

# THE AUGMENTOR-WING: A NEW MEANS OF ENGINE AIRFRAME INTEGRATION FOR STOL AIRCRAFT

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## INTRODUCTION

The main objective of STOL technology from an aerodynamic standpoint is to develop wing lift to a maximum while keeping installed power to a minimum in order to satisfy an overall aircraft requirement which includes a specified short field length. The subject under consideration here concerns the ultimate in STOL technology. This is not to suggest that the augmentor-wing concept is necessarily the ultimate solution to STOL aircraft design, but rather that there is a limit to the development of such aircraft beyond which the law of diminishing returns sets in. This is illustrated in Fig. 1, using data from Ref. 1. The diagram shows clearly that, at a given value of thrust/weight ratio ( $T/W$ ), the takeoff distance can be reduced by increasing the value of  $C_{L_{max}}$ ,\* but that at values of  $C_{L_{max}} = 6$  or more the gain in terms of takeoff distance diminishes rapidly. In the particular case under consideration ( $W/S = 50$ ), this corresponds to a takeoff distance to the 50 ft obstacle in the region of 750 ft provided that we restrict ourselves to reasonable values of installed thrust/weight ratio, say not in excess of 0.6.

When the installed thrust to weight ratio exceeds 0.80 approximately, then it is necessary to reexamine the whole question and decide whether it might not pay to go all the way and provide a VTOL capability with STOL performance at maximum or overload weights. In order to illustrate this possibility an arbitrary cutoff at  $C_{L_{max}} = 6.0$  is shown on Fig. 1 and

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\*  $C_{L_{max}}$  here does not include the lift component of the deflected jet.

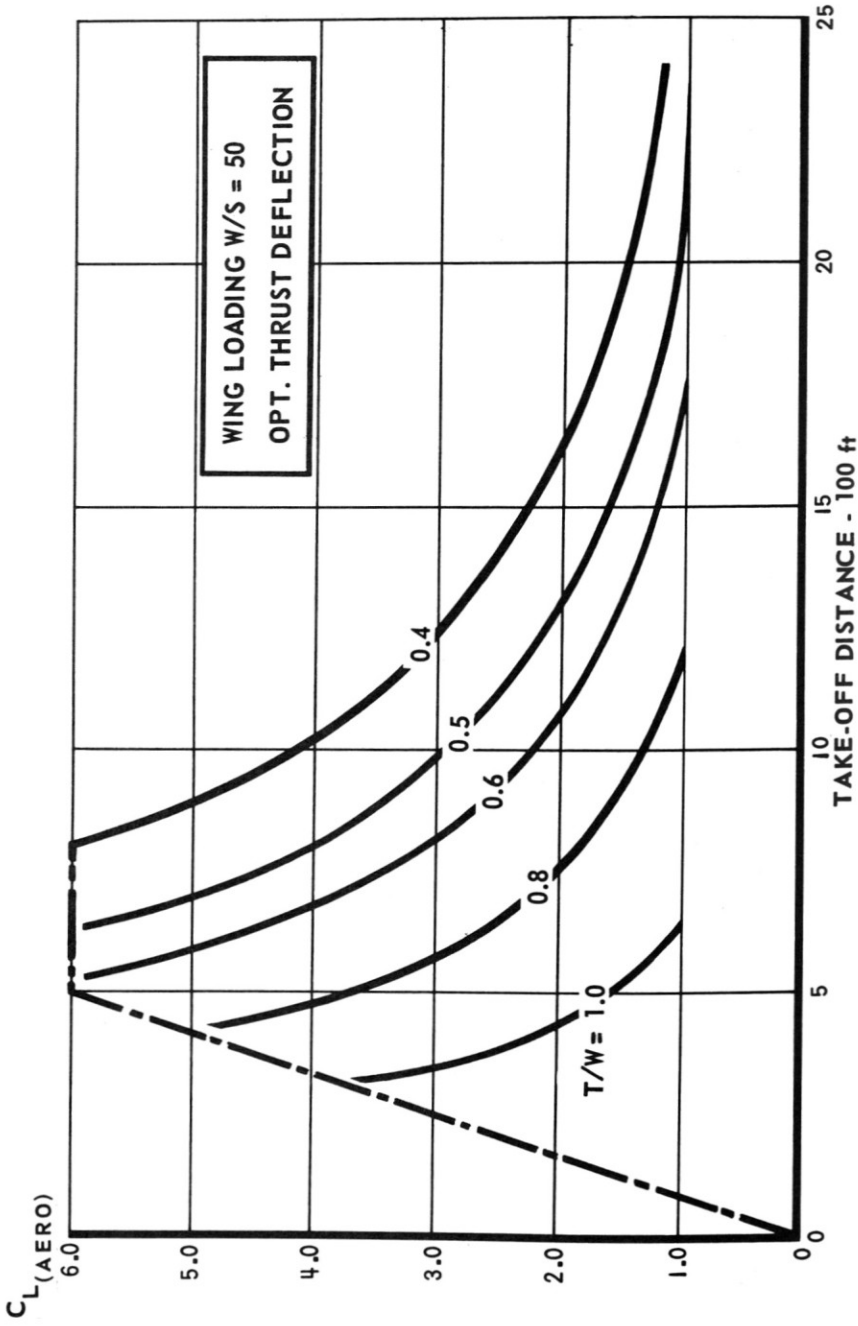


Figure 1. Lift coefficient required for short take-off.

a second line is drawn through the axis (the VTOL point) to define approximate boundaries for V/STOL operation. Note that, using the safety rules of Ref. 1, a thrust/weight ratio greater than one is required for VTOL. The economy and flexibility of a VTOL design can be improved considerably by taking advantage of the STOL mode and so this realm of operation assumes considerable importance. When thrust/weight ratio is close to unity, as in the VTOL design, then there is no longer any requirement for very high lift coefficients, and the opportunity to exchange the complication and weight of a high lift STOL wing for a corresponding VTOL penalty due to greater installed power becomes a most interesting possibility. So there would appear to be two quite distinct ways of achieving "ultrashort" takeoff and landing; one by overloading a VTOL design and the other by development of the STOL aircraft to the ultimate practical limit. (The word *ultrashort* is used here to indicate distance to the 50 ft obstacle of 750 ft or less, the corresponding ground roll being 300 ft or less, approximately.) The relative merits of these two approaches will become evident only after some years of operational experience and it may be found that the two concepts are complementary rather than competitive to the extent of exclusion of one or the other, but it would appear that STOL aircraft must be developed toward ultrashort field lengths if they are to retain a place in the future, in view of increasing competition from V/STOL.

It is in this context that consideration is now given to some work on the augmentor-wing which has been undertaken during the past three years, with special emphasis being given to ultra-STOL capability. For the sake of clarity in presentation I shall deal first with the basic concept, secondly, with some possible applications and finally, with the research program.

## THE CONCEPT

The concept is essentially that of obtaining circulation round an aerofoil by inducing flow through it. This is achieved by means of a thin primary jet located within a spanwise wing slot. The flow around the aerofoil is profoundly modified and augmentation of thrust occurs due to mixing of the primary jet and the entrained secondary flow within the slot. The flow pattern differs from that for the classical case of a simple flapped wing and gives rise to supercirculation and a modified chordwise distribution of pressure. These ideas are believed to have possible applications to both STOL and VTOL aircraft.

In Canada, suggestions along these lines were first made by T. Higgins in 1960 at Avro Aircraft. Subsequently, another reference to similar ideas

become known to us and it is most appropriate that I can refer to the work of a French researcher, J. Bertin, who published a paper in 1960 entitled "*Les trompes appliquées au vol vertical, vers l'aile-trompe*" [2].

The number of spanwise slots may vary according to design requirements and, by way of illustration, Fig. 2 shows the cross section of a wing with a single spanwise slot. In this design, the jet issues from one side of the slot only, whereas in other arrangements the jet may issue from both sides of the slot. Figure 3 shows a proposed transport aircraft based on the arrangement in Fig. 2. For takeoff and landing the "cold" bypass flow of a turbofan engine is ducted to the wing-augmentor by means of a diverter valve and the flow from each engine is distributed equally to each wing panel by means of transfer ducts. A double duct/nozzle arrangement is used, rather than a common single duct, so that nozzle areas do not require adjustment in the event of engine failure.

Various aspects of the augmentor-wing are now discussed in turn. For the sake of clarity some claims are made without proof: substantiating data, such as is available at present, will be found in a later section which describes the research program.

## THRUST AUGMENTATION AND VECTORING

Experimental work at De Havilland and at the Flight Research Section of the N.A.E.\* [3] has shown that thrust augmentation ratios in excess of 1.50 can be achieved with simple geometric arrangements suitable for wing installations. It has also been shown that the Coanda type of nozzle is beneficial. Internal duct losses vary, depending upon the particular kind of installation; however, the percentage thrust loss is only half the percentage pressure loss (approximately) and indications are that net (overall) augmentation ratios of 1.30 to 1.45 can be achieved. Further discussion of our research work into static thrust augmentors is given later in the paper.

The thrust augmentor reduces the installed power required for a given takeoff performance and so assists in the problem of cruise matching. Use of diverter valves, which direct flow either to the lift system or straight aft for propulsion, avoids any compromise in cruise configuration. Rearward deflection of the underwing doors and flaps during transition introduces a natural throttling of the ejector so that momentum drag of the secondary flow can be reduced and high propulsive thrust maintained throughout the transition speed range. In the case of a STOL design the vectored thrust relieves weight from the wheels to assist in takeoff from soft ground and, additionally, it would seem that thrust recovery of the deflected jet can be fully realized at moderately high flap-deflection angles. Also, steep

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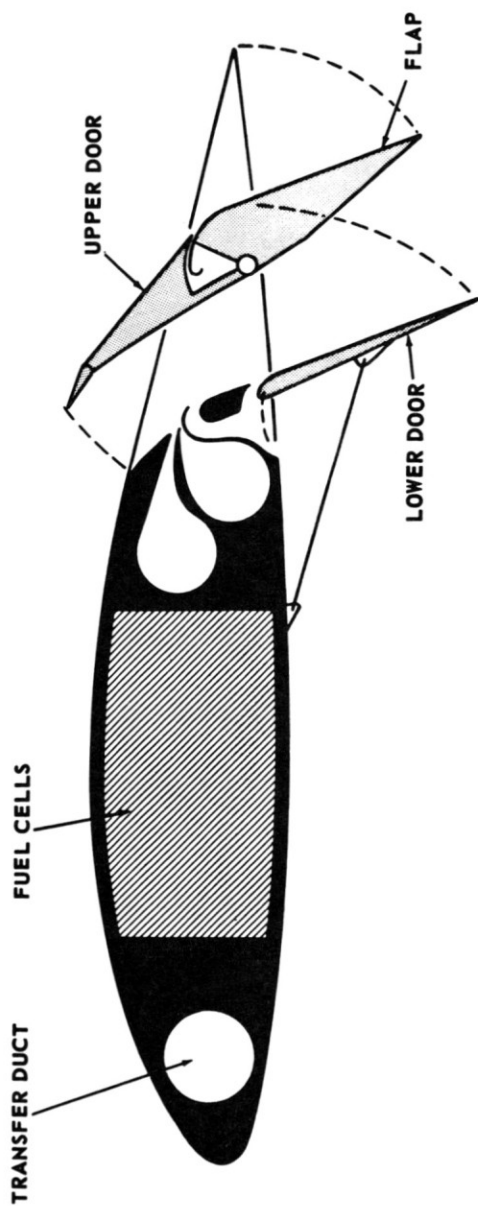


Figure 2. Wing section for twin engine transport.

