

# SAFETY AND RELIABILITY ASPECTS OF VTOL

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## 1. INTRODUCTION

### 1.1 *The Type of Aircraft*

Research on vertical take-off and landing is being pursued in many countries and the number of experimental VTOL aircraft which have now flown is already in double figures. Collectively these experiments have proved the engineering feasibility of VTOL but so far very little attention has been given to the operational feasibility.

This paper is intended to stimulate thought on the problems of airworthiness and of safety, reliability and regularity in all-weather operation of VTOL aircraft.

It has been written as a result of work done on the Short SC.1 (Fig. 1) and applies particularly to aircraft having lifting, control and stabilizing systems of that type. Many of the conclusions may nevertheless be of more general application.



FIG. 1. SC.1 aircraft.

The SC.1 has four jet engines, mounted vertically in the fuselage for lift, and a separate jet engine for propulsion. The lifting engines are mounted on trunnions so that they can be tilted fore and aft to assist the acceleration and deceleration during the transition between jet borne and wing borne flight.

The SC.1 is a delta-winged aircraft with normal ailerons, elevators and rudder. In hovering flight it is controlled by air jets directed downwards at the nose, tail and wing tips. These jets are supplied by air bled

from the lifting engine compressors and are operated differentially through the medium of an auto-stabilizer. It is appreciated that it may be possible to design a control system which does not require autostabilization for hovering flight but, for all-weather operation, an autostabilizer appears to be essential and it is therefore assumed to be part of an operational aircraft.

### 1.2 *All-weather Operation*

Regularity in all weather is an important consideration for civil and military operations alike. To an airline the cost of an occasional lapse from regularity may be out of all proportion to the number of flights actually delayed or cancelled. For example, most passengers want to be certain of reaching their destination by a given time but not all of them trust the airlines to be on schedule, especially if the weather should be adverse. This lack of trust may spring from very few actual postponements or cancellations and yet may cause a significant loss of custom especially in off-season times when the load factor is already at a minimum. Experience shows that, for a well-run airline, the vast majority of cancellations, diversions and postponements greater than two hours arise from weather conditions and not from mechanical defects in the aircraft.

There are two aspects of the weather problem. The first is operation under conditions of limited or zero visibility and the second is operation in gusty conditions or in high winds. It is suggested that in both respects VTOL has advantages to offer over existing aircraft. We will consider them separately.

## 2. BLIND LANDING

### 2.1 *The Landing Sequence*

One of the greatest attractions of VTOL is the ability to let down with no, or practically no, forward speed. Potentially this can confer safety in bad weather conditions.

In recent years great advances have been made in the techniques of blind landing and it is reasonable to expect that it will soon be possible to bring conventional aircraft right on to the runway under completely blind conditions. The fact remains however that there must always be a risk when an aircraft with high kinetic energy flies on to the ground. It is inherently far safer to dissipate the kinetic energy at an altitude clear of all obstructions and to make the final descent with little or no forward speed.

Despite this fundamental advantage the blind landing of VTOL aircraft is in some ways a more difficult procedure than for conventional aircraft. It certainly introduces some new problems.

Figure 2 illustrates a typical approach path in comparison with that of a conventional aircraft landing on a runway. The VTOL aircraft makes what amounts to a landing at 100 ft or more above the landing point, coming to rest at that altitude and then making a final vertical descent. The complete approach consists of three phases:

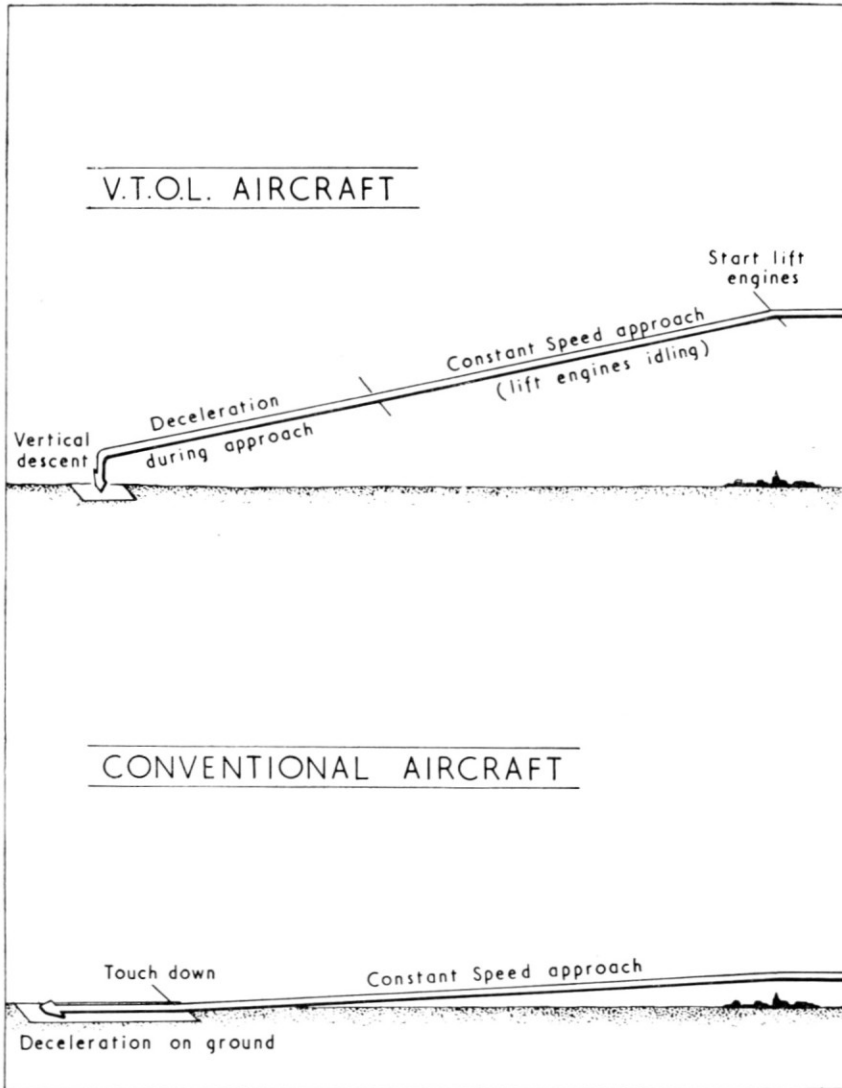


FIG. 2. Comparison of approach paths.

