case for the highly-loaded strike aircraft, less so for the lightly-loaded S.C.1. Nevertheless, it does illustrate a useful increase in flexibility, allowing steeper descent paths to be used, if the thrust vector can be rotated further in the decelerate sense. It must be remembered, of course, that if wing incidence limits are not to be exceeded, then steep paths may necessitate an approach in a nose-down attitude, at least at the start, while the speed is still high.

Finally, the effect of a headwind on the distance to stop from a given ground speed is very small, as shown in Fig.15, though there is, of course, a reduction in distance for a given airspeed. Since instrument or automatic landing systems would probably be based on measurements of ground speed and distance, this result suggests that correction for wind speed might not be a serious problem.

5.2 Corrections to deceleration distance

The previous section has mentioned the effect on the stopping distances of changes in some parameters. In general, some such corrections will be necessary during any landing transition, either because of errors in choosing the starting point, or errors in setting up the required thrust angle, attitude, incidence or glide path.

Whether a visual or instrument approach is considered, it is probable that the necessity for making corrections (either in stopping distance, or in azimuth), whilst being not readily apparent at the beginning of the transition, will become increasingly more so towards the end of the manoeuvre. Obviously, the earlier the correction can be initiated, the more effective it will be.

Pilots with flight experience on the S.C.1 research aircraft claim, with support from flight records, that during a visual landing transition, they can recognise the need for a correction to stopping distance when the speed is as high as 100 knots. According to Fig.14(b), which embraces typical transition configurations, this is at a distance of about 2000 ft from the intended stopping point. This is not to say that a correction is necessarily initiated at this point. If the required correction is small, it would be left till later when it can be done by an attitude or incidence change. Such a change at 100 knots on the S.C.1 produces very little change in deceleration at the time (Fig.11) although it becomes effective later (Fig.12(b)). Further, any early change in incidence necessarily involves a change in thrust in order to hold the glide path.

The preferred means of making early corrections to the deceleration is therefore by a change in thrust vector angle. This is a powerful control, and with the thrust near vertical, the cross-coupling in the lift direction is small.

However, for maximum performance, the thrust vector should be as far as possible into the decelerating sector, so that the available increase in decelerating component may be small - even zero. The pilot's aim, in view of this general limitation, is to undershoot the landing area initially so that any correction will be in the sense of reducing the deceleration for a time.

The final corrections, including the positioning of the aircraft for the vertical let-down, are done by means of attitude changes, in both pitch and roll. The effect of the control power of the aircraft on the ease with which these final corrections are made is discussed in a later Section.

5.3 Wind effects

A headwind has the effect of reducing the distance required to stop from a given airspeed, as shown in Fig.15 but, from a given ground speed, the distance to stop is not much affected. Obviously, therefore, a correction must be made to the starting point of a decelerating transition, but onwards from the point at which the pilot starts to base his judgement of progress on ground speed and distance, the problem is no longer seriously affected by wind. Similarly, any instrument or automatic landing system based on range from the landing area, and rate-of-change of range (i.e. ground speed) would not be seriously complicated by having to deal with a change in headwind component.

The effect of a cross-wind is less easily predictable. As with conventional aircraft, two basic procedures are possible if a decelerating transition must be made across the wind direction.

The first (corresponding to the conventional "drifting" approach) involves flying the aircraft with zero sideslip throughout. The VTOL aircraft, however, tends to end up with very large drift angles - becoming 90 degrees if continued to zero ground speed. This procedure makes control of deceleration along the track very complicated, due to cross-coupling resulting from the skew angle of the thrust vector.

The second technique (corresponding to the conventional side slipping approach) involves holding the aircraft on a constant heading, and removing the effect of the cross-wind by banking into wind. In a constant cross-wind, the bank angle required will not change much as the speed reduces to zero, and is likely to be small, anyway, so that this is the preferred technique. Before the final let-down the aircraft can be turned to head into wind, so that the touch-down can be made with wings level.

However, this preferred technique is not necessarily entirely trouble-free. On both the S.C.1 and the P.1127 there is evidence of the rolling moment due to sideslip - at large sideslip angles - being dependent on bank angle: if the windward wing is lowered it tends to "dig in" and if raised it tends to roll out of wind. There is a danger, therefore, in making the slipping approach, when the windward wing is held down to balance the sideforces, that changes in bank angle, made to correct errors from the desired track, may result in an increase of the into-wind rolling moment which can absorb a large proportion of available control power.

The origin and control of this additional "dihedral effect" is, at present (in 1964) improperly understood. Meanwhile, it is prudent to treat cross-wind approaches with caution, making lateral corrections gently so that large angles of bank are avoided.

6 MANOEUVRABILITY REQUIREMENTS DURING TRANSITION TO THE HOVER

6.1 Height control

At the start of a decelerating transition the aircraft is still capable of being handled conventionally, and glide path corrections can be made via incidences changes without major cross-coupling affecting the deceleration. The total wing-plus-jet lift available is about twice the weight, so that large normal acceleration increments are possible. However, at this early stage, the need for such corrections to glide path may not be apparent to the pilot.

As the speed decreases, changes in wing incidence become progressively less effective means of controlling the glide path, and the pilot is aware of the need to alter his procedure, so that glide path corrections come to be made by changes in lift thrust, while the stick becomes essentially an attitude control. The point at which this change-over occurs cannot be precisely defined, but pilots find no difficulty in recognising it.

The decrease in available wing lift necessitates a corresponding increase in lift engine thrust, and the lift margin available for glide path control depends, in the end, on the difference between actual and maximum available thrust. Therefore, it pays to carry as much lift as possible on the wings, so that excess thrust available is a maximum. It should be noted, however, that wing-jet lift interference losses may be dependent on incidence, so that the maximum wing incidence is not necessarily the optimum. Wind tunnel data on the particular configuration will indicate the most favourable condition for maximum manoeuvrability.

At low speeds and at the hover, the normal acceleration margin available depends on the difference between the weight and the maximum installed thrust. The latter must include losses due to intakes, interference, control bleed, etc. Ref.11 recommends that the lift margin for landing should be at least 15% for adequate manoeuvrability. There is evidence, from both S.C.1 and P.1127 that the normal acceleration increments actually used (by skilled pilots, in non-critical conditions) are less than this. However, a proper statistical analysis of acceleration records is needed in order to establish the probability of exceeding a given acceleration level.

Lack of adequate lift margin also exaggerates the problem of correcting errors of judgement during the final vertical descent before touch-down. This problem is minimised in current operations by keeping the hover height low, but more realistic operations, e.g. into restricted sites, may necessitate much longer vertical descents. It is easy to show, as in Ref.15, that when the lift margin is small, a small error in rate of descent at, say, 100 ft, can have a disproportionate effect on the vertical velocity at touch-down. Fig.16 illustrates the point. It need hardly be emphasised that structural weight economy in VTOL aircraft design will encourage the adoption of the lowest possible design limit for the strength of the landing gear.

These simple calculations make no allowance for any change in lift margin outside the control of the pilot. As the height decreases to zero, there will be changes in interference losses - ground suction effect - and in the loss due to recirculation of hot exhaust gases, causing a rise in engine air intake temperature. Thus, even with a constant engine throttle setting, there will be a variation in thrust margin with height. The effect on impact vertical velocity can be calculated on an energy basis, the increase in kinetic energy between the initial point and touch-down being given by

$$(K.E.)_{T.D.} - (K.E.)_o = \int \Delta T \, dh$$

where ΔT is the amount by which the weight exceeds the thrust at a height h.

While one can certainly sympathise with the designer's plea to keep the thrust margin and the landing gear weight as small as possible, it must be accepted that the smaller these margins, the greater the probability that the pilot will meet a situation where the total lift thrust is inadequate to prevent the aircraft striking the ground with excessive vertical velocity - or colliding with an obstacle. It is also worth remembering that plan-position manoeuvring (discussed below) necessitates the inclination of the thrust vector to the vertical. Certainly, the loss in vertical component is small when angles are small, but if angles up to 25° are ever required, even the recommended 15% margin will be reduced to 5% unless a height loss can be accepted.

6.2 Plan-position manoeuvres

Under this heading are included manoeuvres involving both fore-and-aft and lateral displacements and velocities. In general, the analysis can be applied, to a first order at least, to either case, in the absence of significant aerodynamic effects. We are interested in the angular displacements involved, the time taken and in the effect on manoeuvrability of limitations in control power, i.e. in angular acceleration. Stabilisation in the form of rate damping, may also be significant if it limits the angular rates that can be used.

A simple analytical treatment of plan-position manoeuvrability is possible if we assume the aircraft to execute, in time T, a lateral or longitudinal manoeuvre in which the variation of bank or pitch angle with time is sinusoidal, i.e.

$$\phi = \phi_{max} \sin \frac{2\pi t}{T} .$$

This results in zero bank (or pitch) angle at the start and finish of the manoeuvre but the initial and final angular rates are not zero.

The maximum angular rate is

$$\dot{\phi}_{max} = \phi_{max} \frac{2\pi}{T}$$

and the maximum angular acceleration (i.e. the required control power) is given by

$$\ddot{\phi}_{max} = \phi_{max}\left(\frac{2\pi}{T}\right)^2 .$$

If angles are small, the linear acceleration resulting from the angular displacement ϕ is $g\phi$. Hence the total linear displacement can be obtained by integration, thus

$$y = \frac{g\,\phi_{max}}{2\pi} T^2 ,$$

the linear velocity being zero at the start and finish of the manoeuvre. This expression is exactly the same as that derived for a conventional aircraft performing a symmetrical "sidestep" manoeuvre during a landing approach in Ref.16.

As already noted, the above simple assumption results in large peak angular rates at the beginning and end of the manoeuvre, as well as in the middle. In Appendix C a more realistic variation of angle with time has been assumed, giving zero rate at the start and finish, and the total displacement is shown to be

$$y = g\,\phi_{max}\,T^2\,\frac{3}{8}\left(\frac{1}{4} + \frac{1}{\pi^2}\right)$$

which, because of the slightly smaller <u>average</u> angles used, is some 20% less than that given by the previous expression. However, the peak angular acceleration is now twice the previous value, i.e.

$$\ddot{\phi}_{max} = 2\,\phi_{max}\left(\frac{2\pi}{T}\right)^2$$

Fig.17 illustrates the assumed manoeuvre for one particular case. The complex shape of the angular acceleration time-history required to produce the smooth variation of angular displacement is noteworthy. In this manoeuvre, lasting only 4 seconds, it can be seen from the last equation, above, that only small peak bank angles can be used (numerically, about one-fifth of the peak angular acceleration).

It is not, of course, essential for the pilot to generate this complex control input, and a similar cyclic response could be achieved by a series of pulses of control power, with somewhat lower peaks than those required here. The present assumptions are considered adequate for comparative purposes, but absolute values should not be taken too literally.

In Fig.18, some numerical results are shown for a range of typical bank (or pitch) angles, and the corresponding peak angular accelerations are also given. For the reasons given above, the peak accelerations may be somewhat exaggerated, nevertheless the orders of magnitude, and the effects of changes are probably quite realistic.

Fig.19 shows the effect of bank angle or angular acceleration on the translational velocity changes that can be achieved in a given time, assuming the same type of manoeuvre as before. The derivation of Fig.19 is given in Appendix C. The quoted angular accelerations are subject to the same qualifications as those relating to linear displacements.

These simple calculations show, as expected, that large displacements - or large velocity changes - can be achieved with very modest requirements for angular acceleration. For example, a 100 ft displacement can be achieved in about $8\frac{1}{2}$ seconds, using only $20^{\circ}/\text{sec}^2$ angular acceleration. This time is only reduced to about 7 seconds by doubling the acceleration to $40^{\circ}/\text{sec}^2$, while the peak angular displacement increases from 18 to 26 degrees. If there is some additional limitation to the angular displacement that the pilot is willing to use, then he may not need all the available angular acceleration. There may, of course, be some connection between this pilot-limited pitch or bank angle and the angular acceleration available that is not revealed by the above analysis. For example, pilots appear to be unwilling to use large bank angles during such a manoeuvre if it takes too long to restore wings level at the end of it, because of the anticipation required. Even though the manoeuvre may be of such a size that there would be time to use larger angles, it is likely that this limitation might be over-riding.

When we examine the ability to make small rapid translational manoeuvres, the effect of limited angular acceleration capability is more noticeable. The enlarged portion of Fig.18, for example, shows that the bank (or pitch) angle that can be used while making a correction of, say, 10 ft in hovering position is severely restricted, and even with the highest angular acceleration considered ($120^{\circ}/\text{sec}^2$) cannot exceed 15°. Conversely, if we assume that, due to some external disturbance, a bank or pitch angle of, say, 10 degrees is imposed on the aircraft, then it will suffer a displacement of 15 ft if only

$40^\circ/sec^2$ acceleration is available, before coming to rest once more. If, on the other hand, $120^\circ/sec^2$ is available, the displacement will be only 5 ft. This difference illustrates the need for adequate control power much more clearly than does the case of making large displacements.

Similarly, Fig.19 shows that if, for example, the aircraft acquires a velocity of, say, 10 ft/sec for any reason, it can be brought to rest in about 1.7 sec, if an angular acceleration of $120^\circ/sec^2$ is available, but if only $40^\circ/sec^2$ is available, the correction will take twice as long, because only half the bank or pitch angle can be used.

To summarise, while no analysis of the above type will indicate the minimum acceptable control power, it is clear that lack of such power will be mainly noticeable as an inability to correct the effect of disturbances, or to perform small precise manoeuvres at the hover. Large changes in plan-position can always be achieved in time, but the lower the control power the longer will be this time - which is embarrassing in itself - but, more important, the accuracy will deteriorate because of the need to programme control inputs on a more protracted time scale.

Finally, mention must be made of the effect of autostabilisation in the form of angular velocity damping. If it has full authority, that is, if full input by the pilot results in a steady rate, then the pilot's input needed to produce the assumed manoeuvre will be more like the angular rate time-history (Fig.17) than the acceleration curve, the degree of similarity depending on the time constant of the response. If this is short, then control will be improved by being changed from 4th to 3rd order, but if this is achieved by high damping, the manoeuvrability will suffer because angular rates, and thus angular displacements will be limited. As always, a compromise must be sought. Ref.11 attempts to define just such a compromise, but the optimum can probably only be found by trial and error for each particular configuration.

7 LANDINGS IN RESTRICTED SPACES

In this Section an attempt is made to forecast some of the expected difficulties, and to suggest solutions to some of the problems of operating these aircraft away from normal, unobstructed airfields, and getting them safely and reliably into small, restricted landing sites. "Normal" visibility is assumed for the moment; the additional problem of restricted visibility is touched upon later.

For purposes of illustration, the typical "dispersed" site is assumed to be some 500 ft in horizontal extent, with 50 ft obstacle more-or-less continuous around the perimeter. The topography outside the perimeter is not defined. In some cases a level approach just clearing the 50 ft obstacles may be feasible (e.g. a clearing in a level, wooded area); in others, there may be hills, buildings etc. that may force the adoption either of a much higher level approach, or of a steeply-descending path aimed at the landing area.

It must be admitted that, with the notable exception of helicopters, there is little full-scale operational experience on which to base these forecasts. However, some preliminary attempts at simulation of the operational problem have been made with the Short S.C.1 and the results and pilot experience are considered relevant.

7.1 Main problem areas

The small size of the landing area, and the "unfriendly" nature of the surface outside it, emphasise the need for accuracy in plan-position for the final hover and let-down, if a vertical landing is to be made. The pilot may not have the assistance of familiar landmarks from which to judge where and when to start the decelerating transition. The extreme - and near-impossible - case seems to be an approach to a site of unknown dimensions located on a featureless plain. Some means of augmenting the pilot's judgement of range, in the 2000-5000 ft bracket, may become essential. Some geometric pattern of lights or markers may be of assistance here, and experiments are planned to study this.

In conjunction with this problem is the obvious need for the pilot to be able to locate the landing area quickly and certainly. There is plenty of experience to show that a target which seems easily identifiable when seen in plan view, either in real life or on a diagram, is much less so when viewed from low altitude, at a shallow angle. The pattern of lights or markers, already mentioned, would, of course, serve this purpose as well.

Next, the presence of obstructions around the site and beyond it will dictate either a high level approach and a prolonged vertical descent, or a continuous steep descent. The former has the advantage that deceleration performance is better, so that the transition can be started later, closer to the landing area, and also that overshoot errors are no more than wasteful of time and fuel. Against these advantages, the line of sight to the landing area gets progressively steeper and steeper, and will inevitably pass below the nose of the aircraft sooner or later. To combat this, the approach could be aimed off to one side, since view downwards from the average cockpit is usually significantly better in these sectors. The final vertical descent would have to be made in this way, also. However, a serious problem with the long vertical descent is the pilot's lack of appreciation of height, and particularly of rate-of-change of height, until the height is below 100, or even 50 ft. No great help could be expected from sophisticated instrumentation, since the pilot's visual attention must be outside the cockpit. Provision of a "head-up" visual display may be feasible, but the wide range of directions in which the pilot may want to look must raise serious problems. However, an audio aid would not suffer from this problem, and pilots already find the change in engine noise as the aircraft approaches the ground to be of some help in the last few feet of the descent.

The steep descent, on the other hand, has the advantage of keeping the "aim point" more nearly along the line of flight, so that visual flight path information can be provided from the landing site itself. The pilot's judgement of the progress of the transition would be improved, compared with the high, level approach. The disadvantage is that, for a given geometric configuration of aircraft and lift engines, the deceleration distance will be greater (e.g. Fig.13) and last longer. Secondly, errors of judgement of where to start the transition (already further away than before) will result in errors not only in plan-position but also in height at the hover. Obviously, safe margins will have to be allowed.

7.2 Simulated "operational" landings with Short S.C.1 aircraft

In order to obtain some preliminary information on the problems of making descending transitions into a small, unfamiliar landing site, a test programme has been initiated with the Short S.C.1 experimental jet-lift aircraft.

All operations were necessarily carried out in normal visibility, on the airfield at R.A.E. Bedford. The pilots who took part were thoroughly familiar with the airfield (and the aircraft). No attempt was made to erect artificial obstacles near the landing area.

However, some claim to realism can be made. Whereas the pilots had hitherto made nearly all their transitions along the direction of the main runway, without any great concentration on precision of the final hover point, transitions were now to be made in a variety of directions, and the hover point was closely defined beforehand. Of course, new landmarks were soon found by the pilots, and no artificial "range markers" were provided.

The desired landing point was always at some recognisable feature of the concrete/grass pattern on the airfield, but was not otherwise marked or emphasised. In fact, 7 such points were nominated, and in some tests, simulating the effect of restricted visibility, or of breaking out of low cloud, the pilot was told (by R/T) which of the 7 possible sites he was to use, only at a late stage in the initial approach. He then had to identify this point and decide quickly where to start the transition. This part of the exercise confirmed the need for clear marking of the landing site.

7.2.1 Level transitions

Level transitions at 50-100 ft, whether to a previously-nominated point or to a lately-recognised one could be performed with adequate consistency, although in the latter cases the pilot's work-load was considerably increased. The essence of the technique was to aim always to undershoot the landing point, and then to "stretch" the transition in the late stages by lowering the nose of the aircraft and reducing the deceleration. Previous measurements of transition performance had indicated the "ideal" point for the start of transition for a given configuration (lift engine tilt angle and attitude) of the aircraft, and the pilots generally aimed to start at or before reaching this point. Some latitude was possible because neither the lift engine tilt angle, nor the attitude were extreme values, so that the deceleration could be increased (or decreased) as necessary. As previously shown (Section 5.2 and Fig.12), attitude or incidence changes are relatively ineffective in changing the transition distance on the S.C.1, if they are made at speeds above 100 knots, but become very effective at lower speeds. Engine tilt angle was not used for precise control of distance, being merely set to the desired value at the start and returned to zero just before the aircraft came to rest.