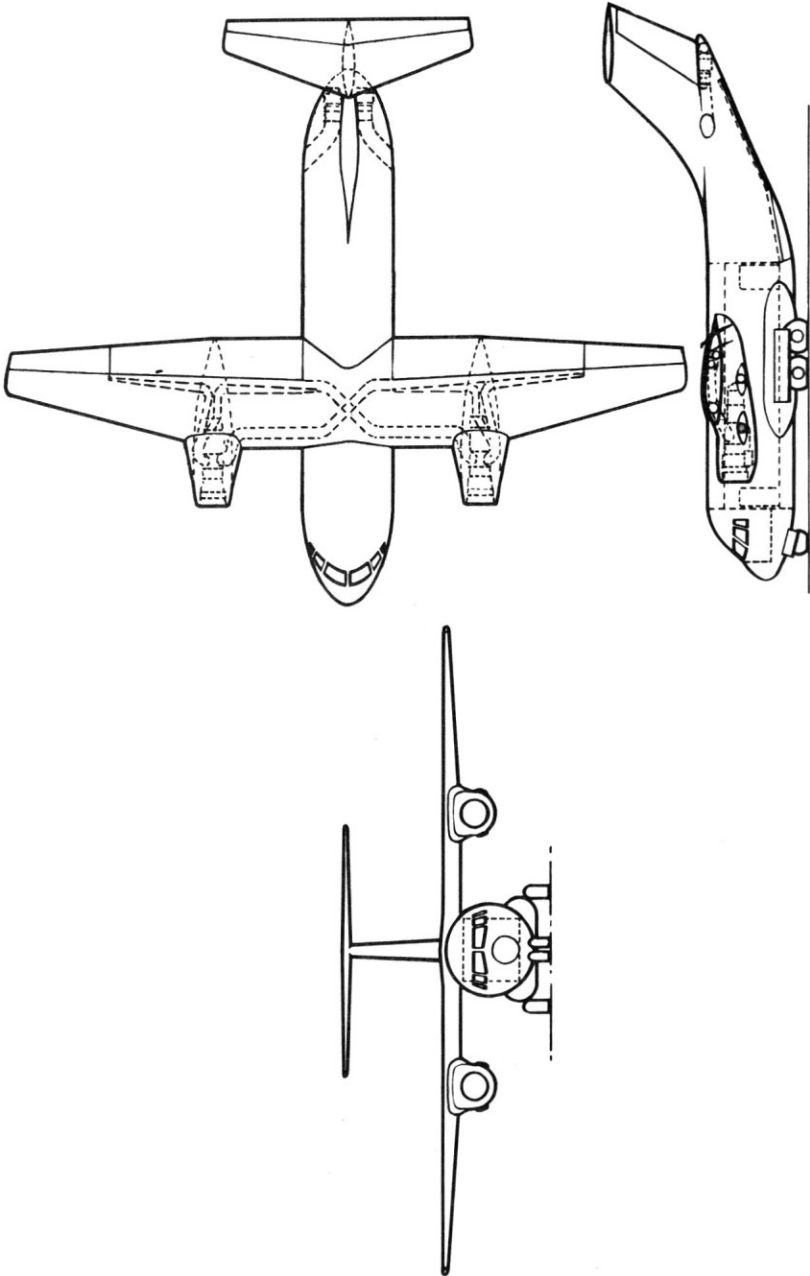


Figure 3. Augmentor-wing transport with booster engines.

power-on descents for landing can be made by virtue of thrust vectoring, using large flap deflection angles of  $90^\circ$  or more.

### ENGINE INSTALLATION

The system uses standard turbojet or turbofan engines and so has a wide choice of power plants for various applications. In the general case, mixing of a hot primary jet with the cold secondary flow produces a lift jet of moderate temperature and velocity which greatly alleviates the ground erosion problem often associated with jet V/STOL aircraft. The low jet velocity also helps to reduce noise level. For the STOL application shown in Fig. 3, a choice in favour of a turbofan engine with only the "cold" flow ducted to the lift system avoids the structural complication of hot ducting in the wing and the fan engine provides good cruise economy. Use of a double (rather than a single) spanwise jet nozzle avoids the need to adjust the exit area in the event of engine failure. Engine-out asymmetry is avoided by suitable arrangements of cross-feed to the wing jets and this means that short takeoff distances can be achieved even under civil safety regulations. The fact that the cross-feed does not require moving parts also adds to the safety aspect.

### LIFT COEFFICIENT

The system is capable of generating values of maximum lift coefficient greater than the pure jet flap because it can be combined with a fairly large chord geometric flap. This claim can be further substantiated when it is realized that the jet coefficient of the ejector wing corresponds to the augmented thrust and also that the gross thrust (and therefore the jet coefficient) increases with forward speed, due to the dynamic head of the secondary flow.

### PITCHING MOMENT

Pitching moment of the augmentor-wing is influenced substantially by the induction of secondary flow through the wing. This inflow creates a nose-up movement at forward speed. In a VTOL configuration the centre of jet lift, the centre of aerodynamic lift, and the centre of gravity must all coincide (approximately) and control power must be provided to offset the nose-up moment during transition. However, this problem is not a severe one because the rearward deflection of underwing doors during transition has the effect of throttling the ejector, thus reducing the secondary flow and hence, also, the nose-up moment. Fortunately, the ejector takes very kindly to this throttling process.

In a STOL application the problem is quite the opposite since the centre of jet reaction is now well aft of the c.g. and a large nose-down reactive moment exists which is in addition to the aerodynamic moment created by the flap. The nose-up moment due to inflow tends to offset these nose-down moments and the c.p. position is held reasonably well forward. Thus, problems of longitudinal trim, which are often associated with high lift devices such as the jet flap [1,4] are greatly alleviated.

### THE AUGMENTOR AT FORWARD SPEED

Some of our early research work was concerned with the efficiency of the augmentor itself while operating at forward speed, at high angles of attack or close to the ground. Results have shown that the augmentor-wing is surprisingly insensitive to such conditions; for example, if a separated region forms on the wing at high angles of attack, then turning of flow into the slot is made easier. Similarly, with two spanwise slots in the wing, the rear one has been shown to operate more efficiently than the front one. Again, if a separation bubble forms, it is terminated at the ejector slot and thus rendered very stable. Lift continues to rise steadily in spite of the separated region and when the stall finally sets in, it is usually very gentle. Forward speed has been shown to have a beneficial effect on augmentation since it permits greater diffuser angles in the shrouded passage. This is particularly true of the configuration with jet flow on one side (as Fig. 2). A typical chordwise pressure distribution around the augmentor-wing is shown in Fig. 4.

### SOME POSSIBLE APPLICATIONS

It would appear that the augmentor-wing has a broad range of possible applications and it is quite beyond the scope of the present paper to deal adequately with all of these. It is my intention, therefore, to touch very briefly on some of them in order to focus your interest more clearly on a subsequent section which describes the experimental research program.

### MULTIPURPOSE STOL TRANSPORT

This is one application which has received more than superficial investigation. Here, the objective is to design an aircraft with ultrashort field performance which can fulfil the tactical support role, serve as a medium range, high speed transport and also have future potential in the civil market. Takeoff distance to 50 ft is in the range of 500-750 ft with liftoff speeds of approximately 90 f.p.s. The installed thrust/weight ratio is about 0.5.



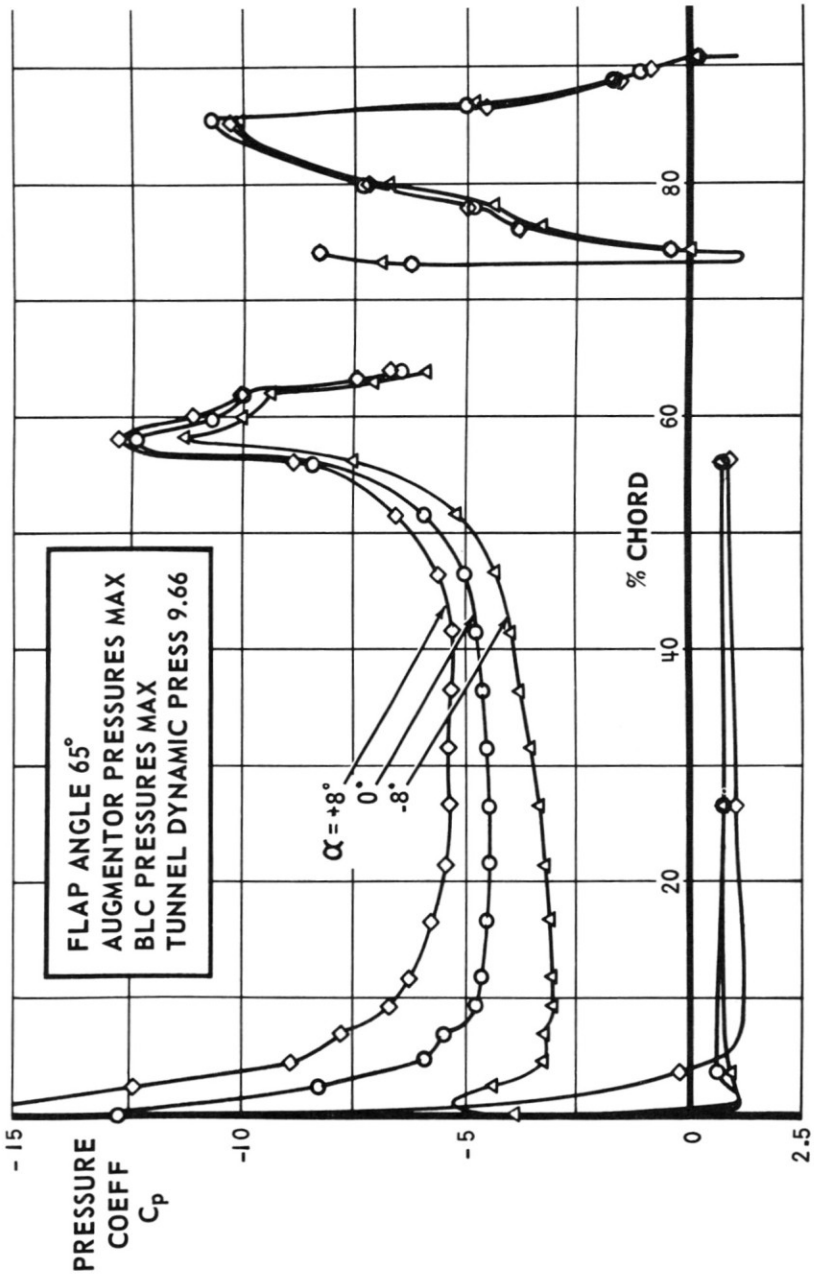


Figure 4. Chordwise pressure distribution—model 'D'.

The design was based on the Bristol-Siddeley BS-94 engine which splits the thrust roughly 50:50 between hot flow and cold flow. A double set of off-takes from the plenum chamber and a rotary diverter valve in the engine casing were proposed to direct the flow to the wing for takeoff and landing or to the standard propulsion nozzles for cruise.

When consideration is given to a STOL transport such as this with deflected thrust and very low liftoff speeds, then serious consideration must also be given to the question of safety in the event of engine failure.

The particular design shown in Fig. 2 attempts to satisfy the requirement for engine-out safety in the following ways:

1. Cross-feed of "cold" flow to the wing system almost eliminates roll asymmetry.
2. The asymmetric yawing moment results from the hot thrust of only about half the total thrust of one engine.
3. Pitching moment of the augmentor-wing at high lift coefficients is not excessive (on account of inflow through the wing slot) and therefore, ample reserves of elevator power are available for pitch control.
4. Lift loss due to engine failure is more severe with a twin-engine layout (as compared to four) but design studies and experiment show that sufficient lift margin can be provided without undue penalty to takeoff performance.
5. Booster engines can be added to the twin-engine design to further reduce the takeoff distance and improve engine-out safety aspects.

A four-engined transport layout makes engine failure less critical and separate transfer ducts can be avoided since it now becomes feasible to gang the bypass flow from the four engines into two spanwise ducts containing the nozzle (that is, the twin nozzle arrangement of Fig. 2 is retained). A shutoff valve is provided in each wing in one of the twin ducts outboard of the engines. These valves close when failure occurs in any one of the engines and the outer panels of the augmentor-wing then receive only half thrust (this results in a smoother and more efficient span loading in the engine-out case). Selection of diverter valve to in-flight position is made on the failed engine to prevent backup of the flow.

Finally, consideration has also been given to use of specially designed load compressor engines to power the lift system. This would eliminate the need for diverter valves on the main engines and also permit separate control of power to the lift system. The Rolls Royce RB176 represents one such engine and Fig. 5 shows a proposed transport based on this arrangement.