*Phase A*—Constant speed descent to a given point fixed accurately in both height and slant distance from the landing point. During this phase the lifting engines are idling.

*Phase B*—Decelerating approach during which the speed falls to zero and the loss of wing lift is progressively compensated by opening the throttles of the lifting engines. The object of this phase is to attain zero velocity at a height of, say, 100 ft as nearly as possible over the landing point.

*Phase C*—Vertical descent modified to give some positional correction if required.

Several interesting points emerge from a study of this landing sequence. Firstly, the good terrain clearance arises largely from the steep approach gradient which would probably be of the order of  $10^\circ$  or  $15^\circ$ . The gradient can be chosen purely from safety considerations although the steeper gradients do involve a very small weight penalty due to the slower deceleration and longer time that the lift engines must be kept running.

Secondly, on the conventional aircraft the approach is made at sensibly constant speed and the final deceleration is done on the runway when the pilot is no longer concerned with approach path control. The problems of deceleration and of approach path control are therefore separated whereas, on a VTOL aircraft they occur together and have to be co-ordinated one with the other.

During this phase (Phase B) the pilot is thus faced with the need to control one extra variable. It is suggested that he should therefore have the assistance of an autostabilizer to relieve him of the need to control the attitude.

At first sight it would appear that the best form of control on the landing approach would be as follows:

Attitude—held constant by the autostabilizer.

Deceleration—fixed by a preset angle of engine tilt and by the constant attitude.

Flight path—controlled by lift engine throttles operated through an I.L.S. coupler.

If the starting point is accurately determined by radio altimeter and radar ranging it appears that the errors would be within the acceptable limits and that not very much in the way of new equipment or new techniques would be required. The procedure is closely comparable to a conventional aircraft approaching below its minimum drag speed. The main difference is the steeper gradient of descent and that lifting engine instead of propulsive engine throttle is used to control the flight path.

The final phase of the landing is the vertical descent. The requirements here are for positional indication by radar and for accurate control of the rate of descent. This last requirement deserves special consideration.

## 2.2 *Height Control*

Perhaps the most individual and significant problem in the control of VTOL aircraft is that of altitude and vertical velocity in hovering flight. A high rate of response and an adequate margin for vertical deceleration are the first essentials.

Figure 3 shows the limiting rates of descent plotted against altitude for different values of the thrust : weight ratio. It is calculated on the simple assumptions that there is no ground effect, that drag and control lag can both be neglected and that the touchdown is to be made at zero vertical velocity. The curves are in fact lines of constant deceleration.

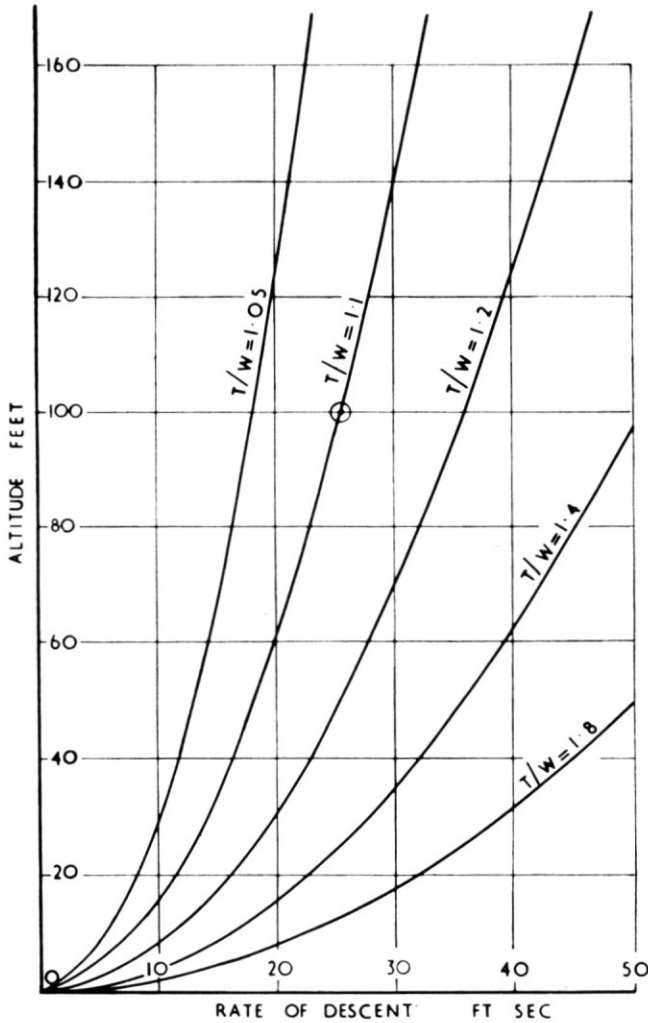


FIG. 3. Maximum rate of descent for touchdown at zero vertical velocity.

It will be seen, for example, that with  $T/W = 1.1$  the rate of descent at 100 ft must not exceed  $25\frac{1}{4}$  ft/sec.

Similar curves can be drawn for any other value of the vertical velocity at touchdown. Figure 4 shows the picture for 12 ft/sec and it will be seen that with  $T/W = 1.1$  the limiting rate of descent at 100 ft has only gone up to 28 ft/sec. An increase of less than 3 ft/sec at 100 ft has produced an increase of 12 ft/sec at the ground.

Figure 5 illustrates the point. The error at 100 ft is plotted against the resulting error at the ground. (It only applies, of course, to this particular example of descent at the limiting rate associated with the particular throttle setting.)

