CRANFIELD
INSTITUTE OF TECHNOLOGY

THE WEIGHT, ECONOMIC AND NOISE PENALTIES OF SHORT HAUL TRANSPORT AIRCRAFT RESULTING FROM THE REDUCTION OF BALANCED FIELD LENGTH

by

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SUMMARY

The results of a series of design studies of short haul transport aircraft in the RTOL, STOL and VTOL categories have been analysed to establish their respective performance penalties relative to CTOL types. The main criteria used for comparison are weight, direct operating costs and 80 PNdB noise footprint areas but some consideration is also given to low speed control characteristics. The basis of all the designs was a requirement to carry 108 passengers over a stage length of 600 n. miles plus reserves.

The main conclusions reached are threefold:-

a) The 4000 ft RTOL design represents an optimum solution if noise is considered to be a prime requirement, in spite of its having significant weight and cost penalties relative to a 5000 ft CTOL design.

b) The choice for 2000 ft operation lies between the augmentor wing and fan lift STOL concepts.

c) The tilt wing rotorcraft concept compares well with the fan lift VTOL when high fuel costs are assumed.

CONTENTS

NOTATION

For the notation used in the tables and figures see the Key to the tables and Figure 5.

The notation used in the Appendices is as follows:-

b	Wing span (ft)
B	Fuselage breadth (ft)
C_1, C_2	Coefficients used in weight equations
C_{L_t}	Rotor tip lift coefficient
H	Fuselage depth (ft)
L	Fuselage length (ft)
N	Ultimate acceleration factor
R	Engine bypass ratio
S	Wing area (sq ft)
S_b	Rotor blade plan area (sq ft)
SHP	Shaft horsepower
T	Engine thrust, static (lb)
T_R	Reduced engine thrust (lb)
V	Velocity (ft/sec)
V_D	Design diving speed (knots)
V_t	Rotor tip speed (ft/sec)
W	All up weight (lb)
W_a	Weight of empty equipped airframe less engines (lb)
W_F	Fuselage weight (lb)
W_W	Wing weight (lb)
λ	Wing taper ratio
ϕ	Wing quarter chord sweep
τ	Wing root thickness/chord ratio

1. INTRODUCTION

A programme has been undertaken in the Aircraft Design Division at Cranfield during the past four years to study the characteristics of short haul transport aircraft. Initially the emphasis was placed on vertical and short take off aircraft but subsequently the work was extended to include designs for longer runway operation. Although work on these classes of aircraft had been undertaken previously, as for example Ref.1, the present investigation represents a systematic approach to the problem. A general appraisal of the important performance characteristics for this class of aircraft has already been reported (Ref. 2). Particular emphasis was placed on the influence of passenger comfort considerations on runway performance in as much as it affects minimum wing loading and maximum tolerable decelerations. A general conclusion reached was that it should be possible to design aircraft to operate safely from 4000 ft long runways without the need for power augmented lift, and that this should be regarded as the lower limit of reduced take off and landing (RTOL) design. It was shown that the true short take off and landing (STOL) designscapable of operating from runways of the order of 2000 ft length require a substantial degree of powered lift together with a high installed thrust/weight ratio. The possibility of serious low speed control difficulties exists with this class of aircraft due to the inevitably low take off safety and approach speeds although these can be largely eliminated by essentially vertical take off and landing (VTOL) operation. As well as passenger comfort considerations noise and economics were identified as two design requirements of vital importance. However the general comparison of these last two considerations is not readily achieved due to their dependence upon relatively detailed considerations.

The present work is concerned with a comparison of a number of particular designs for short haul transports. These were undertaken as a series of case studies to enable the general conclusions of Ref.2 to be checked and to provide specific information on economic and noise characteristics. An attempt is made to draw general conclusions from this specific information. The studies have all been based on the requirement to carry 108 to 120 passengers over a design stage length of 600 n. miles with a reserve fuel allowance. Cruise speeds varied somewhat according to the actual type of aircraft and the particular operation within the range of 0.67M to 0.83M. Certain of the individual designs have been used as a basis for the annual students' project studies and have therefore been examined in considerable depth. Others have been an individual student's research investigation in which case the emphasis has been placed on their special features. Data derived from existing conventional take off and landing (CTOL) aircraft is used for comparison.

The concepts investigated include fan lift and tilt wing VTOL; fan lift, externally blown flap and augmentor wing STOL; AND RTOL designs.

2. BRIEF DESCRIPTION OF AIRCRAFT

A summary of the more important characteristics of the various designs is given in Table 1. In each case the design weight and thrust has been normalised to a datum of a 108 passenger payload carried over 600 n. miles design range so that direct comparison can be made. The scaling factors used for this process are discussed in section 3. The approach angle was limited to that giving 1000 ft/min rate of descent in each case.

2.1 Fan Lift VTOL (FL)

The fan lift VTOL aircraft used is the A70 design study. The details of this project have been reported fully in Ref. 3 and a general arrangement drawing is shown in Figure 1. In general concept and performance the design has many similarities with the Hawker-Siddeley HS 141 design. The layout is however different in several respects, the reasons for the one chosen being discussed in Ref.3. The two propulsion engines are based on half scale versions of the Rolls-Royce RB211-22 and the twelve lift engines are of the RB 202 family. Although the maximum limited cruise speed is 0.83M the normal condition is 0.78M at 20,000 ft altitude. The assumed fuel reserve allowance includes sufficient fuel for a 100 n. mile diversion and vertical landing after a baulked approach to just above ground level.

2.2 Tilt wing VTOL (TW)

A small tilt wing transport aircraft, known as the E67, was the basis of the annual design project as long ago as 1967 (Ref.4). Whilst this work is not directly relevant to the present investigation the results obtained did suggest that the concept was worthy of consideration for the 108 passenger short haul transport especially as it has potentially a low fuel usage and noise level. An initial investigation was undertaken by Martin (Ref.5) and this confirmed the anticipated advantages. The study is now being taken to a greater depth as the R73 design project with the particular intention of ascertaining the extent of the mechanical complexities of the design (Ref.6). A general arrangement drawing is shown in Figure 2, with the wing in the take off and landing mode. The layout is very similar to the twin rotor convertiplane concepts proposed by Hafner (Ref. 7) and the designs proposed by Westland Helicopters Ltd. Hover disc loading is 36 lb/ft^2 and each rotor is driven by two 9000 HP turboshaft engines of the Rolls Royce M57HH type. Cruise Mach number is limited to 0.72 but the usual speed at 20,000 ft altitude is somewhat less than this.

2.3 Externally blown flap STOL (BF)

The A71 design study is used as the basis for the externally blown flap versions of the STOL aircraft considered here. The basic A71 work is reported in Refs. 8 and 9. and a subsidiary investigation of the low speed control problems was undertaken by Ward (Ref.10). The layout of the design is shown in Figure 3 and apart from one aspect is very similar to projects proposed for this class of STOL aircraft both in Europe and North America. The flaps are of the double slotted variety. The unusual feature is the wing mounted nacelle used for housing the long stroke undercarriage. As originally designed the A71 was powered by 4 engines of the Rolls Royce M 45S (RB410) type to give it a static thrust ratio of 0.5. The engines have a variable pitch fan with a bypass ratio of rather more than 10. The intention was that the aircraft should be capable of operation from runways of 2000 ft length but the detail performance evaluation revealed that the engine failure case on take off precluded this due to the consequent loss of both lift and thrust. Increase of lift off speed to give the required margin of safety necessitated the take off balanced field length being increased to approximately 2600 ft although there is adequate margin for landing on to a 2000 ft runway. Safe take off from a 2000 ft runway requires the static thrust/weight ratio to be increased to nearly 0·7 with a consequent overall increase in aircraft size and weight. It is this modified version of the A71 which is used in this report as the datum 2000 ft externally blown flap STOL design. The Mach limited cruise at 30000 ft altitude is 0.8 but a more useful condition is rather less than 0.7M at 20,000 ft altitude. This lower cruise speed is determined by cruise comfort conditions resulting from the relatively low take off wing loading of 74 lb/sq ft.

2.4 Augmentor wing STOL (AW and QAW)

A preliminary study of the effect of replacing the externally blown flaps of the A71 by the augmentor wing concept was made by Van Twisk (Ref. 11). For simplicity the basic A71 design was used as the datum and the powerplants replaced by units of the RB 419 type with the addition of a facility for tapping large quantities of air for the lift augmentation system. The additional gas generator size necessary to enable this to be done results in a thrust increase of about 30%. This extra thrust and the relatively higher efficiency of the augmentor wing resulted in an aircraft capable of operation from 1600 ft runways. The nozzle augmentor pressure ratio is approximately 1.9. At the same time the low speed control problems, especially those associated with the engine failure case, are likely to be less severe. The penalty for these advantages lies in the greater all up weight and the mechanical complexity of the flap system. The degree of the latter and the low speed control characteristics are the subjects of a current study. Landing rather than take off was found to be critical in determining the runway length.

A further potential advantage of the augmentor wing relative to the externally blown flap is the possibility of reducing noise levels by the use of multi-element nozzles

and acoustic lining within the flap segments. This feature has been investigated by the Boeing Company as part of an STOL project study (Ref.12), use has been made of this information to derive the quiet augmentor wing (QAW) as a somewhat larger and heavier aircraft.

2.5 RTOL (UW and RE)

The basic A71 design has also been used as the starting point of the design investigation for an RTOL aircraft but in this case there are numerous differences in the final layout. This work was carried out by Jesse (Ref.13). The major differences consist of replacing the double slotted flaps of the A71 by triple slotted units and drooped ailerons, increase of the wing loading to 84 lb/sq ft and reduction of the static thrust/weight ratio to 0.46. The latter requirement may be met either by two or four underwing engines (UW) in which case the layout is similar to the A71 or by two or three rear fuselage mounted engines (RE). The merit of the rear engine version is that it enables a low wing to be employed with consequent advantages in the flap and undercarriage layout. It also introduces the possibility of using the wing to assist in noise reduction by employing it to shield the intakes. The three engined layout proposed in Ref.13 appears in Figure 4. Noise shielding could be carried further by introducing a low mounted tailplane in association with two powerplants. In all cases the powerplants are of the Rolls Royce M53 family. Take off requirements dictate the use of a runway of 4000 ft nominal length with the design landing requirments being somewhat less. The higher wing loading relative to the A71 enables the normal cruise Mach number at 20,000 ft to be increased to 0.73 without a reduction in passenger comfort.

2.6 Fan lift STOL (FL)

One way of achieving RTOL or STOL performance is to use a number of fan lift engines to give a vertical thrust component thereby augmenting the wing aerodynamic lift. The layout and concept of the aircraft is thus an exact intermediate between the conventional and fan lift VTOL designs unlike other STOL types where the lift augmentation is indirect. For purposes of comparison a 2000 ft runway STOL design has been derived by the simple device of adding six fan lift engines to the 4000 ft RTOL layout discussed above. It is visualised that the additional powerplants would be mounted along the sides of the fuselage fore and aft of the structural box of the low mounted wing. During take off the lift engines would be inclined at approximately 30^{o} to the vertical to provide a substantial forward thrust component. The resultant equivalent static thrust/weight ratio is about 0.63. This design is not necessarily an optimum 2000 ft STOL fan lift aircraft but is regarded as a possible development from the 4000 ft RTOL.