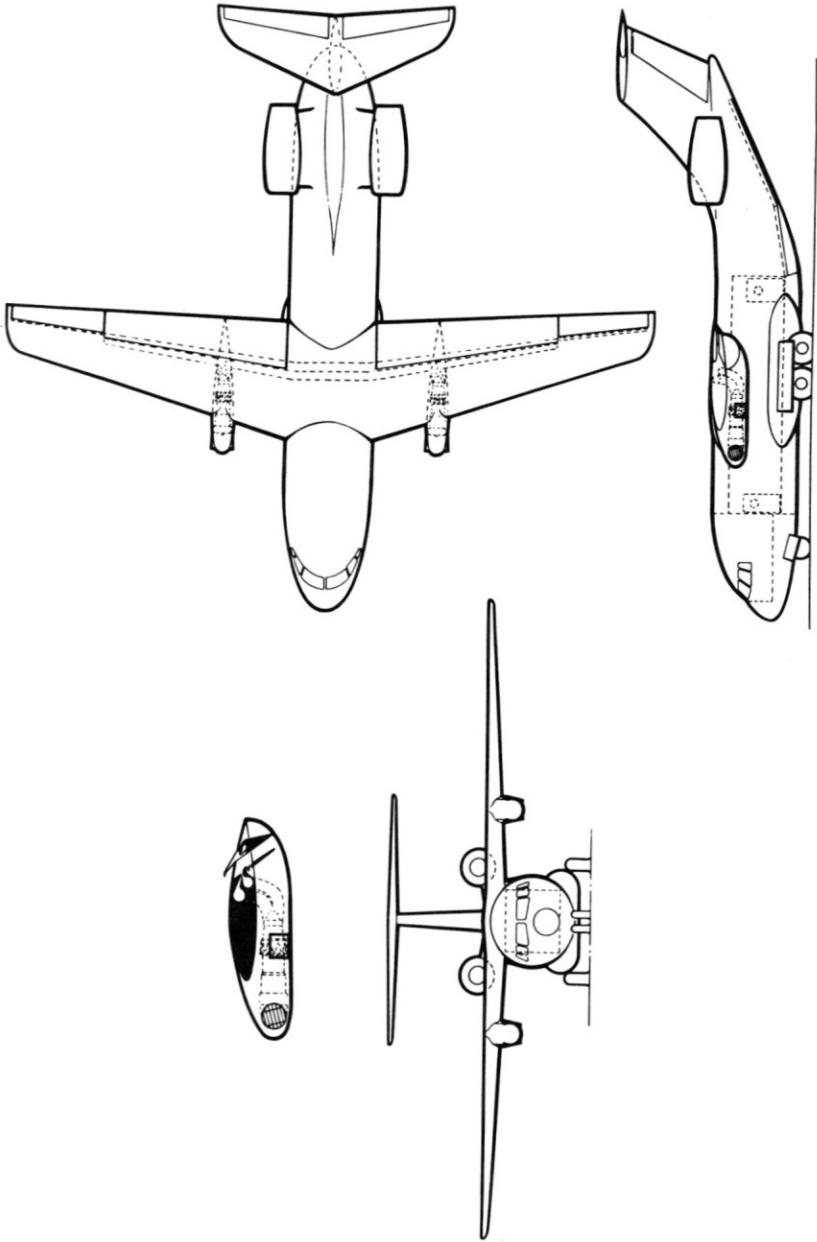


Figure 5. Augmentor-wing transport using flap blowing engines.

### STOL TACTICAL FIGHTER

Two designs are shown, one capable of supersonic speeds, the other designed for high subsonic speeds. Figure 6 shows the layout of the former in which hot exhaust gas is ducted to multiple spanwise slots in the wing. Some wind-tunnel tests were carried out on a model based on this design. Figure 7 shows a possible layout for a tactical fighter design and for high subsonic speeds. A fan engine is used with "cold" flow only to the lift system. The wing ducting is particularly simple in this case.

### VTOL TACTICAL FIGHTER

Some consideration was given to the design of a single engined VTOL low level strike aircraft using the augmentor-wing (Fig. 8). Figure 9 shows the ducting arrangements for this design but wind-tunnel tests were not performed.

### MISCELLANEOUS

The augmentor-wing might also be effective in improving the marginal takeoff and landing performance of high speed aircraft which use standard

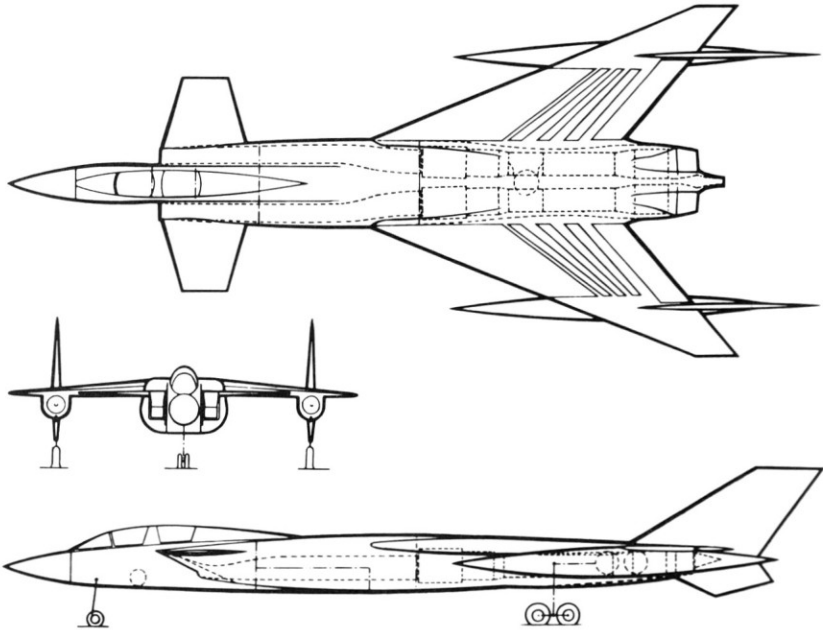


Figure 6. Supersonic tactical fighter.

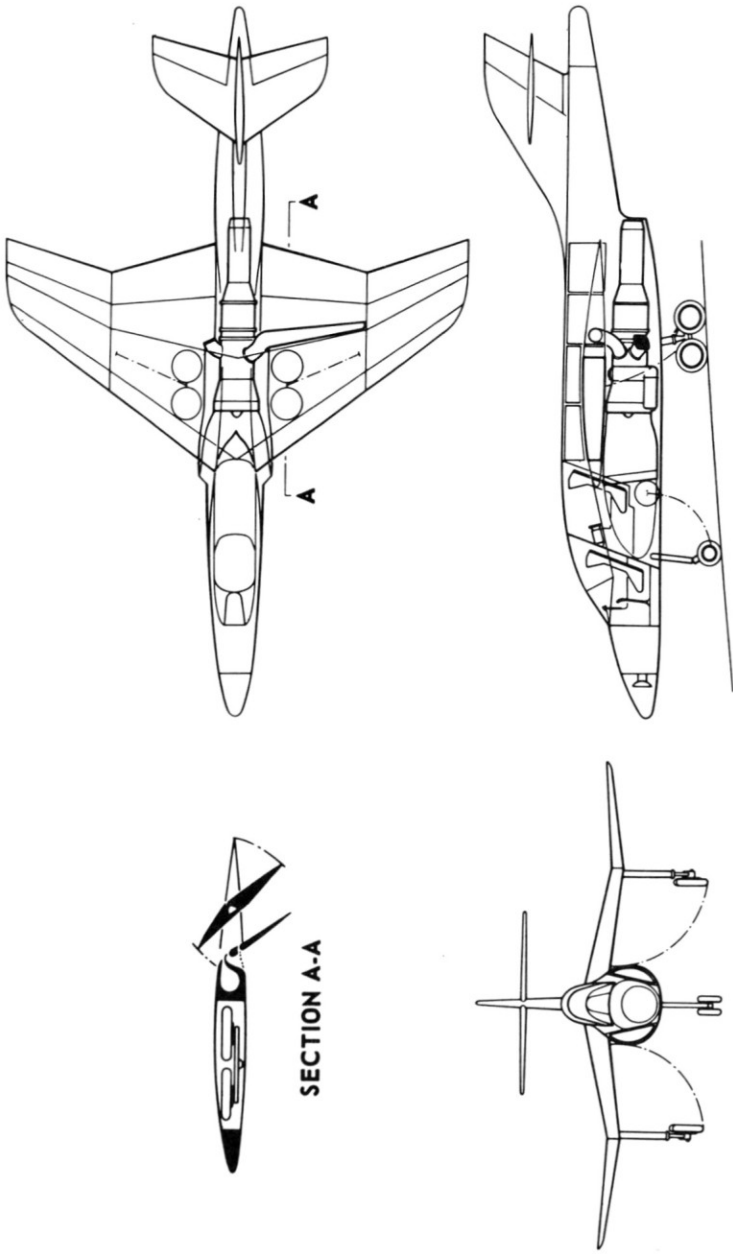


Figure 7. Sub-sonic tactical STOL fighter.

runways—a supersonic transport, for example. Here again, special load-compressor units might be used or possibly bleed air from the main engine compressors.

Application of the augmentor-wing as a flap system for high speed subsonic transport aircraft has also been suggested. This can be considered as a special kind of blown flap which would replace the double or triple slotted flaps now in current use. Blowing coefficients would be to b.l.c. standards ( $C_{\mu} = 0.1$  say) and flap layout would be of a simplified nature.

### EXPERIMENTAL RESEARCH

Our research work on the augmentor-wing has been in progress for nearly three years. This work has been directed toward both STOL and V/STOL applications and therefore the models which were built for research purposes reflect this variation. In particular it will be noticed that for an STOL design the angle of the ejector slot in the wing was set at about  $60^{\circ}$  to the chord line, whereas for VTOL application the angle became  $75/80^{\circ}$

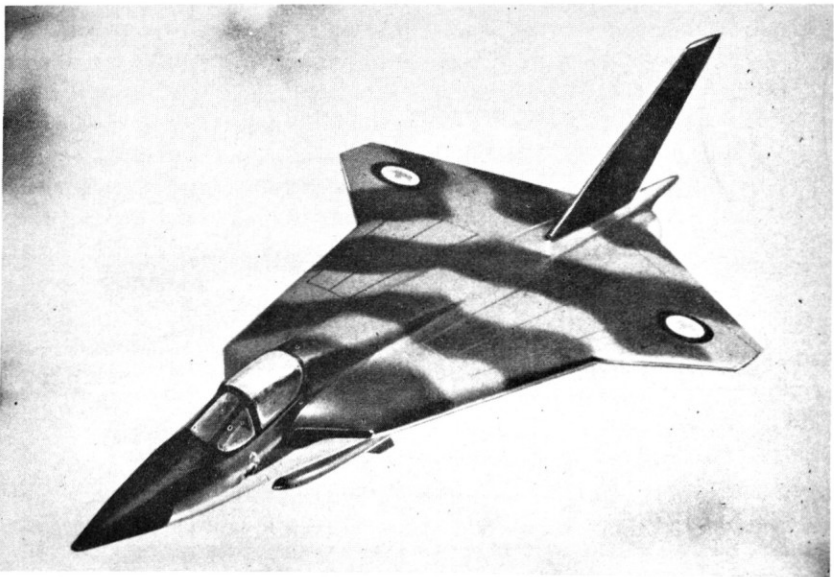


Figure 8. V/STOL tactical fighter.

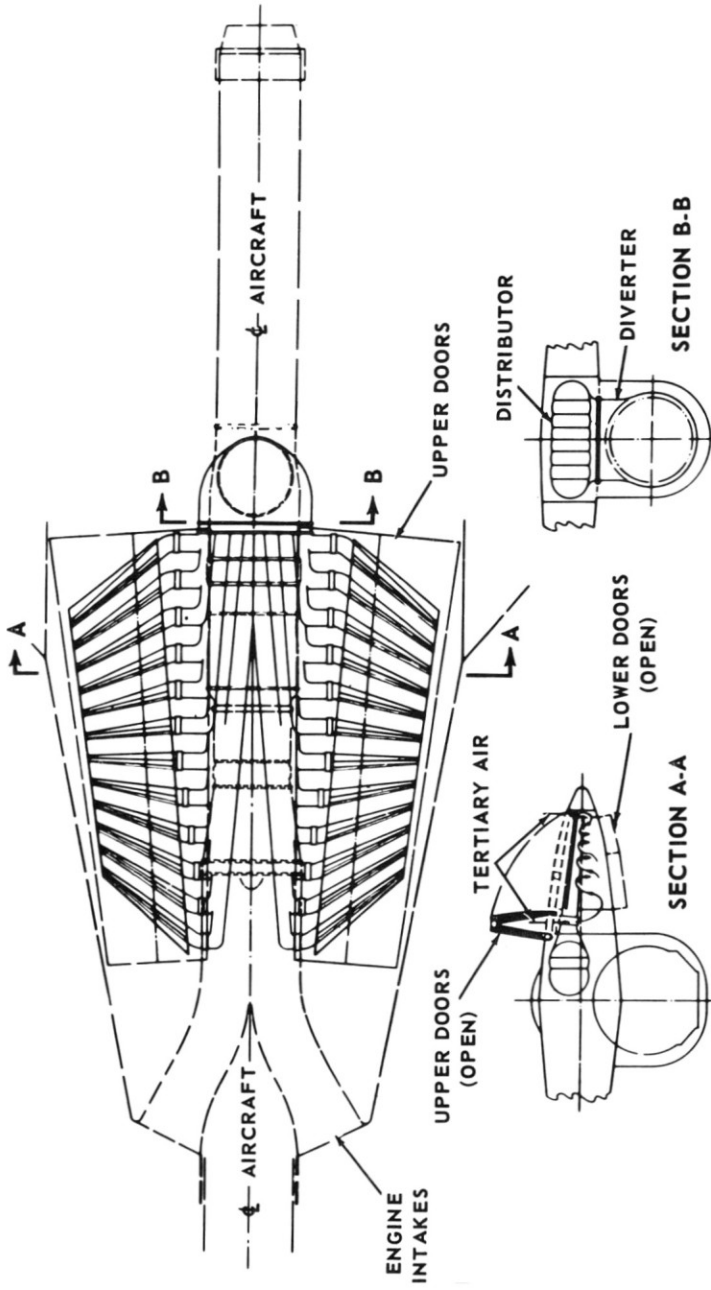


Figure 9. V/STOL tactical fighter, ducting arrangement.