The pilot's judgement of the progress of the transition was surprisingly good, and from about 100 knots they were well aware whether or not they would eventually stop at the desired point.

7.2.2 Descending transitions - unaided

Descent angles up to 8 degrees have so far been investigated in flight on the S.C.1. The lift engine tilt angle was increased, relative to that used for the level transitions, so as to produce the same stopping distance as before.

Initially, these descending transitions were made without assistance for the pilot. He was told to approach at, say, 500 ft and to start the deceleration when 3500 ft from the landing point, if an 8° path was required. Lift engine thrust was adjusted, to hold the glide path, and if the attitude was held at the correct value (generally, with fuselage level) the speed should have decreased to zero over the landing point - if the transition had been started at the correct point.

In fact, although the terminal accuracy was as good as before, the paths actually followed deviated from the desired straight descent. One common feature of the few approaches made in this series was a marked tendency to descend too slowly at the start, and for the path to get steeper towards the end, producing a roughly parabolic profile with a fairly constant rate of descent as the speed decreased down to about 20 knots, at which point the approach was usually broken off.

No simple explanation for this effect is offered. However, a comparison with the analogous case of the approach of a conventional aircraft, also without a visual aid, suggests that the pilot's judgement of were the projection of his instantaneous flight path will intersect the ground plane may be compromised by the fact that the speed is continuously decreasing in the present case. With the conventional aircraft, the constant approach speed allows the pilot to get some assistance from the development of the "streamer pattern" by which objects on the ground appear to move radially away from the point where the projection of the flight path intersects the ground. When the speed is decreasing, this streamer pattern may perhaps become progressively less informative, for in the end, at zero speed, there is no movement at all.

The other important difference between the conventional and VTOL aircraft is the fact that the latter, during a decelerating transition, cannot be trimmed on to the glide path, nor has it any stability, in the sense of tending to return always to a basic speed/glide angle condition. The whole manoeuvre is transient, with the pilot having to vary the lift thrust continuously, with little or no feedback except for his appreciation of normal acceleration ("seat of the pants" effect).

These departures from the intended flight path are of more than academic interest, because when the path is steeper than intended there is a danger of exceeding stalling incidence at an airspeed high enough for the result to be serious. In these tests with the S.C.1, there were no obstacles near the path, but real obstacles may well be obscured from view by cockpit limitations. Further, unless the obstacle is of a familiar size and shape, it may not be easy to judge whether the projected flight path will clear it by an adequate margin. Of course, if the obstacle <u>is</u> clearly defined <u>and</u> properly positioned, it could provide a valuable glide path aid by functioning as one half of a simple aiming sight, the other half being a point on or near the landing area itself.

7.2.3 Descending transitions with visual aid

The value of a simple optical glide slope indicator was clearly demonstrated in these tests. The device used was a Naval "HILO" glide slope indicator, which, through a series of high-intensity narrow-beam lamps with 2-colour filters, gives the pilot an indication of his angular position relative to the intended glide slope. This device, used only because it was readily available, could be tilted to give any desired glide angle, although the information zone extended only about $\pm\frac{1}{2}$ degree in elevation.

The pilots found, and records confirmed, that this device greatly improved the accuracy of glide path holding, and made descending transitions not much more difficult than those in level flight. The display, which appeared as a vertical row of lights which changed progressively from red to white as the aircraft approached the glide path in initially level flight, was easily recognised and interpreted. However, no attempt was made to find the optimum sensitivity of such a device, nor to increase its coverage, which was decidedly too small - it was all too easy to fly right through the information zone ($\pm\frac{1}{2}$ degree only) before getting established on the descent path.

These tests merely served to demonstrate the value of a simple, easily-read visual glide slope indicator in terms of consistency of flight path and pilot work-load. No doubt, other devices, possibly simpler and lighter, could be and should be investigated.

More work needs to be done, also, on the longitudinal dynamics of the behaviour of the aircraft on changing from a level to a descending flight path while decelerating, since these tests showed that it took an appreciable time to get settled on the new path. Statistical analysis of control usage, and of normal acceleration will also be of great value for design purposes.

8 LANDINGS IN RESTRICTED VISIBILITY

8.1 Assumptions and definitions

With almost no practical experience to call upon, discussion under this heading deals only with theoretical possibilities, and it is important to define the conditions under which a particular procedure might be recommended.

"Restricted visibility" is taken to refer to a cloud-base height of 200 ft above local obstacles coupled with a slant visual range of $\frac{1}{2}$ mile, i.e. it is assumed that the pilot can see the ground up to $\frac{1}{2}$ mile ahead while at a height of 200 ft, whether or not these limitations occur simultaneously in actual weather conditions. It is common experience that while visibility ahead may be restricted, it is often possible to see the ground more nearly below the aircraft. Thus, with the steeper glide slopes appropriate to these aircraft, it might be reasonable to expect that ground-based visual guidance information would become available earlier - or at a greater height - than for a conventional aircraft in the same conditions.

However, in the present context, these numerical values are used literally, meaning that all flight above 200 ft will be assumed to be on instruments, and that nothing will be seen of the landing site itself beyond a range of $\frac{1}{2}$ mile (3000 ft). Flight below 200 ft will be considered as visual, on the assumption that the view ahead provides enough cues for the flight to be continued without the use of guidance information. Flight experience so far in similar conditions is encouraging, but has all been carried out over level, familiar terrain. A different result might be obtained in more realistic circumstances. On the other hand, these limited-visibility flights did not have the benefit of any aid such as a lighting pattern, or a head-up attitude display. It is therefore reasonable to assume that, in the future, flight below 200 ft could be treated as visual, in the sense that no elaborate guidance information would be required.

Obstacles near the landing area may extend above the 50 ft level, but it is assumed that at least part of the final approach path can be made below 200 ft in more-or-less level flight, if required.

Consideration of the navigational accuracy needed to ensure acquisition of the terminal guidance system is outside the scope of this paper. It is assumed that the aircraft can, in fact, be flown through some "gate" from which the final descent will be initiated.

8.2 Possible procedures and recommendations

Two basically different procedures can be recognised. One assumes that some instrument or automatic flight control system can be provided such that the transition can be performed along the same path that would be followed in unrestricted visibility. The technical feasibility of this procedure is not questioned, but the problems involved are mainly in the realm of equipment development and are not dealt with here.

The second procedure assumes that the pilot will only be provided with a minimum of additional equipment and that a descending decelerating transition on instruments is not feasible. Two further possibilities have then to be considered. In the first, the initial descent is made at, or just below minimum conventional flight speed, on instruments. At 200 ft, the pilot is in visual contact with the ground, and the final deceleration can be completed visually. Navigational accuracy is assumed to be such that the pilot can at least get within visual range of the landing area before coming to the hover.

The second of these further possibilities is really a generalisation of the first. Serious objections can be raised to the concept of breaking cloud over unfamiliar, uneven ground, at speeds in the region of 150-200 knots. On the other hand, if the instrument approach can be made at 100 knots - or even 50 knots - then the pilot's difficulties should be greatly eased in that he has more time to appraise the situation, recognise obstacles and set up a course to avoid them. The concept of "feeling one's way down" in bad weather can be put into practice in this class of aircraft provided that the aircraft can be flown on instruments at steady speeds in this intermediate, partially jet-borne state.

This preferred procedure can therefore be broken down into the following phases.

(a) Deceleration in level flight from conventional flight speed to the chosen intermediate speed. Any convenient height may be used, and great precision is not required, provided that this intermediate speed is achieved before the descent is started.

(b) Descent at constant speed along the required glide path until visual ground contact is made, or some minimum break-off height is reached.

(c) Completion of the deceleration to the hover over the landing area. These 3 phases are discussed in detail below and are illustrated in Fig.20.

8.2.1 Initial deceleration

Previous to this stage, the aircraft is assumed to be flown at about the minimum conventional flight speed, at some convenient low altitude, and on a track headed roughly towards the landing area. The speed is not important, except that the higher it is, the further away must the whole process be started. Some sort of range information will be necessary, in any case.

The height should also be as low as possible. Obviously, terrain clearance is the first important consideration and probably a minimum of 500 ft above local obstacles should be maintained. But even without this limitation, a certain minimum time must be allowed for the aircraft to become settled on the glide path. At present, only vague estimates of this time can be made, but experience with the S.C.1 suggests that acquisition of the glide path can hardly be completed in under 20 seconds, and U.S. experience with helicopters would put the figure at over 1 minute. Allowing a further short interval - say, 10 seconds - of steady flight on the glide path, the total descent time could be between $\frac{1}{2}$ and $1\frac{1}{2}$ minutes. U.S. experience with helicopters also suggests that descent rates must be limited to not more than 1000 ft/minute, so that in the extreme, 1500 ft of height might be lost on the glide path, before breaking cloud. Therefore, the initial approach may need to be made as high as 2000 ft above the level of the landing area - nevertheless, for fuel economy reasons, every effort should be made to keep this height as low as possible.

The range for starting the initial deceleration should be such that the desired approach speed can be achieved before reaching the leading edge of the glide path information zone. Allowance must therefore be made for errors in setting up the desired attitude and/or incidence, which will result either in an error in distance to achieve the desired speed, or in speed at the point of entering the glide path. Since the essence of this procedure is that the pilot should not have to monitor speed changes during the deceleration, it seems prudent to allow, say 10 seconds of flight as a "buffer margin" between the programmed end of the initial deceleration phase and the start of the glide path.

The distances required for this phase can be determined by the process already described (Section 5.1) and can be read off Fig.13, for example, for 2 particular types of aircraft, by taking the difference in stopping distances for the two speeds considered. Obviously, this phase can be performed at any convenient flight path angle, but for simplicity a level path would be preferable.

This first stage ends with the aircraft in steady flight, partially jet-borne, and on instruments, entering the glide path information zone and initiating the descent.

8.2.2 Steady descent

The dynamics of the manoeuvre required to change the flight path angle from near-zero to the more-or-less steep angle appropriate to these operations has not been studied in detail. However examination of the effect of thrust vector magnitude and direction on the final steady conditions shows that the engine will obviously be a powerful control in this respect. Whether the descent is initiated by change in thrust, or in vector angle will depend on the actual steady flight condition.

Starting with the equations of motion as outlined in Section 5.1, and adding the condition of zero acceleration along the flight path, the speed and glide path angle may be calculated for any given thrust vector. Using, for simple illustrative purposes, lift and drag coefficients which include, respectively, the interference lift loss and the momentum drag of the intake flow, the resultant flight path angle, γ, is given by the solution of the equation

$$\frac{C_D}{C_L}\left[W \cos\gamma - T\cos(\alpha+\theta)\right] + T\sin(\alpha+\theta) - W\sin\gamma = 0$$

where the symbols are as defined previously in Fig.10. Similarly, the speed corresponding to this condition is given by

$$V = \sqrt{\frac{\sin\gamma - \frac{T}{W}\sin(\alpha+\theta)}{C_D \frac{1}{2}\rho\, S/W}} \quad .$$

The inclusion of the above additional terms into the lift and drag coefficients introduces some over-simplification into the analysis, since both are functions of the dependent variable, V. However, the results illustrated in Fig.21 do, at least, serve to illustrate the powerful effect of thrust magnitude and direction for a hypothetical vectored-thrust aircraft, even though the absolute values should not be read too literally.

With these qualifications, it appears that speeds in the 50-100 knot range, at flight path angles around 10 degrees require vector angles near zero (i.e. normal to the wing chord line) and quite high thrust levels. Fig.21 shows that the thrust vector angle has a powerful influence on flight path angle; for example, at a constant thrust/weight ratio of, say, 0.8, and at 10 degrees incidence, the variation in steady flight path angle is about 70% of the vector angle change, while the corresponding speed increment is very small. Alterations to the final steady speed are very effectively made by variations in thrust when the vector angle is in the decelerate sector. Incidence changes are also effective, producing flight path angle variations with small speed increments when the thrust vector is in the decelerate sector, i.e. at low speeds and speed changes with small flight path angle variations when the vector is in the accelerate sector, at higher speeds (> 100 knots).

These simple calculations serve only to provide a preliminary survey of the variety of aircraft configurations that will produce a given flight condition. The stability of that condition is not immediately apparent, but the general shape of the curves for constant thrust/weight ratio suggests the possibility of speed stability problems analogous to those met in flight at speeds below minimum drag speed on conventional aircraft. However, if the elevator is used to control the attitude (or incidence), holding a chosen glide path by means of lift thrust changes, the indications from these calculations, and from flight tests on the S.C.1, are that the aircraft will settle at the chosen speed, confirming the pilot's impression that "speed can be left to take care of itself".

Certainly, more theoretical and flight test work is needed to examine the stability and control problems of this phase of the suggested procedure in more detail, but there are grounds for the hope that instrument flight will be possible without excessive complication.

Discussion of the problem of the provision and display of flight path guidance information is outside the scope of this paper. It is to be hoped that the choice of a straight descent path will ease this problem. The location of the glide path origin (Fig.20) relative to the landing area will be dictated by the horizontal distance required for the next phase, and by the chosen flight path angle. In general, fast, steep approaches will require the glide path origin to be farther away, and it is unlikely that this origin could be located within the confines of the landing area itself, as is probably desirable from the point of view of simplicity, unless very slow approaches can be made, or unless a decelerating, descendingtransition is accepted - a procedure that has already been considered likely to be excessively difficult for the pilot, unless an automatic flight control system is adopted.

Finally, the speed used in this stage should be as slow as possible, and will be dictated by cloud base and visibility limits existing at the time. It must be low enough to allow the pilot to complete the next and final stage without overshooting the landing area.

8.2.3 Final deceleration and let-down

This final stage starts with the aircraft in steady, descending flight in the partially jet-borne state, and either emerging from cloud or otherwise coming within visual contact with the ground. The pilot's problem is very similar to that facing the pilot of a conventional aircraft at the end of an instrument approach, involving transfer to visual guidance, but with the added difficulty of operating over unfamiliar terrain. The advantages of a low approach speed in these circumstances should need no emphasis.

Unlike the conventional aircraft, however, the vertical landing aircraft does not have to maintain its initial descent rate until it is close to the ground, and a flare can be initiated at any time. It is suggested that, on making visual contact, this should be the first step in this final stage, as illustrated in Fig.20, and should be completed before starting the final deceleration. It may even precede the pilot's identification of his exact plan-position or location of the landing area, so as to increase safety by removing any risk of flying into the ground while trying to get a visual "fix".

Flare manoeuvrability obviously depends on initial flight conditions. Reference to Fig.21 shows that the initial thrust/weight ratio will be in the region 0.8 - 0.9 with the vector angle near zero. Since a thrust/weight ratio around 1.10 - 1.15 should be available for the final vertical landing, it appears that, typically, a normal acceleration increase of $\frac{1}{4}$g should be available from lift engine thrust change alone, with no danger of stalling. This is sufficient to reduce the initial descent rate from 1000 ft/min to zero in about 2 seconds at maximum thrust. Allowing a reasonable time interval for decision and action by the pilot it should, if necessary, be possible to achieve level flight within about 5 seconds of first visual contact with the ground. For an initial condition of 100 knots at 1000 ft/min descent (about 6°) the height loss would be about 70 ft from the "break-out" point.

With the aircraft in near-level flight, in visual contact, final course corrections can be made. Preliminary flight studies have been done with the S.C.1. In these tests, starting from low, level flight at 130 knots, the pilot was told (by R/T) only at a late stage which one of 7 previously-chosen sites on the airfield was to be used for landing. He had to locate this site, set up a course towards it and initiate the deceleration so as to arrive at the hover near the site. It was found that the problem of identifying a designated landing point and deciding where to start the transition is certainly a demanding but by no means impossible task, even when started from conventional flight speed. The task will be easier at lower approach speeds, but, as shown by those tests, there is a vital need to have the site clearly marked and readily identifiable.

The deceleration distance obviously depends on the initial conditions and the aircraft configuration. As previously noted, the thrust vector angle will already be near that required for maximum deceleration. Some indication of the order of distance involved can be obtained from Fig.13. The distance will be around 1000 ft, in level flight from 100 knots, but only about one-third of this from 50 knots. It should be assumed (Section 7.2.1) that the pilot will still aim to undershoot the landing point, and, perhaps, 2-300 ft should be added to the distance estimated, to allow for this.

The total horizontal distance required from cloud-break to the hover point, for an initial approach at 100 knots, is thus about 2000 ft, so that the pilot should be well within visual range of the site on breaking out of cloud. If slant visibility is less than this, a lower approach speed can be used, so that the flare and final deceleration may still be carried out within this visual range.

The near-vertical let-down from the hover point is, of course, subject to just the same considerations as those already covered in Section 7. The importance of keeping an adequate thrust/weight margin is again emphasised, and prolonged vertical descents are not recommended.

8.3 Discussion of proposed procedure

It cannot be claimed that the above procedure defines the best all-weather landing system for jet VTOL aircraft. Nevertheless, it is believed that it does form the basis for a workable system, as far as the aircraft/pilot combination is concerned. Nothing has been said about either the form of instrument display which the pilot will need, or of the system that will provide the guidance and other information which might be required to operate such a display.

The procedure has the merit of flexibility, in that an infinite variety of speed/descent angle combinations is theoretically possible for the steady descent phase. The chosen procedure can thus be matched to the existing terrain and weather conditions, without change in the basic principle.

In practice, this matching process would best be started by consideration of visibility and terrain conditions on and around the landing area itself. This should fix the point at which the final decelerating transition could be started, and, hence, the maximum allowable speed at that point. Working back through the flare, in turn, determines the point at which the steady instrument approach phase must end. The approach flight path angle will be chosen to suit the local topography and the likely rate of descent limitation at the chosen approach speed (which will be the same as the speed at the start of the final deceleration). Thus, the guidance requirement for the steady instrument approach can be specified in terms of angle and point of origin.

This guidance phase can be entered at any convenient height consistent with terrain clearance and with a minimum time to allow the aircraft to settle down on the steady descending flight path. Means must be provided to inform the pilot when to start the initial deceleration before joining the beam, and this point will vary with altitude. However, great precision in range indication is not required, provided that allowance is made for a period of steady, near-level flight at the chosen approach speed, before entering the guidance system.

The procedure described here takes longer, and uses more fuel than a simple level decelerating transition in good visibility. The extra penalty is that associated with the steady descent, plus the allowances for time before joining the guidance system and at the end, before starting the final deceleration. With the allowances suggested above, this total extra time would be at least 45 seconds, and could be over twice this. Typically, this represents an extra fuel margin penalty of between 1 and 2% of the landing weight, compared with the level transition procedure in good visibility.

However, the alternative low-visibility procedure of a descending decelerating transition, on instruments, carries the penalty not only of more complex (and heavier) equipment but also of extended time and higher fuel consumption due to the reduced deceleration during the descent. This penalty clearly increases as the descent angle increases. Reference to Fig.13 shows that changing from a level deceleration to a 10 degree descent increases the distance (and, therefore, the time) by over 50% for the vectored thrust strike aircraft, and by even more for the S.C.1, assuming no change in thrust-vector angles. Any comparison of the relative penalties in fuel allowances for these two techniques should take account of this reduced decelerating performance, as well as that associated with the likely extra equipment weight.

9 CONCLUDING REMARKS

This Paper has reviewed some of the capabilities of V/STOL aircraft in terms of their ability to operate from small, semi-prepared sites, without the usual airfield aids, in normal and restricted visibility. Accumulated data from experimental operations (mainly with jet-lift VTOL aircraft) has been used as a basis for a tentative extrapolation to situations and conditions not yet (in 1964) examined in flight.

The general tone of the Paper has been deliberately one of qualified optimism. Certainly there are many problems still to be solved, many questions unanswered. Solutions to some of these problems may result in further performance penalties, but it is believed that the fundamental benefits of V/STOL for specialised military operations can make such penalties acceptable.

Subject to these qualifications, it is concluded that operations out of, and into the typical 500 ft "strip" will be possible in "normal" visibility with only very simple visual aids for the pilot. "Normal" visibility is assumed to be such that the landing area can be identified visually, and a course set towards it, before the start of the decelerating transition.