2.7 CTOL (UW and RE)

Existing data from aircraft such as the Boeing 737 and BAC 1-11 has been used to derive datum CTOL aircraft of underwing and rear fuselage powerplant layout respectively. It has been assumed that the powerplants used are of the M53, bypass

ratio 10 family and that the normal cruise speed at 20,000 ft is approximately 0.7. A nominal runway length of 5000 ft has been regarded as the datum value for comparative purposes, but the effect of relaxing this to 7000 ft has also been considered. It is worth noting that the Boeing 737/200 can carry the design payload of 108 passengers over the 600 n.mile stage length when operating from 5000 ft long runways. The take off weight is approximately 90000 lbs in this condition.

3. WEIGHT SCALING

Although all the project studies compared here have very similar design requirements certain small differences did exist in the basic specification. It has thus been necessary to undertake a weight scaling process to bring them all to a common base and at the same time to make allowance for different augmentation systems, engine location, etc. This was done by using simple empirical relationships appropriate to short haul transport aircraft to modify the component weights estimated from the detailed design studies. The formulae used were derived from Ref.14 and the assumptions made are stated in Appendix A. No weight scaling was required for the VTOL designs.

The final weight breakdowns are given in Table 2. The gross weights related to that of the datum 5000 ft CTOL aircraft with underwing powerplants are shown as a function of balanced field length, in Figure 5.

Only in the case of the augmentor wing was allowance made for the weight of noise reduction techniques. In other cases it was considered that the necessary development would be achieved within the weights predicted. This is discussed in Appendix A.

4. LOW SPEED OPERATING CHARACTERISTICS

Brief comments on the low speed operating characteristics of the various designs are of interest. The variation of the approach and take off safety speeds with balanced field length are shown in Figure 6. The major limitation imposed upon the augmented lift STOL designs arises from the loss of lift as well as thrust when engine failure occurs. This is more serious during take off than landing since in the latter case it is possible to open the throttles of the remaining functioning engines to compensate for the loss although it is necessary to cope with a missed approach. For balanced field lengths down to just under 2000 ft the take off case is more critical. However for field lengths below 2000 ft the landing case becomes more important in establishing the required length of runway due to the comfort limit imposed on the mean design braking deceleration (Ref.2). The augmentor wing design requires a 1600 ft long runway for landing rather than take off reasons.

Two particular problems associated with reduced take off and approach speeds are the control problems which arise when engine failure occurs or when there is a large cross wind component. The severity of the engine failure case depends upon the design layout and nature of any lift augmentation system

employed. Inevitably it is severe for the externally blown flap concept (Ref.10) where it gives rise to very high roll and yaw control demands. The use of an augmentor-wing reduces the magnitude of this problem by virtue of the possibility of using cross ducting for the blowing air to tend to equalise both the lift and thrust distributions. Van Twisk (Ref.11) has shown that the potential improvement is considerable and this is why the more detailed analysis of this and other low speed characteristics of the augmentor wing concept is being undertaken. In the case of the fan lift designs it is reasonable to assume that the difficulty is overcome by ensuring that the number of lift engines used is adequate. For the vertical take off case the minimum number appears to be twelve. The four engines of the tilt wing design are mechanically interconnected and adequate emergency power is available to cope with the case of single engine failure during take off. A measure of the severity of the cross wind problem can be gauged by reference to Figure 7, which shows the cross wind component as a function of balanced field length corresponding to two particular equivalent yaw angles on the approach. The lower of these, 12.5 degrees is representative of current practice whilst the higher, 20 degrees probably represents the absolute limit and may well imply some form of castoring main undercarriage. It is shown in Ref.2 that in the case of aircraft operation from exposed single runway aerodromes the mean cross wind is likely to exceed about 22 knots for a significant number of hours per year. Thus an unusually severe problem exists for aircraft designed to operate from balanced field lengths of less than 4000 ft. From the control point of view it is necessary to be able to deal with the lateral gusting associated with the cross wind condition. Ref. 10 indicates that the gust velocity is just under half the mean cross wind component.

5. DIRECT OPERATING COST EVALUATION

A comparison of the direct operating costs of the different designs has been undertaken. The B.E.A. method (Ref.15) was used as a basis for this but it was necessary to make a considerable number of changes to cater for the different types of design and probable escalation of costs. All the assumptions made are stated in Appendix B and the results are summarisedin Table 1. These have been based on the case of a one hour block time and a fleet of 20 aircraft of any given design. The one hour block time implies a sector length of 300 n. miles in all cases except that of the lift fan VTOL where the higher cruise Mach number results in a sector length of 360 n.miles. Two different fuel costs have been used in order to establish the sensitivity of the direct operating costs to this parameter. The lower of these referred to as fuel cost A is 1.5 p per lb and the higher, fuel costs B, is 4.5 p per lb. Whilst it is impossible to forecast fuel costs with any degree of certainty at the present time it is hoped that these values relative to the other costs do cover the range likely to be experienced within the time scale appropriate to the study, that is in the decade beginning about 1980. The relative fuel loads are shown in Figure 8, both on a total provision and sector basis.

The direct operating costs of the fan lift designs are initially dependent upon the prime costs of the engines and the spares carried and it is considered that reasonably optimistic assumptions have been made for these values. Likewise the costs of the tilt wing design depend very much upon data associated with transmission and rotor systems. The assumptions made here were based on rather sparse evidence and are therefore open to criticism. It is hoped that more accurate information can be estimated when the detail design work on the concept has been completed but in the meanwhile it is felt that the results obtained form a reasonable basis for comparison with other designs. In evaluating the engineering costs an attempt was made to allow for such items as the complexities of flap and control systems and changes in undercarriage operation. It was found that with the possible exception of the fan lift VTOL design the net changes were of negligible significance and even in the exception the overall effect was well within the anticipated accuracy of the total calculation.

Figure 9 shows the variation of direct operation costs with balanced field length and also the variation of the ratio of the costs to gross weight. The different fuel costs have negligible relative effect except for the VTOL designs.

6. NOISE CHARACTERISTICS

The noise characteristics of the design have been compared using the best available, consistent, information. The assumptions made and the source of references used are given in Appendix C. The comparison is based upon the noise level at 500 ft on the sideline and where appropraite below the flight path, and more particularly on the area of the 80 PNdB noise footprint. The latter is regarded as the real criterion for aircraft operation from urban located sites in the future; see for example Ref.23. A very important assumption in the evaluation of the footprint area is the rate of sound attenuation. The 500 ft noise levels were based on published data much, if not all, of which assumed a 6.3 dB attenuation for each doubling of the distance from the source. However there is reason to believe that the ground level attentuation at least is greater than this. Therefore it was assumed that the attentuation beyond 500 ft is at the rate of 8 dB for each doubling of the distance, see for example Ref. 22. In the noise evaluation an attempt was made to allow for the results of engine and airframe developments in the direction of noise reduction. These are discussed in Appendix C and in most cases have resulted in two sets of noise figures appropriate to 'existing' and 'quietened' designs. It is necessary to note that even the 'existing' design assumptions do anticipate significant improvements relative to current operational aircraft. The comparisons are summarised in Table 1 and shown in Figures 10 and 11. The latter of these shows the relative 80 PNdB footprints for the quietened designs whilst the former gives the absolute values of the areas for both cases.

The transition altitude for all the VTOL examples was taken to be 2400 ft, with the flight up to and down from this condition being essentially vertical. The elongation of the circular footprint due to the climb away was, of course, allowed for. The airframe noise was found to be significant in the approach noise level of the noise shielded designs, that is those cases where engines are arranged relative to the lifting surfaces to give a blanking effect. In these cases the perceived airframe and engine noise components on the 500 ft sideline are approximately equal. A reduction of 14dB was assumed for the quietening of the augmentor wing flap system and this brought the noise from this source to below that of the basic powerplants.

7. DISCUSSION

7.1 General

The relative smoothness of the variations of the weight, costs and noise with field length is encouraging. There are, of course, points which are off the curves and these are the result of a difference in concept, as with the tilt wing, or indicate a particular characteristic of note. The trends of the curves are as anticipated.

7.2 Relative weights (Figure 5)

The designs studied show clearly that increase of gross weight associated with reduction in field length. Relative to the 5000 ft CTOL with underwing powerplants there is about 12% weight penalty for each 1000 ft reduction in field length down to 2000 ft. It is interesting that below this distance the penalty is proportionally less severe which may well be due to the use of more directly derived powered lift. For example considering the fan lift engine designs relative to the 4000 ft RTOL with rear fuselage powerplants the weight penalty is only about 7% for each 1000 ft reduction in field length. The rear engine noise shielded designs are about 3% heavier than the underwing powerplant aircraft and the 4000 ft RTOL referred to above is some 16% heavier than the datum.

Of the two VTOL concepts the tilt wing is some 5% lighter than the fan lift engine version. This is due to the use of the one set of powerplants for both vertical and forward flight and the lower fuel requirements. The heaviest aircraft is the quiet augmentor wing. This is some 4% heavier than the basic version and about 1% heavier than the fan lift VTOL though it requires a 1600 ft field length.

7.3 Low speed operating characteristics (Figures 6 and 7)

It is clear that aircraft designed to operate from field lengths of less than 4000 ft suffer from increasingly more severe low speed problems unless they are designed for essentially vertical operation. Of the STOL designs the augmentor wing introduces a smaller engine failure problem than the externally blown flap design but the fan lift concept could be even better due to the greater scope available in layout. The approach crosswind problem is a function of the nature of the operation as well as field length and is not primarily dependent upon the particular design concept.

7.4 Fuel requirements (Figure 8)

With the probable long term restriction and high cost of fuel supplies the fuel requirements become a particularly important consideration. The 4000 ft RTOL requires about 10% more fuel than the 5000 ft CTOL aircraft used as the datum. However reduction in field length below 4000 ft necessitates the provision of about 20% extra fuel for each 1000 ft reduction in runway length as far as the basic family of aircraft is concerned. The fuel actually used during the one hour flight assumed for cost evaluation is relatively greater for the fan lift designs. However it must be remembered that the VTOL version actually flies 12% further on the fuel used, so that on an aircraft-mile basis it requires 75% more fuel than the datum design. The tilt wing concept is relatively efficient from this point of view and on the evidence available uses only about 6% more fuel than the 5000 ft CTOL. This is presumably due to the very much higher effective bypass ratio of the powerplant/rotor system.

7.5 Direct operating costs (Figure 9)

The trend of the direct operating costs follows closely the trend of take off weight although there is an indication of a somewhat greater relative penalty for the shorter runway design. The two exceptions are the fan lift STOL and the tilt wing VTOL. The former has a consistent operating cost relative to other 2000 ft concepts in spite of its lower weight. The assumptions made for the latter indicate that it is relatively expensive to operate and as has been noted previously there may be an undue weighting against this design due to lack of precise data. However it is important to note that if fuel costs rise considerably it could be less expensive to operate than the fan lift VTOL, even on the basis of the assumptions made.

The basic curve suggests a 14.5% penalty on direct operating costs for each 1000 ft reduction in balanced field length in the range of 5000 ft down to 2000 ft, and about 60% penalty for VTOL relative to the datum if the higher fuel costs are assumed.