At the outset, it was realized that problems associated with the augmentor-wing fell quite naturally into three categories as defined below:

- (i) A basic understanding of thrust augmentation and nozzle efficiencies with particular reference to thin jet sheets of a two-dimensional kind (as distinct from an annular kind).
- (ii) The effects of forward speed and angle of attack on the operation of the ejector as a local or isolated unit. This includes operation of single and multiple spanwise ejector slots.
- (iii) Operation of the wing/augmentor as a combined unit with particular reference to supercirculation and stall characteristics.

The experimental research program will now be reviewed under these headings and mention made of important results and conclusions.

## THE THRUST AUGMENTOR

This is a broad subject which has been discussed in many technical papers. The area of interest is narrowed in the present context because of our specific interest in thin jets which issue from long straight nozzles. We also restrict the pressure ratio to the range 1.5 to 3.0, approximately.

It is generally known that the secondary/primary area ratio must be in the region of ten or more in order to generate an appreciable augmentation of thrust. Also, to provide an adequate length for mixing and diffusion, the ratio of length to width of the shrouded passage must be about five. These geometrical requirements can be satisfied within the confines of the wing structure if thin spanwise jets are used and if the underwing doors are designed to form an extension to the shrouded passage. The jet thickness depends upon the particular installation under consideration but in practice it turns out to be about half an inch.

It is also well known that the mixing rate of a jet which issues from a "Coanda" nozzle is considerably greater than one of the same initial thickness which issues from a plain nozzle. Some of our earlier experiments were therefore concerned with the efficiencies of long narrow nozzles and with a comparison between plain and Coanda nozzles when used as the primary jet of a thrust augmentor. Coanda nozzles were found to generate higher augmentation because of the greater mixing rate. Other means of increasing the mixing rate have also been investigated; these include corrugating the external surface of the nozzle and addition of vortex generators in the jet stream.

From the wide range of experiments which have been carried out I have chosen to show simply some data relating to the nozzle efficiency of long



narrow jet slots, since these represent a basic ingredient of the augmentor-wing system. Measurements were made on the nozzle which formed part of a thrust-augmentation model. The nozzle was 15 in. long and jet thickness could be varied from 0.05 to 0.15 in. Coanda nozzle blocks of radius 1 in. and 2 in. were also available to turn the flow through 60° and 90° in each case. Another block permitted one side of the nozzle to be corrugated (sinusoidally) to increase the surface area of jet for greater mixing. Tests were made on a plain round nozzle for comparison.

Results are shown in Fig. 10. An increase in nozzle perimeter/nozzle area from 2 to 14 shows negligible change in thrust efficiency and therefore it can be concluded that large losses are not necessarily incurred by introduction of a long thin nozzle within the geometry range of interest. However, the results indicate a more definite loss associated with turning the flow by means of the Coanda surface. This loss ranges from 5 to 10 per cent depending upon turning angle and "aspect ratio." Corrugation of the nozzle introduced negligible loss on a plain jet. All values of efficiency shown may be slightly low due to incorrect measurement of mass flow but values relative to the round nozzle are considered to be quite reliable. More recently, tests have been made with the Coanda surface separated from the thin primary nozzle so that the jet sheet jumps the gap and

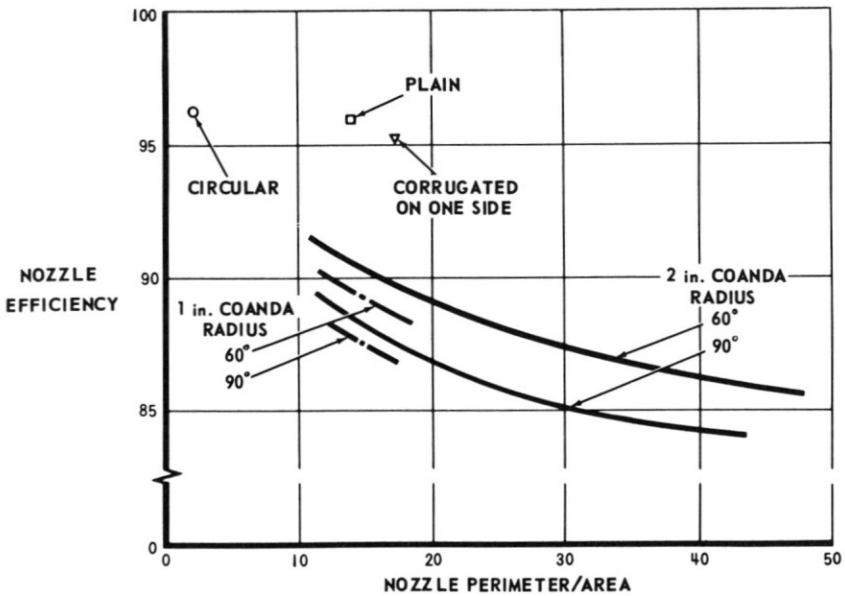


Figure 10. Efficiency of rectangular nozzles.

attaches itself to the surface some distance around the bend. Nozzle efficiencies in excess of 1.05 have been measured for such "jump Coanda" configurations and corresponding improvements in thrust augmentation result when shrouds are fitted. It is believed that this "jump Coanda" nozzle was investigated first by Dr. G. Korbacher at the University of Toronto.

Space does not permit mention of the many tests which have been carried out to investigate static augmentation of jet thrust. With the relatively simple configurations suitable for wing installations we have obtained values of augmentation in excess of 1.40 (net), whereas Ref. 3 records values in excess of 1.50 for similar configurations. Net augmentation is defined relative to the isentropic value of thrust for the corresponding experimental values of weight flow and pressure ratio.

#### EFFECTS OF FORWARD SPEED ON AUGMENTOR PERFORMANCE

This section deals with local effects and describes the way in which forward speed and angle of attack influence the performance of the ejector as an isolated unit.

A model was designed for the wind tunnel which would incorporate one of the static augmentor test specimens. The specimen was mounted between end plates with a fairing fore and aft to represent the wing section and with ejector axis at  $60^\circ$  to the wing chord (see Fig. 11). This will be referred to as Model "A." Only the augmentor itself was mounted on the force balance, the fairings being secured to ground via the tunnel turntable. In this way a fairly direct measure of the ejector performance could be made and effects of deflection and throttling of the underwing doors could also be investigated. Total and static pressure measurements at the exit of the diffuser were also made and these, together with the force measurements, confirmed that intake losses were not large, that the exit momentum  $J$  increased steadily with forward speed and that angle of attack did not seriously affect the performance. For example, Fig. 12 shows the steady increase in jet momentum with forward speed as obtained from force measurements and, inset, typical velocity distributions obtained from the exit pressure probes.

Rearward deflection of the underwing doors tends to throttle the exit area and this is a desirable trend as speed increases. Results of one set of tests, in which the two underwing doors were deflected but maintained parallel to each other, are shown in Fig. 13. This is in vector form and shows first, that deflection (with consequent throttling) prevents a large increase in the momentum vector  $J$  as speed increases and secondly, that

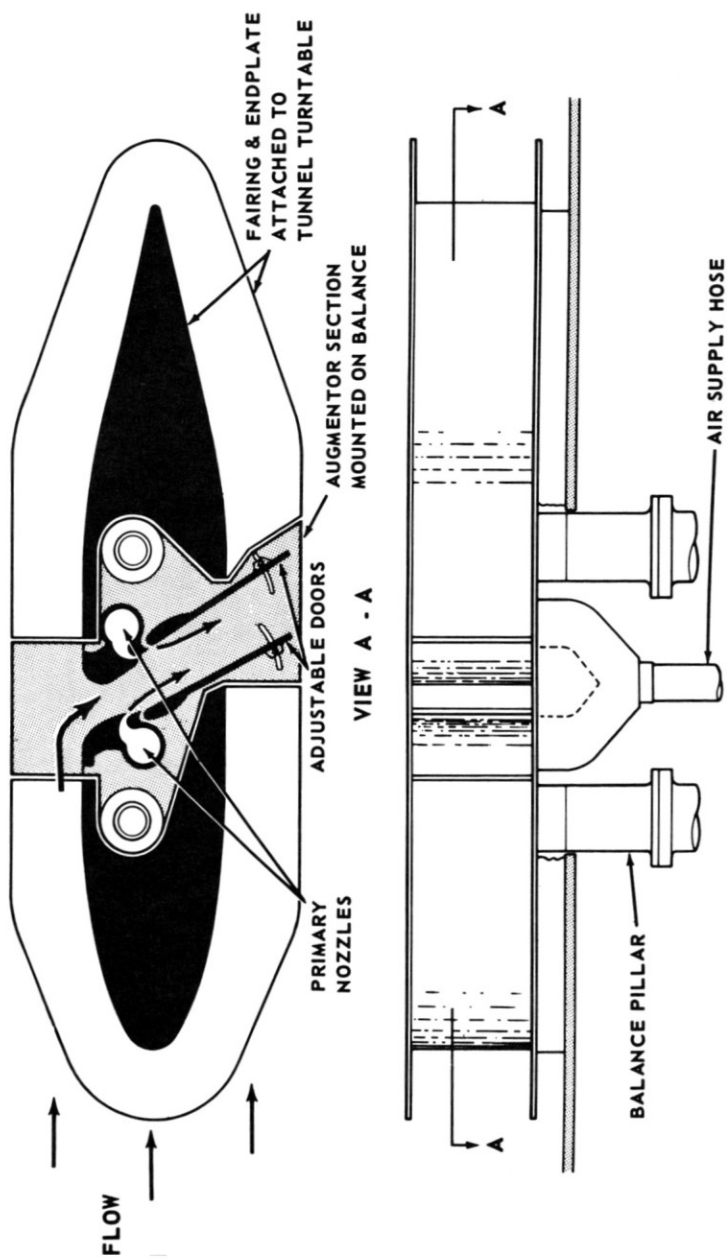


Figure 11. Model 'A'.

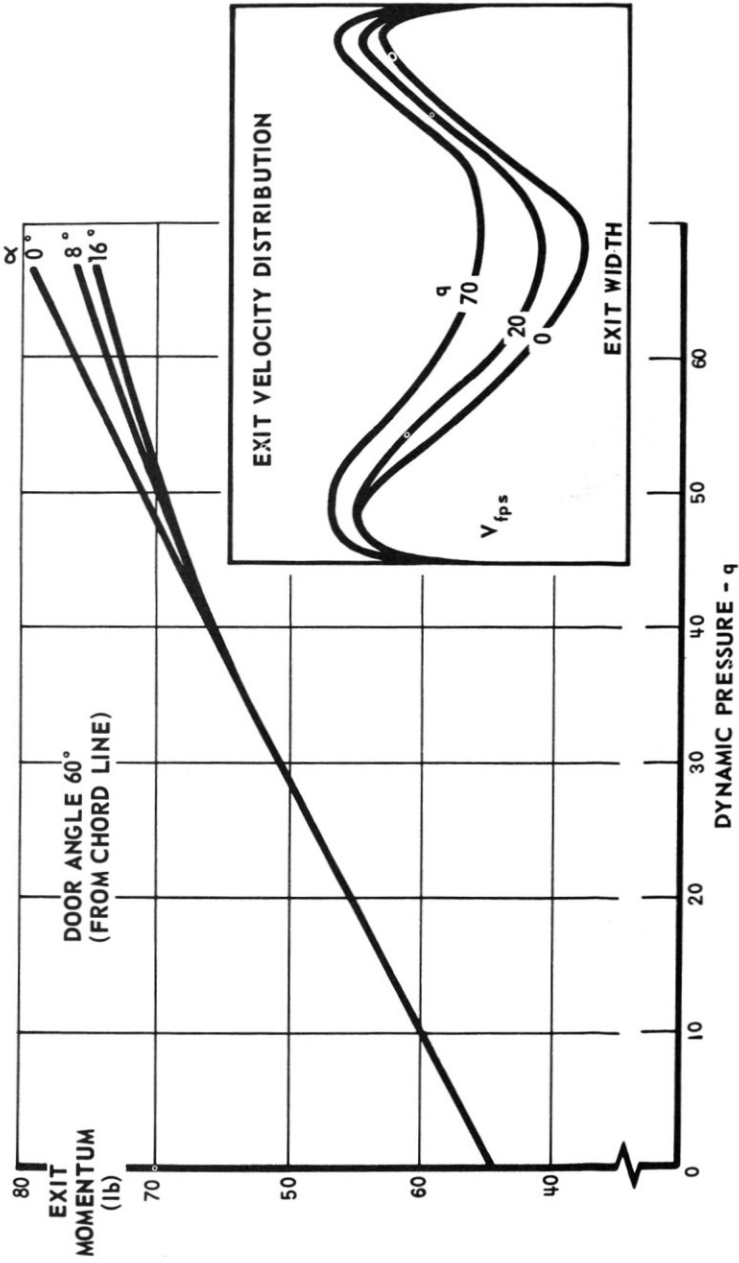


Figure 12. Variation of thrust with speed—model 'A'.

