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On the Application of Boundary Layer Control to a Slender Wing Supersonic Airliner Cruising at M = 2.2

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SUMMARY

The use of suction or injection to reduce the drag of a supersonic airliner is considered. It is shown that injection gives no reduction in operating costs. With suction applied to an M = 2.2 aircraft on the London - New York route, the basic operating cost of 13.30d per short ton statute mile is expected to be reduced by 0.5d for the same payload assuming no change in configuration. If the theoretical maximum skin friction reduction could be obtained the payload could be increased by 4750 lb. and the direct operating cost could be reduced to 10.63d per short ton statute mile.

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* This investigation was undertaken by the authors in conjunction with the Department of Aerodynamics, The College of Aeronautics, Cranfield.

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1. Introduction

Recent theoretical and experimental investigations have shown that gas injection into a turbulent boundary layer can be used to decrease the wall shear stress considerably. Equally it is well known that, if the laminar boundary layer can be stabilised by suction through a porous surface or slots, the skin friction may be reduced to a small fraction of its value for the naturally turbulent boundary layer on the same surface.

Unfortunately the criterion of economy for an aircraft fitted with boundary layer control by either suction or injection methods is not skin friction alone. In evaluating the suction process it is necessary to take into account the drag equivalent of the momentum losses, pump power and the internal losses through the ducting and the porous shell. For injection, the source of the injected gas must be considered and its penalties evaluated in addition to those due to internal losses.

From single momentum arguments for an incompressible flow, Edwards[1] and Granville[2] have shown that injection of air into a turbulent boundary layer using a ram intake as the source, increases the overall drag of the configuration even though the wall shear stress is reduced. This result is not surprising in view of the throttling necessary to reduce the large intake pressure to the near-ambient pressure required at the surface. Furthermore Edwards suggests that the air used for injection could be more profitably discharged rearwards to provide extra thrust. This thesis is based on values of skin friction coefficient determined by Rubesin[3] using mixing length arguments. However experimental values of the skin friction coefficient at supersonic speeds obtained by Rubesin, Pappas and Okuno[4] and by Tendeland and Okuno[5] are considerably less than Rubesin's theoretical values particularly for small values of the injection mass flow ratio. Using these experimental results, the necessary condition for superiority of the drag reduction due to injection over the corresponding extra thrust with the same air mass flow is more nearly satisfied.

It has been shown conclusively by Head, Johnson and Coxon[6] that, at high subsonic speeds, a laminar boundary layer can be maintained by suction with a significant reduction in skin friction. The total drag (including pump drag) is markedly lower than that for the same configuration with a natural, turbulent boundary layer. Applying these principles Lachmann[7] has calculated that savings in direct operating costs of between twenty and twenty-five per cent are possible by applying laminarization to an aircraft flying from London to New York with 150 passengers and cruising at $M = 0.84$ at 40,000 ft.

The purpose of this paper is to consider the application of boundary layer control, both by suction and injection, to reduce the drag of a typical supersonic transport aircraft cruising at $M = 2.2$ and, in particular, to determine whether an appreciable reduction in operating cost can be effected. It must be emphasized that no large degree of optimisation is attempted and thus the results obtained in the study could probably be improved upon by the appropriate changes in configuration.

2. The Basic Aircraft

The first version of the College of Aeronautics 1960 design project was chosen as the basis of this study. This project was a supersonic airliner designed to cruise at M = 2.2 climbing from 56,000 ft. to 65,000 ft. in two hours and capable of carrying 120 passengers and baggage, a payload of 26,000 lb., from London to New York in approximately three hours. The aircraft (Fig. 1) has an integrated tailless layout of slender delta configuration. The wing-fuselage has an ogee planform of area 5,090 sq.ft. and aspect ratio 0.945. The weight of the aircraft without fuel is 156,000 lb., the fuel load 154,000 lb. giving a total all-up weight at take-off of 310,000 lb. Thrust is provided by eight scaled down Bristol-Siddeley Olympus 591/2 turbo-jet engines each giving 14,500 lb. sea-level static thrust.