An operating base of this size will permit "rolling" take-offs at slightly less thrust than would be required for vertical take-off. The improvement in maximum all-up weight is not large, but in terms of payload or range it may be very attractive. Similarly, less thrust is required for a "rolling" landing, compared with a vertical let-down, but the main benefit here (and a large part of the benefit for take-off) results from alleviation of adverse ground effects.

Landing operations in rugged, unfamiliar terrain are considered to be very different from a landing on a familiar, unobstructed airfield, whatever the visibility. The advantages of being able to use steep descents are examined, and the ability to fly on instruments at steady, partially jet-borne speeds is shown to be particularly attractive when operating in restricted visibility and/or low cloud base. A procedure for such operations is described, which might form the basis for the specification of a bad-weather landing system.

In the course of this survey, a number of problem areas have been encountered. It is not claimed that any of these are new problems, and all have been, or are being examined to some extent already. Nevertheless, it may be as well to list these areas under 3 headings, thus:-

(a) Operating problems

(1) Further work is required on erosion and ingestion of debris, particularly under transient conditions.

(2) More full scale data is needed on ground effects, generally, particularly with a view to improving model/full-scale correlation.

(3) A clearer definition of a typical landing area is required, including the nature of the surface itself and the probable size and location of obstacles within, say, 1-2 miles of the area.

(4) In connection with (3), above, it will be necessary to define a take-off and landing procedure for demonstration purposes.

(b) Handling problems

(1) Statistical data are required on vertical accelerations used and margins available, during typical vertical and short take-off and landing manoeuvres.

(2) Stability and control problems during the acquisition and following of various glide paths requires both theoretical analysis and flight test examination.

(3) Procedures for operations in cross-wind conditions need to be developed.

(c) Equipment development

(1) A simple, portable visual glide slope indicator may be required.

(2) As a first step in the development of a bad- or all-weather landing system, instrument displays for flight at partially jet-borne speeds require examination.

Appendix A

DECAY IN VELOCITY AND TEMPERATURE OF A SINGLE ROUND JET NORMAL TO A SURFACE

Ref.17 gives approximate relationships for the maximum velocity and temperature in the surface flow originating from a single round jet impinging on a flat surface. With the jet exit within 10 diameters of the ground, the maximum velocity and temperature away from the immediate vicinity of the point of impact of the jet are given approximately by:-

$$\frac{U - U_o}{U_1 - U_o} = \frac{1.5}{x/d}$$

and

$$\frac{T - T_o}{T_1 - T_o} = \frac{1.1}{x/d}$$

where U is the velocity, T is the temperature, x is the radial distance and d is the nozzle diameter. Suffixes o and 1 refer to ambient and nozzle exit conditions respectively. These velocities and temperatures refer to conditions along a line inclined up at about 1 degree to the surface, originating at the point of impact of the jet. Conditions on the surface itself would be less conducive to the onset of erosion, and the constants in the above expressions should probably be reduced to, say, 1.2 and 1.0 respectively.

The above approximate relationships result in a variation of dynamic pressure of the surface flow with radial distance which follows an inverse square law if the flow is cold, but falls less rapidly if the flow is hot, because of the increase in gas density due to cooling. The ratio of surface flow to exit dynamic pressures is given by:-

$$\frac{q_s}{q_{exit}} = 1.44 \Bigg/ \left[\frac{T_o}{T_1}\left(1 - \frac{1.0}{x/d}\right) + \frac{1.0}{x/d}\right]\left(\frac{x}{d}\right)^2 .$$

Since the ratio cannot exceed unity, this simple relationship breaks down at small radial distances, of the order of 2 diameters and less.

Fig.1 shows the estimated variation of surface flow dynamic pressure with radial distance for a range of exit temperatures. The curves have been faired-in roughly to give unit pressure ratio at a distance of about 1 nozzle diameter. Using these results, Fig.2 has been prepared for three typical cases, of the same total thrust, roughly, that of an RB 162. One is a high-velocity hot jet, one is a low-velocity lifting fan, of larger diameter and lower temperature and the third, a lightly loaded unshrouded propeller. The dynamic pressures at which erosion will start on various surfaces (from Ref.3) have been marked. Because the cooler, low velocity jets are necessarily of larger diameter, the radii at which a given dynamic pressure is reached are only slightly greater for the hotter, higher velocity jets, except near the point of impact.

While the constants in these formulae are open to question, so that absolute figures must not be taken too literally, the general trend is fairly well established. The important points are the rapid decay in surface dynamic pressure, and the relative insensitivity of this pressure, except near the point of impact, to conditions in the lifting jet itself. Despite an exit dynamic pressure variation of almost 20 to 1 between extreme cases in Fig.2, the change in radius at which a given surface flow dynamic pressure is reached is generally less than 2 to 1.

Appendix B

ROLLING TAKE-OFF DISTANCES TO UNSTICK

We suppose, for the first example, that the nett resultant thrust, T, which is less than the weight, W, is deflected at an angle, θ, to the vertical, and has to be held fixed at that angle throughout the ground roll, up to the unstick speed, V. At unstick, the total lift just equals the weight, and is made up of the direct thrust component, $T \cos \theta$ and the aerodynamic lift, $C_L \frac{1}{2} \rho V^2 S$. The horizontal acceleration during the ground roll is produced by the thrust component $T \sin \theta$, compared with which the drag and rolling friction may be neglected.

The unstick speed is given by

$$V = \sqrt{(W - T \cos \theta)/C_L \tfrac{1}{2} \rho S}$$

and the ground roll distance is approximately

$$D = (W - T \cos \theta)\, W/C_L \tfrac{1}{2} \rho S\, 2T \sin \theta\, g \quad .$$

Differentiation for minimum distance gives

$$\theta_{opt} = \cos^{-1} \left[\frac{T}{W}\right]$$

for the optimum deflection angle, and the corresponding minimum distance becomes

$$D_{min} = (W^2 - T^2)/C_L\, \rho\, S T g \sqrt{1 - \frac{T^2}{W^2}} \quad .$$

For a take-off without a significant vertical thrust component, the conventional unstick speed, V_{min}, is

$$V_{min} = \sqrt{W/C_L \tfrac{1}{2} \rho S}$$

and the ground roll distance up to unstick is D_{con}, where

$$D_{con} = V^2_{min} / 2g \frac{T}{W} \quad .$$

Hence, for the deflected thrust case, the minimum distance may be written as

$$D_{min} = V^2_{min} \sqrt{1 - \frac{T^2}{W^2}} \Bigg/ 2g \frac{T}{W} \quad .$$

Thus, compared with the case of a conventional take-off with horizontal thrust, the use of this fixed optimum angle reduces the ground roll by multiplying it by a factor $\sqrt{1 - T^2/W^2}$, so that substantial gains are possible at high thrust/weight ratios.

If, however, the thrust vector angle can be adjusted during take-off, then a further improvement in performance is possible. The ground roll can be made with the thrust line horizontal, giving maximum acceleration. The thrust line is then deflected towards the vertical at unstick. In the extreme case, used here for purely comparative purposes, we will assume the thrust line to be vertical at unstick, ignoring the fact that the aircraft could not then accelerate horizontally.

The unstick speed then becomes

$$V' = \sqrt{(W - T)/C_L \tfrac{1}{2} \rho S}$$

and the ground roll distance is approximately

$$D' = (W - T)\, W/C_L \tfrac{1}{2} \rho S \, 2 T g$$

$$= \left(1 - \frac{T}{W}\right) V^2_{min} \Bigg/ 2g \frac{T}{W} \quad .$$

Thus the reduction factor in this case becomes $\left(1 - \frac{T}{W}\right)$, relative to the conventional take-off, or $\sqrt{\left(1 - \frac{T}{W}\right) \Big/ \left(1 + \frac{T}{W}\right)}$ relative to the case with the fixed deflection angle, θ_{opt}, above.

The above expressions indicate zero distance, (i.e. true vertical take-off) at unit thrust/weight ratio, whereas in fact an excess of thrust over weight of about 5% would normally be required for VTO, as recommended in Ref.11. Therefore, somewhat less than the maximum thrust available is actually used during these take-offs. In the case of the fixed deflection angle procedure, the actual thrust/weight ratio used is less than the maximum available by an amount which would result in a vertical acceleration increment of 0.05g when maximum thrust is applied. This margin is simply

$$\frac{\Delta T}{W} = 0.05/\cos\theta$$

and, since the optimum angle is being used, the margin used in Fig.4 is

$$\frac{\Delta T}{W} = 0.05\Big/\frac{T}{W} \; .$$

For the extreme procedure, with thrust vector angle adjusted at the unstick point, the thrust/weight ratios actually used in Fig.4 are a constant 0.05 less than the maximum available, because the thrust line is assumed vertical at unstick.

To give some realism to this latter case the estimated distances shown in Fig.4, for the 3 values of the "conventional" unstick speed, 100, 150 and 200 knots, include the effect of a 1 second delay at the unstick speed, while the thrust line is rotated from the horizontal to the vertical.

Appendix C

CALCULATED MANOEUVRE PERFORMANCE AT THE HOVER

We will assume the aircraft to be initially in a steady hover, with zero attitude and angular rate and zero translational velocity. The manoeuvre to be studied is that required to move the aircraft to a new hover position, finishing with zero attitude and angular rate and zero translational velocity.

Records of similar manoeuvres in flight show that, to a good approximation, the bank or pitch angle varies with time in a sinusoidal manner. For simplicity, we will divide the time taken for the manoeuvre into 3 intervals, the first and last occupying t_1 seconds each, while the middle interval is t_2 seconds, and the total manoeuvre time, T, is $(2t_1 + t_2)$ seconds. Fig.17, discussed more fully later, illustrates this division.

During the first interval, the variation of angle, ϕ, with time, t, is assumed to be

$$\phi = \frac{1}{2}\,\phi_{max}\left(1 - \cos\frac{\pi t}{t_1}\right)$$

where ϕ_{max} is the maximum angle reached. Then, the angular rate, $\dot{\phi}$, is

$$\dot{\phi} = \frac{1}{2}\,\phi_{max}\,\frac{\pi}{t_1}\,\sin\frac{\pi t}{t_1}$$

and the angular acceleration $\ddot{\phi}$, is

$$\ddot{\phi} = \frac{1}{2}\,\phi_{max}\left(\frac{\pi}{t_1}\right)^2\cos\frac{\pi t}{t_1}\quad .$$

With the usual approximation for small angles, the translational acceleration, $\ddot{y}$, resulting from this angular displacement is $g\phi$, and the resulting velocity, $\dot{y}$ is given by

$$\dot{y} = \frac{1}{2}\,g\,\phi_{max}\left(t - \frac{t_1}{\pi}\,\sin\frac{\pi t}{t_1}\right)$$

and the velocity at the end of this first interval is

$$(\dot{y})_1 = \frac{1}{2}\,g\,\phi_{max}\,t_1\quad .$$

Similarly, the displacement, y, is given by

$$y = \tfrac{1}{2} g \phi_{max} \left[\frac{t^2}{2} - \frac{t_1^2}{\pi^2} \left(1 - \cos \frac{\pi t}{t_1} \right) \right]$$

so that the displacement achieved in this interval is

$$(y)_1 = \tfrac{1}{2} g \phi_{max} t_1^2 \left(\tfrac{1}{2} - \frac{2}{\pi^2} \right) .$$

In the second interval, extending from time t_1 to time $(t_1 + t_2)$, the angular displacement is reversed, from ϕ_{max} to $-\phi_{max}$, according to

$$\phi = \phi_{max} \cos \frac{\pi}{t_2} (t - t_1)$$

so that the angular velocity, $\dot{\phi}$ is given by

$$\dot{\phi} = -\phi_{max} \frac{\pi}{t_2} \sin \frac{\pi}{t_2} (t - t_1)$$

and the angular acceleration, $\ddot{\phi}$, is

$$\ddot{\phi} = -\phi_{max} \frac{\pi^2}{t_2^2} \cos \frac{\pi}{t_2} (t - t_1) .$$

There is thus no discontinuity in angular displacement or velocity, but the angular acceleration is discontinuous at time t_1, unless

$$t_2 = \sqrt{2}\, t_1 .$$

If, however, it is assumed that the maximum angular rate in this second interval is to be the same as that in the first, the alternative condition is

$$t_2 = 2\, t_1 .$$

Integrating, as before, with constants adjusted to ensure continuity with the previous interval, the translational velocity is

$$\dot{y} = g\,\phi_{max}\left[\frac{t_2}{\pi}\sin\frac{\pi}{t_2}(t - t_1) + \frac{t_1}{2}\right]$$

and the velocity at the end of this second interval is the same as at the beginning, i.e.

$$(\dot{y})_2 = \tfrac{1}{2}\,g\,\phi_{max}\,t_1 \quad .$$

Further integration, with proper choice of constants for continuity gives the displacement as

$$y = g\,\phi_{max}\left[\frac{-t_2^2}{\pi^2}\cos\frac{\pi}{t_2}(t - t_1) + \frac{t_1\,t}{2} - t_1^2\left(\frac{1}{4} + \frac{1}{\pi^2}\right) + \frac{t_2^2}{\pi^2}\right] \quad .$$

The displacement at the end of this second interval is then

$$(y)_2 = g\,\phi_{max}\left[t_1^2\left(\frac{1}{4} - \frac{1}{\pi^2}\right) + \frac{t_1\,t_2}{2} + \frac{2t_2^2}{\pi^2}\right] \quad .$$

During the third interval, extending from time $(t_1 + t_2)$ to time $(2t_1 + t_2)$, the angular displacement is returned to zero, according to

$$\phi = -\tfrac{1}{2}\,\phi_{max}\left[1 + \cos\frac{\pi}{t_1}(t - t_1 - t_2)\right]$$

and the angular velocity also decays according to

$$\dot{\phi} = \tfrac{1}{2}\,\phi_{max}\frac{\pi}{t_1}\sin\frac{\pi}{t_1}(t - t_1 - t_2)$$

while the angular acceleration (again, discontinuous with that at the end of the previous interval) is given by

$$\ddot{\phi} = \tfrac{1}{2}\,\phi_{max}\,\frac{\pi^2}{t_1^2}\cos\frac{\pi}{t_1}\left(t - t_1 - t_2\right) \quad .$$

Accordingly, the translational velocity also reduces to zero, thus,

$$\dot{y} = \tfrac{1}{2}\,g\,\phi_{max}\left[-t - \frac{t_1}{\pi}\sin\frac{\pi}{t_1}\left(t - t_1 - t_2\right) + 2t_1 + t_2\right]$$

and the displacement becomes

$$y = \tfrac{1}{2}\,g\,\phi_{max}\left[\frac{-t^2}{2} + \frac{t_1^2}{\pi^2}\cos\frac{\pi}{t_1}\left(t - t_1 - t_2\right) + t\left(2t_1 + t_2\right) - t_1^2\left(1 + \frac{3}{\pi^2}\right) - t_1\,t_2 - t_2^2\left(\tfrac{1}{2} - \frac{4}{\pi^2}\right)\right] \quad .$$

Thus, the total displacement at the end of the manoeuvre is

$$(y)_3 = \tfrac{1}{2}\,g\,\phi_{max}\left[t_1^2\left(1 - \frac{4}{\pi^2}\right) + t_1\,t_2 + \frac{4t_2^2}{\pi^2}\right]$$

and with the previously-mentioned assumption that the maximum rate of rotation should be the same during the 3 intervals, requiring that

$$t_2 = 2t_1$$

the total displacement becomes, after a total time $4t_1$,

$$(y)_3 = \tfrac{3}{2}\,g\,\phi_{max}\,t_1^2\left(1 + \frac{4}{\pi^2}\right) \quad .$$

In terms of the total manoeuvre time, T, this can be written

$$(y)_3 = g\,\phi_{max}\,T^2\,\tfrac{3}{8}\left(\tfrac{1}{4} + \frac{1}{\pi^2}\right) \quad .$$

Referring again to Fig.17, time variations of all the relevant parameters are shown for one particular case, where the first and last time intervals occupy 1 second each, while the middle interval is 2 seconds. For convenience, the angular accelerations, rate and displacement are shown as fractions of their respective maxima, while the translational velocity and displacement are both divided by $g\,\phi_{max}$, where the angle is, of course, in radians.

The total displacement achieved by the time the aircraft is again at rest depends on the bank (or pitch) angle used and on the time taken to reach the first peak angular displacement. With the assumptions made here, the total manoeuvre time is 4 times this initial interval, and cannot be made less than this without using a larger angular rate in the recovery.

Actual displacements achieved for a range of peak angles are shown as functions of total time taken in Fig.18. The peak angular accelerations required for these manoeuvres are also shown.

Another aspect of manoeuvrability which is of some interest is also covered by the foregoing simple analysis. This concerns the problem of changing the translational velocity, starting, typically, with the aircraft stationary and ending with a translational velocity, but again with zero attitude and zero angular rate.

Referring to the above analysis, we can now assume that, instead of terminating the first interval at time t_1, it is allowed to continue with the same laws up to time $2t_1$. This will restore both the angle and the angular rate to zero, but leave the aircraft with a translational velocity (or velocity change) given by

$$\dot{y} = g\,\phi_{max}\,t_1$$

after a time $2t_1$, during which period it will have covered a distance (starting from rest) given by

$$y = g\,\phi_{max}\,t_1^2 \;.$$

The velocity change produced in a given time, for a range of angular displacements is shown in Fig.19, along with the required peak angular accelerations. The same results will apply, whether the velocity is to be increased from zero or decreased to zero.