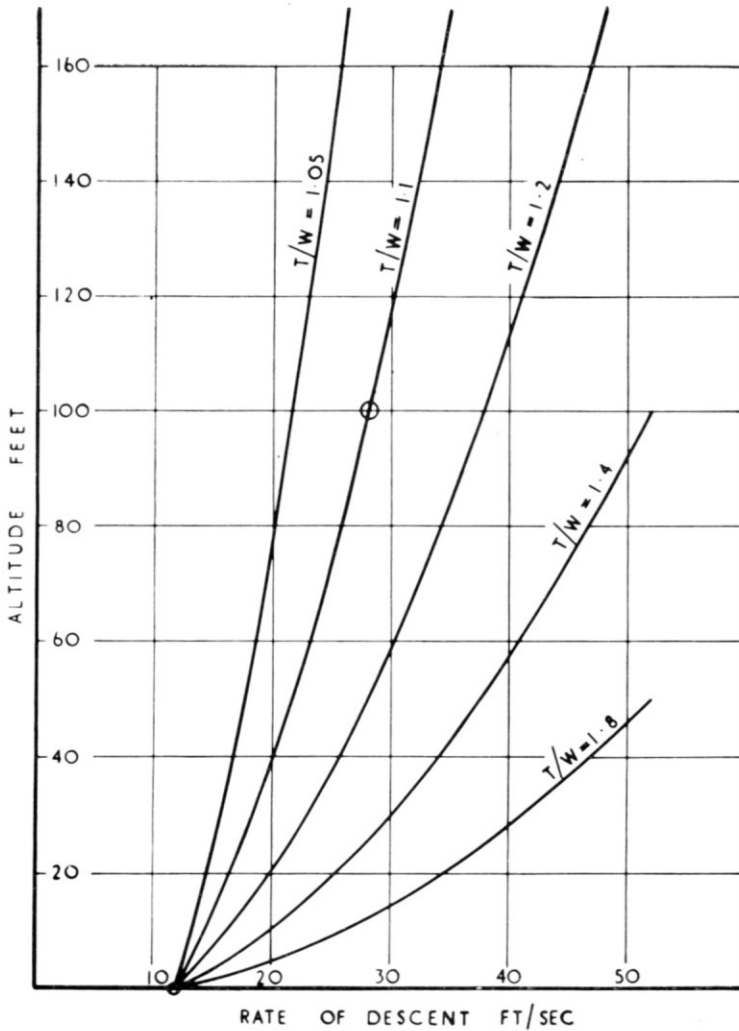


FIG. 4. Maximum rate of descent for 12 ft/sec touchdown.

There are two morals which can be drawn from these curves. Firstly, we must strike a balance between the penalties of restricting the rate of descent and of providing additional thrust so as to allow higher rates of descent. In general it appears that we need a margin of thrust over weight of something like 10%, in order to provide sufficient vertical deceleration for touchdown under calm conditions. In gusty air we may need more. Moreover, the foregoing simplified treatment neglects the effects of control lag. Returning to the example of  $T/W = 1.1$ , altitude 100 ft and rate of descent  $25\frac{1}{2}$  ft/sec, if it took  $\frac{1}{2}$  sec to develop the 10% thrust increase we would hit the ground at about 6 ft/sec.

It is therefore suggested that a margin of thrust of 15–20% is desirable. Even this is small by comparison with conventional aircraft which usually have about 70% available on the approach. This margin, while it is applicable to the maximum landing weight, need not necessarily be applied to the full load take-off weight. On the other hand some margin for vertical deceleration must still be available after an engine failure.

The second moral is that we need an instrument display which will tell the pilot his height and rate of descent clearly and accurately. We cannot rely on guesswork especially in poor visibility.

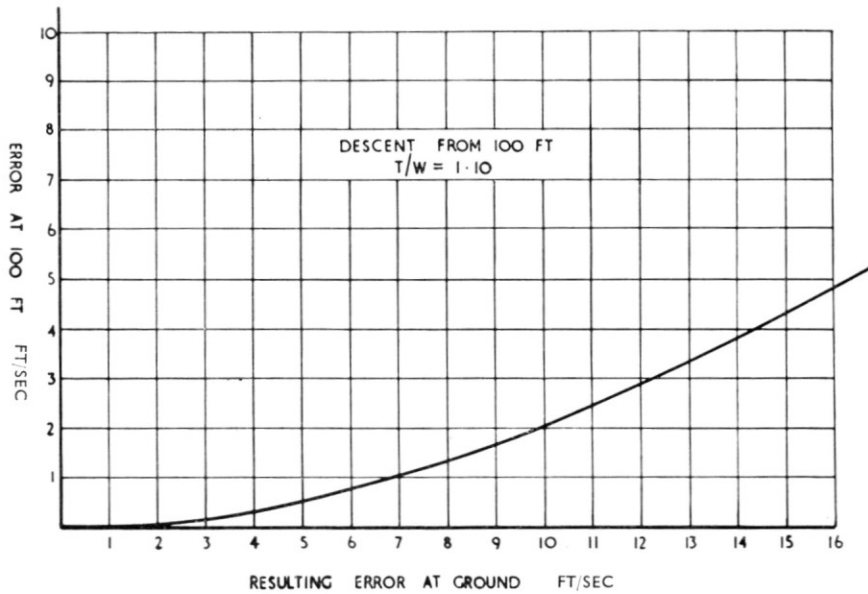


FIG. 5. Vertical deceleration.

Lag in the control system has an important bearing on the accuracy with which the pilot can fly the aircraft. The thrust of a jet engine does not respond to demand as quickly as the lift of a helicopter rotor and it may be necessary to incorporate some form of automatic height control to assist the pilot. If such automatics are fitted and linked with the height and rate of descent signals, we have the first stages towards the automatic aids required for blind landing. Alternatively, control on the landing approach could, as already suggested, be monitored by means of the normal I.L.S. coupler operating on the lifting engine throttles.

### 3. GUSTS AND HIGH WINDS

#### 3.1 *The Potential Advantages of VTOL*

The other aspect of all-weather operation is take-off and landing in gusty conditions or in high winds. Here also VTOL offers certain advantages.

In the first place the omni-directional nature of the landing pad removes the problem of cross wind take-off and landing.

Secondly there is no need to make the approach with a high incidence on the wing and so any danger of stalling can be eliminated.