7.6 Noise (Figures 10 and 11)

The 80 PNdB noise footprint areas shown in Figure 10 have been included to show the absolute values predicted for this important parameter, for the cases of both shorter and longer term development. By and large the figure show considerable improvement relative to existing aircraft. For the purposes of the present investigation the relative 80 PNdB footprint areas shown in Figure 11 are of more significance. The data in this case applies to the longer term developments as this is regarded as being more justified for the newer design concepts.

The first point of note is the very unfavourable characteristics of the externally blown flap design. It is very difficult to visualise any means of improving this and it does seem that this concept must have a footprint area which is some five times that of the other designs examined.

There is relatively little variation in the other cases. Unlike the curves shown for weight and cost there is some evidence of an optimum field length. It is not a particularly strong tendency but occurs at about 4000 ft RTOL. The noise shielded designs do show significant improvements relative to the comparable underwing ones. This amounts to about 25% less area for the 5000 ft design and over 30% at 4000 ft. The tilt wing VTOL footprint area is rather less than 70% of that of the fan lift VTOL.

Unlike the externally blown flap design the augmentor wing in its quiet version has very similar characteristics to the fan lift aircraft and like them is not very much worse than the datum design.

7.7 Overall comparisons

In an attempt to compare the designs on a more comprehensive basis two merit indices have been introduced. The first of these is essentially an environmental one since it is the product of the relative fuel requirements and the 80 PNdB footprint ratio. The variation is shown in Figure 12. As would be expected the externally blown flap and basic augmentor wing have undesirably high values of the index. The underwing engine family has the datum index of unity for balanced field lengths above about 4200 ft and below this the index increases by about 0.3 for each 1000 ft reduction. The rear engined 4000 ft RTOL is the best with an index of 0.75 but the tilt wing VTOL compares very favourably with an index of 0.85.

The second index is based on the direct operating costs and is therefore classified as an economic merit index. The 80 PNdB footprint ratio is included again since this must be of prime importance in any future design. The values of this index are given in Figure 13 where it can be see that the general pattern is very similar to the previous one. The main differences are at the VTOL end of the spectrum where the tilt wing shows up less favourably than before but is still better than the fan lift design. There is relatively little between the fan lift and quiet augmentor wing STOL and the VTOL concepts.

In general it may be concluded from these two figures that the 4000 ft RTOL has much in its favour, particularly in the noise shielded rear engine version. It should not introduce any severe low speed control problems. In the light of the present work it represents the best compromise between the various environmental and economic considerations and in this sense may be regarded as an optimum.

Should STOL applications at around 2000 ft field length be required the choice lies between the quiet augmentor wing and fan lift concepts. Both have development problems associated with them, although the augmentor wing may prove to be the less severe of the two since it can be approached more gradually than the production of a complete new lift engine design. On the other hand the fan lift STOL is a natural step on the road to VTOL which cannot be said for the augmentor wing.

Perhaps one of the more interesting results is the potential shown by the tilt wing. In spite of its undoubted complexity and the consequential high operating costs it does have favourable

fuel and noise characteristics. In the present climate these are likely to prove the dominant issues. At the very least the tilt wing concept deserves a renewed appraisal and the same comment could be made in the context of other rotorcraft designs, such as the blown rotor. However having said this it must be admitted that the fan lift VTOL does have a greater speed potential and hence work capacity. It can be derived more directly from current transport aircraft practice once the lift engine is available. In its developed form the noise footprint should be acceptable and the main disadvantage is the high fuel consumption.

8. CONCLUSIONS

8.1 Although the 4000 ft RTOL concept implies some increase in direct operating cost relative to more conventional designs, when consideration is given to noise characteristics it represents an overall optimum. This is especially true for a rear engine, noise shielded layout.

8.2 The externally blown flap concept is ruled out when noise is of any importance. Its low speed control problems are also more severe than those of the augmentor wing.

8.3 For STOL operations from fields of about 2000 ft length there is little to choose between a quietened augmentor wing and a fan lift design. The former may prove to be a more straightforward development but the latter is a natural step towards VTOL.

8.4 The tilt wing concept shows up very promisingly when the basis of comparison is environmental, that is fuel usage and noise. The results suggest that this concept and other forms of rotorcraft should be reviewed in the present, changed circumstances. However in spite of its high fuel consumption the fan lift VTOL should be acceptable from a noise point of view and has a greater work capacity than rotorcraft.

8.5 The 80 PNdB noise footprint areas of the CTOL aircraft have been estimated to be similar to those of the RTOL, STOL and VTOL designs on the basis of developments in the noise reduction likely to be achieved in the next decade or so. This is different to earlier predictions and arises primarily from the use of quietened powerplants of high bypass ratio.

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APPENDIX A

WEIGHT SCALING FACTORS (Ref.14)

1. WING WEIGHT

The weight of the wing, including the flap system for a conventional design can be expressed as:-

$$W_W = C_1 \left[\frac{bS}{\cos\phi} \left(\frac{1+2\lambda}{3+3\lambda} \right) \left(\frac{WN}{S} \right)^{0.3} \left(\frac{V_D}{\tau} \right)^{0.5} \right]^{0.9} \quad \text{lbs}$$

where b is the wing span, S the area, λ the taper ratio, τ the thickness/chord ratio at the root, N the ultimate normal acceleration factor, ϕ the quarter chord sweep and V_D the design diving speed in knots. All dimensions are in feet units and W is the all up weight in lbs.

C_1 is 0.003 approximately when the engines are carried on the wing and 0.00315 when they are located elsewhere. For a consistent wing geometry, wing loading and design requirements this yields:-

$$W_W \propto W^{1.85}$$

This was used in conjunction with the weights derived from the detail investigations but it was also necessary to make a correction to allow for the major differences in the flap systems used. This has been carried out in absolute terms using the following values of weights per unit planform area of the flaps and slats:-

Double slotted trailing edge flaps	4 lb/sq ft
Triple slotted trailing edge flaps	6.5 lb/sq ft
Augmentor flaps	8.0 lb/sq ft
Kruger flaps	5.0 lb/sq ft
Leading edge slats	7.0 lb/sq ft.

2. FUSELAGE WEIGHT

Fuselage weight can be expressed as:-

$$W_F = C_2 \left[L(B+H) V_D^{0.5} \right]^{1.5}$$

where L is the fuselage length, B the breadth and H the height, in feet.

C_2 is 0.001 normally, but 0.0011 when the powerplants are fuselage mounted. In fact in this case it was only necessary to use this as a correction on the established design weights.

3. TAIL UNIT

For the present purposes tail unit weight was assumed to be proportional to $W^{0.83}$.

4. UNDERCARRIAGE

The weight of the undercarriage was taken as being directly proportional to all up weight for consistent geometry

5. SYSTEMS, INSTALLATIONS AND EQUIPMENT

Fuel system and the flying control system were each assumed to be proportional to all up weight. Air conditioning and de-icing were taken together and allowance made for change in wing and tail area. All other items of equipment, installations, disposables, etc. were assumed to be constant.

6. POWERPLANT AND FUEL

Powerplant weight was assumed to be proportional to thrust and hence to all up weight for a given static thrust/weight ratio. The gross installed weight of the bypass ratio 10 powerplants was taken as 0.275 times the static thrust. In the case of fan lift engines the gross installed weight, excluding nacelle structure, was assumed to be 0.076 times the thrust. Lift engine nacelle structure for the 2000 ft fan lift STOL design was deduced to be 2000 lbs from the estimated weight of the fan lift VTOL aircraft, the A70. Similar deductions for pylon and propulsion engine nacelle weight were made from the other design studies.

Fuel weight was assumed to be proportional to the gross weight for the small weight variations associated with the scaling process.

7. WEIGHT PENALTY FOR QUIET DESIGNS

In the case of the propulsion engines it was considered to be reasonable to assume that developments in technology would enable approximately 3.5 dB reduction in noise level without significant weight increase above that already provided.

The improved noise level of the lift fan engines was assumed to be 6 dB less and due to the use of silencers. There is no doubt that these would involve a weight penalty but it was assumed that provision was already made for this in the gross installed weight allowance. Thus the 'existing' design weights may be considered to be somewhat high but in reality are probably not too unrealistic for early production engines.

The internally blown flap design has a very high noise level although it may possibly be reduced by about 5 dB by using mixers on the powerplants. No weight allowance has been made for this since the whole issue is very tentative.

On the other hand specific information is given in Ref.12 on the penalty for noise reduction of an augmentor wing system by using acoustic lining and multielement nozzles. This reference implies a weight penalty of about 0.14% of the all up weight for each 1 dB noise reduction up to 14 dB. This figure has been used in evaluating the data for the Quiet Augmentor Wing STOL.

APPENDIX B

DIRECT OPERATING COSTS (Ref.15)

The direct operating cost evaluation was based on the BEA method modified to cover the different types of aircraft and possible future cost evaluation. The evaluation was based on a fleet on 20 aircraft in each case and 100% load factor.

1. BLOCK TIME, UTILISATION AND SECTOR DISTANCE AND FUEL

The block time was assumed to be 1 hour in each case resulting in an annual utilisation of 2200 hours. With the exception of the fan lift VTOL each aircraft was assumed to cruise at 300 knots EAS at 20,000 ft to give a sector distance of 300 n. miles and hence a block speed of 300 knots true. Analysis of the performance of these designs carried out in detail indicated that for this case the sector fuel was 36.5% of the total provided with the 108 passenger payload. In the case of the fan lift VTOL the cruise speed is higher, being 350 knots EAS and in this case the sector distance is 360 n.miles with a block speed of 360 knots true. The fuel used was found to be 42% of the total provided.

2. PRIME COSTS

The prime cost of the equipped airframe was taken to be basically £50 per lb of As Prepared for Service weight. However because of the very high powerplant content of some of the designs a correction was applied to allow for this on the basis of the assumed powerplant costs. This correction was found to have little effect apart from the case of the fan lift aircraft. The 2000 ft fan lift STOL was corrected to £51.8 per lb and the fan lift VTOL to £56.8 per lb.

Propulsion engines were assumed to cost £15 per lb of static thrust and fan lift engines £7 per lb of static thrust. This last figure is very critical in determining the operating costs of the fan lift aircraft.

The 9000 HP shaft engines used in the tilt wing VTOL design were each assumed to cost £140,000, less gearbox. The gearbox unit couples pairs of engines and together with the cross shafting was estimated at £160,000 each. Rotor unit costs are somewhat problematical to predict but were assumed to amount to £320,000 each.

3. SPARES

Airframe spares investment was taken as 12% of the prime cost of the equipped airframe.

Engine spares holdings were assumed to be as follows

Propulsion engines:-
2 engine aircraft: 45% of total in fleet
3 engine aircraft: 40% of total in fleet
4 engine aircraft:37.5% of total in fleet
Lift engines:-
6 engine aircraft: 16% of total in fleet
12 engine aircraft: 16% of total in fleet

Gearbox and rotor spares investment were taken as equivalent to 40% of the total in the fleet. This item would probably be held as components rather than complete units.

4. AMORTIZATION, INTEREST AND INSURANCE

The total investment per aircraft was assumed to depreciate to zero over 14 years, that is over 26400 flight hours. The investment was taken as the prime cost plus the proportion of the spares holding allocated to each aircraft.

Interest was taken as 5% of the investment per annum, and insurance as 2% of the investment per annum.