REFERENCES

No.	Author(s)	Title, etc.
1	J.R.C. Fearon D.N. Norman	VTOL and STOL. Simple solutions to some of the operation problems during take-off and landing. J. Roy. Ae. Soc. February 1962
2	J. O'Malley Jr.	Flow phenomena experienced with VTOL aircraft in ground proximity. Proceedings of the Symposium on vertical/short take-off and landing. AGARD Paris, June 1960
3	R.E. Kuhn	An investigation to determine the conditions under which downwash from VTOL aircraft will start surface erosion from various types of terrain. NASA Technical Note D. 56, September 1959
4	A. Morse	VTOL downwash impingement study. Summary Report. Hiller Report No.61-3 (Contract DA 44-177-TC-655) August 1961 (See also Hiller Reports 60-15, 60-84, 60-88)
5	P.E. Colin	Ground proximity and the VTOL aircraft. AGARD Report No.409, 1962
6	W.A. Abbot	Studies of flow fields created by vertical and inclined jets when stationary or moving over a horizontal surface. A.R.C. C.P. 911, October 1964
7	D. Lean H.W. Chinn	Review of general operating experience with a jet-lift VTOL research aircraft (Short S.C.1). A.R.C. C.P. 832, August 1963
8	J.K.B. Illingworth H.W. Chinn	Variable stability and control tests on the S.C.1 aircraft in jet-borne flight, with particular reference to desirable VTOL flying qualities. A.R.C. R.& M. 3584, May 1963

REFERENCES (Contd)

No.	Author(s)	Title, etc.
9	L.A. Wyatt	Tests on the loss of vertical jet thrust due to ground effect on two simple VTOL planforms, with particular reference to the Short S.C.1 aircraft. A.R.C. R.& M. 3313, May 1958
10	J.H. Otis, Jr.	Induced interference effects on a four-jet VTOL configuration with various wing planforms in the transition speed range. NASA TN D-1400, September 1962
11	-	Recommendations for V/STOL handling qualities. AGARD Report 408, October 1962 A.R.C. 24,657
12	P.L. Sutcliffe V.K. Merrick A.R. Howell	Aerodynamics and propulsion of minimum-field aircraft. Proceedings of the Eighth Anglo-American Conference. Royal Aeronautical Society. September 1961
13	I.A. Fisher	Some thoughts on the take-off performance of a deflected jet thrust aeroplane. Report No. A. & A.E.E. Memorandum No.3, January 1964
14	J.K.B. Illingworth J.S. Shayler	Blind flying of V/STOL aircraft, with particular reference to take-off and landing. Symposium on V/STOL Aircraft. AGARD, Paris, June 1960
15	D. Keith-Lucas	Safety and reliability aspects of VTOL. Proceedings of the First International Congress of the Aeronautical Sciences. Madrid. September 1958
16	D.H. Perry W.G.A. Port J.C. Morrall	A flight study of the sidestep manoeuvre during landing. A.R.C. R.& M. 3347, July 1961
17	D. Johnson	A note concerning the temperatures and velocities in the efflux from jet engines during take-off. R.A.E. Technical Memorandum Naval No.164, April 1962

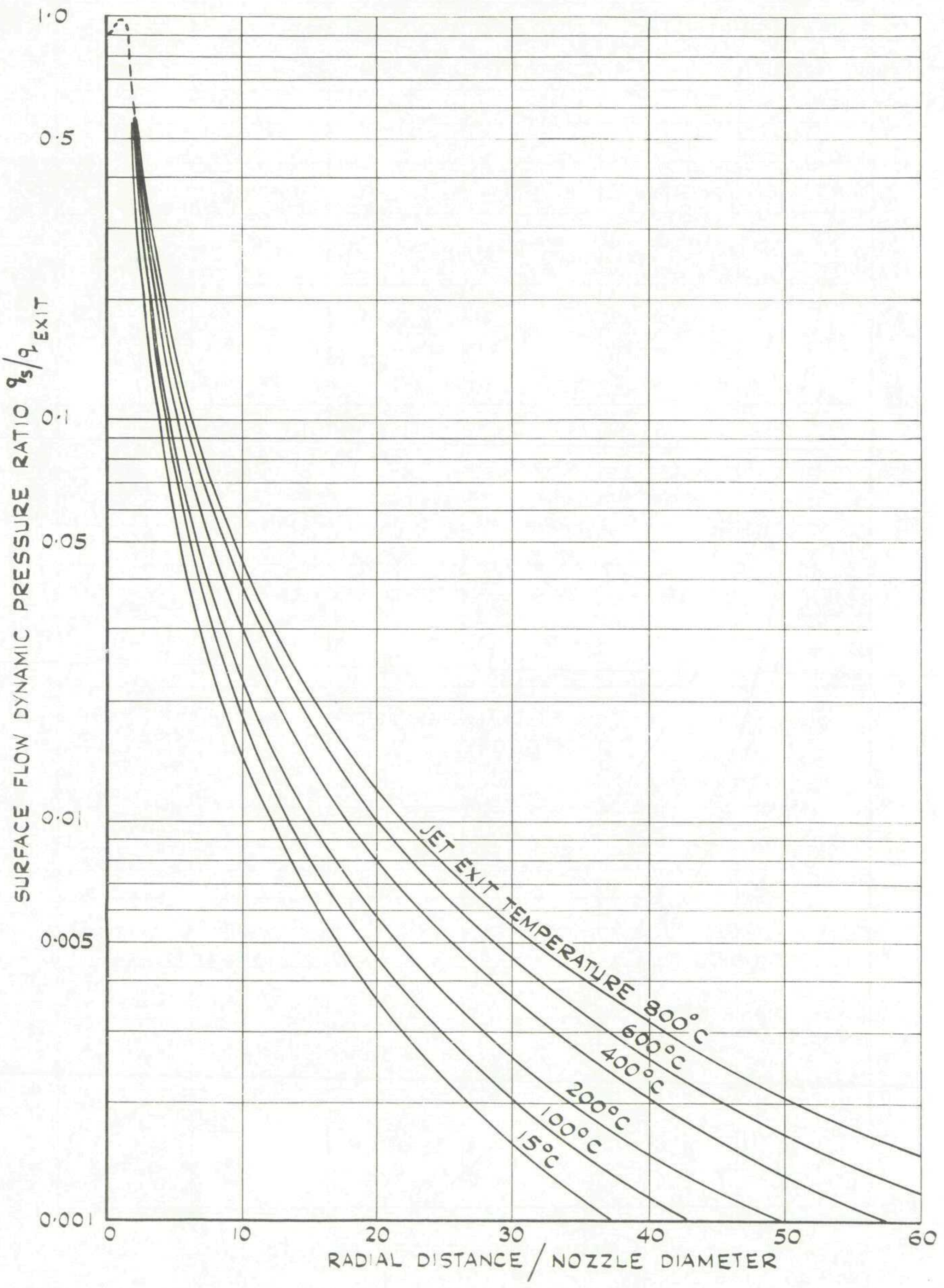


FIG. 1 ESTIMATED VARIATION OF SURFACE FLOW DYNAMIC PRESSURE WITH RADIAL DISTANCE

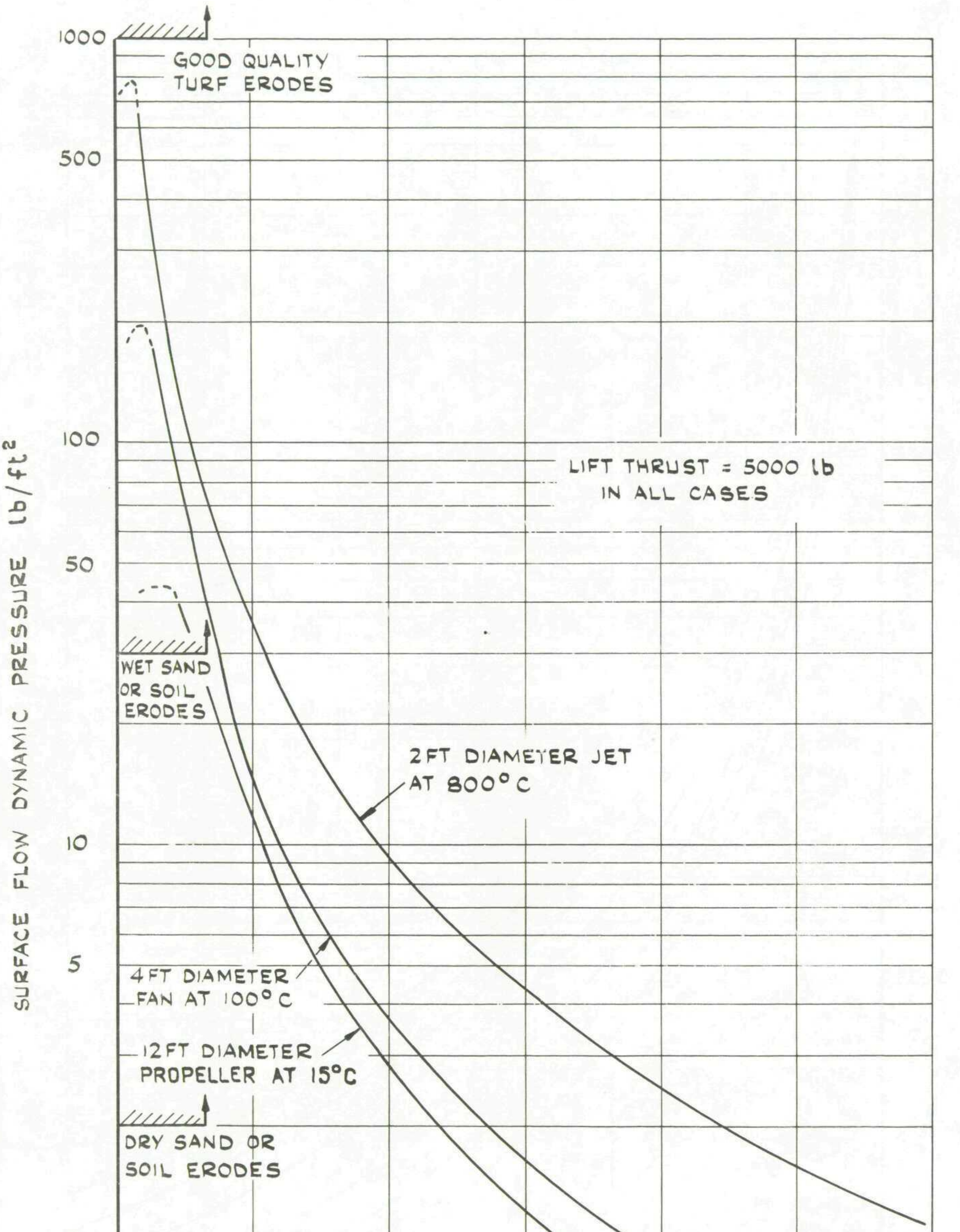


FIG.2 ESTIMATED EFFECT OF NOZZLE LOADING ON SURFACE FLOW

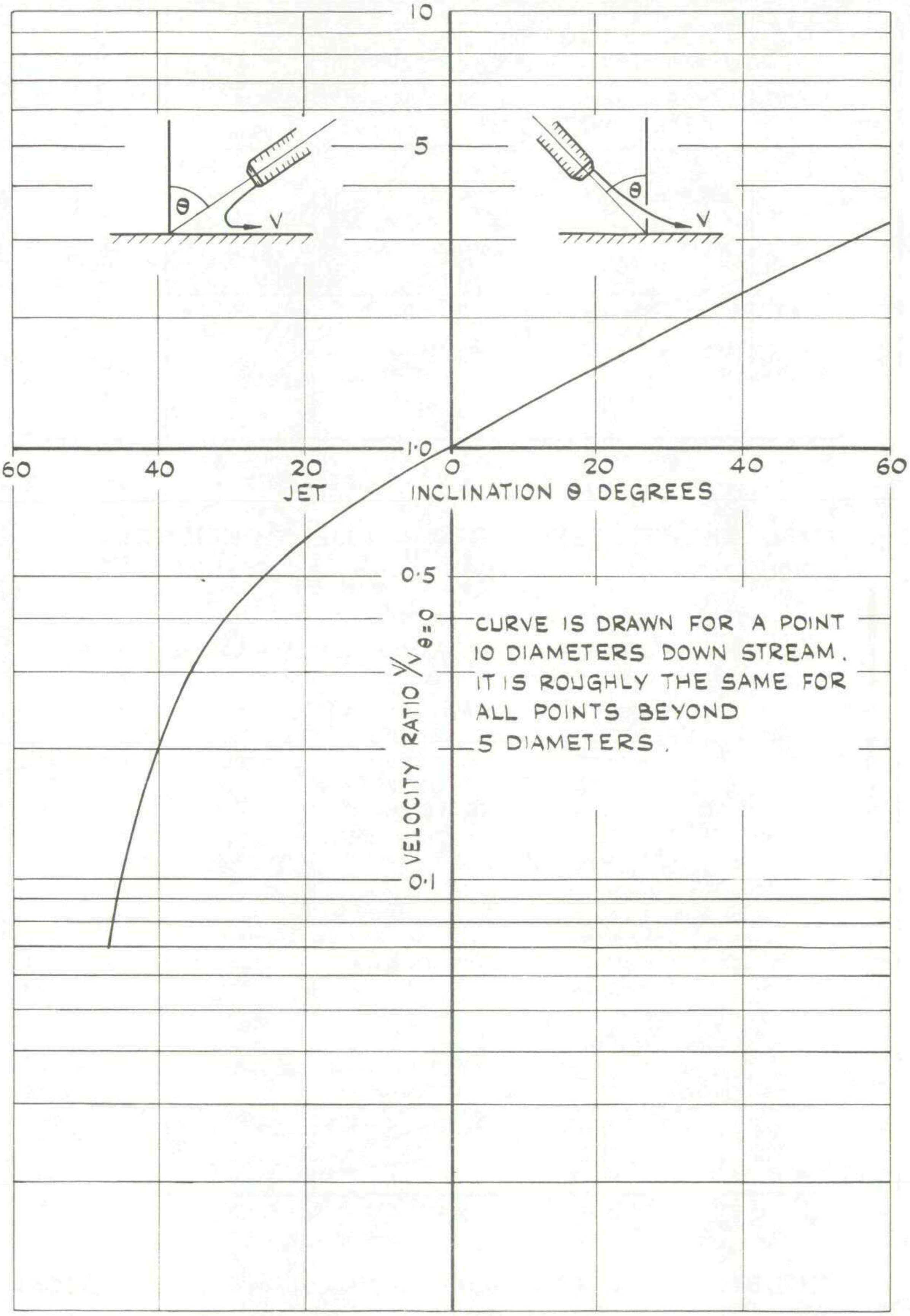


FIG. 3 EFFECT OF JET INCLINATION ON FLOW VELOCITY

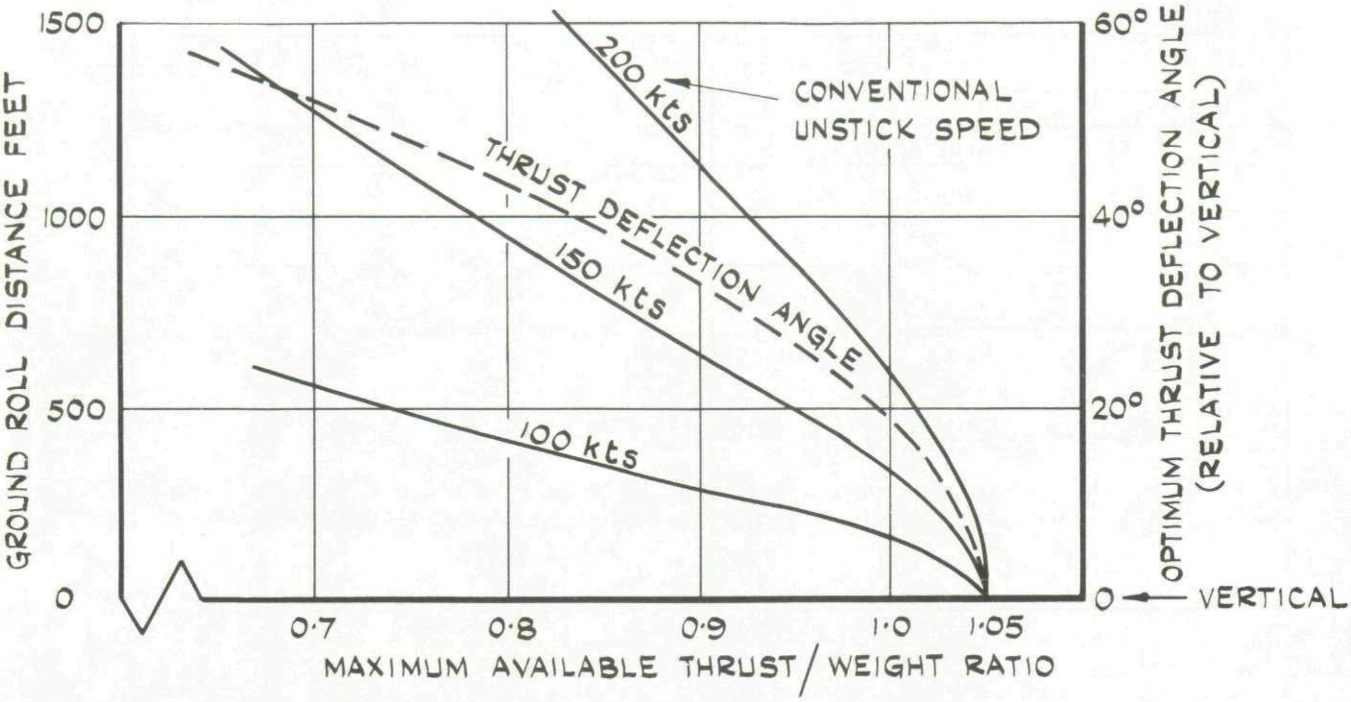


FIG. 4 (a) FIXED THRUST DEFLECTION ANGLE THROUGHOUT GROUND ROLL AND UNSTICK

NOTE:

IN ALL CASES USE OF MAXIMUM AVAILABLE THRUST AT UNSTICK WILL PRODUCE VERTICAL ACCELERATION INCREMENT OF 0·05g. THRUST/WEIGHT RATIO ACTUALLY USED GIVES TOTAL LIFT EQUAL TO WEIGHT AT UNSTICK (SEE APPENDIX 2)

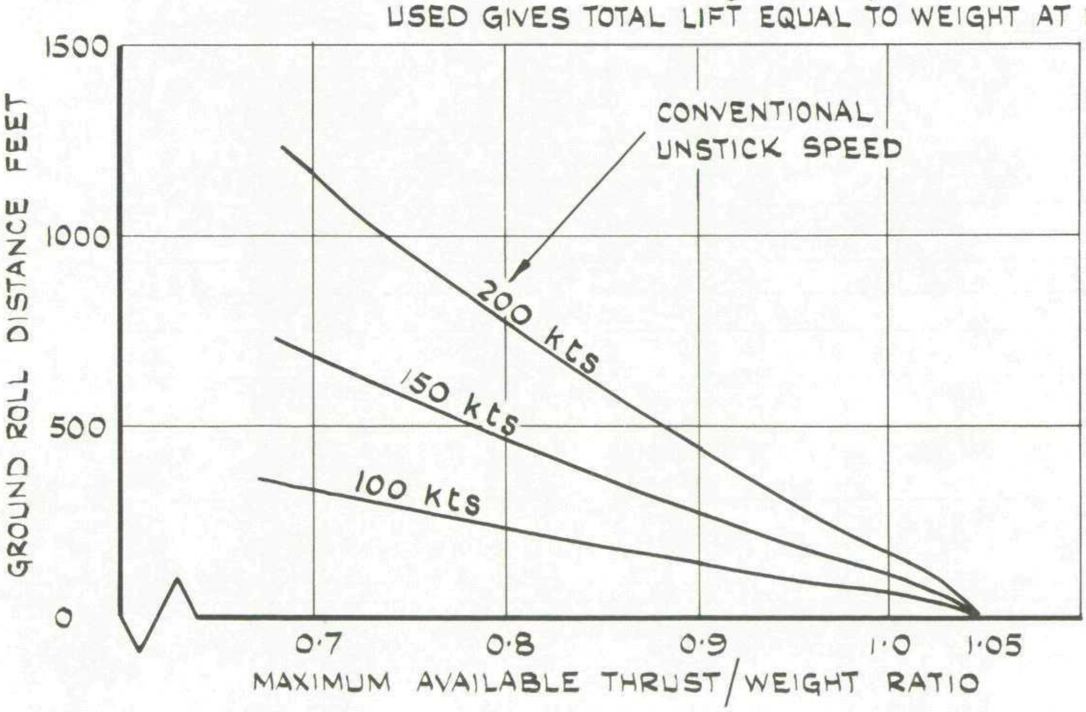


FIG. 4 (b) THRUST VECTORED FROM HORIZONTAL TO VERTICAL AT UNSTICK

(DISTANCES INCLUDE EFFECT OF 1 sec DELAY FOR THRUST ROTATION AT UNSTICK SPEED)