Thirdly the low forward speed reduces the actual effect of the gusts. For example, if we make the comparison on the basis of the same weight, wing area and drag and an approach to land at the same vertical rate of descent, then the increment in drag, the deceleration and the error in speed and in ground position are all proportional to  $(2Vu + u^2)$  where  $u$  is the velocity of a horizontal gust or the change of wind speed with height and  $V$  is the forward speed of the aircraft. The VTOL aircraft with zero forward speed therefore responds least to the gust or wind gradient.

Finally, VTOL aircraft are likely to have a higher wing loading than conventional aircraft and therefore to respond less to gusts at all speeds.

### 3.2 Control Requirements

These potential advantages can only be realised if the control system is adequate to the task. The first essential is to have enough control power to cope with the gusts. This can only be determined finally by flight experience but an approximation can be made by comparison with conventional aircraft. As an example we will investigate the rolling power requirements.

On conventional aircraft it has been usual to define the rolling performance in terms of the helix angle,  $\frac{pb}{2V}$

$$(p = \text{rate of roll, rads/sec}$$

$$b = \text{span, ft}$$

$$V = \text{forward speed, ft/sec.})$$

A figure of 0.08 is usual for civil aircraft but experience has shown that this criterion is inadequate if the aircraft is equipped with high lift devices which enable it to make the landing approach at lift coefficients greater than about 1.2. Pilots then complain that in gusty conditions they cannot pick up a wing quickly enough.

It can easily be shown that for geometrically similar aircraft the linear acceleration of the wing tip produced by application of aileron is independent of scale. It can also be shown that the linear acceleration of the wing tip produced by a gust (acting on one wing only) is also generally independent of scale.

It therefore seems reasonable to take this linear acceleration as the criterion of rolling power. It is in fact a measure of the ability to pick up a wing quickly.



We will assume that the acceleration we require is that of a conventional aircraft having  $\frac{pb}{2V} = 0.08$  and flying at a lift coefficient,  $C_L = 1.2$ . The control power of such an aircraft is of the order of

$$M = 2 \frac{I}{b}$$

( $M$  = rolling moment, lb/ft

$I$  = moment of inertia in roll, lb/ft<sup>2</sup>

$b$  = span ft.)

From this we can calculate the gust velocities which would produce the same accelerations and level these gusts at the VTOL aircraft. We then find that the control power required in hovering flight is given by

$$M = 0.17 \frac{I}{b}$$

This is only 8½% of the control power of the conventional aircraft and is a graphic example of the small response of hovering aircraft to gusts.

However, the VTOL aircraft will presumably have conventional ailerons for cruising flight and bleed air jets or "nozzle" controls for hovering flight. At intermediate speeds the nozzle controls must supply the required acceleration to overcome gusts less that supplied by the conventional ailerons.

This is illustrated on Fig. 6 from which it will be seen that the effect of gusts decreases linearly with speed whereas the power of the conventional ailerons decreases as (speed)<sup>2</sup>. The maximum moment demanded of the hovering controls is at a speed just below half the normal airborne approach speed and is given by

$$M = 0.58 \frac{I}{b}$$

which is roughly 30% of the control power of the conventional aircraft.

This is submitted as a logical if crude approach to the problem but the results must be accepted with caution. For example, it may be that pilots will demand greater accuracy of lateral positional control on a VTOL aircraft than on a conventional aircraft merely because it is expected to land in a smaller space. The margin which the above criterion gives over the bare requirement in actual hovering flight may therefore be very acceptable if not definitely necessary.

Other points are that allowances must be made for engine failure including the ability to trim out the resulting moment, for the possibility

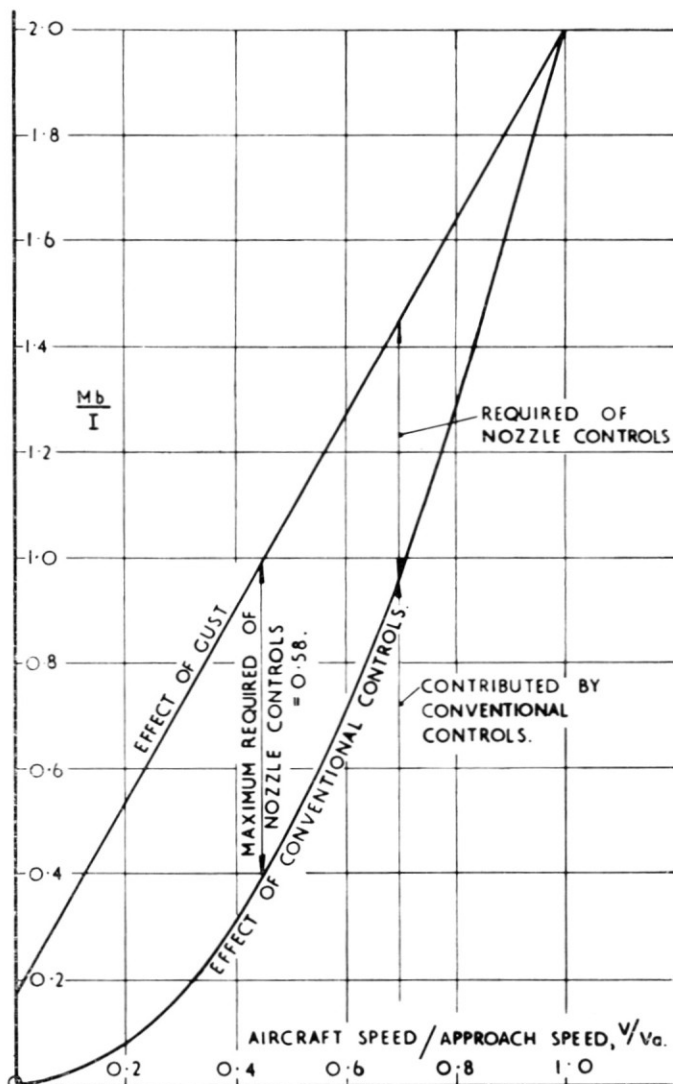


FIG. 6. Control power in roll.

of VTOL controls having more lag than conventional controls and for any possible reduction in the power of the conventional controls on the VTOL aircraft below the normal requirements of a conventional aircraft.