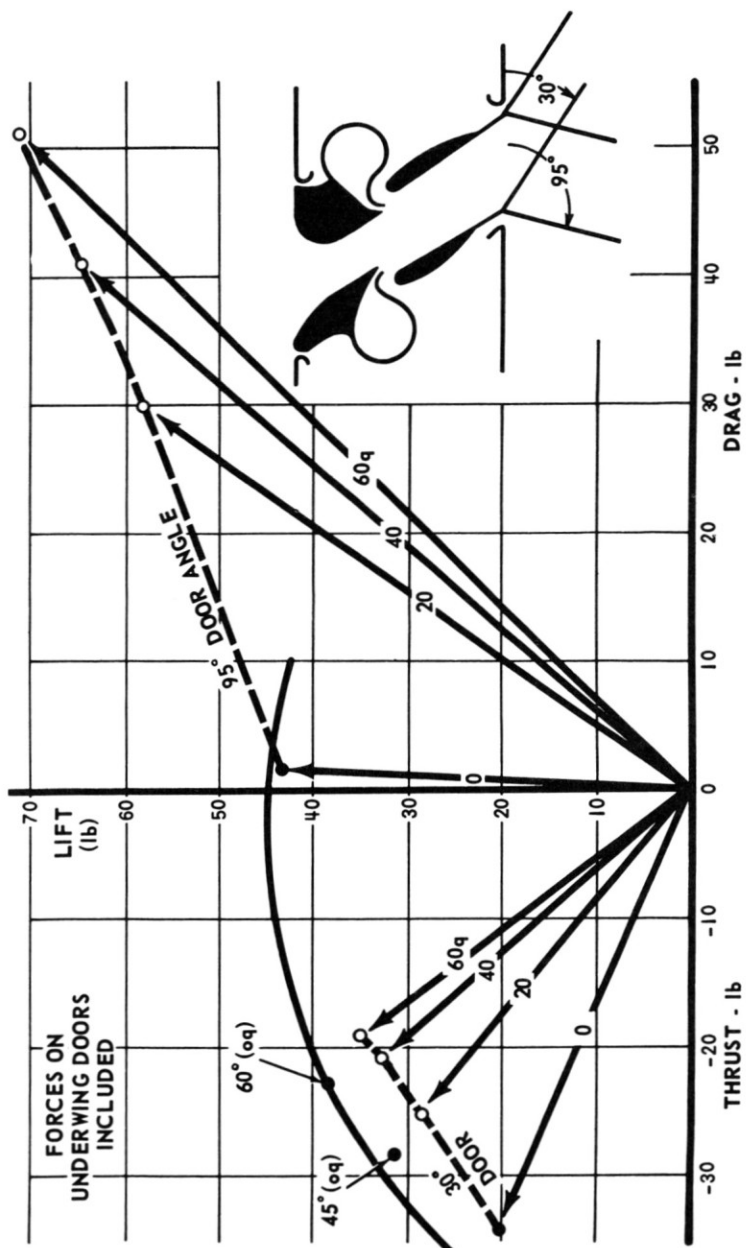


Figure 13. Effect of door angle on thrust—model 'A'.

by suitable choice of door movement with speed the thrust (and lift) of the augmentor unit can be maintained almost constant throughout the transition speed range. Reduction of flow through the augmentor as speed increases can be very beneficial, particularly for VTOL applications, because in this way the nose-up moment due to inflow and the momentum drag can be greatly reduced. For example, a change in underwing door angle from  $80^\circ$  to  $30^\circ$  in these same experiments caused the secondary flow to fall by 60 per cent at  $q = 65$ .

These tests proved to be very useful because the model augmentor components were sufficiently large to incorporate tertiary flow, various nozzle configurations and moving underwing doors. However, the wing section could only be considered as a fairing round the augmentor and not as a true wing because the aspect ratio was so low. Therefore, pressure traverses of the exit flow were made subsequently on various quasi two-dimensional models in which the external flow environment of the augmentor was more closely simulated. These results confirmed previous findings and also indicated that the rear slot (of two, in this particular case) suffered less due to changes in speed and angle of attack.

## TWO-DIMENSIONAL AERODYNAMIC CHARACTERISTICS OF THE WING-AUGMENTOR

Basic information concerning the aerodynamic characteristics of the wing-augmentor was required. Since air supply at the wind tunnel was limited, it was decided to build a model wing section of limited span, mount it between end plates and obtain quasi two-dimensional data.

*Tests on Model "B."* At this time our interests centred around VTOL applications in which the slots would be mounted well forward in the wing. Therefore, the model was fitted with an alternative nose portion and with extensions to the trailing edge in order to simulate various chordwise positions of the augmentor slots. Furthermore, it was possible to block up either slot (faired to wing contour) and operate them singly. The model configuration was as follows:

Wing span (between end plates) . . . . .	20 in.	Thickness/chord ratio . . . . .	0.10
Wing chord . . . . .	30 in.	Slot angle to chord line . . . . .	$75^\circ$

Some of the model configurations are shown in Fig. 14. Space does not permit any discussion of results on this model but mention is made here to illustrate the scope of investigations which have been carried out.

*Tests on Model "C."* Model "B" was extensively modified to become Model "C" although the main blowing slots were retained to conserve funds. The thickness/chord ratio was increased to 0.16 and a drooped

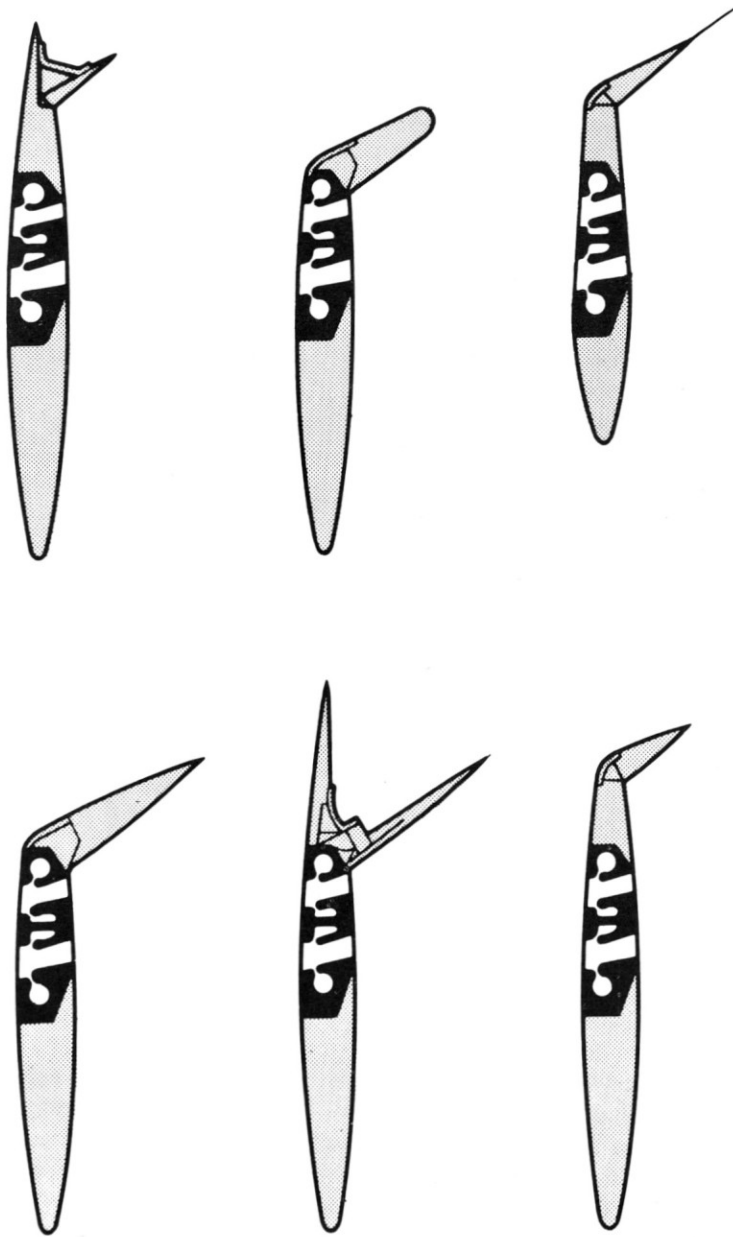


Figure 14. Some configurations of model 'B'.

leading-edge was provided. Also, a blown flap was incorporated with deflection angles of 30°, 45°, 60° and 75°. The configuration of Model "C" was as follows:

Wing span (between end plates) . . . 20 in.	Thickness/chord ratio . . . . . 0.16
Wing chord . . . . . 20 in.	Aerofoil section . . . . . NACA 0016-65
	Slot angle to chord line (mean) . . . 76.5°

Underwing doors were provided to correspond to each flap angle, also blocks were made to simulate a forward facing upper door set at various angles. Once again, wooden blocks were used to seal the augmentor slots so that characteristics could be obtained for the plain aerofoil and also for the blown flap at various deflection angles. The main features of the wing cross section are shown in Fig. 15 and some particular aspects of the tests are now reviewed.

*Effect of Flap Blowing on Lift.* Tests were run to compare the blown flap with the augmentor slot. Of particular interest is the case with both augmentor jet ( $C_j$ ) and BLC jet ( $C_\mu$ ) operating. Results are shown in Fig. 16 for the case with flap angle 60° at  $\alpha = 0^\circ$ . The bottom line labelled  $C_j = 0$  is the case with augmentor slots sealed (blown flap case) and it shows the typical sharp rise in lift due to flap blowing. When the augmentor slot is opened and as the jet strength ( $C_j$ ) is increased the sharp rise in the curve of  $C_L$  vs.  $C_\mu$  tends to disappear, indicating that flap blowing becomes unnecessary when  $C_j$  is sufficiently high. This presumably means that the augmentor flow is then strong enough to attach the flow over the flap and so prevent separation.

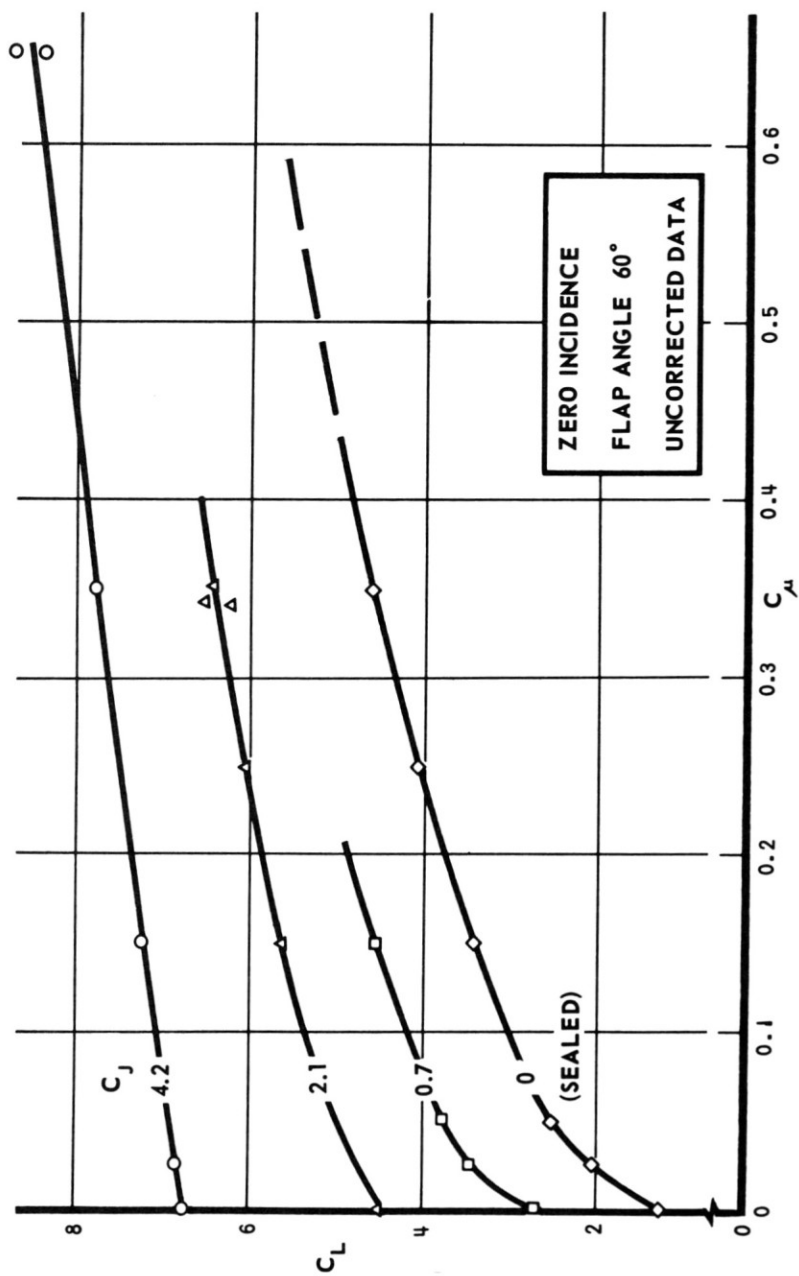
*Pitching Moment.* A comparison between the augmentor and the blown flap with regard to centre of pressure position is shown in Fig. 17. The more forward c.p. position in the case of the augmentor is due, in part, to flow into the upper surface of the wing. Analysis of test results in the manner described in Ref. 5 yielded values for the nose-up moment shown in Fig. 18. Once again, close agreement is shown between theory and experiment. The method of analysis requires test data at  $\alpha = 0^\circ$  in which lift varies but inflow conditions remain constant. For the case in question, this was achieved very simply by variation in flap b.l.c. pressure with constant air supply to the augmentor system.