FIG. 4 EFFECT OF THRUST/WEIGHT RATIO ON GROUND ROLL DISTANCE TO UNSTICK

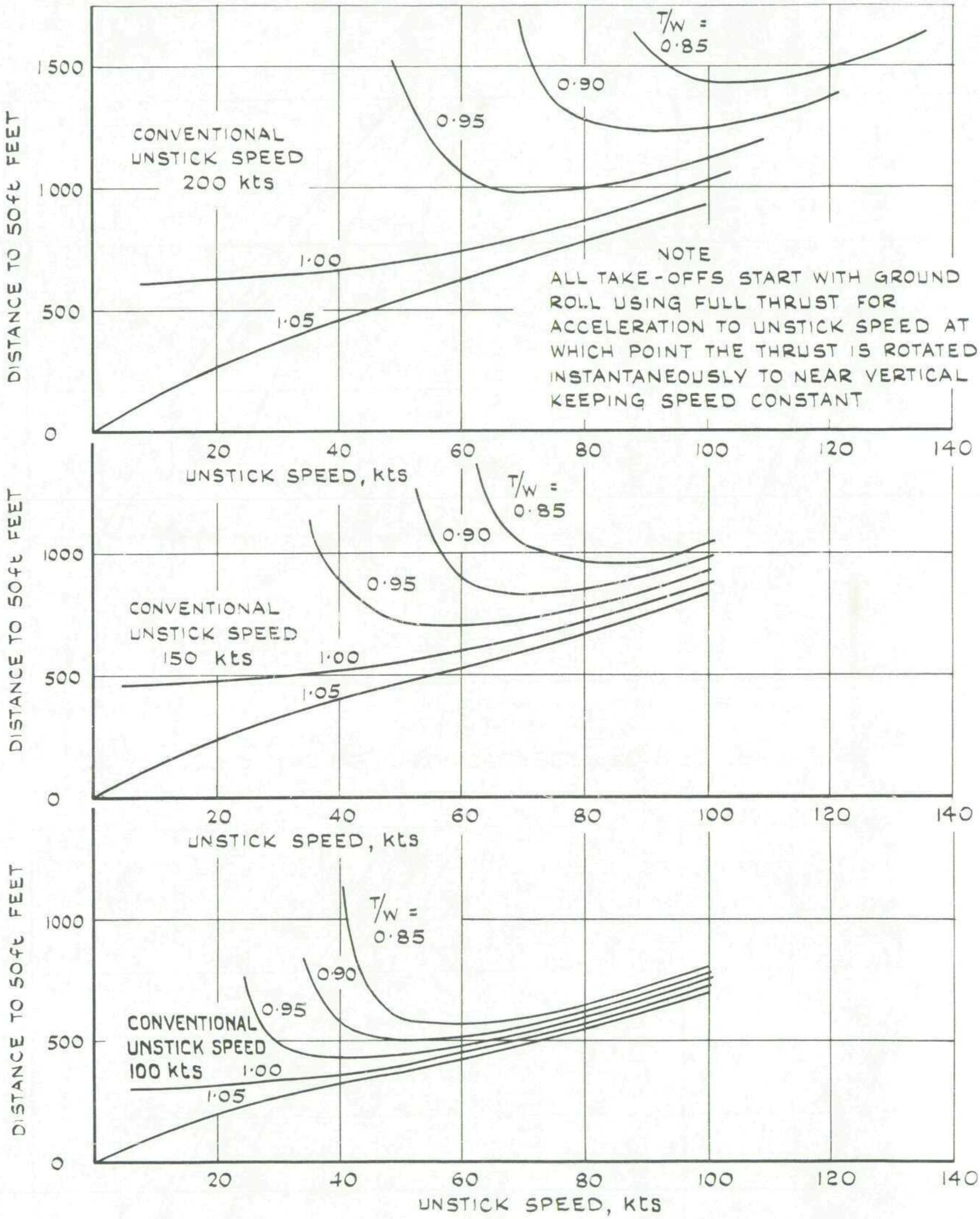


FIG. 5 EFFECT OF THRUST/ WEIGHT RATIO ON TOTAL TAKE - OFF DISTANCE (VECTORED – THRUST CONFIGURATION)

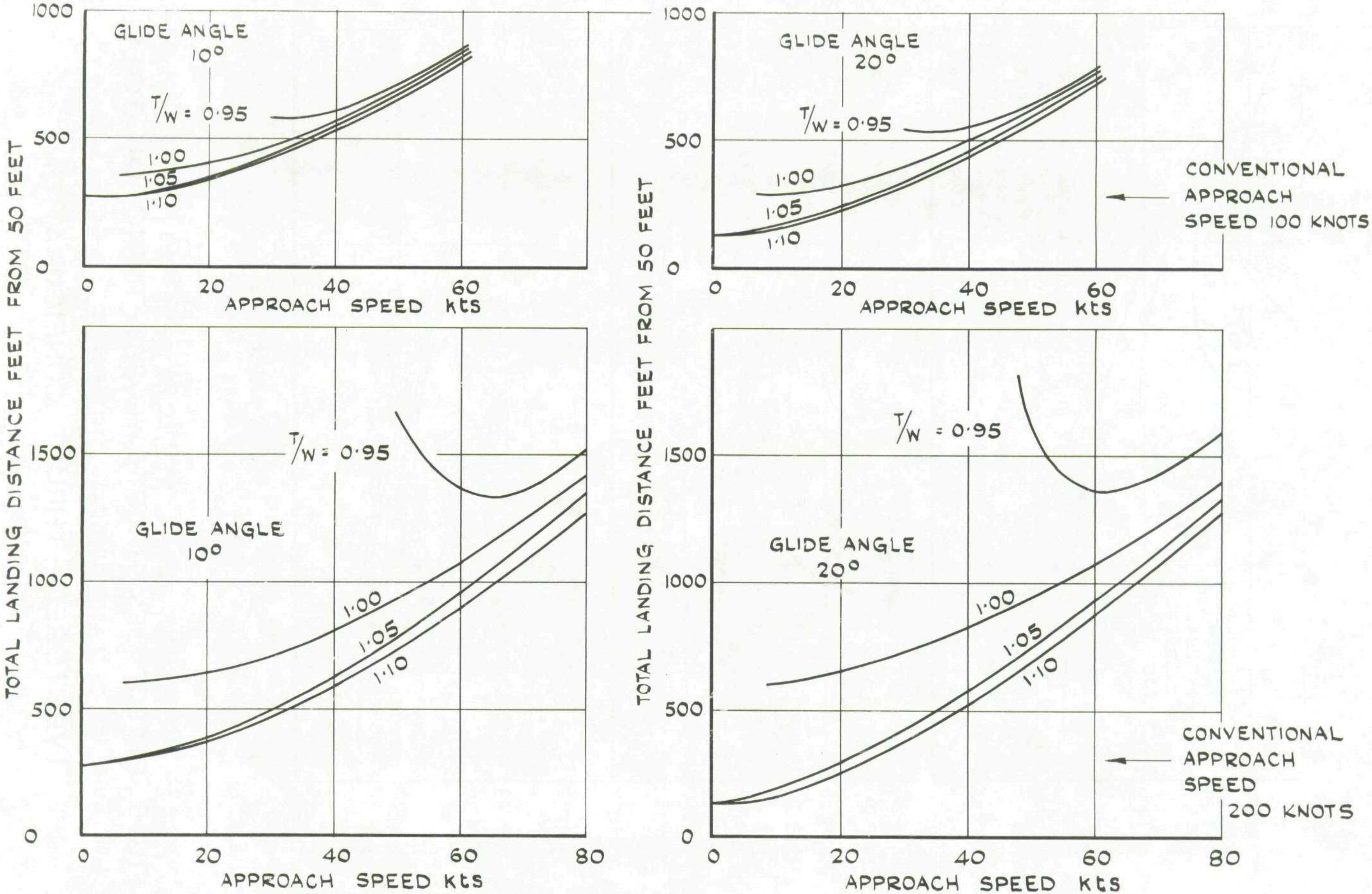


FIG. 6 EFFECT OF THRUST/WEIGHT RATIO ON LANDING DISTANCE

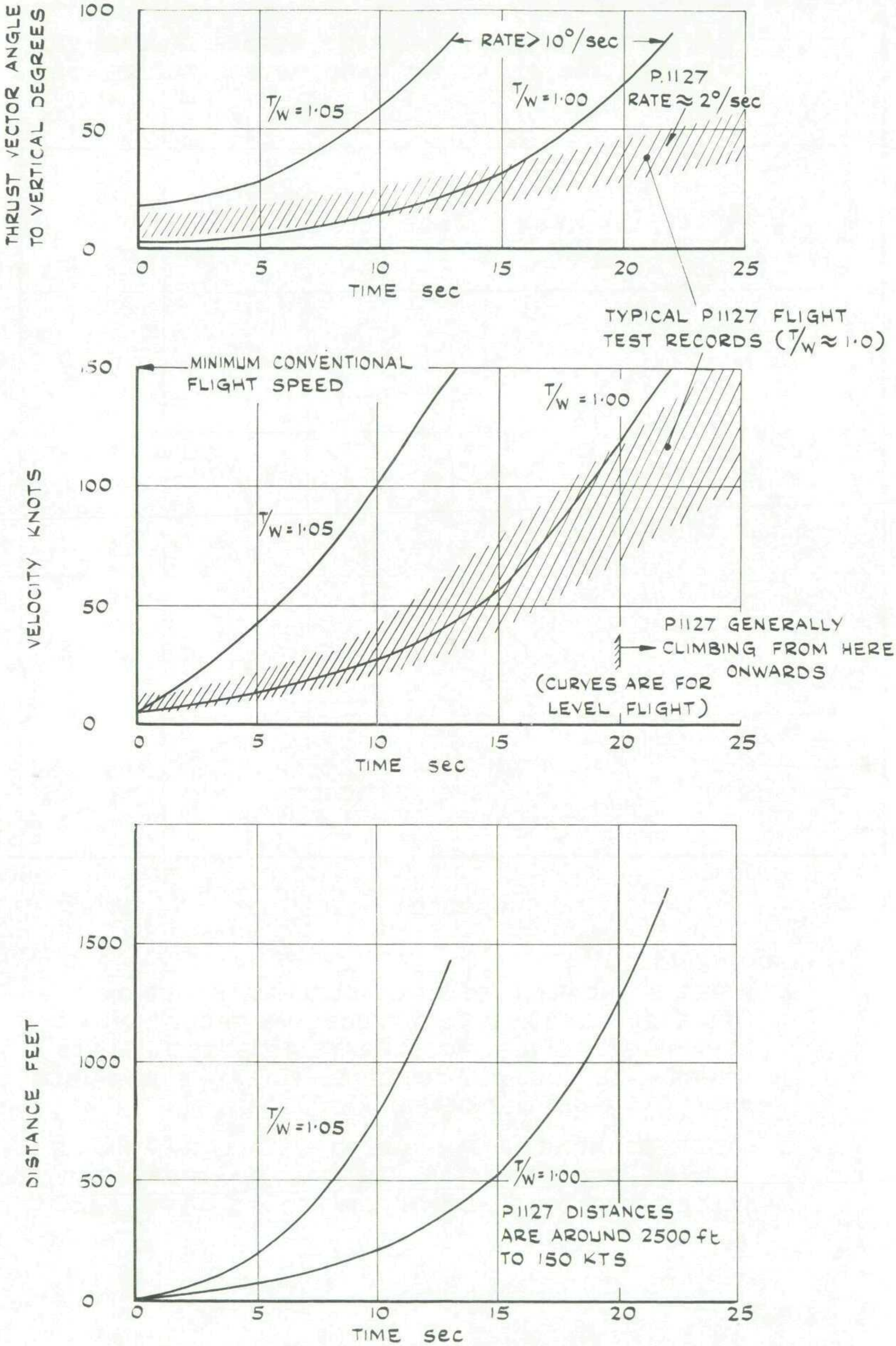
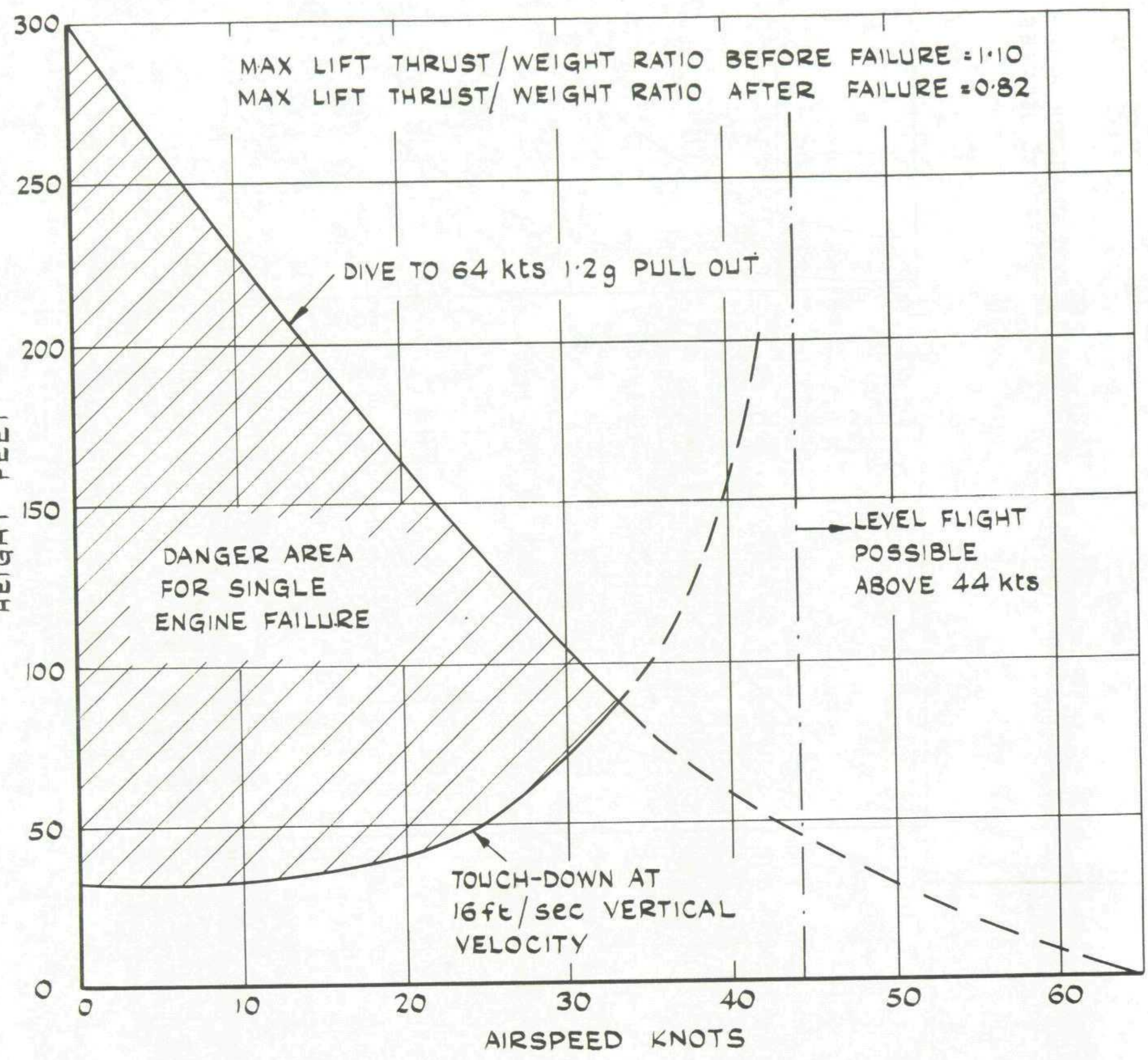


FIG. 7 COMPARISON OF MAXIMUM AND ACTUAL ACCELERATING TRANSITION PERFORMANCE – VECTORED THRUST CONFIGURATION



ASSUMPTIONS

1 UPPER BOUNDARY. USE MAX. ACCELERATE TILT ON LIFT ENGINES (3), LEVEL ATTITUDE, MAX THRUST ON ALL REMAINING ENGINES. ACCELERATE TO SPEED (64 kts) WHERE 1·2g PULL-OUT TO LEVEL FLIGHT IS POSSIBLE WITH $C_L = 0{\cdot}65$ (INCIDENCE = 15°)

2 LOWER BOUNDARY. MAX THRUST ON ALL REMAINING ENGINES, THRUST VECTOR VERTICAL, $C_L = 0{\cdot}65$, VERTICAL VELOCITY AT TOUCH-DOWN LIMITED TO 16 ft/sec

FIG. 8 SAMPLE "DEAD MAN'S CURVE" FOR SCI IN INITIALLY LEVEL FLIGHT.

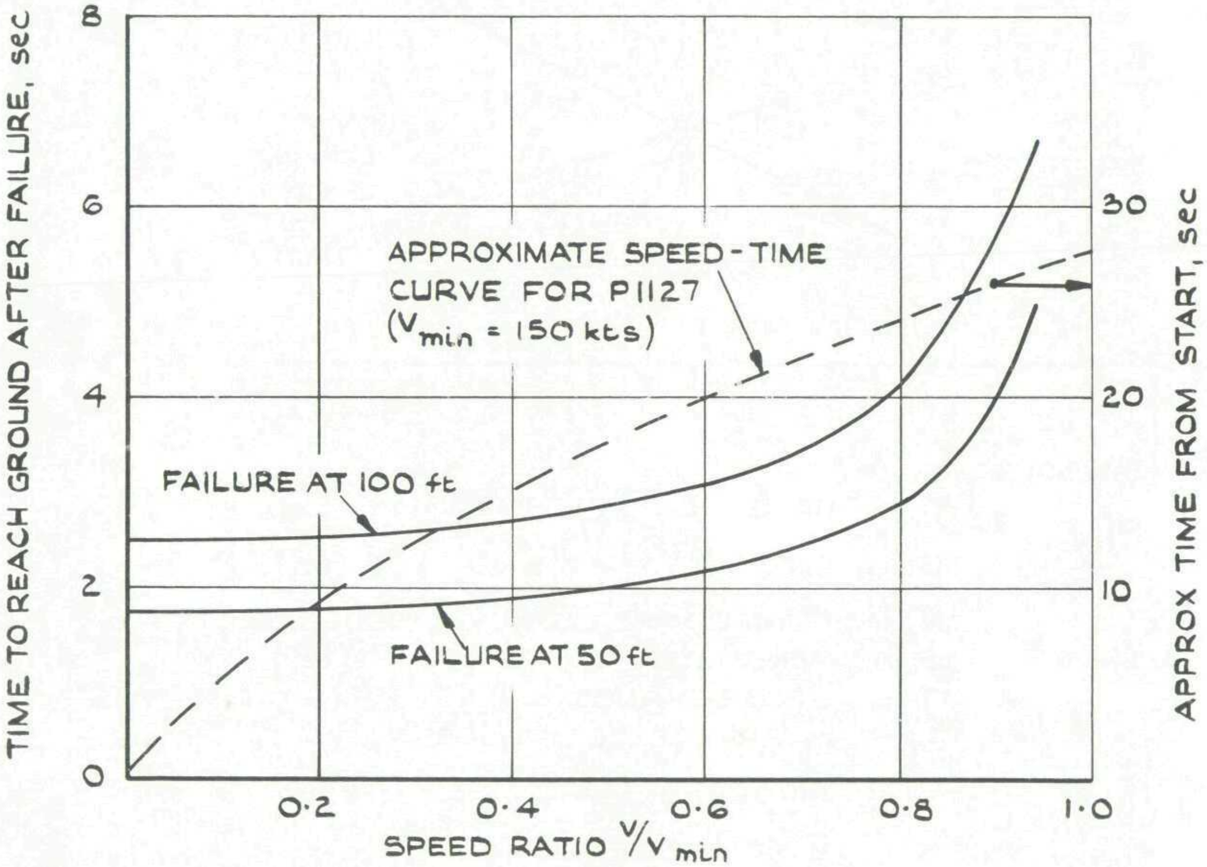
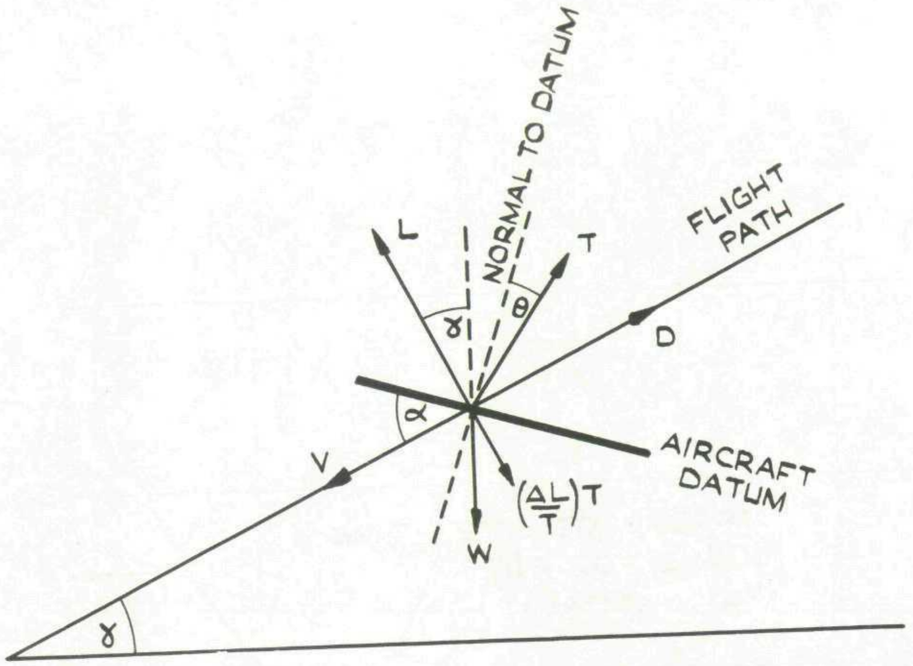