Finally, the whole treatment is based on geometric similarity between VTOL and conventional aircraft—which may very well not be true. Nevertheless, the generalized approach has its value as an illustration of the problem and, incidentally, it throws some light on the control requirement of STOL aircraft.

## 4. LANDING ALLOWANCES

The high consumption in hovering flight makes it necessary to give careful consideration to the landing allowances for VTOL aircraft. For convenience we can divide them into diversion, stand off and error correction. These are shown in tabulated form on Table 1.

TABLE 1  
*Landing allowances*

	Conventional	VTOL
<i>Diversion</i> Aerodrome limitations	Weather Obstructions on runways Landing aid faults	Not necessary (except for city centre operations)
	Aircraft faults Brake failures Flap failures Undercarriage	Not practicable, must be able to land vertically
		Nil
<i>Stand off</i>	Airspace congestion Runway congestion	Approach from all directions More landing sites available
		$\frac{1}{2}$ Conventional
<i>Error correction</i>	Overshoot	Errors in height plan position timing
		$1\frac{1}{2}$ min hover

4.1 *Diversion*

With conventional aircraft the causes of diversion fall into two types. The first is failure on the part of the aerodrome to accept the incoming aircraft due to weather, obstruction on runways or possibly the failure of landing aids. If our future VTOL aircraft can be operated in any weather and if we duplicate the actual landing pad and landing aids, there should be no need for this type of diversion except possibly when operating into the centre of cities.

The second type is failure of some component or function of the aircraft itself as, for example, brake failure, flap jamming, undercarriage jamming, etc. The diversion is then made to an aerodrome with a longer runway and easier approaches or to a less busy one where an aircraft which has belly-landed will not hold up other traffic. The equivalent case for VTOL aircraft would be a failure to start the lifting engines or to deflect the thrust, a failure of the autostabilizer or control system or any fault which would impair the ability of the aircraft to make a vertical landing. If we are to budget for such faults we must of course make it possible to divert to the nearest aerodrome and there to make a conventional runway landing. The problem is not then so much the fuel allowance as the wing area, flaps, brakes and undercarriage which would not be required except in this emergency. To provide them would in many cases impose an unacceptable penalty especially if we envisage future VTOL supersonic aircraft with the wings designed solely for high-speed flight. The question then becomes one of airworthiness. Can we design VTOL aircraft to be safe without equipping them to land on runways? The future of VTOL aircraft, especially for civil operation, may turn largely on this point. It is in fact imperative that we should do so.

#### 4.2 *Stand Off*

The stand off allowance is mainly a matter of congestion at the destination aerodrome. VTOL landing bases should be so much less expensive and use so much less space than runways that it should be possible to provide them in sufficient quantity that there is no serious congestion.

This argument is reinforced if, as seems likely, VTOL aircraft can make their approaches from any direction and not only into wind. It is suggested therefore that the VTOL stand off allowances could be half those of conventional aircraft.

#### 4.3 *Error Correction*

If the pilot of a conventional aircraft coming into land makes an error in height, plan position or speed which is detected only when it is too late to make the necessary correction, he has no alternative but to "wave off", go round again and make a second approach.

On a VTOL aircraft this does not apply. On coming to rest the VTOL aircraft can be manoeuvred into the correct position in spite of any initial error. There is no case for accelerating up to flying speed and going round again.

On the other hand some fuel allowance must be provided to cater for error corrections. These errors may be in plan position or height or, possibly, in time as, for example, when the pilot starts his lifting engines too soon or too late and so departs from the optimum approach path. The extent of the allowance necessary to cover these errors can only be determined by experience but, for the purpose of performance and route analysis a figure of  $1\frac{1}{2}$ -2 min at hovering thrust is suggested. Even

this is quite a serious penalty on a jet lift aircraft and may amount to something like 3% of the take-off weight.

5. ENGINE FAILURE

5.1 *Number of Engines and Thrust required*

In the above discussion on allowances the question is asked whether we can design VTOL aircraft to be safe without equipping them to land on runways. There are many aspects to this question but perhaps the most important is that of engine failure. Indeed it is not only engine failure but engine failure-to-start which must be considered.

Before arguing the probabilities we can draw up a chart to show number of engines against thrust : weight ratio and plot on it lines of one spare engine, two spare engines, etc.

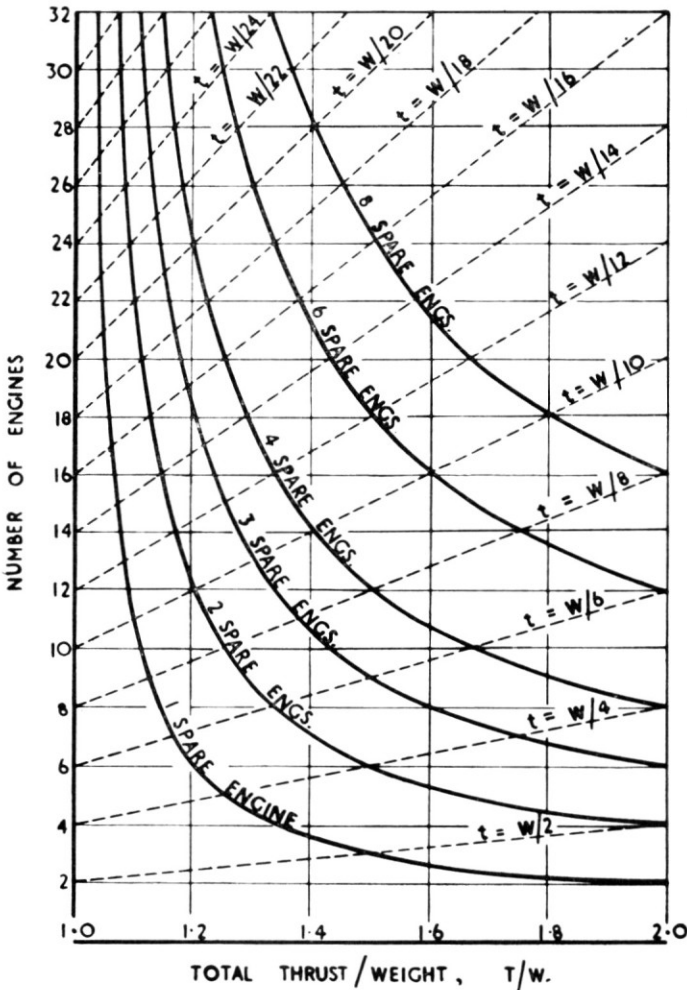


FIG. 7. Thrust required vs. number of engines.