The aircraft takes off at zero time at 200 kt. (340 f.p.s.) and climbs at subsonic speed (690 f.p.s. E.A.S. to 20,000 ft. and M = 0.9 from 20,000 ft.) to 40,000 ft. which is reached in ten minutes. At this altitude acceleration from M = 0.9 to M = 1.5 (720 f.p.s. E.A.S.) is achieved in four minutes. A further climb at a constant 720 f.p.s. E.A.S. brings the aircraft to 56,000 ft. and M = 2.2 twenty-four minutes after take-off. The total weight of the aircraft at this stage is 285,000 lb. A cruise climb at M = 2.2 is now initiated which, in 118 minutes, takes the aircraft to its maximum altitude of 65,000 ft. 142 minutes have elapsed since take-off and the weight has been reduced to 190,000 lb. At mid cruise the overall drag coefficient is 0.0122. Descent at 325 kt. E.A.S. to 40,000 ft. and at 200 kt. E.A.S. thereafter brings the aircraft into the circuit 166 minutes after take-off. Approach to landing is made at 150 kt. at an aircraft weight of 180,000 lb. three hours after take-off.

The fuel load of the basic aircraft allows for an extra 15 minutes at 30,000 ft. and M = 0.9 and for 45 minutes stand-off at 20,000 ft.

3. The Application of Suction

3.1. The experimental data

Experimental data vailable to the authors on the use of slot suction to stabilise the laminar boundary layer at supersonic speeds is very limited particularly in the Reynolds numbers of the tests and in the fact that a favourable pressure gradient existed on all the models tested. Laminar flow to at least 0.9375c was obtained by Groth(8) on a two-dimensional 5% thick biconvex aerofoil of 20 in. chord at Mach numbers of 2.23 and 2.77 and a Reynolds number of 7.5×10^6 per foot. The model was kept at zero incidence and suction applied on the portion of the wing between 0.23c and 0.90c. The suction coefficient* was 0.00010. The sum of the drag coefficient calculated from the momentum thickness of the boundary layer at 0.9375c and the equivalent suction drag coefficient (C_Q in this case) for one surface only was 0.00052 and 0.00054 for the two Mach numbers respectively compared with 0.00035 for a laminar boundary layer and 0.0020 for a turbulent layer at the same Reynolds number.

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* Suction coefficient C_Q is defined as the ratio of the suction mass flow to the free stream mass flow referred to the area of suction surfaces.

Tests by Strike and Donaldson[9] on a 20 calibre tangent ogive cylinder with a base diameter of 3.25 in. showed that, at M = 2.5, laminar flow could be maintained to a distance of 18.8 in. from the nose (0.3 in. downstream of the last suction slot) with a suction coefficient of 0.00018 at a Reynolds number of 12×10^6 per foot. At best the equivalent skin friction coefficient was reduced to 61% of the normal turbulent value. With a similar model of the same dimensions but incorporating an improved suction system, Strike and Pate[10] could not obtain laminar flow at M = 2.5. This failure was attributed to incorrect slot spacing and the authors imply that, with a different spacing of the slots, laminar flow could have been obtained at M = 2.5. At M = 3.0 laminar flow was obtained to a length of 18.8 in. giving a maximum of 58% reduction in equivalent skin friction with a suction coefficient of 0.00016 at a Reynolds number of 10.5×10^6 based on the length of 18.8 in. (i.e. 6.4×10^6 per foot). At this Reynolds number the natural transition without suction occurred at 9.6 in. from the nose and with optimum suction at 18.8 in. at which point the pressure gradient was approximately zero. When the Reynolds number was raised to 8.6×10^6 per foot (13.5×10^6 based on the extent of the suction surface) there was no drag reduction even though the optimum suction coefficient for the experiment ($C_Q = 0.00028$) was applied.

In the earlier tests Strike and Donaldson obtained a 27% decrease in drag at M = 3.0 at $R = 4.28 \times 10^6$ per foot with a suction coefficient of 0.000124. An increase of Reynolds number to 5.88×10^6 per foot produced no drag reduction even though optimum suction was applied.

Comparison of these results with theory suggest that, at M = 2.2, a laminar boundary layer can be maintained with a suction coefficient of 0.00015 and an equivalent skin friction coefficient* of 0.00056 at a chord Reynolds number of 10^8. The corresponding value at $R = 10^7$ would be .00088. The minimum attainable equivalent skin friction coefficient with $C_Q = 0.00015$ are 0.00045 and 0.00075 at $R = 10^8$ and 10^7 respectively.