FIG. 9 TIME OF FALL AFTER ENGINE FAILURE
(SINGLE ENGINED AIRCRAFT)



SYMBOLS:-

D	=	DRAG $= C_D \cdot \frac{1}{2}\rho V^2 S + M_e V$	(lb)
L	=	LIFT $= C_L \cdot \frac{1}{2}\rho V^2 S$	(lb)
M_e	=	ENGINE MASS FLOW	(SLUGS/sec)
S	=	WING AREA	(ft^2)
T	=	GROSS THRUST	(lb)
$\left(\frac{\Delta L}{T}\right)$	=	INTERFERENCE LIFT LOSS RATIO	
V	=	AIRSPEED	(ft/sec)
α	=	WING INCIDENCE	
γ	=	FLIGHT PATH ANGLE	(+VE IN DESCENT)
θ	=	THRUST VECTOR ANGLE RELATIVE TO NORMAL TO WING CHORD	(+VE IN DECELERATE SENSE)

FIG.10 FORCES AND ANGLES FOR DESCENDING DECELERATING TRANSITION

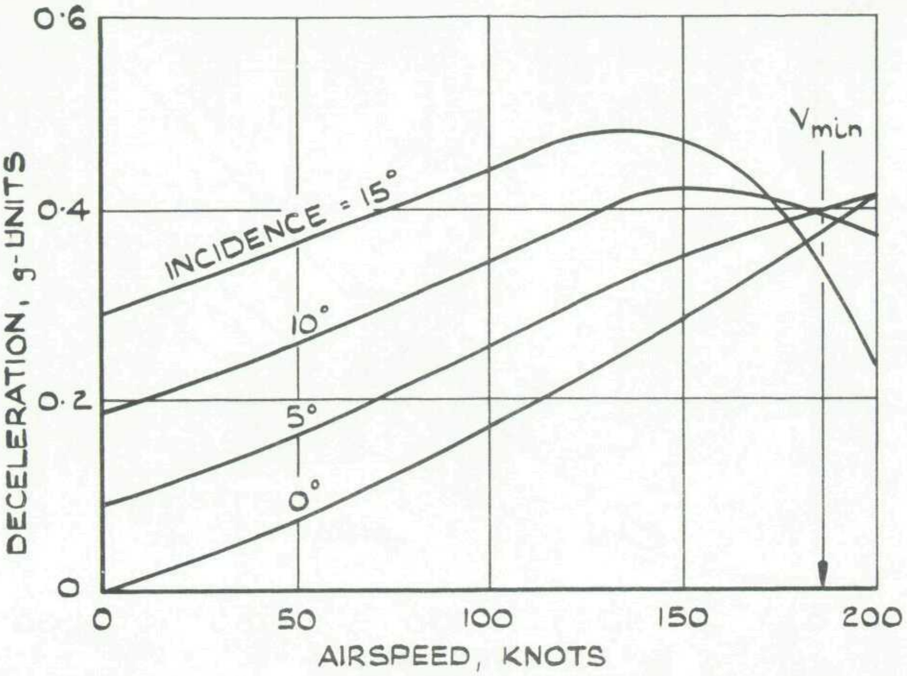


FIG. 11(a) VECTORED - THRUST STRIKE AIRCRAFT. - WING LOADING = 100 lb/ft²
THRUST VECTOR ANGLE = 10°
GLIDE SLOPE = 10°
V_{min} AT 15° INCIDENCE (POWER OFF) = 186 kts.

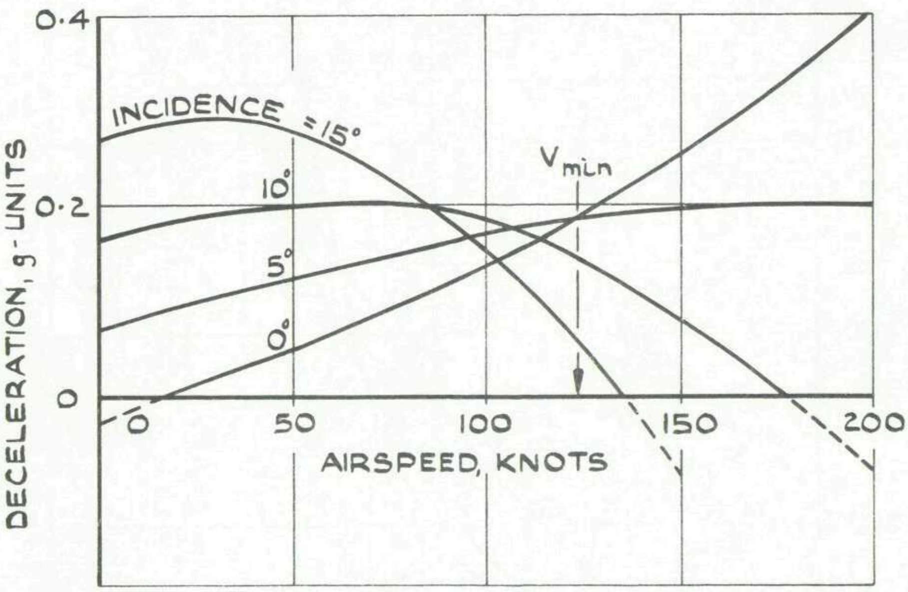


FIG. 11(b) SEPARATE LIFT & PROPULSION ENGINED AIRCRAFT (SC1)
– WING LOADING = 32 lb/ft²
LIFT THRUST ANGLE = 12°
PROP. ENGINE IDLING THRUST/WEIGHT RATIO = 0·06
GLIDE SLOPE = 10°
V_{min} AT 15° INCIDENCE (POWER OFF) = 124 kts

FIG. 11 EFFECT OF INCIDENCE ON DECELERATION, FOR TWO CLASSES OF AIRCRAFT

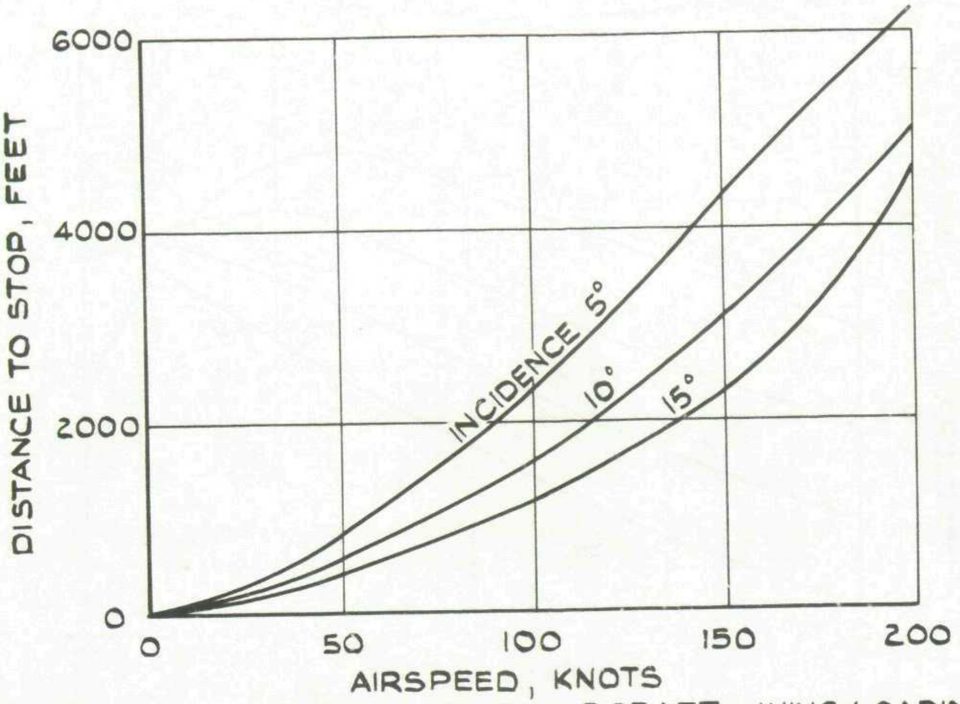


FIG. 12(a) VECTORED - THRUST STRIKE AIRCRAFT - WING LOADING = 100 lb/ft²
THRUST VECTOR ANGLE = 10°
GLIDE SLOPE = 10°

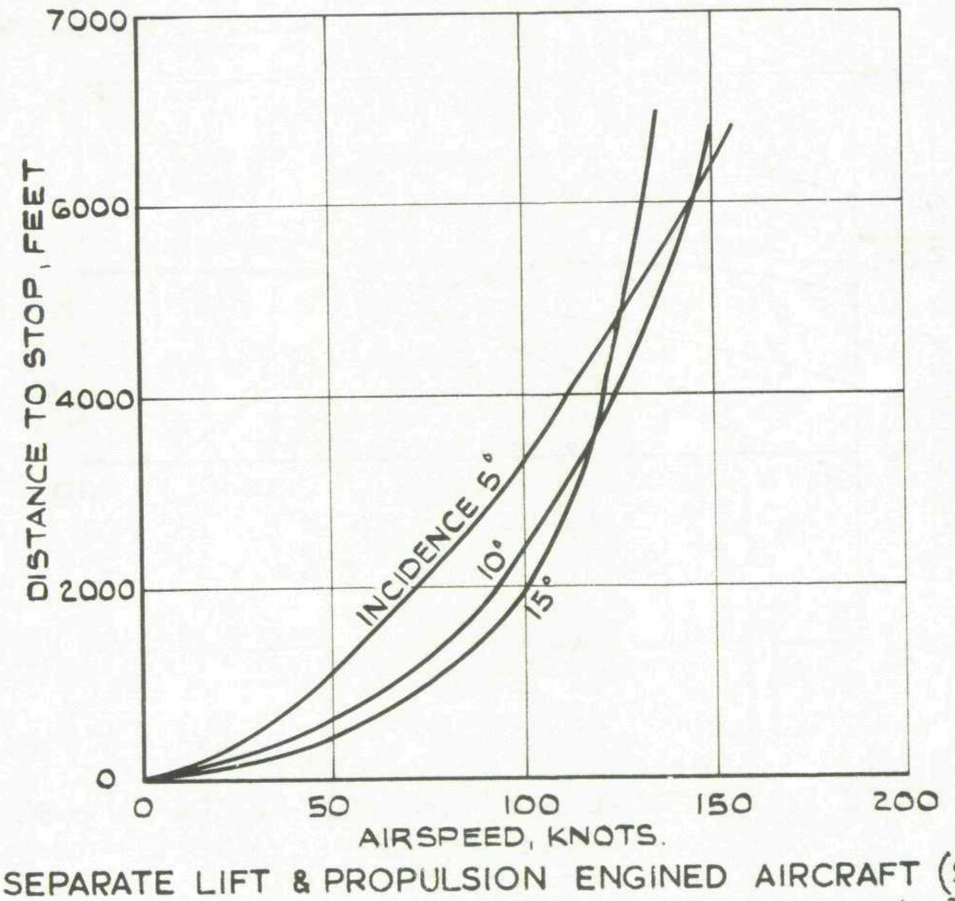


FIG. 12(b) SEPARATE LIFT & PROPULSION ENGINED AIRCRAFT (SCI)
WING LOADING = 32 lb/ft²
LIFT THRUST ANGLE = 12°
GLIDE SLOPE = 10°

FIG. 12 EFFECT OF INCIDENCE ON DECELERATING TRANSITION DISTANCE (ZERO WIND)

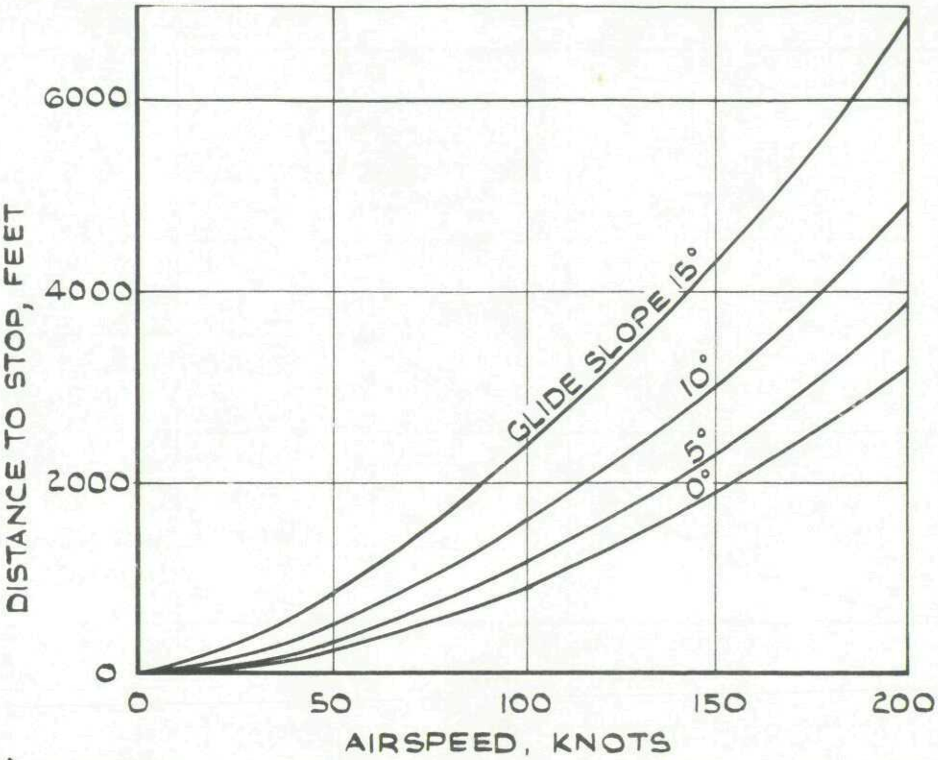


FIG.13(a) VECTORED - THRUST STRIKE AIRCRAFT. - WIND LOADING = 100 lb/ft²
THRUST VECTOR ANGLE = 10°
INCIDENCE = 10°

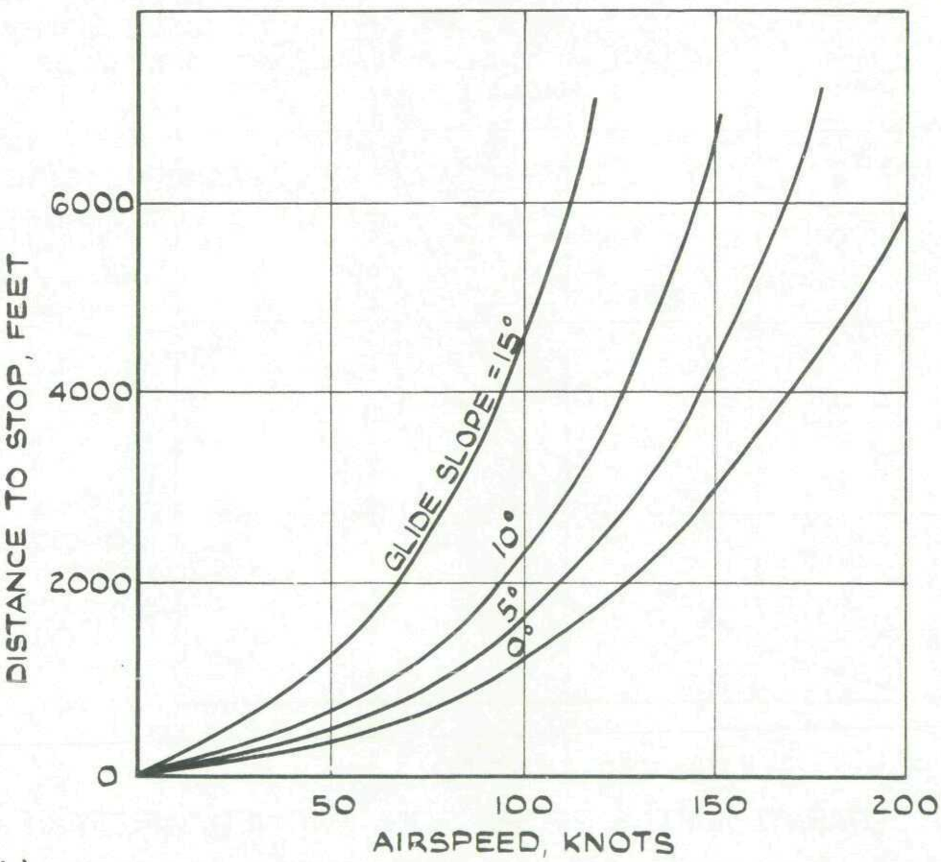


FIG. 13(b) SEPARATE LIFT & PROPULSION ENGINED AIRCRAFT (SC1)
WING LOADING = 32 lb/ft²
LIFT THRUST ANGLE = 12°
INCIDENCE = 10°

FIG.13 EFFECT OF GLIDE SLOPE ON DECELERATING TRANSITION DISTANCE (ZERO WIND)

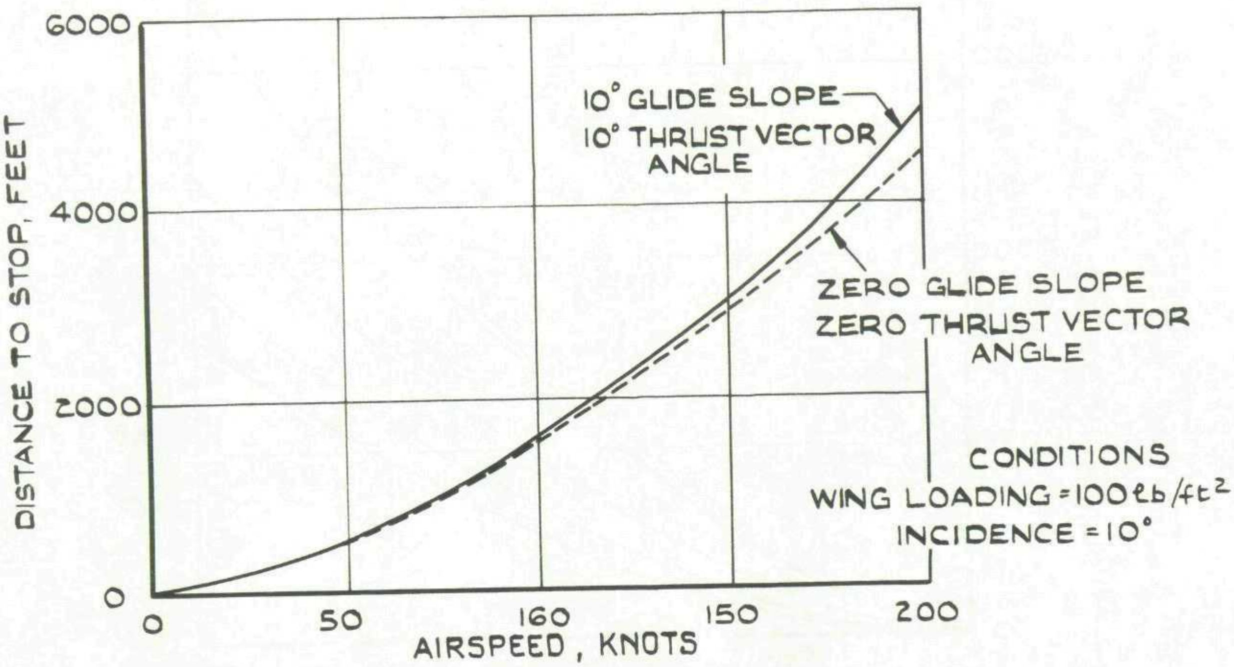


FIG. 14 (a) VECTORED–THRUST STRIKE AIRCRAFT.