This is done in Fig. 7 on which  $T$  is total thrust,  $W$  is all up weight and  $t$  is the thrust of one engine. So far the treatment is purely factual. The problem now is to assess probabilities. Let us assume that we want the same reliability as a four-engined conventional civil aircraft which is designed to be safe if one engine fails but not if two engines fail during take-off.

The first point we must settle is the reliability of individual engines. For conventional aircraft experience has shown that the probability of any single engine failing in any one take-off is of the order of 1 in  $10^5$ . This is roughly true of piston, propeller turbine and jet engines, presumably because the type tests to clear an engine for any given overhaul life have been fixed in a way that gives equal reliability. By this argument it would seem justifiable to assume that the same law will apply to VTOL engines of all types; in other words we can start from the standpoint that the reliability of individual VTOL engines is the same as for conventional engines.

Turning to Fig. 7 we can then say that if the VTOL aircraft has four engines,  $T/W$  must be 1.33 to give the same reliability as a conventional four-engined aircraft. But what if the VTOL aircraft has more than four engines?

By simple theory of probability we arrive at the rather startling result that, if the failure rate is 1 in  $10^5$ , the probability of one failure in four is equivalent to two failures in about 900. For practical numbers of engines the probability of two failures in any one take-off is always less than the probability of one failure on a four-engined aircraft.

The suggestion is therefore offered that we should design for two engines to fail if the total number of engines is more than four and for one engine to fail if the total number of engines is four or less. The associated values of  $T/W$  are shown on Fig. 8.

There are several important reservations in the application of this rule:

(a) *Failure due to common cause*—The designer must guard against the possibility of a group of engines failing as a result of a common cause such as fuel starvation. If such mutual dependence does exist it becomes necessary to treat the group as a single engine and to increase the value of  $T/W$  accordingly.

If separate lifting engines are used it might be worth while to carry their fuel in a separate tank. It would then always be possible to make an emergency vertical landing even after the main fuel tanks are empty. Such a landing could be made in almost any open space and therefore as long as the flight is over land it would provide a means of safety unparalleled by conventional aircraft.

(b) *Trimming*—When an engine fails it may, on some designs, be necessary to shut down an opposite engine so as to restore trim. One could postulate cases where it would be necessary to shut down two, three or even more engines for this reason but no designer would be

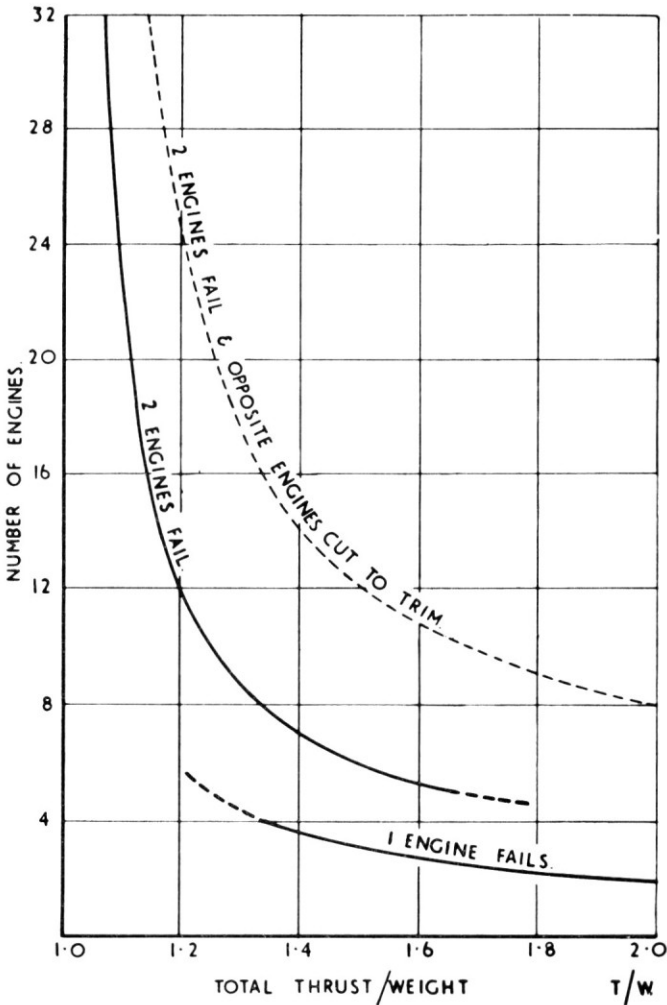


FIG. 8. Thrust required vs. number of engines.

likely to countenance such a situation. We will therefore only look at the case of shutting down one opposite engine. This is shown by the dotted line on Fig. 8.

With some lifting systems it is virtually impossible to provide sufficient control power to hold the moment due to an engine failure even for a short time. It may then be necessary to develop automatic means of sensing the failure and shutting down the opposite engine. Incidentally, the "failed" engine must be shut down positively at the same time in case the sensing device operated in error or as a result of only a momentary engine failure.

(c) *Failure to start*—When considering the number of engines to be installed we must always remember that although a multiplicity of engines

will provide safety in the air, it will tend to provide unreliability on the ground because of the greater probability of at least one engine failing to start. If really large numbers were to be considered seriously it might be necessary to provide one or two additional engines and allow take-off to proceed even though one or two engines had failed to start. There is no logical objection to this except the generally accepted principle of airworthiness that everything should be functioning correctly before take-off may proceed.