5. ENGINEERING

For the case of a one hour block time the total engineering labour and material costs was taken as:-

Airframe:- £$(10+0.0013W_a)$ per hour

where W_a is the difference of the empty weight equipped and installed powerplant weights, lb.

Propulsion engines:- £(12+0.00062T) per hour, per engine

where T is the static thrust of each engine

Lift engines:- £(0.0009T) per hour, per engine

9ooo H.P. shaft engines:- £18 per hour, per engine

Gearboxes and transmission:- £24 per hour for each gearbox unit.

Rotor system:- £32 per hour for each rotor unit.

Auto controls and APU:- £14 per hour, total.

In estimating the airframe engineering costs an attempt was made to make allowance for the more complex flap and flying control systems used in some of the designs. This was based on the work of Coughlin Ref.16. Consideration was also given to reduced undercarriage engineering costs with reduction of approach speed. It was found that the various effects tended to cancel apart from the case of the VTOL designs where a slight relative reduction could reasonably be anticipated. This amounted to less than 1% of the total direct operating costs and for

simplicity was neglected.

6. FUEL

Calculations were based on two fuel costs which are anticipated to cover the range likely to be experienced in the forseeable future.

Fuel costs A:- 12p/gallon (1.5 p/lb)
Fuel costs B:- 36p/gallon (4.5 p/lb)

7. CREW

In each case allowance was made for two aircrew at £55/hour and four cabin staff at £30/hour, total.

8. LANDING AND NAVIGATION FEES

Landing fees were calculated as $£0.6 \times 10^{-3}W$

En route navigation fees were assumed to be

$$£1.5(W \times 10^{-3})^{0.5}$$

APPENDIX C

NOISE

A simplified approach has been made to the problem of estimating the noise characteristics of the various designs. This was felt to be justified in view of the paucity of information in some cases and the prime requirement to establish relative rather than absolute values.

The method used was to estimate the sideline noise levels at 500 ft distance for both take off and landing conditions and use these to determine the area of the 80 PNdB ground footprint. This was done by assuming cylindrical noise fields defined relative to the ground plane by the climb out and approach angles. Where a significantly different noise level below the flight path was anticipated a correction was applied, and directivity was allowed for in the case of vertical takeoffs. In all cases the noise was assumed to be attenuated at 8 dB for each doubling of the distance from the 500 ft datum.

1. PROPULSION ENGINES

The take off noise level at 500 ft was estimated from the following formula, partly derived from published Rolls Royce data and quoted in Ref.17:-

$$PNdB = 10 \log\left[\text{Antilog}\{8.8+\log R\}+\text{Antilog}\{11.5-1.7\log R\}+\text{Antilog}\{12.8-3\log R\}\right] + 10\log\left(\frac{T}{80000}\right) - \Delta$$

The three terms in the square brackets represent, respectively, the compressor, turbine and exhaust noise.

R is the bypass ratio and T the static thrust in lbs.
Δ is a correction to allow for development and layout of the airframe/engine combination

Δ was assumed to be 1.5 dB for the basic versions of the powerplants, 5 dB when fully developed from a noise aspect and 7.5 dB when intake noise shielding was present. In all the cases where propulsion engine noise is important the bypass ratio assumed was 10 so that the noise equation reduces to:-

$$PNdB = 102.8 + 10\log(T/80000) - \Delta$$

For the landing and other reduced thrust cases the take off noise level was reduced by :-

$$15\left(\frac{T_R - T}{T}\right) \text{ dB}$$

where T_R is the reduced thrust.

2. FAN LIFT ENGINES

The same equation was used for the propulsion engines except that a bypass ratio of 12 was assumed and Δ was taken as 1.5 dB initially and 7.5 dB for the fully noise developed engines:-

$$PNdB = 101.9 + 10\log(T/80000) - \Delta$$

The directivity effect during vertical flight was allowed as in paragraph 6 for the tilt wing concept.

3. AIRFRAME

Using the little evidence available and comparing it with rotor broad band noise Ref.17 suggests that at 500 ft distance

$$PNdB = 10\log(\frac{W}{S}) + 10\log W + 20\log V - 31$$

where W is the weight, lbs, S the wing area in sq ft and V the velocity in ft/sec.

4. EXTERNALLY BLOWN FLAPS

The data used for estimating the noise of the externally blown flap aircraft was derived from Refs. 18, 19 and 20. Some difficulty was encountered in reconciling the various sets of information and because of the severity of the noise problem in this case the most optimistic assumptions were made. The exhaust velocity of the bypass ratio 10 engines was assumed to give an equivalent pressure ratio of between 1.3 and 1.5 over the flaps as a whole.

In the take off case, with the flaps set at 10^{o}-20^{o} it would appear that the noise level at 500 ft for 80,000 ln total thrust will be of the order of 113 to 118 PNdB. This range covers the variation of pressure ratio and about 2 dB difference in scaling from the various references. It includes a subjectivity allowance of 8-9 dB, deduced from Ref.19 and applies immediately below the flight path. A noise level of 114 PNdB was therefore taken for this case with the sideline level reduced to 109 PNdB as suggested by Ref.18.

In the landing condition the flap setting is 20^{o}-40^{o} and this by itself causes about 2-3 dB increase in noise level. However this is associated with a reduced thrust and the net result is that the noise level is approximately the same as during take off.

Ref. 19 suggests that use of a mixer nozzle should enable overall noise reduction of 5 dB to be achieved, and this has been assumed for the quiet externally blown flap design.

5. AUGMENTOR WING

The basic augmentor wing noise was calculated using Ref.18. The nozzle pressure ratio as designed is 1.9, and the take off flap angle 20°. Making an allowance of 9 dB for subjectivity the noise level at 500 ft below the flight path for 80,000 lb thrust is found to be 109 dB. The sideline noise is quoted as 5 dB less than this. As with the externally blown flap the extra noise of 3 to 4 dB due to deflecting the flap to the landing position of 50° is partly offset by the reduction of thrust. It is likely that the landing noise level will be up to about 1 dB higher than the take off value, but as this is considered to be less than the accuracy of the prediction, identical values have been assumed.

Ref.12 considers ways of improving the noise level of augmentor wings. It suggests that the use of acoustic lining on the internal flap surfaces together with a multielement nozzle and screech screens should enable a reduction of at least 14 dB to be obtained. Ref.18 quotes a reduction of 8 dB maximum for a particular duct lining alone. The quiet augmentor wing design was therefore based on a reduction of up to 14 dB relative to the basic values quoted above.

6. TILT WING AIRCRAFT

The noise of the tilt wing aircraft is assumed to be due to the shaft turbine engines and the rotors. It is possible to regard the engine/rotor system as a fan engine of large bypass ratio. Thus the basic shaft turbine noise can be evaluated from the formula quoted for propulsive engines by using only the first two terms in the square brackets and relating the power developed to equivalent thrust. If it is assumed that the 9000 HP shaft engine is equivalent to a bypass ratio 10 engine of 15000 lb thrust then the noise level at 500 ft is:-

$$PNdB = 101 + 10\log\left(\frac{SHP}{48000}\right) - \Delta$$

where SHP is the shaft horse power.

As far as the rotor is concerned it is assumed that the design is such that broadband noise is dominant. This is associated with a 7 blade rotor and tip speed of 750 ft/sec.

The noise evaluation was based on information contained in Ref.21, but modified in accodance with the suggestions of Ref.22. For vertical flight in zero wind conditions the noise 500 ft from the source in this case is about:-

$$PNdB = 60\log V_t + 20\log C_{L_t} + 10\log S_b + f(\theta) - 76$$

where V_t is the blade tip velocity, ft/sec, C_{L_t} is the tip lift coefficient, S_b is the total blade plan area, sq ft and $f(\theta)$ is the directivity factor. $f(\theta)$ is zero when the aircraft is vertically above the observer and -15 dB when it is alongside. For the blade characteristics of the design aircraft the noise level at 500 ft on the ground was estimated at 95 dB and 110 dB when 500 ft above the observer. The peak climb out level at the ground 500 ft from the take off point is 101 dB.

KEY TO TABLES 1 AND 2

CTOL - Conventional take off and landing - above 4000 ft runway.

RTOL - Reduced take off and landing - no lift augmentation.

STOL - Short take off and landing - lift augmentation.

VTOL - Vertical take off and landing

RE - Rear fuselage mounted powerplants (Powerplant noise shielding)

UW - Underwing powerplants

BF - Externally blown flap lift augmentation

FL - Fan lift engines for vertical thrust

AW - Augmentor wing system

QAW - Quiet augmentor wing

TW - Tilt wing concept (Twin rotors)

A - Costs with fuel at 1.5p/lb
B - Costs with fuel at 4.5p/lb.

Q - Quietened powerplants and lift augmentation

PNdB } Flyover noise level at 500 ft
PNdB } Sideline noise level at 500 ft

(Landing and take off values similar)

TABLE 1

Summary of Aircraft Characteristics.

Class of aircraft	CTOL			RTOL		STOL					VTOL	
Runway length - ft	7000 UW	5000 UW	5000 RE	4000 UW	4000 RE	2600 BF	2000 BF	2000 FL	1600AW	1600 QAW	0 FL	0 TW
Gross weight lb	82000	87300	89800	97500	101500	111200	118500	113500	121400	126800	125300	120000
Wing area sq ft	680	970	1000	1160	1200	1510	1600	1345	1640	1710	1000	1330
Wing loading, take off lb/sq ft	120	90	90	84	84	74	74	84	84	84	125	90
Wing loading, landing lb/sq ft	110	83	83	77	77	64	64	77	77	77	120	88
Number of propulsion engines	2	2	2	2	3	4	4	3	4	4	2	4
Static thrust of each prop. engine lb	11500	12200	12600	22600	15600	14000	20400	15600	20600	21500	21500	9000 HP
Number of lift engines								6			12	
Thrust of each lift engine lb								8300			14500	
Thrust/weight ratio, static	0.28	0.28	0.28	0.46	0.46	0.50	0.68	0.41	0.68	0.68	0.34	
Take off safety speed, knots	145	130	130	122	122	108	100	86	93	93	0	0
Lift off lift coefficient	1.5	1.5	1.5	1.62	1.62	3.0	3.0	1.6	2.5	2.5		
Climbout angle, degrees	6.5	6.5	6.5	10	10	6	14.5	14	14.5	14.5	90	90
Approach speed, knots	135	114	114	104	104	79	79	79	72	72	0	0
Approach lift coefficient	1.7	1.7	1.7	2.1	2.1	3.4	3.4	2.1	3.6	3.6		
Approach angle, degrees	3	3	3	5.5	5.5	7.5	7.5	7.5	7.5	7.5	90	90
First cost £m	2.41	2.64	2.74	3.08	3.24		3.89	3.76	4.01		4.5	4.3
Investment £m	2.85	3.12	3.24	3.62	3.81		4.82	4.55	4.95		5.44	5.8
Basic cost £/hour	194	213	222	247	250		327	311	336		378	404
Engineering cost £/hour	116	122	126	151	156		194	206	197		290	273
Fuel cost £/hour - A; 1.5p/lb	67	71	76	79	84		106	114	108	112	174	76
B; 4.5p/lb	201	213	228	237	252		318	342	324	336	522	228
Total cost £/hour - A	525	557	577	636	660		799	802	816	852	1019	926
- B	659	699	729	794	828		1011	1030	1032	1076	1367	1078
Cost p/pas.mile - A	1.62	1.72	1.78	1.96	2.04		2.46	2.48	2.5	2.62	2.6	2.96
- B	2.03	2.16	2.25	2.45	2.56		3.12	3.18	3.19	3.32	3.49	3.33
Noise level, take off PNdB	96	96		99			114	101.5	109		111.5	
landing PNdB	87	87		88			109	98.5	104		109.5	
80 PNdB footprint, sq miles	3.6	3.4		3.1			29.5	5.4	7.9		9.4	
Noise level, take off PNdB-Q	92.5	92.5	90	95	93		109	97		98	106	102
landing PNdB-Q	85	85	85	87	85.5		104	93.5		93.5	104	101
80 PNdB footprint, sq.miles-Q	2.3	2.1	1.6	2.0	1.33		10.7	2.33		2.5	2.5	1.7