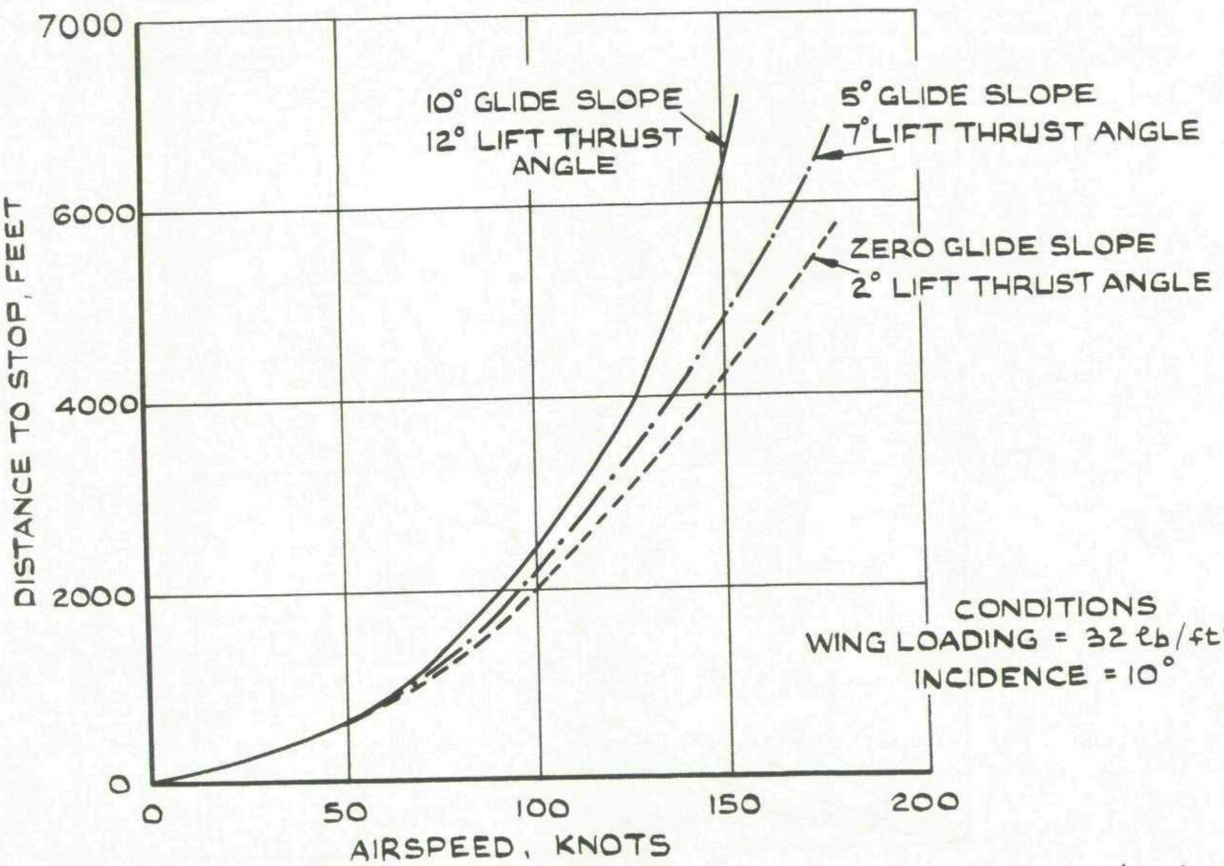


FIG. 14 (b) SEPARATE LIFT & PROPULSION ENGINED AIRCRAFT (SC1)

FIG. 14 EFFECT OF SIMULTANEOUS CHANGES IN GLIDE SLOPE AND THRUST VECTOR ANGLE ON DECELERATING TRANSITION DISTANCE (ZERO WIND)

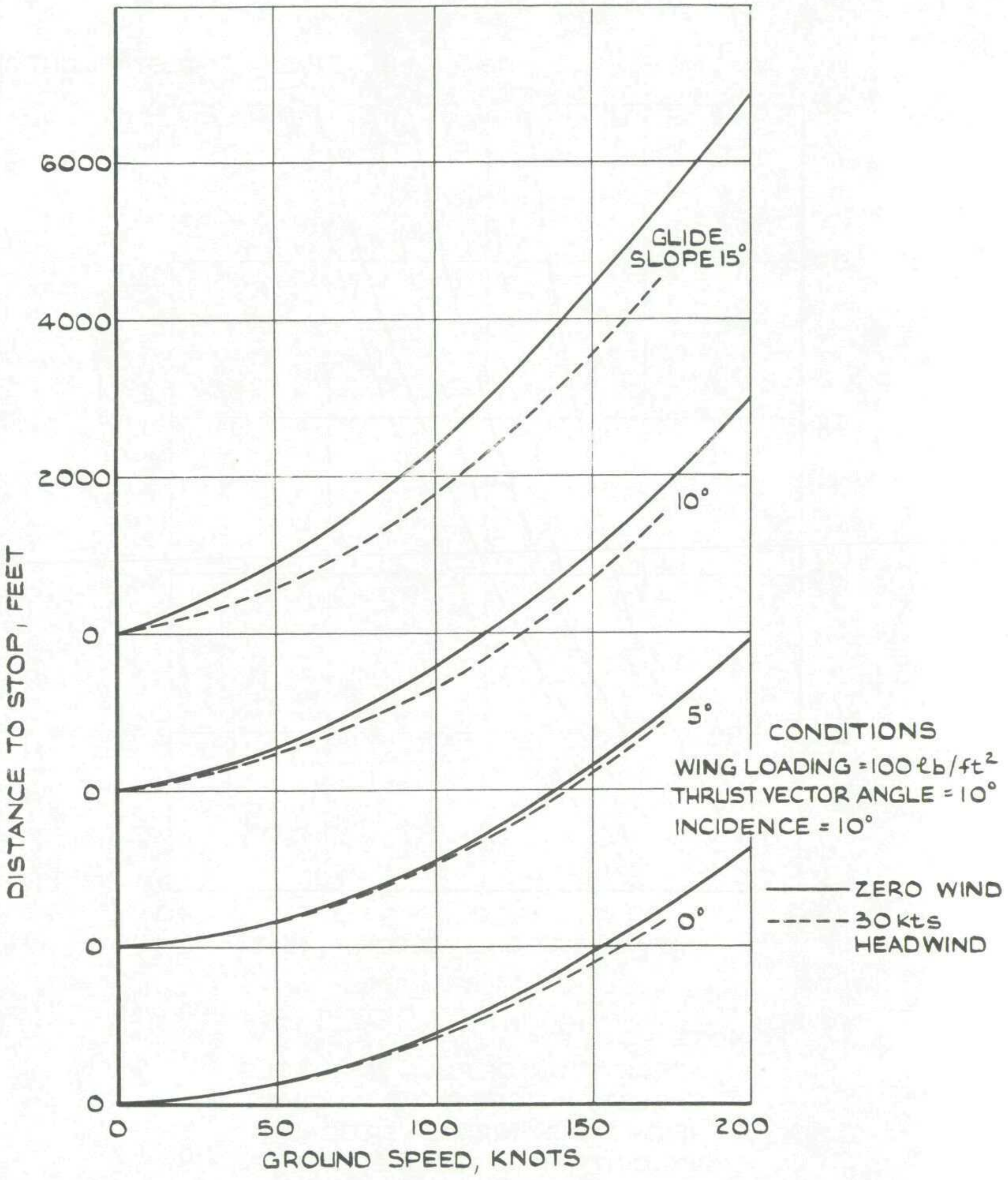
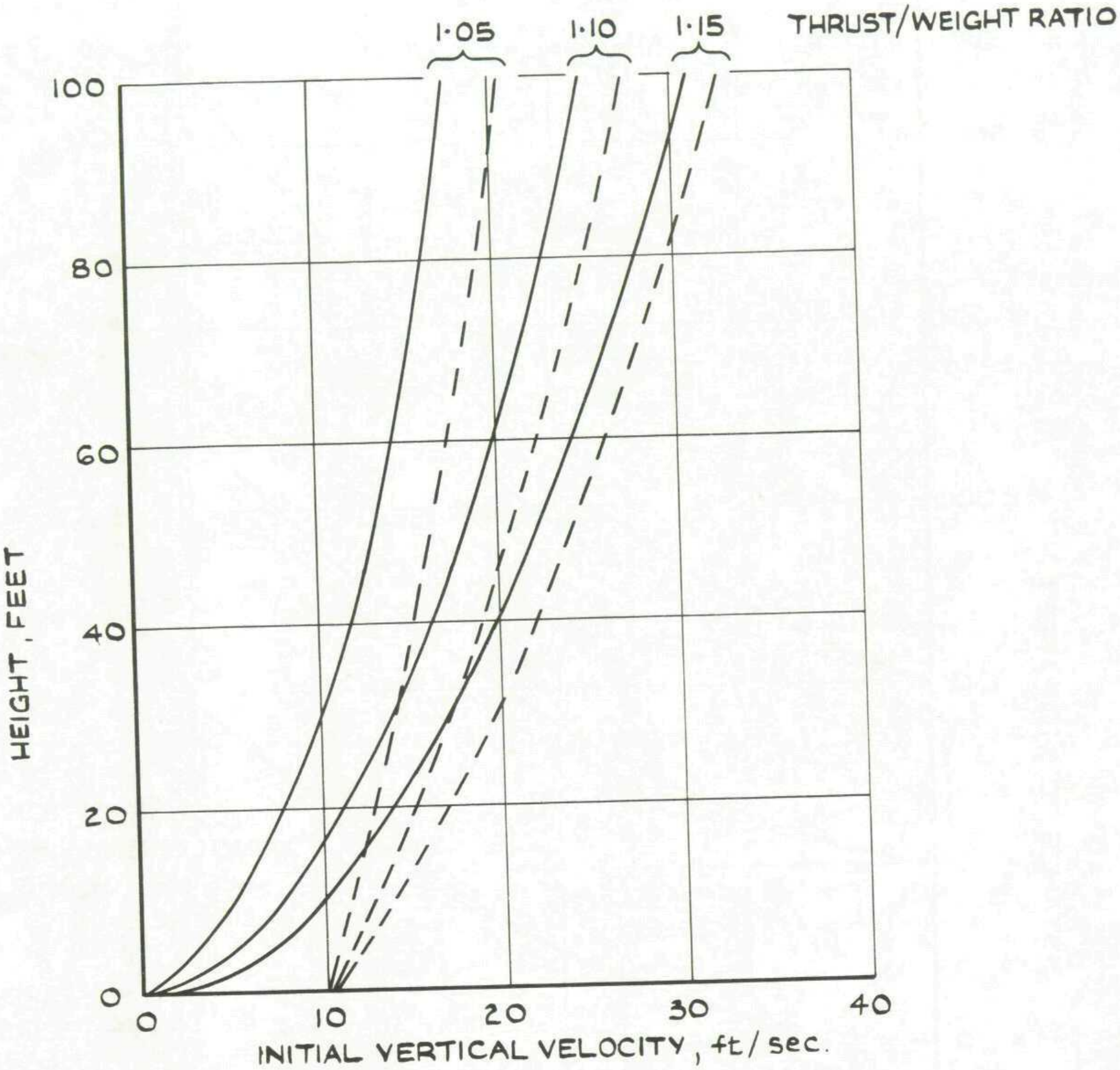


FIG.15 EFFECT OF HEADWIND ON DECELERATING TRANSITION DISTANCE — VECTORED-THRUST STRIKE AIRCRAFT



NOTE :-
APPLICATION OF FULL AVAILABLE THRUST / WEIGHT RATIO AT GIVEN HEIGHT AND INITIAL VERTICAL VELOCITY WILL REDUCE THE VERTICAL VELOCITY AT TOUCH-DOWN
TO :- ZERO ———
10 ft/sec - - - -