*Upper Surface Doors.* Various door configurations have been considered to open and close the inlet to the augmentor. From a structural point of view a forward facing upper door is attractive but on the other hand it might induce flow separation. Preliminary tests were therefore carried out on Model "C" with the door configuration shown in Fig. 15. Generally it was found that the flow remained attached over the upper surface of the door provided that the augmentor jets were operative. This remained





Figure 15. Section—model 'C'.



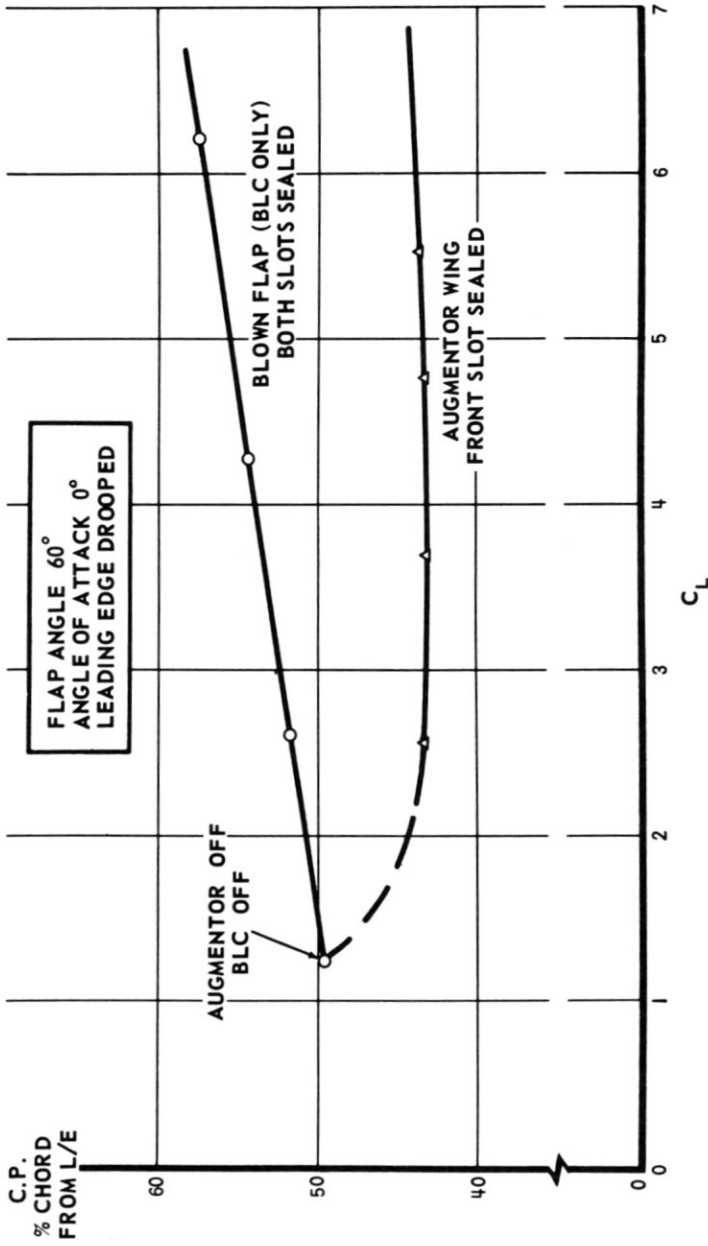


Figure 17. Centre of pressure comparison—model 'C'.

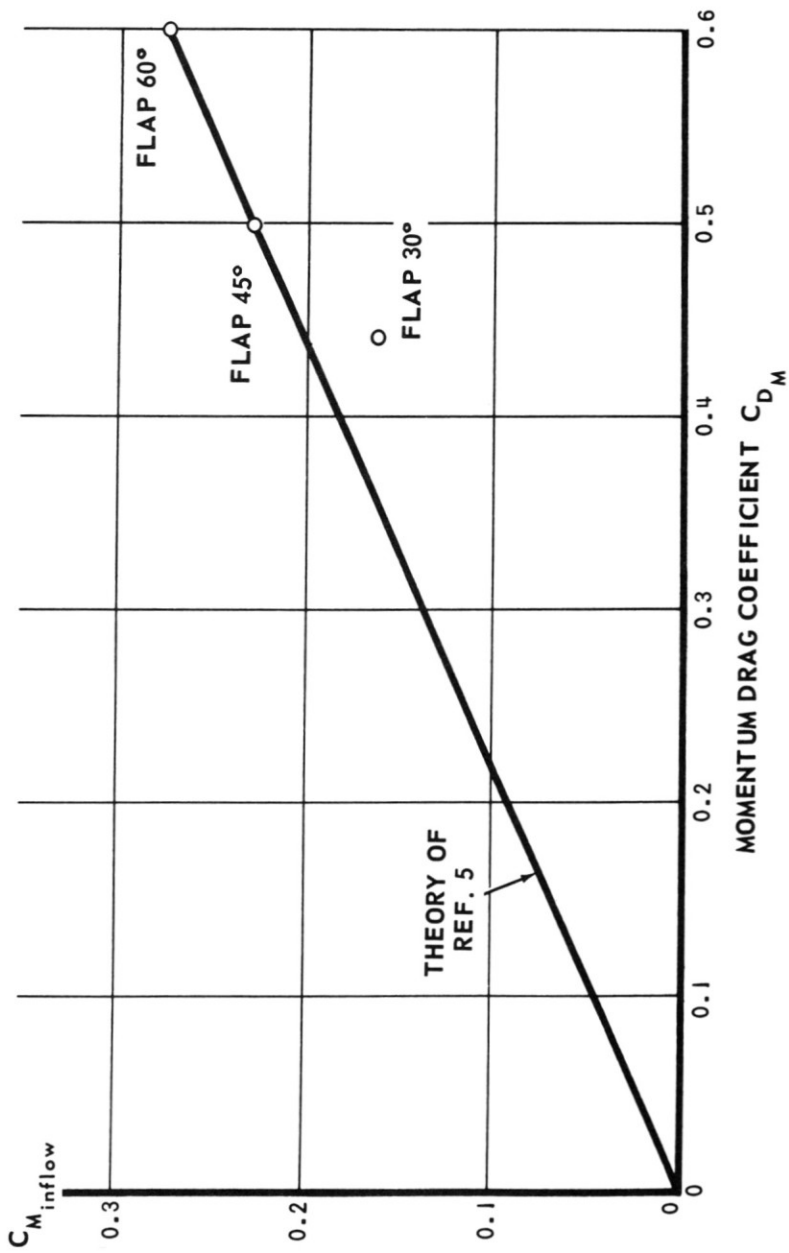


Figure 18. Pitching moment due to in-flow.

true over a wide range of conditions (tunnel speed and angle of attack). One point of considerable interest concerns opening and closing the doors with the augmentor jets off. Test results for such a case ( $\delta F = 30^\circ$ ) show negligible change in drag or pitching moment together with a moderate increase in lift when the augmentor slot is opened (see Fig. 19). Thus, preliminary investigations indicated that a forward facing door remained a distinct possibility and this view has been confirmed by subsequent tests on Model "D."

*Tests on model "D."* Emphasis on STOL, coupled with the desire for simplicity, has led us to concentrate on a single-slot design similar to that shown in Fig. 2. A cross section of the most recent model is shown in Fig. 20. Details of the model were as follows:

Span (between end plates).....	30 in.	Thickness/chord ratio.....	0.16
Wing chord.....	20 in.	Slot angle to chord line (design case).....	60°

The model was fitted with blowing slots for b.l.c. on the flap (0.009 in.) and at the nose (0.004 in.). Thickness of the main jet slot was 0.060 in. Air supply pressures could be varied from 0 to 35 psig.

Test results have shown that very high lift coefficients can be achieved at  $\alpha = 0^\circ$  with a centre of pressure position between 0.45 and 0.50 C.

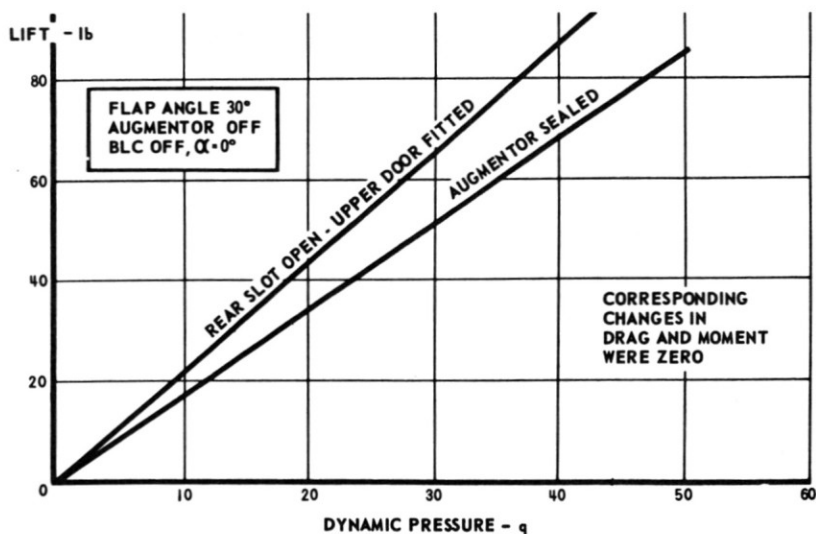


Figure 19. Changes in lift due to opening of wing slot.

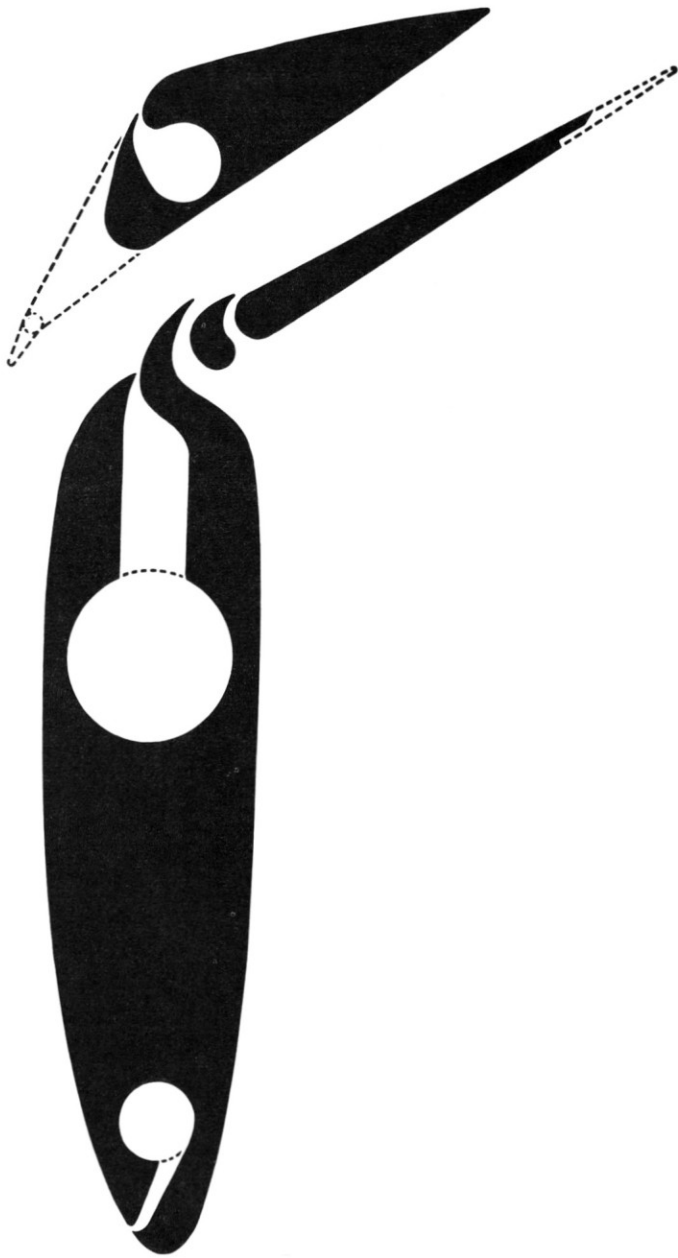


Figura 20 Winer section—model (IV)

Efficiency of the augmentor slot was improved at forward speed (as compared to the static case) and the stall was quite gentle. Flow remained attached over the upper surface of the forward facing door over a wide range of jet coefficients and the blowing coefficients required to attach the flow over the flap were considerably less with the upper door fitted. A typical set of results is shown in Fig. 21. Future tests will include a jet augmented flap configuration on this same model, using the same flap, and so a direct experimental comparison between this and the augmentor wing will become possible. Figure 23b shows Model "D" in the wind tunnel.