See Key for explanatory note

TABLE 2

Summary of Aircraft Weight Breakdowns

Class of aircraft	CTOL			RTOL		STOL					VTOL	
Runway length - ft	7000 UW	5000 UW	5000 RE	4000 UW	4000 RE	2600 BF	2000 BF	2000 FL	1600 AW	1600 QAW	0 FL	0 TW
Fuselage	10400	10400	11500	10400	11500	10400	10400	11500	10400	10400	11500	11250
Wing (less flaps)	4200	6900	7800	7200	8200	9600	9900	9300	10400	10870	9650	10500
Flap system	1450	1900	1900	2500	2700	2400	2600	2700	4200	4390	1500	2300
Tail unit	1830	2420	2480	3000	3130	3940	4060	3140	4200	4350	3500	3600
Undercarriage	2970	3170	2970	4220	4470	5400	5590	4900	4670	4880	3390	3400
Nacelle structure and pylons	200	200	200	300	400	400	400	2000	400	400	5960	2300
Total Structure	21050	24990	26850	27620	30400	32140	32950	33540	34270	35290	35500	33350
Propulsion engine installation	6300	6700	6900	12500	12900	16900	22500	12900	22700	23700	8400	10900
Lift engine installation/rotors								3800			13120	8700
Total Powerplant	6300	6700	6900	12500	12900	16900	22500	16700	22700	23700	21520	19600
Fuel system	1000	1000	1000	1100	1100	1200	1240	1300	1240	1290	1300	1250
Flying controls, auto controls	1140	1220	1260	1440	1520	1600	1670	1900	1690	1760	2000	2950
Air ducting/transmission						400	400		1320	3520		9600
Power supplies	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	3600
Auxiliary power unit	530	530	530	530	530	530	530	530	530	530	530	
Radio and radar	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
Instruments	600	600	600	600	600	600	600	600	600	600	600	600
Total Systems and Installation	8770	8850	8890	9170	9250	9830	9940	9830	10880	13200	9930	19500
Air conditioning and de-icing	2330	2400	2400	2500	2500	2330	2600	2500	2600	2600	2330	2300
Furnishings, cabin service	7450	7450	7450	7450	7450	7450	7450	7650	7450	7450	7650	7600
Passenger service disposables	1250	1250	1250	1250	1250	1250	1250	1250	1250	1250	1250	1200
Crew	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100
As Prepared for Service	48250	52740	54840	61590	64850	71000	77790	72570	80250	84590	79280	84650
Passengers, 108	21600	21600	21600	21600	21600	21600	21600	21600	21600	21600	21600	21600
Fuel, basic	12150	12960	13360	14310	15050	18600	19110	19330	19550	20610	24420	13750
Take off Weight	82000	87300	89800	97500	101500	111200	118500	113500	121400	126800	125300	120000

See Key for expanatory note

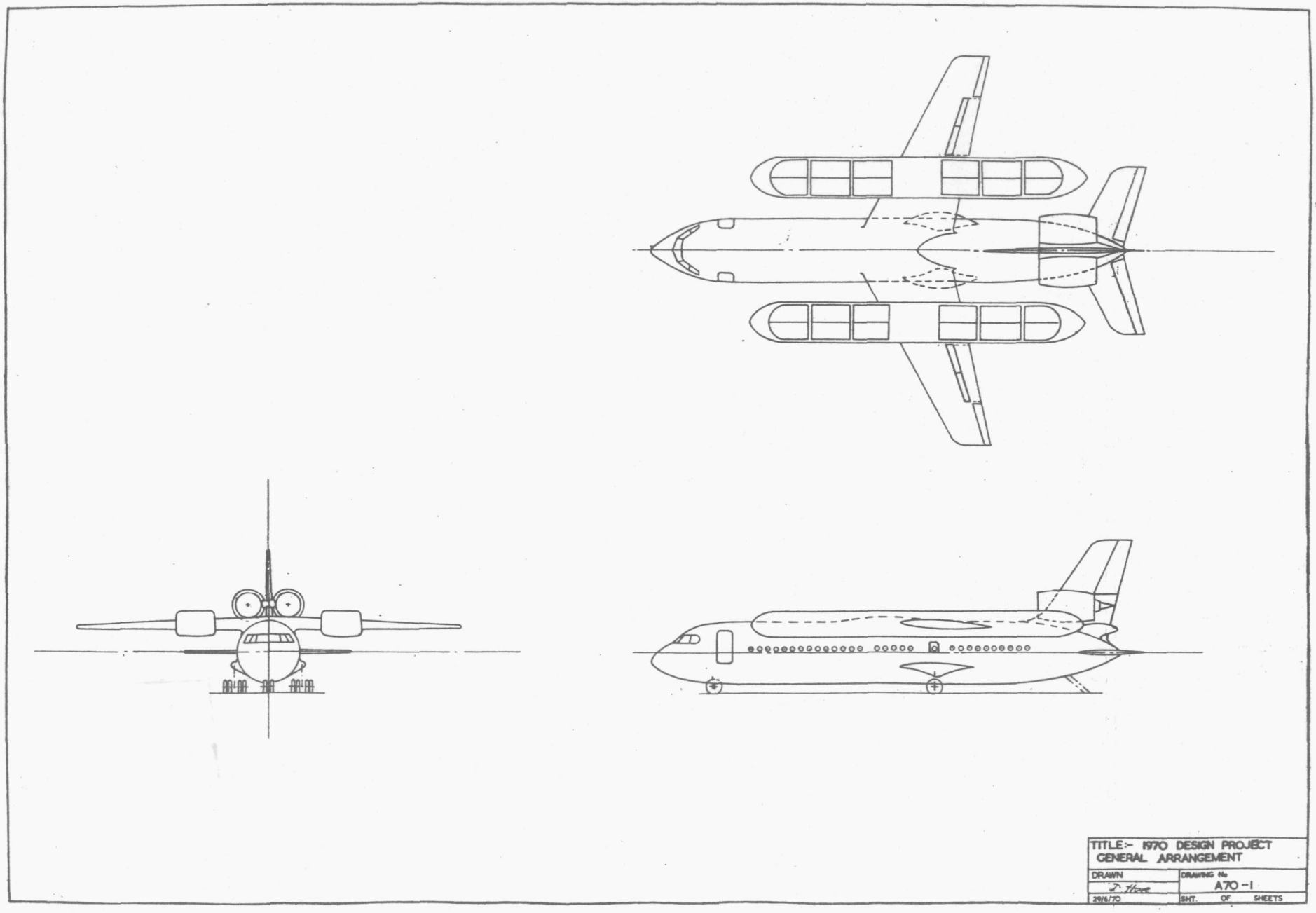

FIG. 1. GENERAL ARRANGEMENT OF A70 FAN–LIFT VTOL.