FIG. 16 EFFECT OF THRUST MARGIN ON ALLOWABLE DESCENT RATES IN VERTICAL LANDING

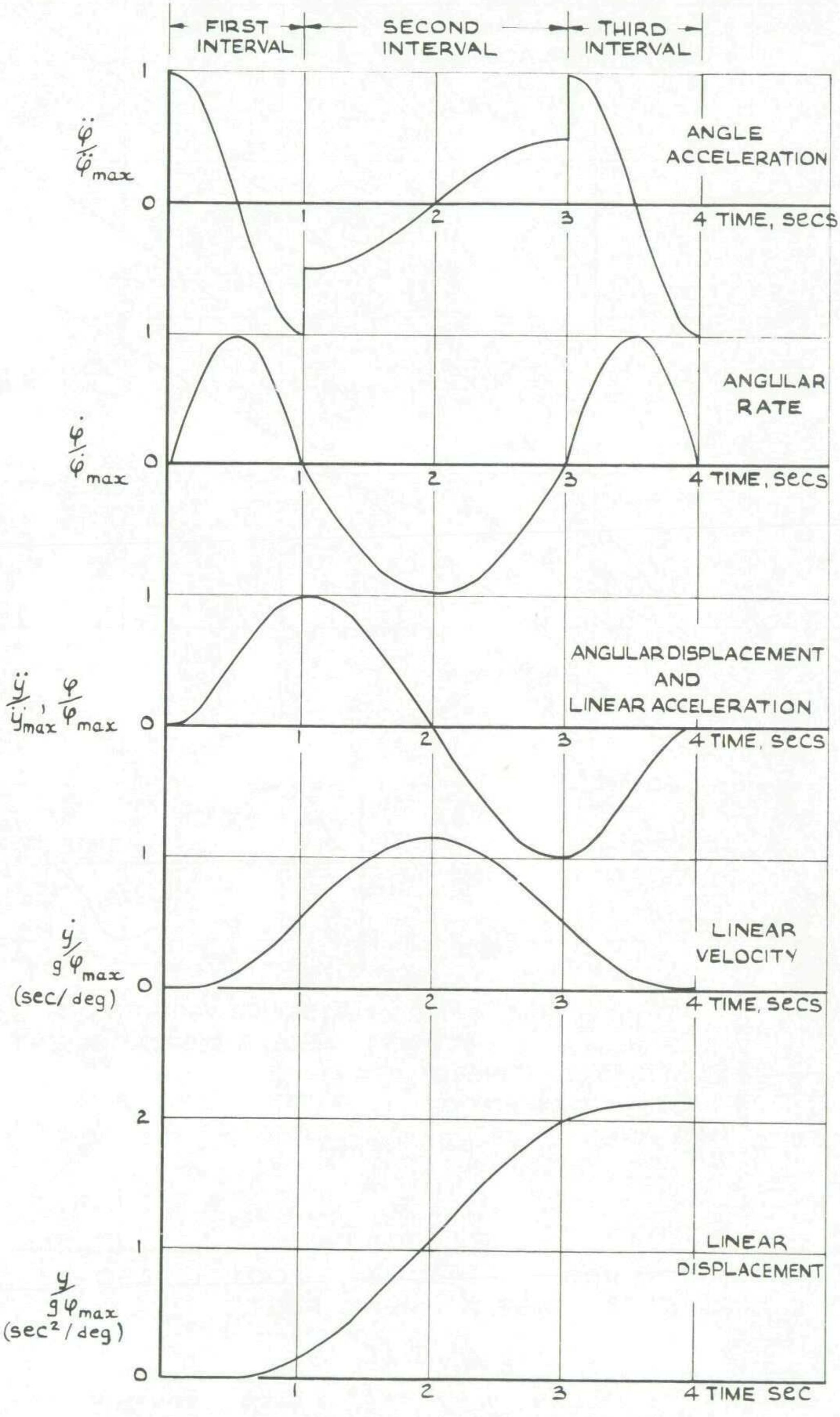


FIG. 17 THEORETICAL TRANSLATIONAL MANOEUVRE

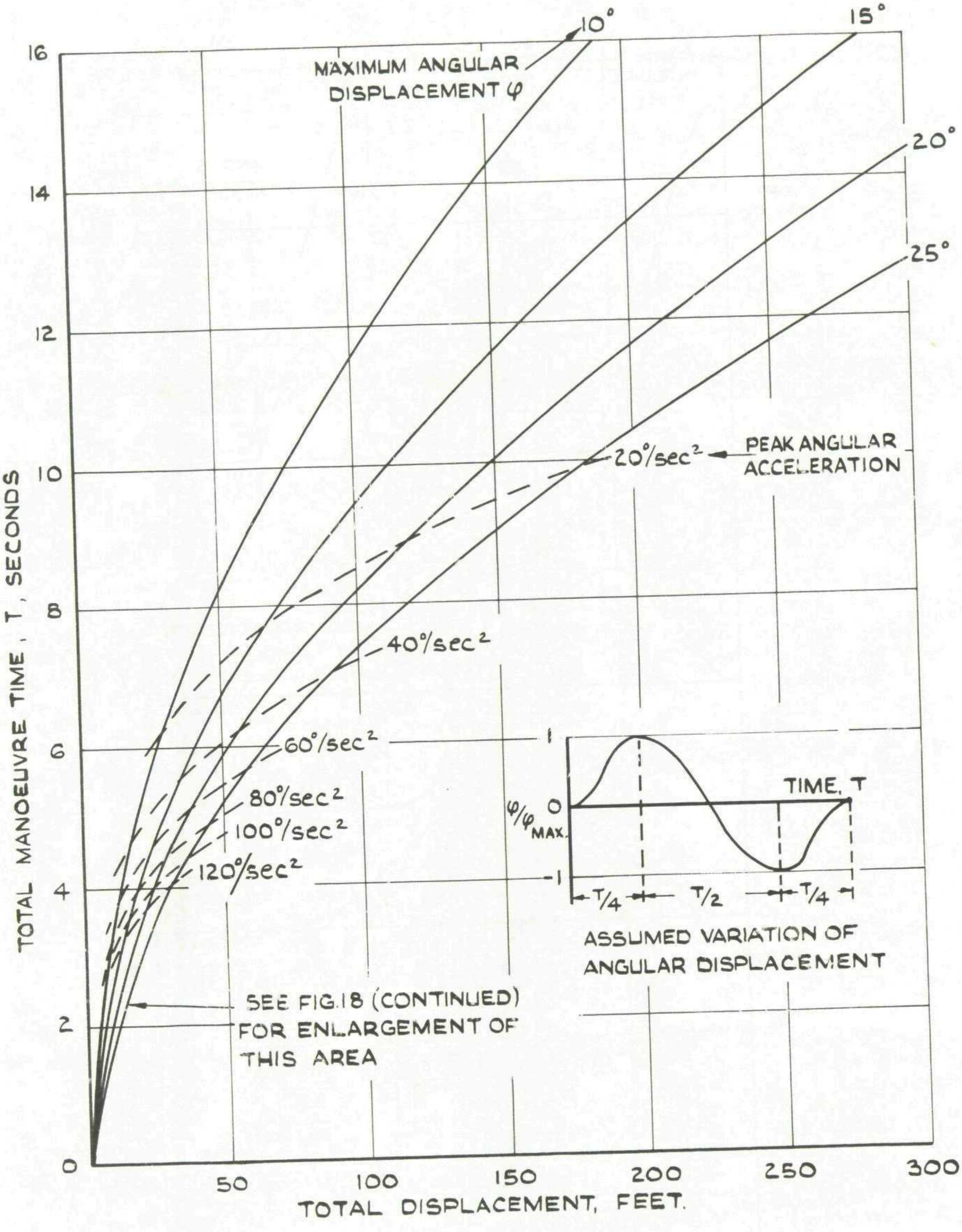


FIG. 18 CALCULATED DISPLACEMENT MANOEVERABILITY

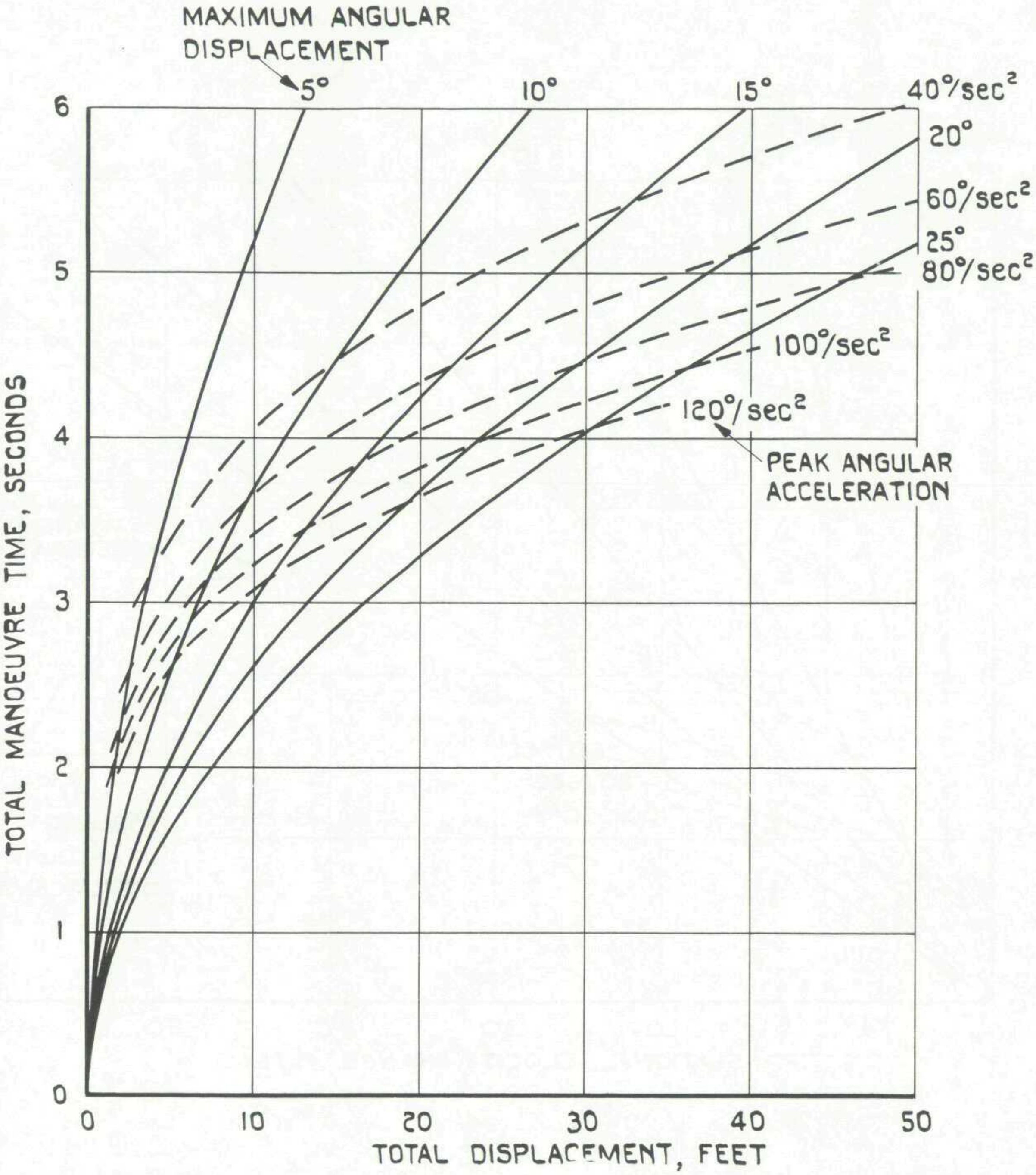


FIG. 18 (CONT.) CALCULATED DISPLACEMENT MANOEUVERABILITY
(ENLARGED SCALE)

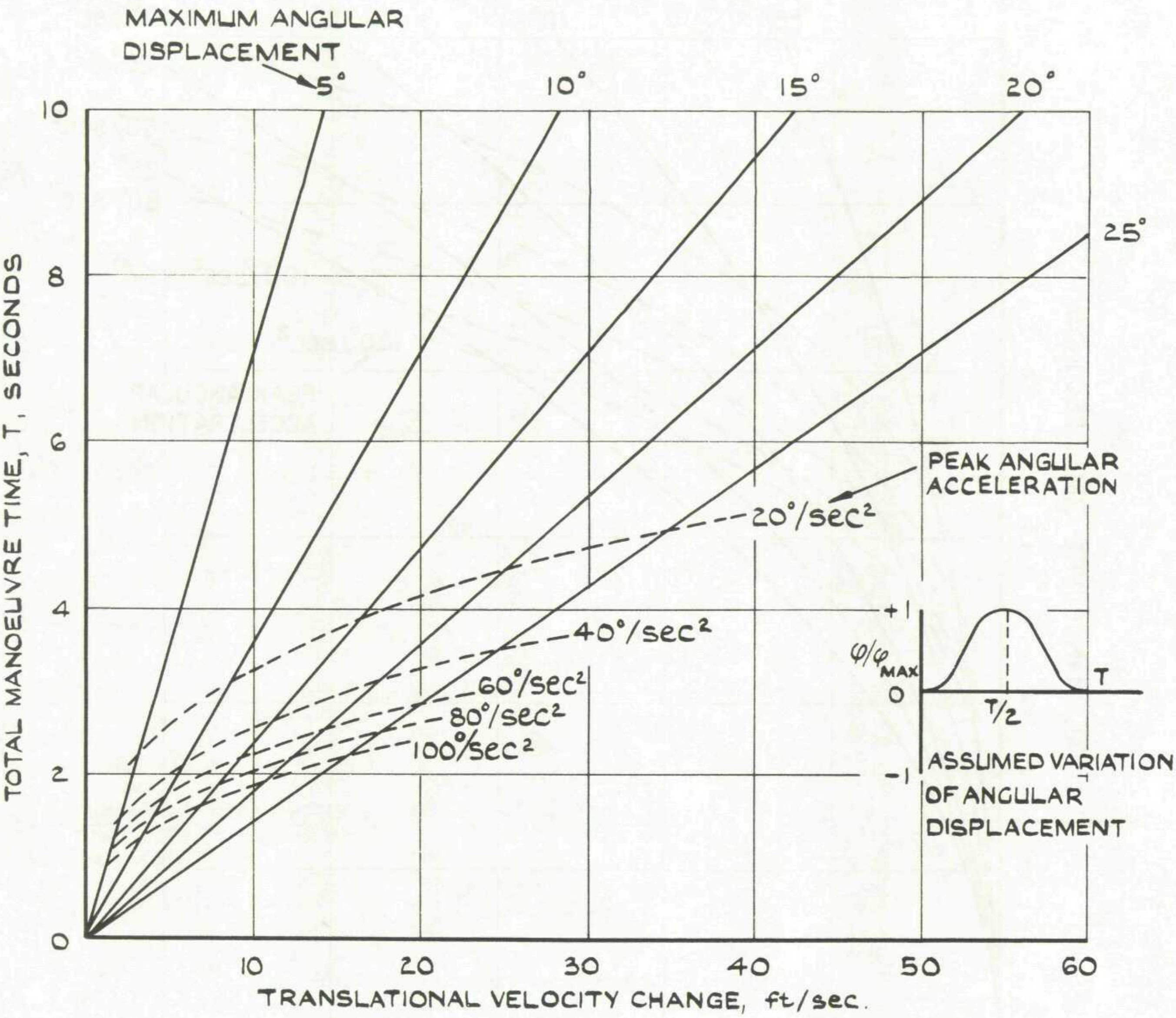


FIG. 19 CALCULATED VELOCITY MANOEUVERABILITY

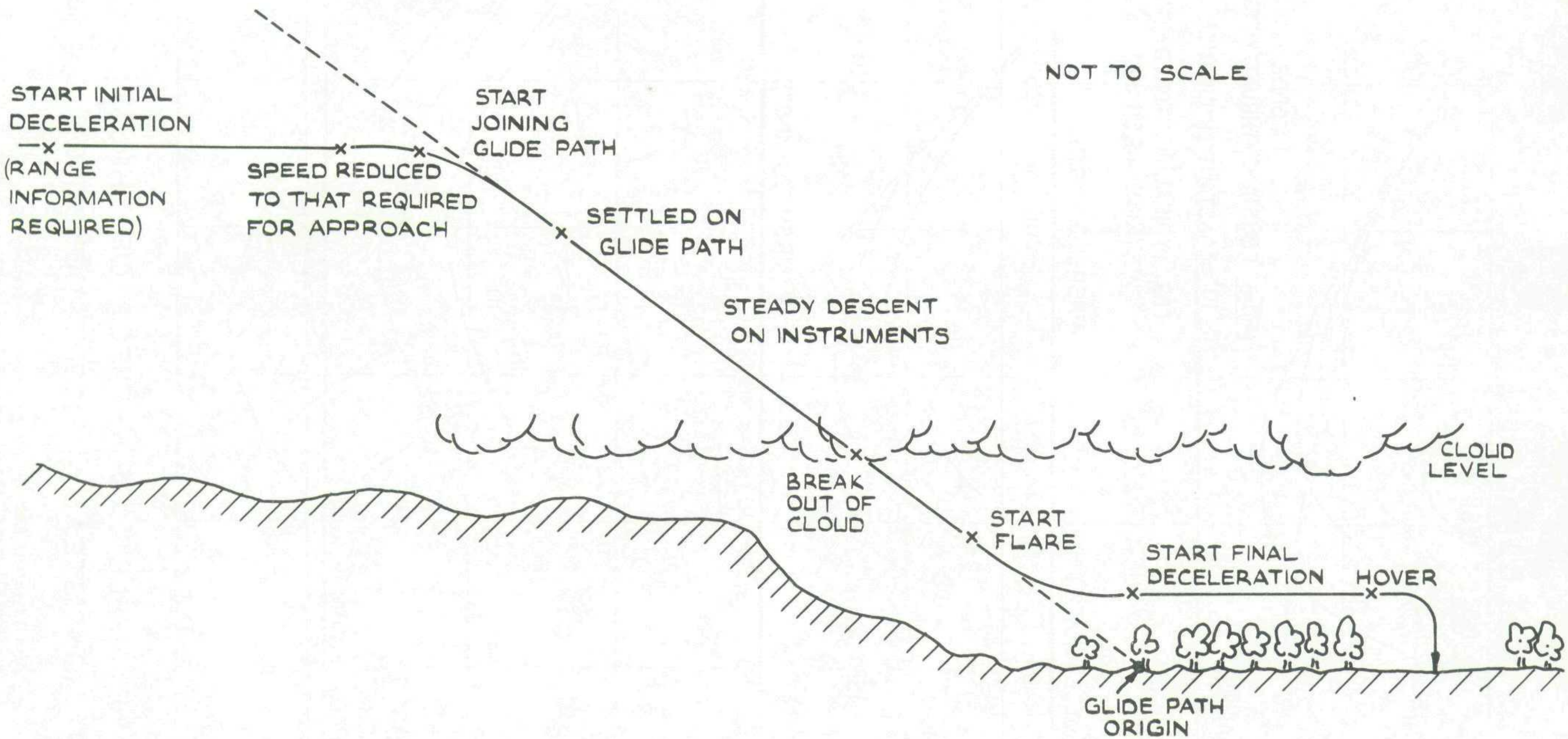


FIG. 20 PROPOSED PROCEDURE FOR LANDING IN RESTRICTED VISIBILITY

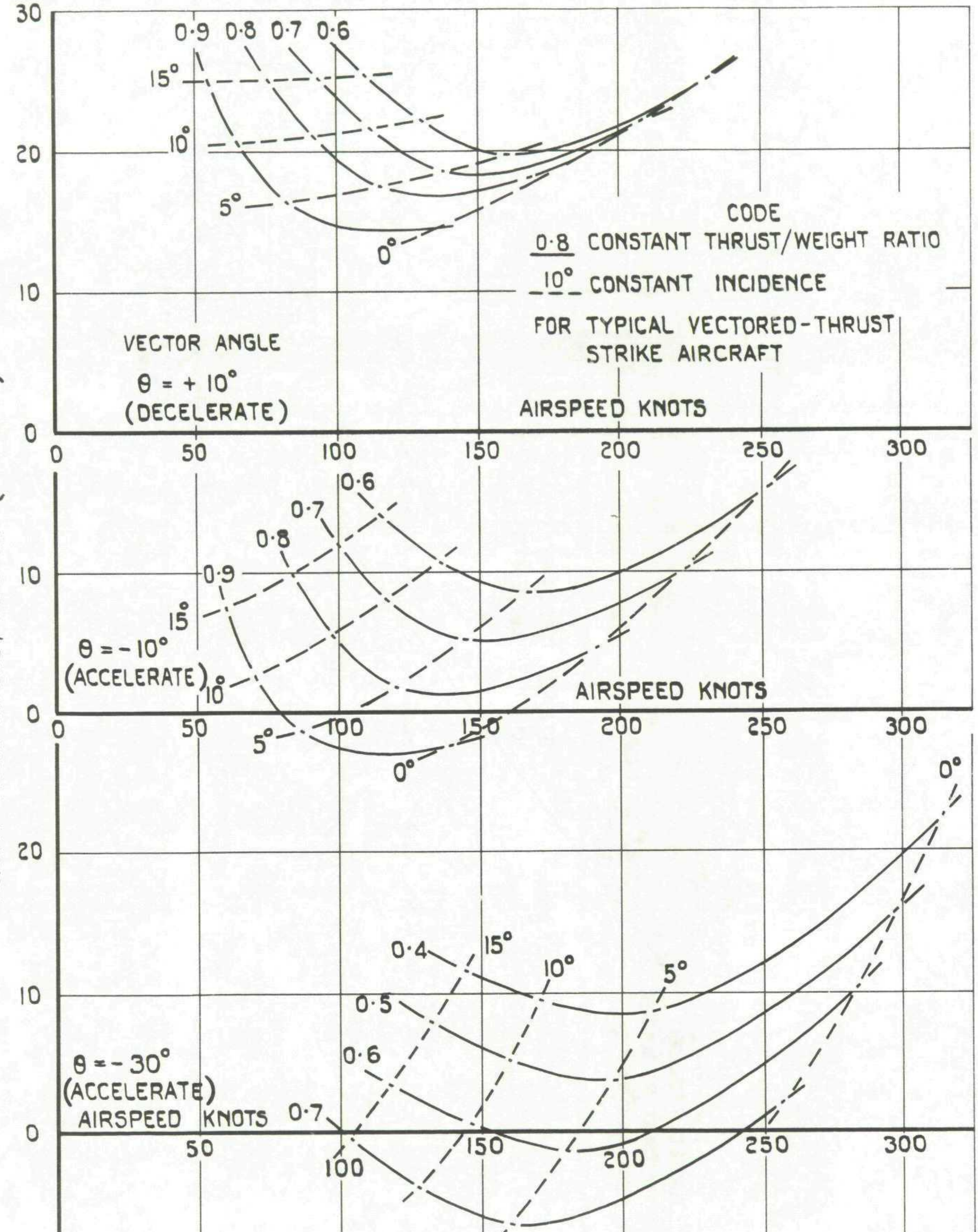


FIG. 21 EXAMPLES OF EFFECT OF THRUST VECTOR ON STEADY FLIGHT CONDITION

Printed in England for Her Majesty's Stationery Office by The Royal Aircraft Establishment, Farnborough. Dd.146915. K.4.

A.R.C. C.P. No. 1082 — 629.136-118 :
June 1966 — 629.136.5 :
Lean, D. — 629.13.081 :
A DISCUSSION OF SOME JET-LIFT V/STOL AIRCRAFT CHARACTERISTICS AND THEIR LIKELY EFFECT ON OPERATIONAL APPLICATIONS — 629.13.087 : 533.682

Some of the characteristics of jet-lift V/STOL aircraft are discussed in terms of their effect on the ability of these aircraft to operate from small, semi-prepared sites, without the usual airfield facilities, in both good and bad visibility. Accumulated experience from experimental operations with jet-lift aircraft has been used as a basis for a tentative extrapolation to situations and conditions not yet (in 1964) examined in flight.

An attempt is made to present these particular capabilities in such a way that future statements of requirements for this class of aircraft, and proposals for their tactical deployment may be formulated to take better

(Over)

A.R.C. C.P. No. 1082 — 629.136-118 :
June 1966 — 629.136.5 :
Lean, D. — 629.13.081 :
A DISCUSSION OF SOME JET-LIFT V/STOL AIRCRAFT CHARACTERISTICS AND THEIR LIKELY EFFECT ON OPERATIONAL APPLICATIONS — 629.13.087 : 533.682

Some of the characteristics of jet-lift V/STOL aircraft are discussed in terms of their effect on the ability of these aircraft to operate from small, semi-prepared sites, without the usual airfield facilities, in both good and bad visibility. Accumulated experience from experimental operations with jet-lift aircraft has been used as a basis for a tentative extrapolation to situations and conditions not yet (in 1964) examined in flight.

An attempt is made to present these particular capabilities in such a way that future statements of requirements for this class of aircraft, and proposals for their tactical deployment may be formulated to take better

(Over)

A.R.C. C.P. No. 1082 — 629.136-118 :
June 1966 — 629.136.5 :
Lean, D. — 629.13.081 :
A DISCUSSION OF SOME JET-LIFT V/STOL AIRCRAFT CHARACTERISTICS AND THEIR LIKELY EFFECT ON OPERATIONAL APPLICATIONS — 629.13.087 : 533.682

Some of the characteristics of jet-lift V/STOL aircraft are discussed in terms of their effect on the ability of these aircraft to operate from small, semi-prepared sites, without the usual airfield facilities, in both good and bad visibility. Accumulated experience from experimental operations with jet-lift aircraft has been used as a basis for a tentative extrapolation to situations and conditions not yet (in 1964) examined in flight.

An attempt is made to present these particular capabilities in such a way that future statements of requirements for this class of aircraft, and proposals for their tactical deployment may be formulated to take better

(Over)

A.R.C. C.P. No. 1082 — 629.136-118 :
June 1966 — 629.136.5 :
Lean, D. — 629.13.081 :
A DISCUSSION OF SOME JET-LIFT V/STOL AIRCRAFT CHARACTERISTICS AND THEIR LIKELY EFFECT ON OPERATIONAL APPLICATIONS — 629.13.087 : 533.682

Some of the characteristics of jet-lift V/STOL aircraft are discussed in terms of their effect on the ability of these aircraft to operate from small, semi-prepared sites, without the usual airfield facilities, in both good and bad visibility. Accumulated experience from experimental operations with jet-lift aircraft has been used as a basis for a tentative extrapolation to situations and conditions not yet (in 1964) examined in flight.

An attempt is made to present these particular capabilities in such a way that future statements of requirements for this class of aircraft, and proposals for their tactical deployment may be formulated to take better

(Over)

DETACHABLE ABSTRACT CARD

advantage of such experience as already exists, and of the provisional conclusions that may reasonably be drawn from that experience.

In addition, attention is drawn to what appear to be some outstanding problem areas, and suggestions are made regarding a possible future programme of theoretical, model and full-scale work.

advantage of such experience as already exists, and of the provisional conclusions that may reasonably be drawn from that experience.

In addition, attention is drawn to what appear to be some outstanding problem areas, and suggestions are made regarding a possible future programme of theoretical, model and full-scale work.

C.P. No. 1082

Published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
49 High Holborn, London W.C.1
13a Castle Street, Edinburgh EH 2 3AR
109 St. Mary Street, Cardiff CF1 1JW
Brazennose Street, Manchester 2
50 Fairfax Street, Bristol BS1 3DE
258 Broad Street, Birmingham 1
7 Linenhall Street, Belfast BT2 8AY
or through any bookseller

C.P. No. 1082

SBN 11 470282 9