(d) *Landing cases*—So far we have considered only the case of engine failure during or before take-off. Normally the landing case will be less exacting than the take-off because with the lower weight the margin of thrust will be higher. Special consideration must however be given to aircraft having separate lifting engines which have to be started in flight. Failure to start must then be considered in addition to failure in flight.

As an example we could examine an aircraft having twelve lifting engines and a  $T/W$  at take-off of 1.2 which is the minimum given by Fig. 8 and represents an acceptable standard of safety. Let us suppose that the maximum landing weight is fixed at 80% of the take-off weight.  $T/W$  at landing is then 1.5 which is equivalent to four spare engines. Working back from this we find that our chosen standard of safety is assured provided that the engine failure plus engine failure-to-start probability is not worse than 1 in 525. This would be a very high rate compared with the assumed take-off failure rate of 1 in  $10^5$ . It appears from this example that the landing case is well covered by the take-off case. This is probably true for most designs provided that the number of engines is not less than about six, but experience of the reliability of starting engines in flight is needed to substantiate this claim. It may not be very easy to start engines which have been subject to low temperature at high altitude possibly for several hours, but this is an engineering problem which will have to be overcome and may have an influence on the layout of the whole aircraft.

### 5.2 *Factors Affecting Engine Reliability*

One reason why it is impossible to make a rigorous mathematical analysis of engine failure probabilities is that the reliability of individual engines is affected by such practical considerations as the number and size of engines.

For example, if we have twenty-four engines the thrust : weight ratio required (by Fig. 8) is 1.1 and the engines must therefore operate at about 90% of their maximum thrust. On the other hand, if we have eight engines the required value of  $T/W$  is 1.33 and the individual engines operate at  $\frac{3}{4}$  of their maximum thrust, i.e., at something below maximum continuous rev/min. We might therefore expect the individual engines of the eight-engined aircraft to be more reliable than the individual engines of the twenty-four-engined aircraft.

Engine size may also affect reliability mainly because small scale mechanisms are inclined to be more delicate than large. A good illustration



is the ingestion of solid particles which could be a serious hazard to the engines especially when the aircraft is operated from unprepared sites. The only protection would be to fit wire mesh guards over the intakes to prevent particles being sucked into the engine. The mesh of this guard could be adjusted so that the diameter of the holes is proportional to the diameter of the engine and therefore to the blade height. It is assumed that this is the requirement for equal protection.

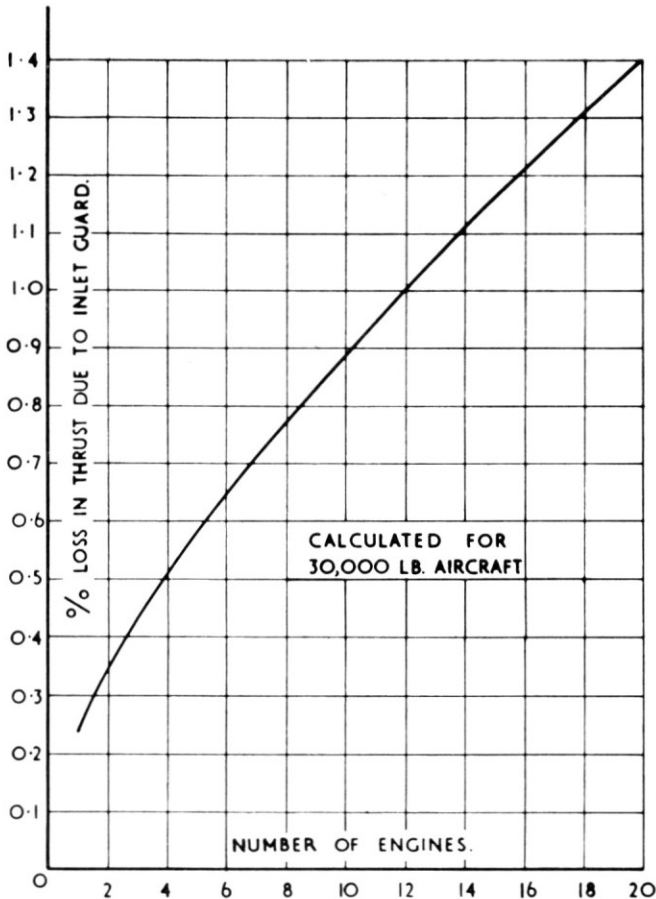


FIG. 9. Losses due to inlet guards assuming equal protection.

The pressure drop across the guard can then be calculated and transformed into the percentage loss in thrust. This is plotted on Fig. 9. As would be expected, the smaller engines show much larger thrust losses. The corollary is that we can afford better protection on larger engines and, presumably, get better reliability in consequence.

## 6. AUTOSTABILIZER

### 6.1 *General Considerations*

An autostabilizer, from the point of view of safety, is a very different thing from the autopilots with which we are familiar on conventional aircraft. VTOL aircraft might have both an autostabilizer and an autopilot.

By autostabilizer is meant a gyro-controlled stabilizer capable of controlling an aircraft which, due to instability, control lag or any other cause, cannot be controlled satisfactorily by the human pilot. An autopilot on the other hand merely does something which tires or bores the pilot.

It is obvious therefore that a simple failure of the autostabilizer will always put the pilot in difficulty and may be catastrophic whereas a similar failure of an autopilot is of much less consequence. Still more important is the effect of a runaway. It is fundamental that the autostabilizer must have a quicker reaction time than the human pilot and, in the event of a runaway, cannot therefore be beaten by him. Autopilots, on the other hand, are designed to give a low rate of application of the controls so that the human pilot can beat them. Typical figures for the rates of application might be  $25^\circ/\text{sec}$  for an autopilot and  $200^\circ/\text{sec}$  for an autostabilizer.

It must not be forgotten, too, that when a pilot flies an aircraft through the medium of an autostabilizer, his control is dependent on the correct functioning of a complex electro-mechanical system involving quite delicate components.

In the aggregate we have an inherently delicate piece of equipment which must never be allowed to fail. There can be no alternative but first to make it as reliable as we know how and then to duplicate or triplicate or even quadruplicate as necessary.