3.2. The drag reduction for the supersonic aircraft

Since data was not available to the authors from experiments on a larger scale and on other configurations it is difficult to interpret the foregoing results for a large supersonic aircraft of slender delta planform. Three interpretations are possible. Firstly, the application of suction gives no drag reduction if the Reynolds number based on the chord is much in excess of 10^7. Secondly, suction can preserve laminar flow only when a favourable pressure gradient exists. These two interpretations are possibly pessimistic but, if substantiated by larger scale tests, show that suction is of no benefit in reducing the drag of the supersonic airliner studied here. A third interpretation is that, provided the unit Reynolds number does not exceed 6.5×10^6 per foot, completely laminar flow is obtainable at supersonic speeds using slot suction with a suction coefficient between 0.00015 and 0.00020 depending upon the nature of the surface. The equivalent skin friction coefficients (as defined previously) are respectively 40% and 47% of the corresponding turbulent values.

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* Equivalent skin friction coefficient is defined as the laminar skin friction coefficient with suction applied to which is added the appropriate allowance for intake momentum drag.

During the subsonic phases of the flight it is assumed (following Lachmann[7]) that it is necessary to apply a suction coefficient of 0.00045 to halve the profile drag (which includes the intake drag).

In this analysis the layout of the suction slots has not been considered in detail. For project purposes it has been assumed that the whole of the surface area is covered with suction.

The reduction in drag to be expected using suction and the thrust to be obtained from the rearward ejection of the sucked air are given in Table 1. Included in these drag figures is the drag due to the extra weight of the suction installation. This weight penalty has been calculated on the basis suggested by Lachmann, namely that incorporating suction slots adds to the weight of the aircraft 0.5 lb. per square foot of sucked area, ducting 0.13 lb. per square foot and suction pumps 6 lb. per lb. mass per second equivalent sea level rate of mass flow and amounts to 10,400 lb. if suction is applied at all heights above 20,000 ft. and 9,850 lb. if suction is restricted to the cruise only. Not included in Table 1 is the reduction in the lift-dependent drag due to the saving in fuel weight consequent upon the reduction of total drag. This saving in fuel is dependent upon the source and magnitude of the pump power required. The reduction in the lift-dependent drag is included when the net fuel saving is calculated after the evaluation of the penalties arising from the provision of pump power.

The overall drag reductions for the configuration studied in this paper without any allowance for the reduced fuel weight are (i) 29% when suction is first applied at 20,000 ft. (ii) in the cruise 15% for $C_Q = 0.00015$ for 13% if $C_Q = 0.00020$. (iii) in the subsonic descent 12%.

3.3. The power requirements

The power required to maintain the suction process is dependent upon the speed and pressure at which the air is to be ejected and upon the pressure losses within the ducting and porous surface. Several alternative methods of ejecting the suction air exist. It can be passed through compressors driven from the installed engines and allowed to pass to atmosphere at free stream static pressure and low velocity or it can be ejected at flight speed. In the latter case considerable thrust can be obtained but the higher pressure ratios required necessitate larger horsepower to drive the compressors and the compressor weight may exceed the estimate of 6 lb. per lb. mass per sec. equivalent sea level mass flow. This excess weight has not been included in this study. Alternatively, with comparatively simple modifications to the engine intake, the suction mass flow could be taken through the fan of a by-pass engine, the outer parts of the fan blades being used as a suction pump. In this case the "cold" thrust of the engine is derived from the suction air and not from air taken from the ram intake.

A fourth scheme involves the use of the suction air to vent a blunted wing trailing edge. The use of a blunt trailing edge reduces the wave drag since the wing has effectively a decreased thickness chord ratio. There is an added penalty in the form of base drag but this can be reduced considerably by bleeding the suction air into the base region. Although no direct thrust is obtained from the suction air the compressor power is very moderate and it will be shown that the overall drag is considerably reduced.

In each case where auxiliary compressors are installed the power is derived from the installed engines by a mechanical transmission. A more flexible system affording a greater measure of control involves a turbine driving the suction pump, the turbine being driven by air bled from the engine. The disadvantages are the extra weight and the fact that it is less efficient to extract power from an engine by this means than by a direct shaft drive.

For the methods outlined above the horsepower necessary to produce the required suction flow and exit conditions has been calculated. The increased fuel consumption and reduction in thrust of the installed engines as a result of the extraction of the pump power has been found from the appropriate engine brochures on the assumption that the scaled down engines have the same characteristics for power take-off as their prototypes. These penalties were then subtracted from the saving in drag (and the thrust obtained from the suction air) and the result expressed in terms of a reduction in fuel consumption during the flight. A first estimate of the total fuel saving was then made and the total drag recalculated. On this revised drag estimate, a second estimate of the fuel saving was made and it is this figure which is quoted in the following sub-sections.

The application of suction has been considered in the cruise alone and in the case of all flight at and above 20,000 ft. including diversion and stand-off. It is realised that to operate the suction system other than in the cruise will involve controls of some complexity the provision of which has been neglected in this study.