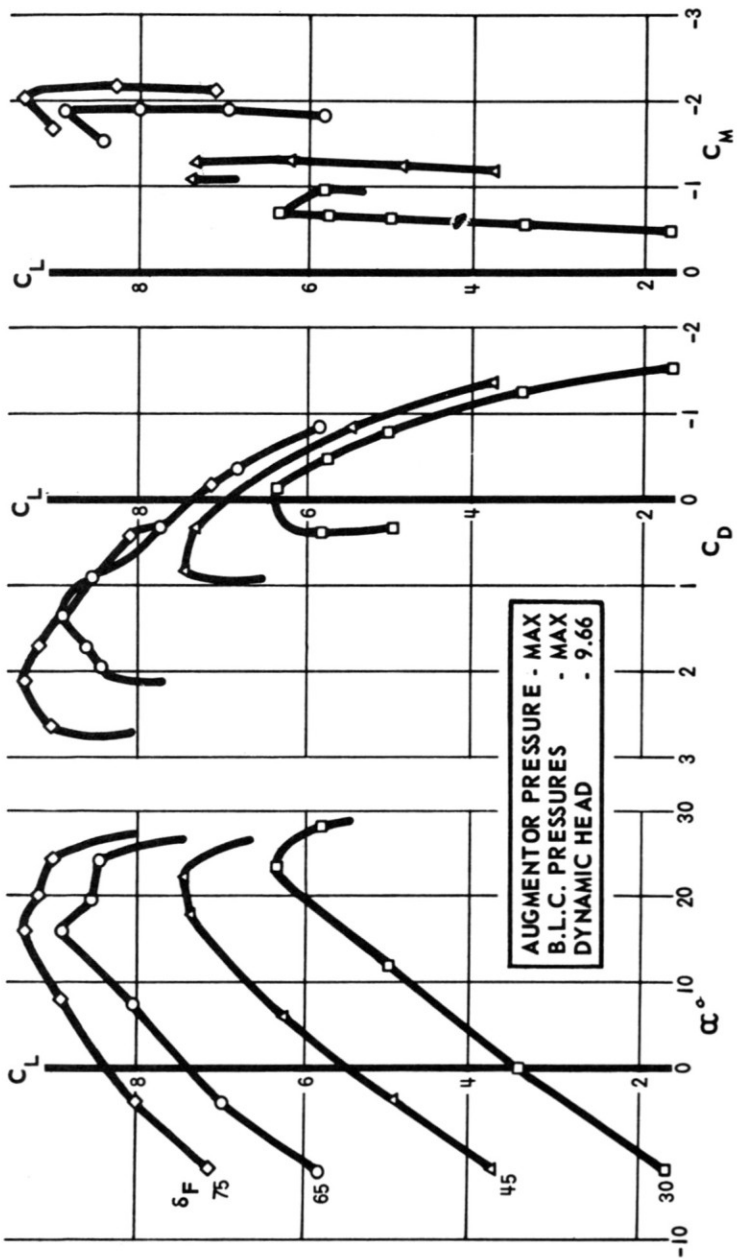
### THREE-DIMENSIONAL AERODYNAMIC CHARACTERISTICS OF THE WING-AUGMENTOR

Two sets of tests have been carried out, both on reflection plane models. The first was on a very low aspect ratio, highly swept wing; the other on a moderate aspect ratio, straight wing.

*Tests on Model "E."* Tests were carried out on a model of the fighter design shown in Fig. 6 (see Model "E," Fig. 22). The primary purpose of these tests was to investigate the interaction or interference effects due to augmentor slots in the wing. Apart from the nose-up moment due to inflow and generation of a certain amount of induced lift, the interference effects were quite small so that the overall result could be closely predicted simply by superposition of static reactive forces and moments to the jet-off results.

*Tests on Model "F."* Model "C" was constructed in such a way that the upper end plate could be removed and an outer wing panel fitted to form a reflection plane model wing of 4.58 aspect ratio. This will be referred to as Model "F" and is shown mounted in the wind tunnel in Fig. 23a. The outer wing panel was fitted with a blown aileron. These tests were intended to investigate part span effects, stall characteristics, downwash, etc., and also, by comparison of lift curve slope, to establish the effective aspect ratio of the quasi two-dimensional Model "C." Some published wind tunnel data on part-span jet flap models have shown large increases in drag as compared to the full span case. Therefore, I have chosen to show results from Model "F" with augmentor flap at 60° and blown aileron at 30° in which no serious change in drag resulted (see Fig. 24). Figure 25 is a photograph of the model in this configuration showing the flow pattern by aid of tufts.

*Tests in the NASA Ames Wind Tunnel.* The problems of testing small scale models of highly blown wings are well known to those who have worked in this field. I refer to effects of wind-tunnel wall interference,





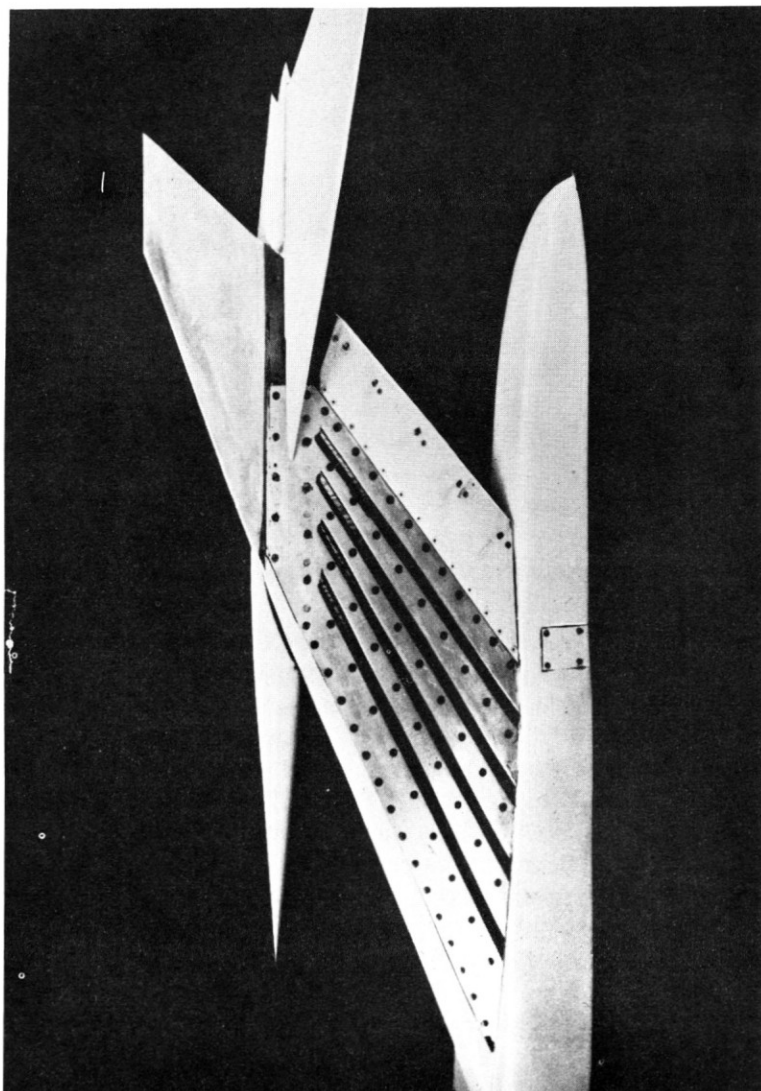


Figure 22. Model 'E'.

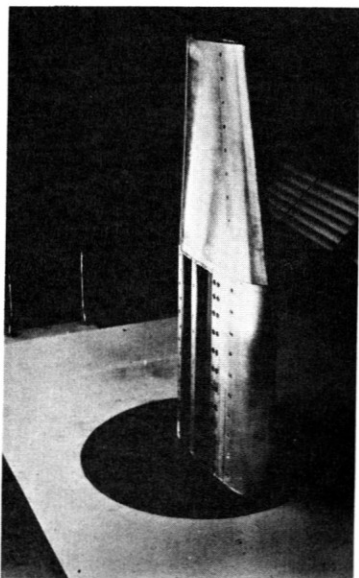


Figure 23A. Model 'F'.

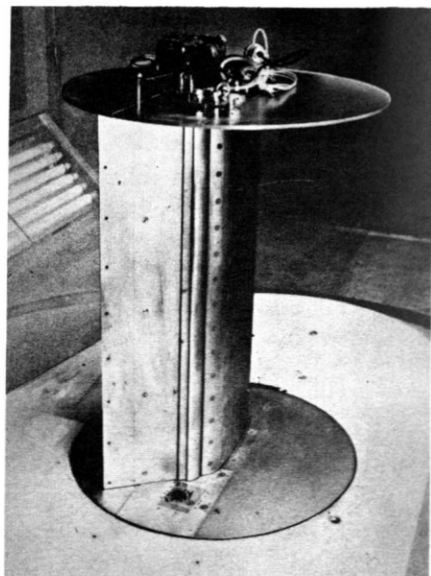


Figure 23B. Model 'D'.

problems of feeding air to the model without causing constraint and design compromises due to small scale. So far, our program has not included six component measurements on a complete model and it was decided that much could be gained by tests on a large full span model. The NASA have kindly agreed to test a model of our design in the 40 × 80-ft tunnel at Ames. This is shown in Fig. 26. Provision of the necessary air supply became a major consideration and, after a thorough review, it was decided to use one gas generator to drive the turbines of two other modified jet engines which operate as load compressor units. This was feasible from a cost point of view because all major components were already in our possession. The Ames wind-tunnel model simulates the design study transport aircraft of Figs. 3 and 5 at half scale. Tests will include an investigation of the effects of ground proximity.

### THEORETICAL ANALYSIS

Our early attempts to study the flow through a slotted wing included work by D. Hague in which he extended Glauert's biplane theory to include the case of tandem aerofoils with flow through the gap between them. The work of Ref. 5 was also intended primarily to study the slotted

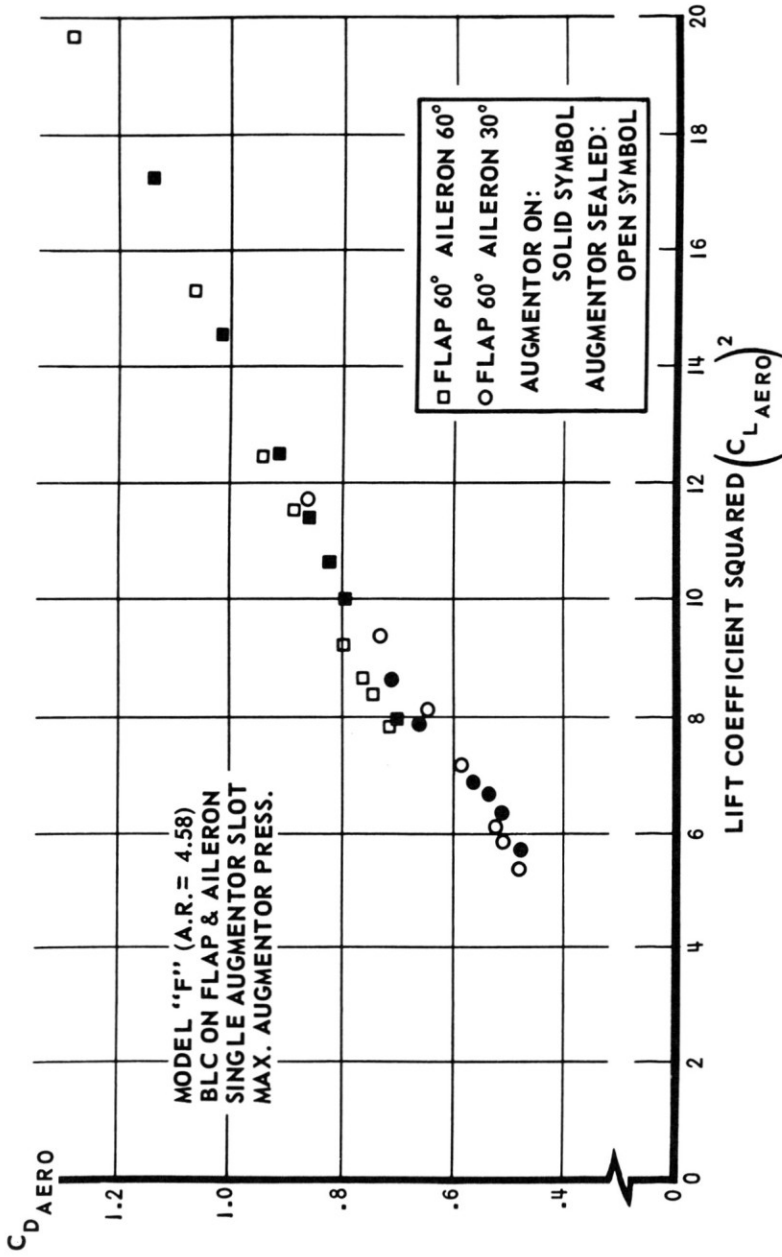


Figure 24. Effect of part span augmentor on drag.