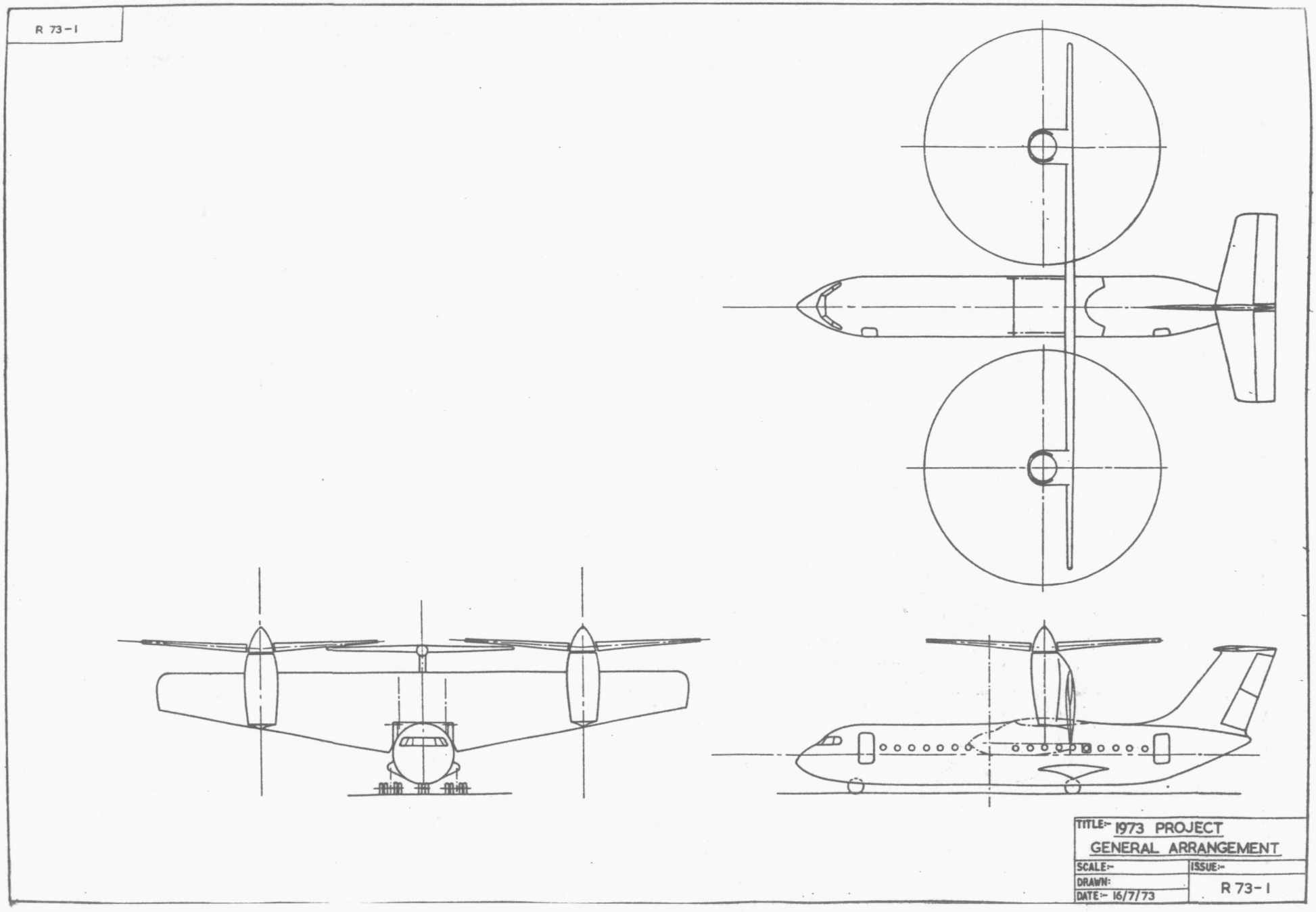

FIG. 2. GENERAL ARRANGEMENT OF R73 TILT WING VTOL

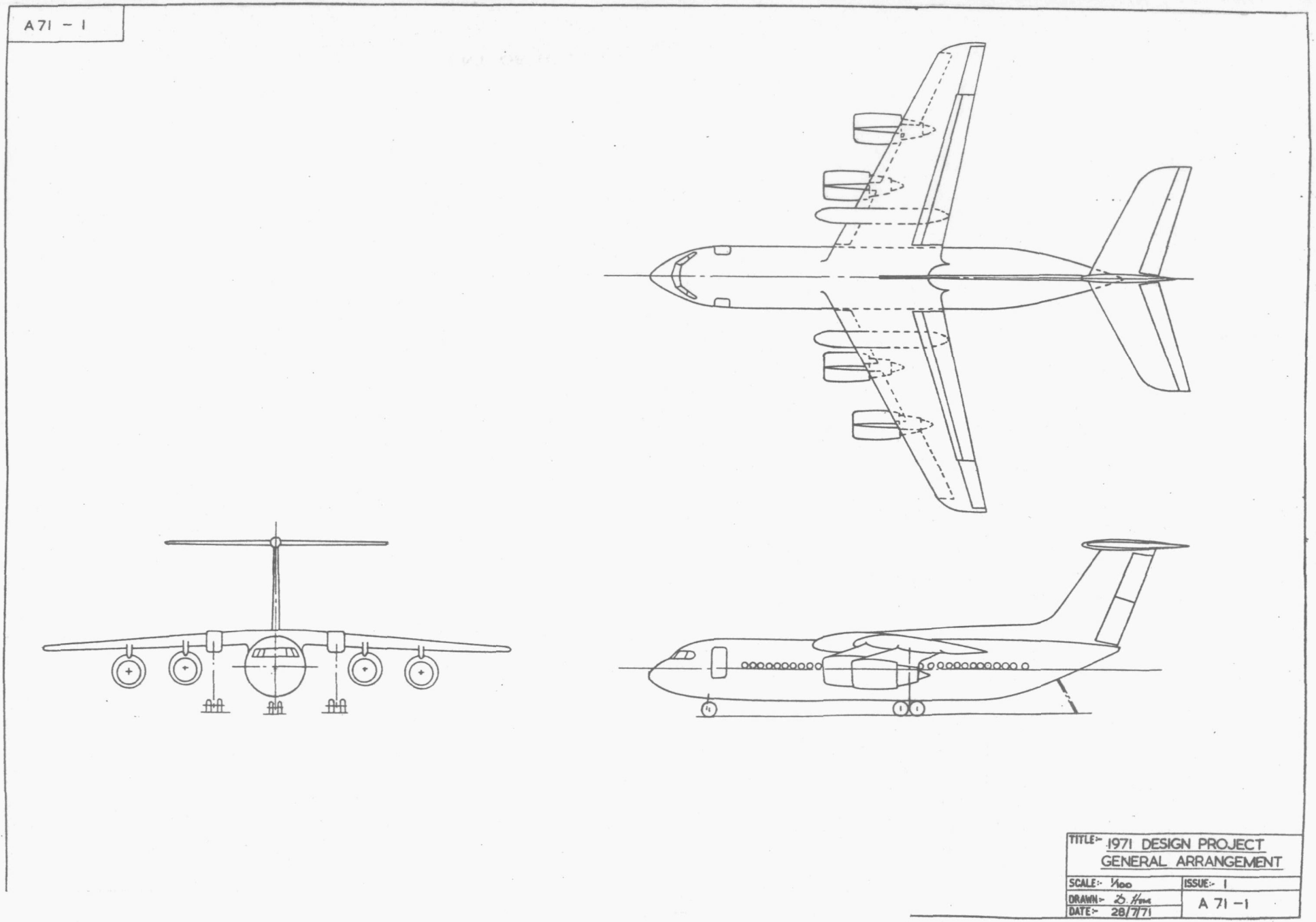

FIG. 3. GENERAL ARRANGEMENT OF A71 EXTERNALLY BLOWN FLAP STOL.

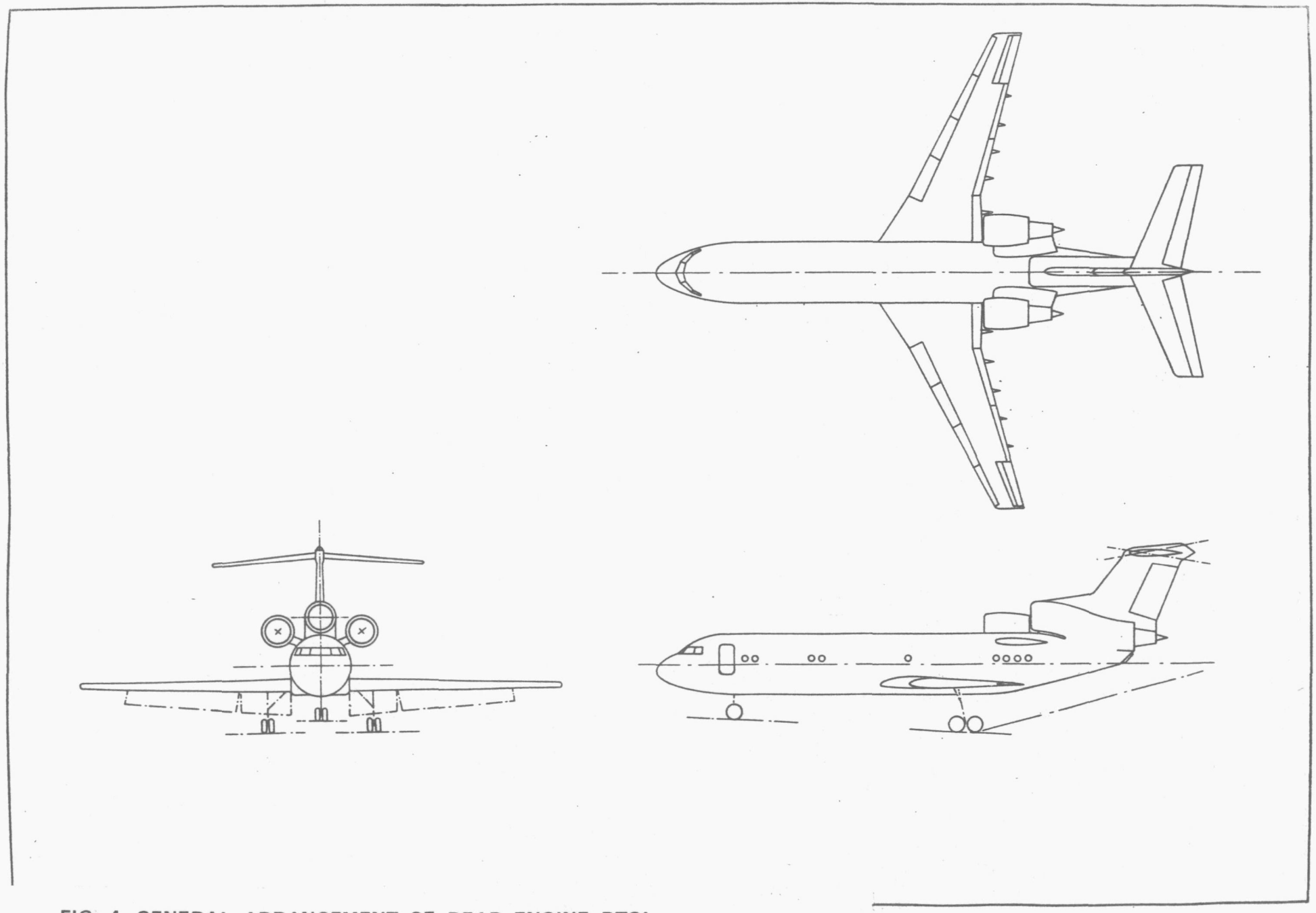

FIG 4. GENERAL ARRANGEMENT OF REAR ENGINE RTOL.

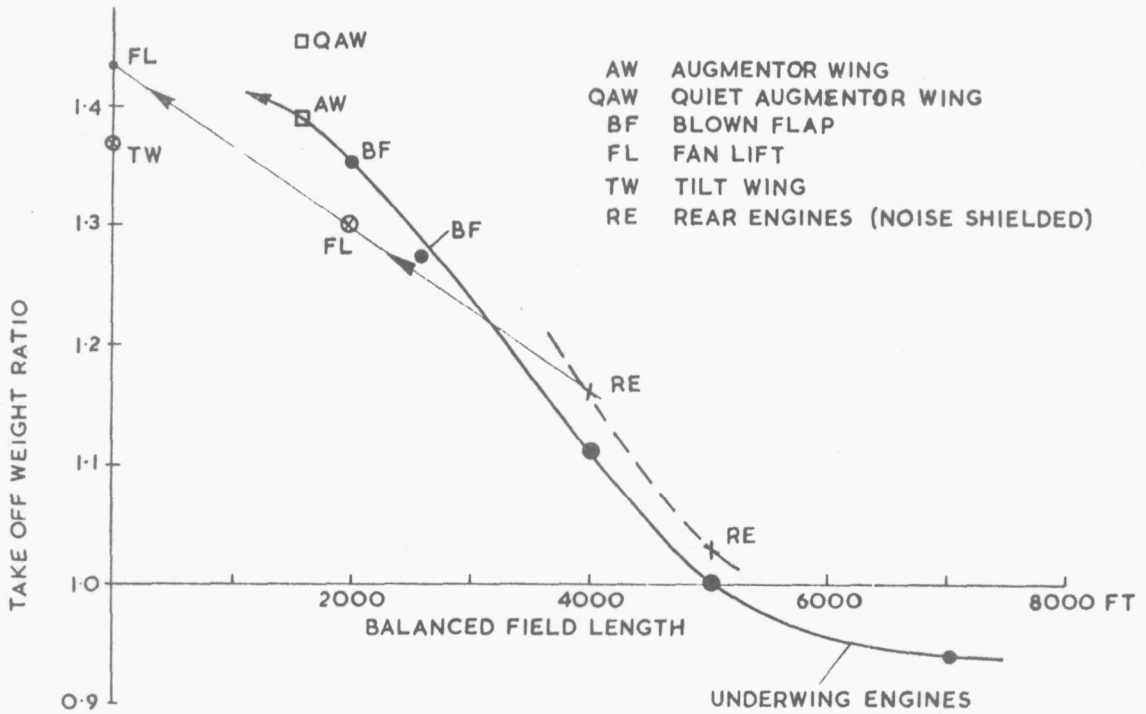

FIG. 5. RELATIVE GROSS WEIGHT.