The duct losses are assumed to be the same for all the schemes outlined above. It is estimated that there will be an overall ten per cent drop in total pressure in the ducting and through the suction slots. With low inlet pressures (less than 1.3 lb. per sq. in. absolute in the cruise) an axial flow compressor will have a comparatively low efficiency. In this study it has been assumed that the compressor efficiency is 90% for flight below 40,000 ft. falling to 75% in the cruise.

In the following four sub-sections the fuel savings quoted are those to be expected on the basic aircraft with laminarisation applied. Any further effects due to possible saving in engine and structure weight are considered in a later section.

3.3.1. Suction air ejected at low velocity

In this system the compressors are doing little more than making good the losses through the porous surface and in the ducting. The power required has a maximum value of 800 HP at 20,000 ft. on the ascent. In the cruise the power required for suction (C_Q = 0.00015) falls from 126 HP at 56,000 ft. to 82 HP at 65,000 ft. For C_Q = 0.00020 these powers are increased to 168 HP and 109 HP respectively. Such amounts of shaft power are very small compared with the total shaft power of the installed engines and using this system there is no risk of the engine limitations being exceeded. Summarising the details of Table 2, the net fuel savings are, for C_Q = 0.00015 in supersonic flight and C_Q = 0.00045 in subsonic flight:

Compressor power derived from	Net fuel saving (lb) in cruise	above 20000 ft.	Effective Cruise L/D
Turbojet H.P. shaft	12000(10300)	14200(17120)	8.85 (8.65)
Turbojet L.P. shaft	12000(10200)	18355(16295)	8.85 (8.65)
By-pass H.P. shaft	12050(10700)	18790(17290)	8.85 (8.65)
By-pass L.P. shaft	12600(10900)	20280(17980)	8.85 (8.65)

The figures in brackets are those appropriate to $C_Q = 0.00020$ in supersonic flight. In this case the mid-cruise overall drag coefficient is not sensitive to the source of compressor power having a value of 0.0103 for $C_Q = 0.00015$ and 0.0106 for $C_Q = 0.00020$.

3.3.2. Suction air ejected at flight speed

While ejecting the suction air at flight speed gives a thrust of the order of 2,000 lb. in the cruise approximately 15,000 H.P. is required (see Table 3). The variation of fuel flow rate and reduction in thrust due to power take-off have been extracted from the Olympia 591/2 and BS100 brochures, but it is realised that the net fuel savings obtained must be optimistic in view of the severe mis-matching within each engine caused by the extraction of some two to three thousand horsepower. Furthermore to obtain the required power in the cruise the jet pipe temperature is likely to exceed the limit by approximately 200°C. The figures for fuel saving given below and in Table 3 should be considered as possibly attainable with engines specially designed to allow considerable take-off of shaft power. Again the figures in brackets correspond to $C_Q = 0.00020$ in supersonic flight.

Compressor power derived from	Net fuel saving (lb) in cruise	above 20000ft.	Effective Cruise L/D	Overall C_D at mid-cruise
Turbojet H.P. shaft	12800(11220)	22500(20780)	9.0(8.75)	0.0102(0.0104)
Turbojet L.P. shaft	1080(-4320)	9150(2020)	7.6(7.10)	0.0114(0.0128)
By-pass H.P. shaft	7190(3560)	14880(11030)	8.15(7.95)	0.0111(0.0116)
By-pass L.P. shaft	8560(5500)	16500(13240)	8.35(8.05)	0.0109(0.0114)

A separate gas turbine installed specifically to boost the suction air to the flight speed is impractical since the turbine inlet temperature during the cruise would be approximately 4000°K.

3.3.3. The by-pass as a suction system

In this scheme it is assumed that at least two units of the installed power plant are by-pass engines. It is envisaged that the intakes of two BS100 engines are modified so that the by-pass air can be taken from the main ram intake during take-off and the early climb and subsequently be drawn from the suction ducts. The fan entry guide vanes are assumed to be rotatable so that the outer part of the fan will accept the suction air without serious loss of efficiency. In practice only one of the engines so modified would be used as a suction pump, the second is installed as a safety measure.

The difference between the normal thrust and the thrust derived from the suction air is calculated and subtracted from the drag reduction. Since the suction mass flow is less than that normally passing through the by-pass, plenum chamber burning is not necessary to eject the air at or above free stream speed. This is a considerable fuel saving to be added to that derived from the drag reduction (Table 4).