### 6.2 *Component Reliability*

The only way to get a reliable system is to ensure that every component, however minor its function, has been proved to be reliable under the environmental conditions in which it has to function.

Reliability is an elusive quality which only comes as the result of thoroughness in detail design, development, testing, maintenance and inspection. It is nevertheless important to start on the right lines and the obvious choice of component is not always the right one. For example, the obvious choice for a positional pick-off would be a potentiometer, but a potentiometer relies on a rubbing contact which is susceptible to vibration and wear. In addition it is often necessary to employ gearing in order to improve the resolution; this increases the accelerations and velocities imposed on the wiper. For reliability it might be better to use the seemingly more complicated arrangement of an a.c. inductive pick-off possibly in conjunction with a demodulator.

Similar problems arise in the choice of amplifiers. Is it best to use thermionic valves, transistors or magnetic amplifiers? Thermionic valves

are susceptible to vibration and shock although "reliable" valves are now available. The choice between transistors and magnetic amplifiers at the present state of the art is difficult and is greatly influenced by the circuit conditions; with transistors, high-gain high-speed amplifiers are readily constructed whereas magnetic amplifiers suffer from the defect that high gain is always associated with very slow response. Both utilize semi-conductors in one form or another and in consequence have temperature limitations.

### 6.3 *Multiplication of Channels*

The policy adopted on the SC.1 has been to triplicate the whole of the autostabilizer and hydraulic actuators. Each of the three channels is sufficiently powerful to control the aircraft on its own. If then any one channel develops a fault of any sort including a runaway, the other two are sufficiently powerful to overcome it and still provide full control.

The output of the three channels is compared by measuring the movement of the hydraulic actuator valves. If any one differs from the other two by more than a specified minimum, a red light (duplicated) warns the pilot who can then switch out that channel. He does not have to do so but it is a wise precaution for mechanical reasons in case the fault were oscillatory.

It is essential that each channel should be tested on the ground before each flight. It would not be safe ever to test the separate channels in flight.

Automatic means of eliminating a faulty channel have not been used because of the danger of a fault developing in the automatic device. Such a fault might develop at any time and, unless a comprehensive testing system were introduced, could go undetected until a channel failed in flight.

In the design of such a system it is important, as with the engine installation, to guard against the possibility of a common cause which could put more than one unit out of action. For example, the electric cable runs should be separated as otherwise quite a minor electric fire could cause a failure of all channels simultaneously. The ideal would be for each channel to be self-contained with its own power supplies and well separated from its neighbours.

There is a case too for duplication within a channel, at least of the more delicate and vital components, but such a policy implies the provision of a ready means of testing that the duplicated components are both working satisfactorily. Testing would be simple when, as in the case of a resistor, failure of one component halved the magnitude of the output signal. It would not be so simple in the case of, say, parallel relay contacts.

The real problem is whether triplication is enough. It only provides for one failure in three channels whereas quadruplication provides for two failures in four channels. There is not yet sufficient evidence on the reliability of individual channels in service but it seems improbable that

they will prove more reliable than engines at least until they have undergone some years of development. It is therefore suggested that if we were designing a passenger aircraft to-day we would be well advised to quadruplicate the autostabilizers.

#### 6.4 *Inspection and Maintenance*

It is quite obvious from the foregoing that reliability is not going to be achieved by the use of components which are 100% reliable, but rather by the use of components which are not completely reliable in a system which is so designed that the malfunctioning of a component has an insignificant effect. Inspection procedure will no longer consist of testing equipment as a whole, but will demand detailed testing of all individual components within the equipment. This is quite a new outlook and appropriate test procedures will have to be devised. Ideally this inspection should be done with the equipment in the aircraft; furthermore such a testing procedure demands that special testing facilities be designed into the equipment.

### 7. CONCLUSION

VTOL offers the hope of improved standards of safety in all weather operation. It also offers a number of new problems which must be overcome if that hope is to be realized. It is not too soon for designers and airworthiness authorities to start thinking about these problems for VTOL is now with us just as soon as we want it.

It is not enough to develop the aircraft, the engines, and the control system. We must at the same time develop the airworthiness requirements and the blind landing aids and techniques. Moreover, we must face up to the full implications of flying an aircraft on which for part of every flight, the lift is wholly dependent on engines and the control wholly dependent on automatic electronic equipment. Without all this we may find that we have the aircraft but not the means of using it.

### DISCUSSION

J. DESCHAMPS\*: L'exposé que nous venons d'entendre se place surtout au point de vue de la sécurité. Le point de vue de l'économie est également important et l'auteur l'a d'ailleurs souligné, en indiquant une consommation de carburant pour l'atterrissage de l'ordre de 3% de poids total.

Il faut donner la poussée des réacteurs verticaux assez tôt pour atteindre le sol avec une vitesse nulle ou suffisamment faible. Il ne faut pas la donner trop tôt, car on atteindrait une vitesse de descente nulle à une altitude non négligeable, l'opération d'atterrissage devenant d'autant plus longue et la consommation de carburant non négligeable.

On conçoit qu'il faille se tenir entre ces deux limites, imposées à la fois par la sécurité et l'économie. Cela ne peut être réalisé que par des détecteurs d'altitude et de vitesse de descente à la fois précis et présentant une faible constante de temps.

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Il m'apparaît que les altimètres et variomètres barométriques ne conviennent pas. Je voudrais savoir si le conférencier pense que les altimètres et variomètres électroniques classiques peuvent suffire ou s'il pense qu'il y aura lieu de développer de nouveaux instruments, adaptés au problème du VTOL.

D. KEITH-LUCAS: I am glad that M. Deschamps has drawn attention to the important question of economy and to the importance of having the right instrumentation to aid the pilot in making the optimum descent.

I believe that it will be necessary to develop instruments specifically for VTOL. This is not because the existing types are insufficiently accurate but because the form of presentation will have to be different in order to give the pilot a clear indication of his vertical rate of descent in relation to his height.

I am of the opinion, moreover, that it will be necessary to develop automatic control of the descent. It would seem that this is the only way in which we can be certain to achieve economy without sacrificing safety.