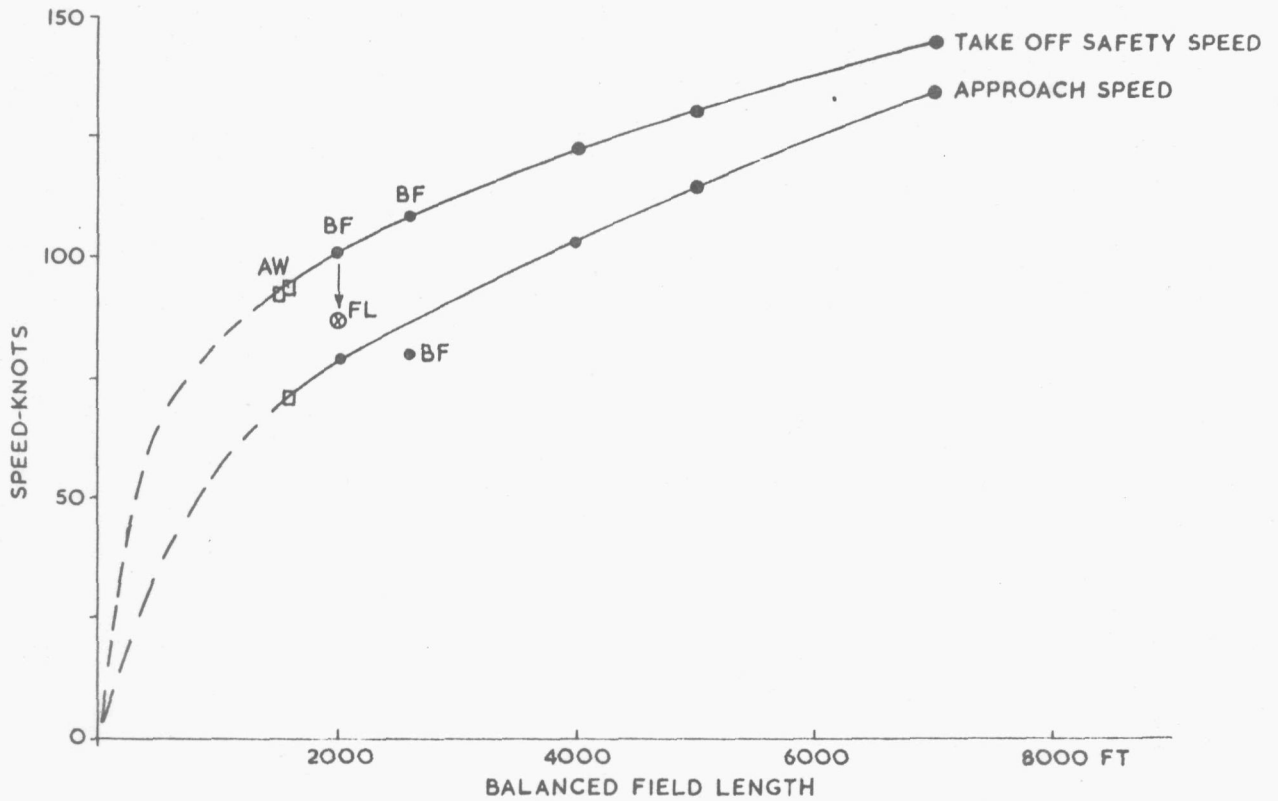

FIG. 6. TAKE OFF SAFETY AND APPROACH SPEEDS

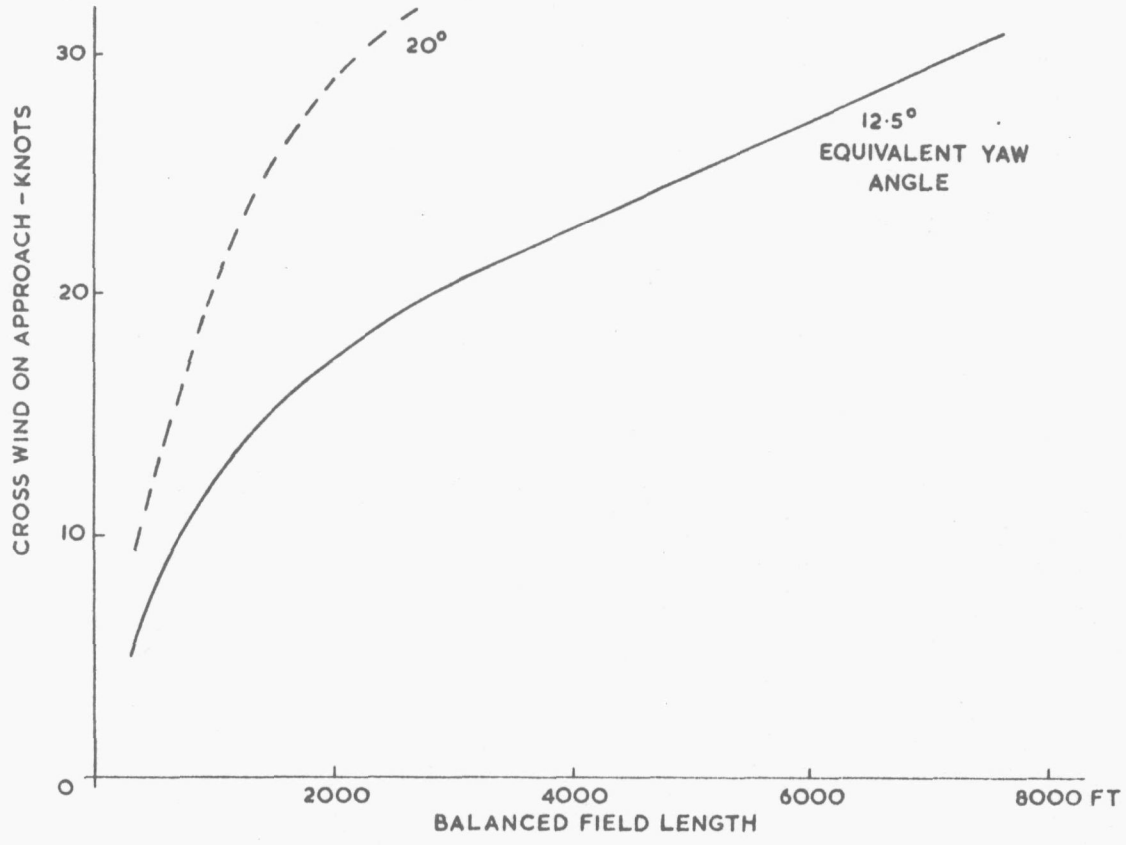

FIG. 7. CROSS WIND APPROACH CONDITIONS.

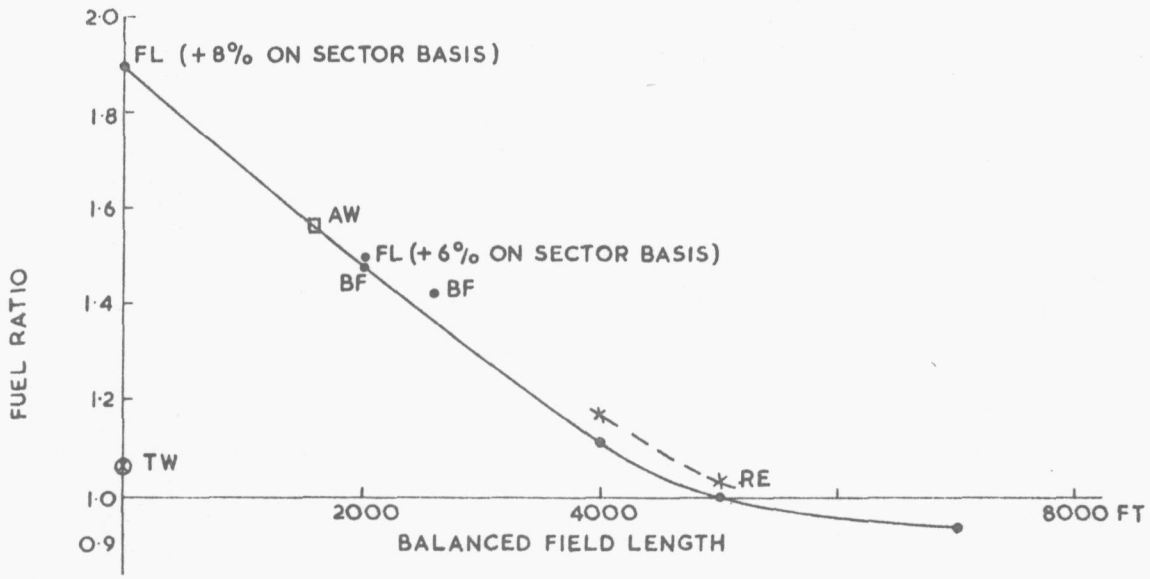

FIG. 8. RELATIVE FUEL LOADS CARRIED.