If used for all the flight above 20,000 ft. one may expect a saving in fuel of 22,750 lb. (21550 lb if C_Q = 0.00020 in supersonic flight). Applied only in the cruise suction derived from such a system would save 14500 lb. of fuel (13500 lb for C_Q = 0.00020). The values for the effective cruise L/D ratio are 9.15 and 8.95 and the overall drag coefficients are 0.0101 and 0.0102 respectively.

The small difference between the results for the two suction quantities lies in the fact that although the drag reduction is less, the mass flow, and hence the thrust, is greater for the larger suction quantity.

3.3.4. Suction air used to vent a blunt trailing edge

It is well known that the wave drag of a wing is reduced by a reduction of the thickness-chord ratio. This can be done in effect by maintaining the maximum thickness and increasing the effective chord by blunting the trailing edge. There is, of course, the disadvantage of an appreciable base drag to be considered in the optimisation of a design but this may be partially offset by a reduction in structure weight. Read and Frazer-Mitchell[11] have shown that such a scheme will incur an overall drag penalty unless there is a very considerable saving in structure weight or unless the base pressure can be raised to 0.80 of the free stream static pressure. The usual ratio of base pressure to free stream static pressure at M = 2.2 is approximately 0.35.

Various workers (e.g. Wimbrow[12]) have shown that slotting the trailing edge and allowing air to flow slowly into the base region through the slots has the effect of raising the base pressure. The increase in base pressure is dependent upon the ratio of slot area to base area and upon the ratio of the bleed total pressure to the free stream static pressure. Provided the area of the slots is greater than three quarters of the base area, a base pressure ratio equal to 0.9 can be achieved when the total pressure of the ventilating air is approximately equal to the free stream static pressure. Thus conditions can be achieved using base bleed which will give a net drag reduction in addition to the drag reduction due to the application of suction.

In the context of this project study, the use of the suction air to ventilate a blunt trailing edge presents some difficulties. Except during the cruise the volume flow of suction air varies and hence the base and slotted areas should be varied also. More serious is the fact that if the jet total pressure rises significantly above the free stream static pressure, the base pressure falls dramatically giving a base drag which may be twice that of the unventilated base.

Severe mechanical problems may be encountered in ducting the air through the hinges of flaps, elevators and ailerons. The use of base bleed may also seriously affect the control characteristics. These two effects are neglected, it being assumed that the air can be successfully ducted and that the control characteristics are satisfactory. Table 5 presents the results of a study of a very elementary system using the suction air to reduce base drag. The original aircraft is assumed to have sharp trailing edges. Taking the bleed total pressure which gives maximum base pressure in the cruise condition one can find the velocity of flow through the trailing edge and the slot area can then be calculated from the suction mass flow. The suggested structure shown in Figure 2 gives a slot to base area ratio of 0.9 which was assumed unaltered during the flight. On the value of base area so calculated, the new wave drag was estimated. During the cruise it is found that the wave drag and base drag of the blunted wing with bleed is approximately 500 lb. less than the wave drag of the wing with sharp trailing edges. In the off-cruise condition the benefits are not so great due to the rapid rise in base drag when the optimum bleed total pressure is not obtained. The 500 lb. drag reduction in cruise is in addition to that afforded by laminarisation.

The net fuel savings are given below:

Compressor power derived from	Net fuel saving (lb) in cruise	above 20000 ft.	Effective Cruise L/D
Turbojet H.P. shaft	12900(11380)	17700(15700)	9.0 (8.8)
Turbojet L.P. shaft	12250(11100)	17800(15800)	8.95 (8.75)
By-pass H.P. shaft	13780(12100)	18550(16100)	9.0 (8.75)
By-pass L.P. shaft	13880(12350)	18650(16250)	9.0 (8.8)

The overall drag coefficients at mid-cruise are 0.0102 and 0.0114 for the two suction quantities.

The foregoing fuel savings have been calculated on the assumption that the system is not adjustable and that all the suction air passes through the trailing edge. This leads to considerable drag penalties particularly in the subsonic climb and diversion phases. If the excess suction air is diverted from the trailing edge to another outlet at free stream static pressure and the bleed total pressure is controlled the drag penalty in the climb at M = 0.9 and in the diversion phase can be reduced to zero*. For such a system the net fuel savings have been re-calculated with the following results:

Compressor power derived from	Net fuel savings (lb) in cruise	above 20000ft.	Effective Cruise L/D
Turbojet H.P. shaft	12900(11380)	19230(17325)	9.0 (8.8)
Turbojet L.P. shaft	12250(11100)	19330(17425)	8.95 (8.75)
By-pass H.P. shaft	13780(12100)	20600(18875)	9.0 (8.75)
By-pass L.P. shaft	13880(12340)	20750(19025)	9.0 (8.8)

Further savings should be possible using a base-bleed system if the area of the base can be increased relative to the slot area without increasing the sum of wave and base drags and if a method of ensuring the correct bleed total pressure throughout the flight can be developed.