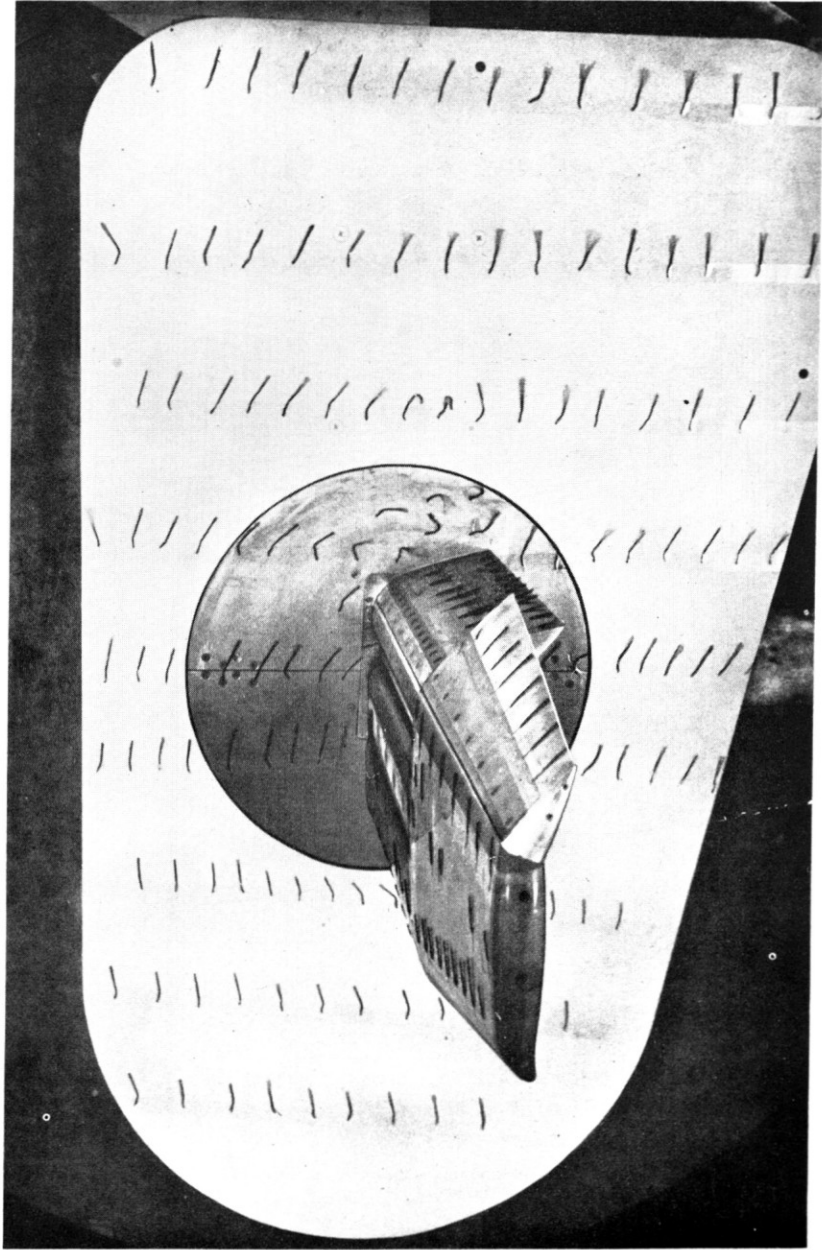


Figure 25. Flow over model 'F' as shown by Tufts.

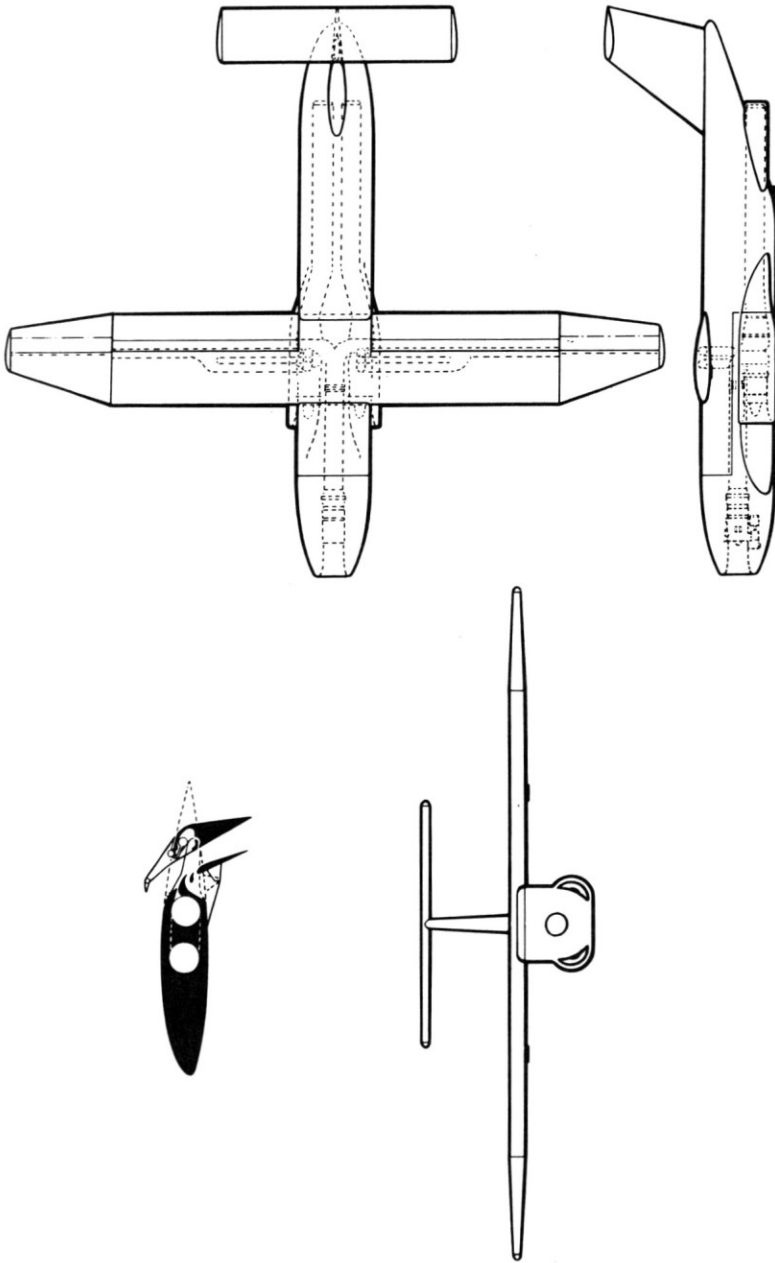


Figure 26. Ames wind-tunnel model.

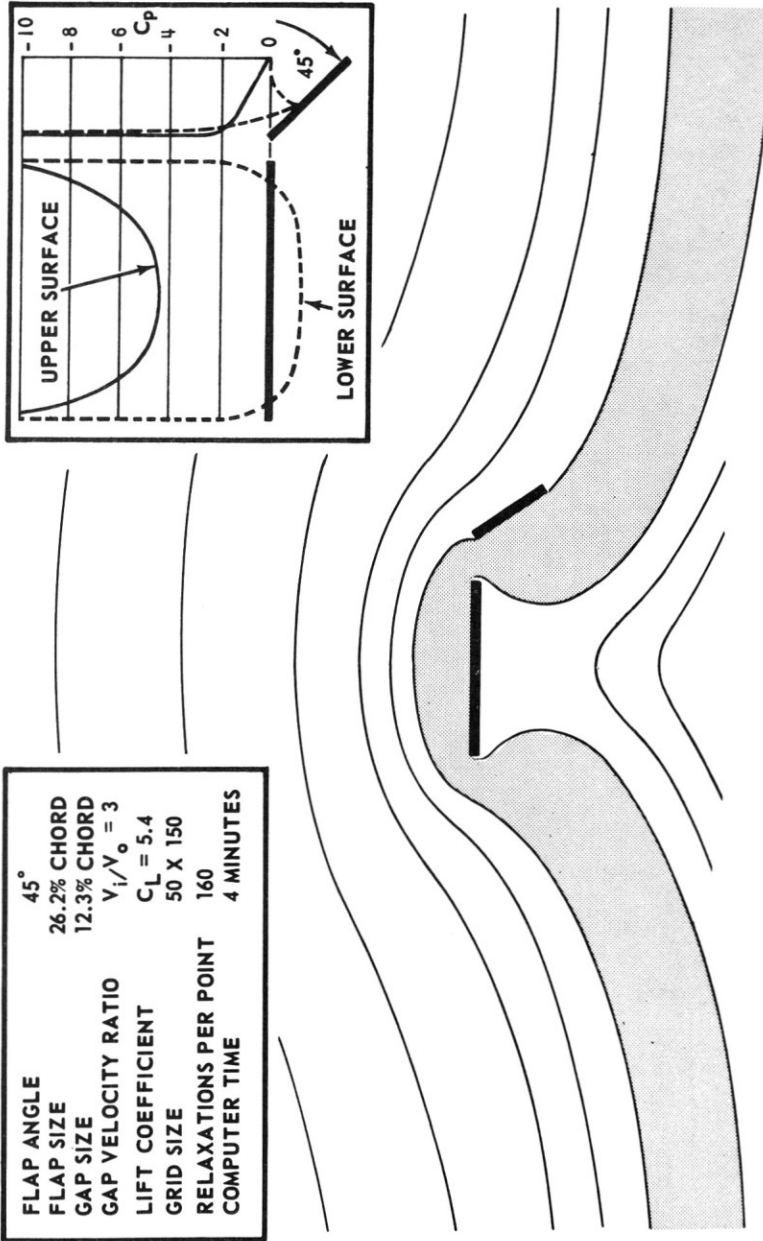


Figure 27. Theoretical flow pattern.

wing. J. Bissell investigated the case of tandem aerofoils with the rear foil set at an angle to represent a deflected flap. This was an extension of a biplane theory by Garrick [6]. More recently L. Marx has tackled a similar problem on a digital computer using relaxation methods. This permits investigation of boundary effects such as wind-tunnel wall interference or presence of the ground. Figure 27 shows the flow lines obtained from one such relaxation calculation. A simple theoretical analysis of the augmentor itself has been made by the present author, this being an extension of work by Von Kármán.

The theoretical work undertaken so far has proved to be very valuable but the mathematical models do not represent an exact simulation of the problem and there remains room for more sophisticated analyses.

### BRIEF COMMENT ON THE PRESENT POSITION

The augmentor-wing is closely related to the jet-flap although it may have a broader application. It represents another attempt at closer integration of the powerplant and the wing to obtain more efficient low speed flight and introduces a modified form of wing aerodynamics which appears to have some beneficial characteristics. More work is required to bring such concepts to operational use and it is hoped that the large scale model tests of the augmentor-wing in the Ames tunnel will provide a useful adjunct to the flight research on the jet-flap now being carried out in the United Kingdom. It must be appreciated that space limitations have permitted only a very brief outline of our work to date.

### ACKNOWLEDGEMENTS

The work described here has been made possible by the support of Avro Aircraft, De Havilland (Canada) and the Defence Research Board. The author also wishes to acknowledge the very considerable contribution to this research effort made by D. B. Garland, K. Lockwood and I. A. King.

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### COMMENTARY

HELMUT LANGFELDER [*Entwicklungsring Süd (Messerschmitt AG), Munich, Germany*]: Very complicated lift-producing devices and augmentor wings have been shown. Have weight estimates been done to compare such installations with other possibilities for the applications mentioned?

What size models have been used up to now and have ground effect tests been done with moving ground planes?

### REPLY

Although various possible applications of the augmentor-wing were described in the paper, emphasis was placed on the STOL transport with a single spanwise wing slot. This is not considered to be particularly complicated as compared to the shafting and flap system of the Breguet 941, for example. It is surprising to consider the complication in flap systems (including leading edge devices) which is considered acceptable for modern civil transport aircraft such as the Boeing 727 or D.H. 121—and these cannot exactly claim STOL performance. Comparative design studies and weight estimates have been carried out.

Model sizes are given in detail in the written paper. Ground effect tests with moving ground plane have not been conducted although we are very much aware of the limitations which ground effects might impose.