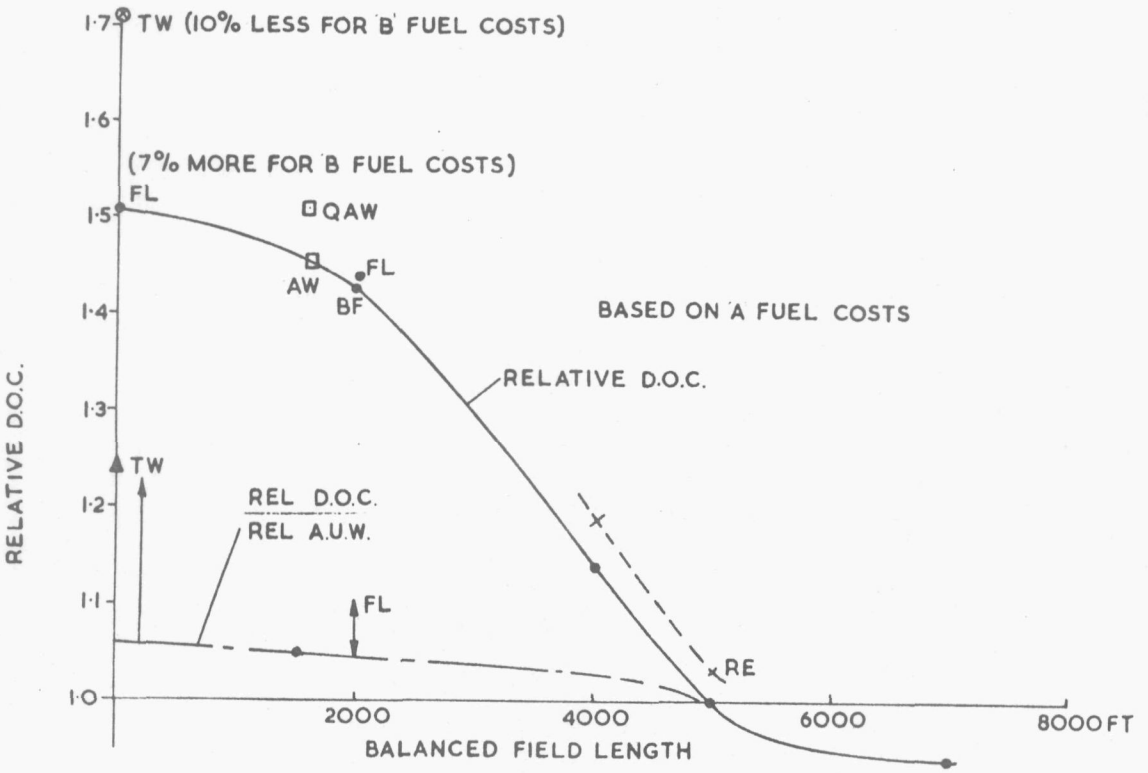

FIG. 9. DIRECT OPERATING COSTS COMPARISON

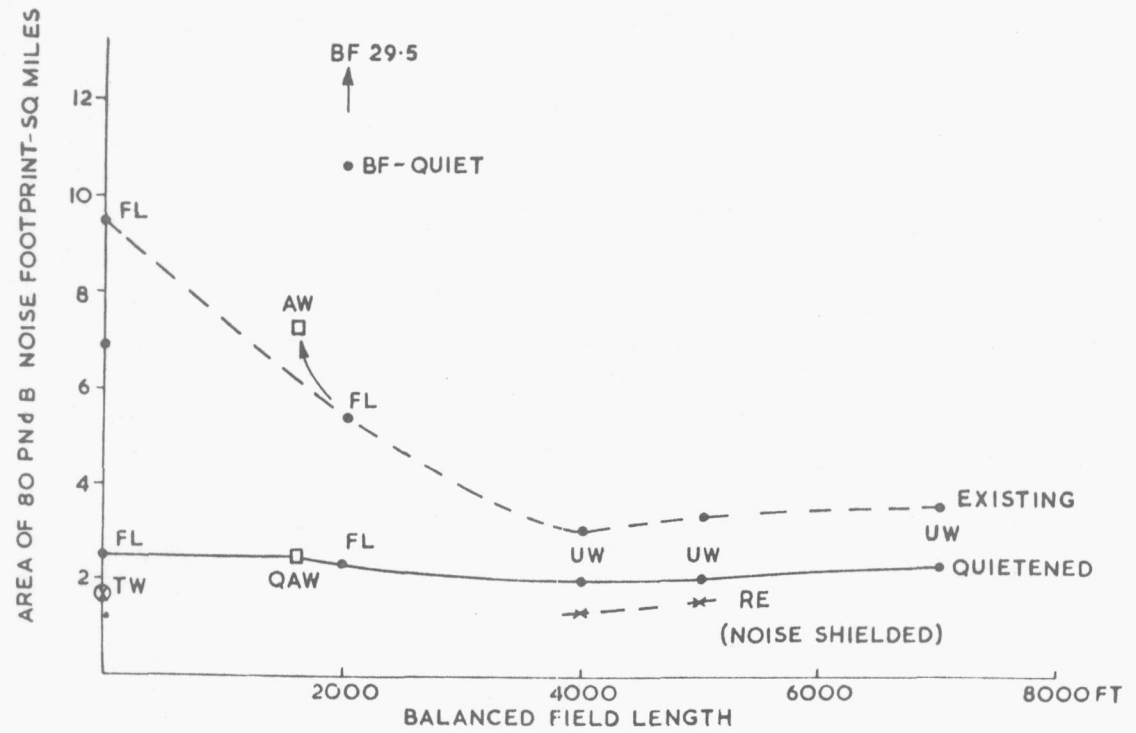

FIG. 10. NOISE FOOTPRINTS.

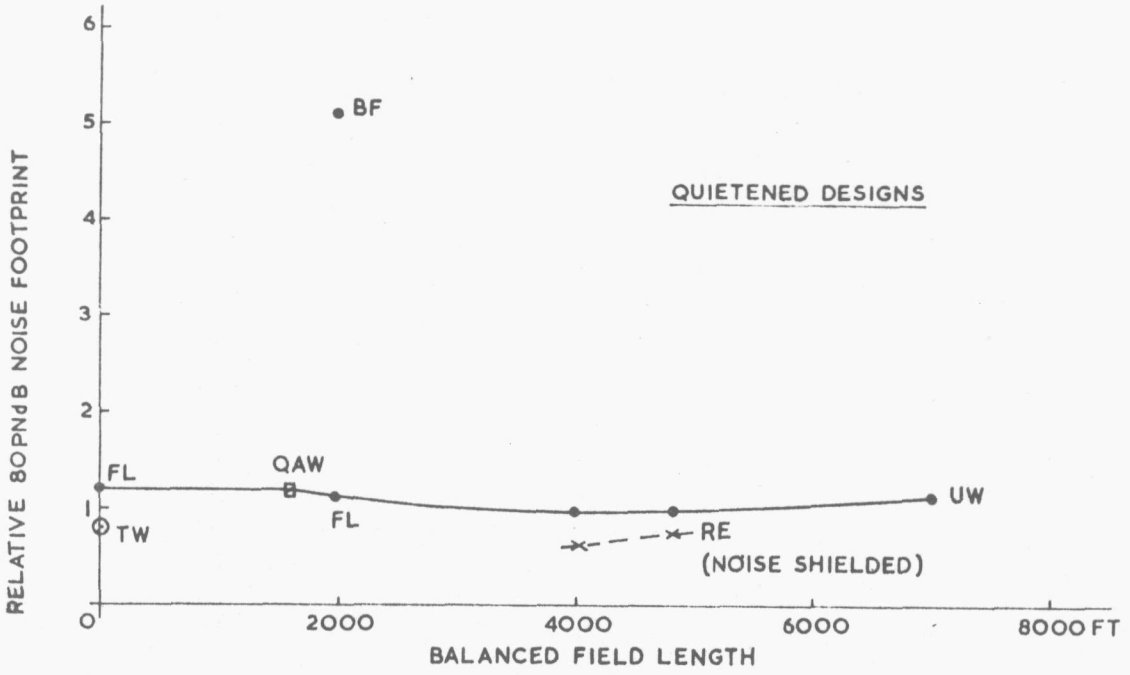

FIG. 11. RELATIVE NOISE FOOTPRINTS.

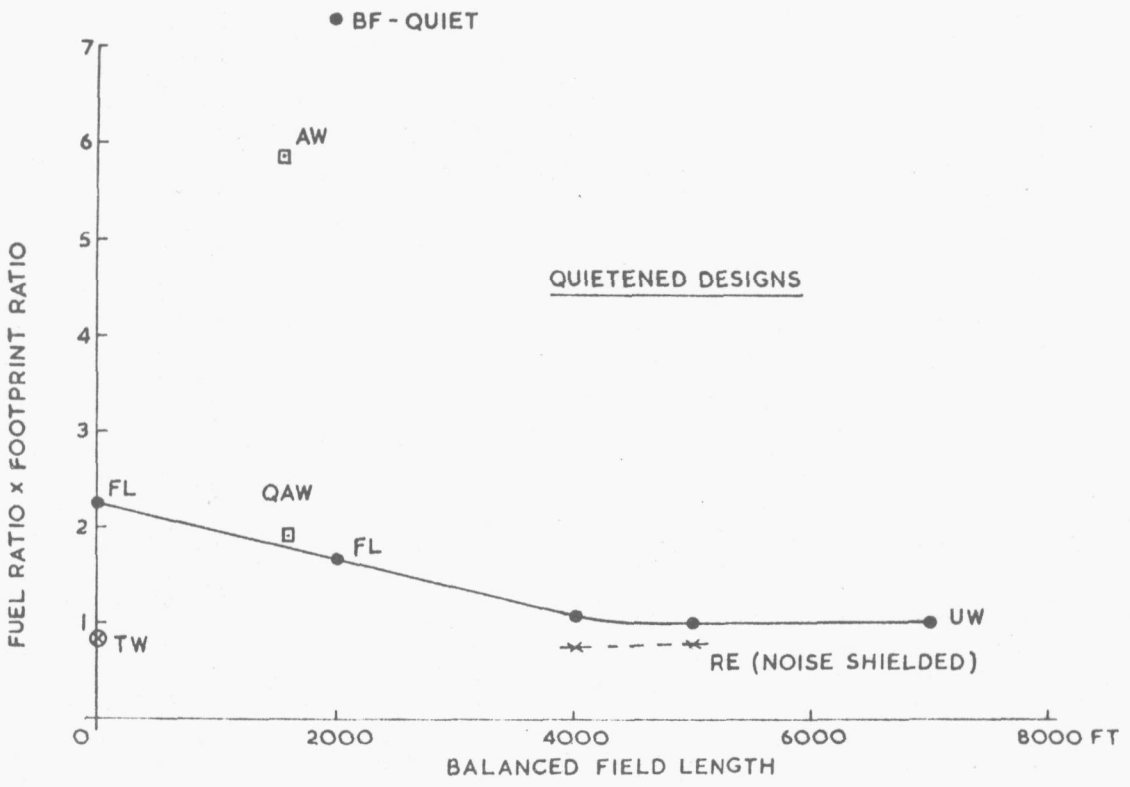

FIG. 12. ENVIRONMENTAL MERIT INDEX.

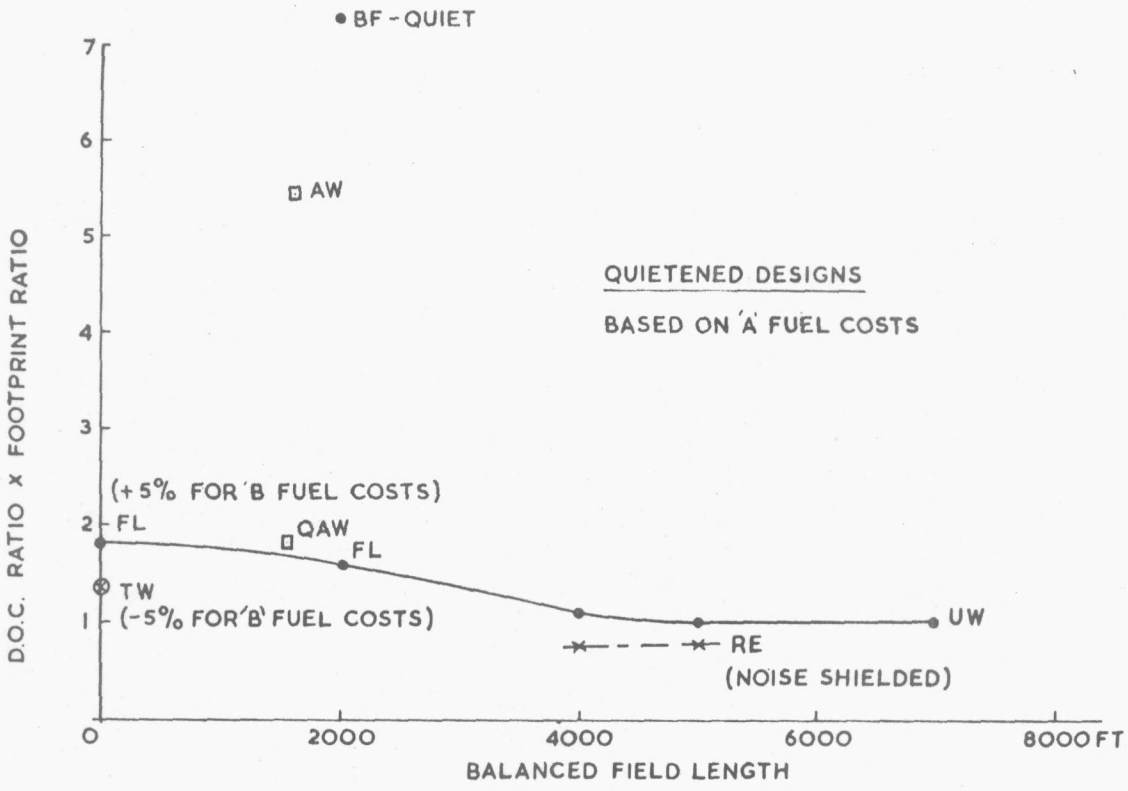

FIG. 13. ECONOMIC MERIT INDEX.