* The data on base bleed at M = 0.9 is derived from recent experiments at the National Physical Laboratory, some preliminary results of which were presented at a meeting of the Royal Aeronautical Society on 15th February, 1962.

3.4. Range and Direct Operating Costs

Ideally any reduction in fuel weight should result in an equal increase in payload or in a substantial reduction in structure weight. Maximum payload benefit could only be achieved by a change in the configuration of the aircraft allowing the volume of the tankage saved to be redistributed to contain payload. Since integral fuel tanks are normally used, a saving in fuel weight would not greatly reduce the weight of an established structure. It could, however, help to reduce the severity of one critical design case. At high incidence the increased pressure in the lower fuel tanks necessitates stiffer panels and alleviation of this pressure by lightening the fuel load could result in some saving in structure weight.

Drag reduction brought about by the application of suction enables considerable aircraft weight saving to be achieved by reducing engine weight. The basic aircraft has a take-off weight of 310,000 lb; its cruise L/D is 7.5 and requires an engine weight of 30,000 lb. to provide the necessary 114,000 lb. sea level static thrust. With suction the maximum fuel saving is obtained using the by-pass as a suction pump. The reduction in fuel load is 22750 lb. and cruise L/D 9.15. Optimising the cruise height it is found that the cruise-climb is best initiated at 52,500 ft. and ended at 61,000 ft. The required sea level static thrust is reduced to 100,000 lb. and the engine weight to 26,500 lb. The take-off weight becomes 294,000 lb. for which the full 100,000 lb. sea level static thrust is required for take-off in the same distance as the basic aircraft.

If the weight of the aircraft with suction can be made up to the 310,000 lb. of the unmodified aircraft by adding 12,750 lb. of fuel the range of the aircraft can be increased by approximately 500 nautical miles. A further 250 nautical miles would be possible if the theoretical maximum skin friction reduction could be obtained.

The direct operating costs have been determined using a method due to Port[13] The following assumptions have been made:

- (i) cruise Mach number 2.2
- (ii) aircraft annual utilisation 3000 hrs.
- (iii) fuel cost 18d per imperial gallon.
- (iv) airframe cost £20 per lb. weight for the basic aircraft
  £26 per lb. weight for the aircraft with suction equipment.
- (v) engines and compressors cost £20 per lb. weight.
- (vi) aircraft operates on 100% load factor.
- (vii) stage length 3000 nautical miles.

On these assumptions the operating cost of the basic aircraft in pence per short ton statute mile is given by

$$1.043 \frac{W_F}{W_P} + 1.018 \frac{W_A}{W_P} + 2.73 \frac{W_E}{W_P}$$

and for the suction aircraft

$$1.043 \frac{W_F}{W_P} + 1.117 \frac{W_A}{W_P} + 2.73 \frac{W_E}{W_P}$$

where W_F = Fuel weight

W_A = Structure weight

W_E = Engine weight

W_P = Payload weight

The operating cost of the basic aircraft is 13.30 d per short ton statute mile which can be reduced, by taking the best practical application of suction, to 12.78d using a very simple base bleed system, and 12.66d using the modified by-pass engine. If it were possible only to use the suction in the cruise the corresponding costs would be 13.06d and 12.89d respectively.

Considering the equivalent skin friction drag to be reduced to the most optimistic minimum value, the additional fuel saved on the complete flight would be approximately 4750 lb. in the two cases considered above. Assuming that all this weight could be utilized as payload without any structural weight penalty or change in configuration, the operating costs could be reduced from 12.78d and 12.66d to 10.81d and 10.63d respectively if the suction operated for all flight above 20,000 ft. and from 13.06d and 12.89d to 11.04d and 10.91d respectively if used in the cruise condition only.

4. The Evaluation of Injection Systems

Air injected through a porous surface into the turbulent boundary layer reduces the wall shear stress and can help to keep the surface cool. In this process there is no lower limit to the rate of injection and the greater the injection rate the lower the wall shear stress. For suction to be effective there is a minimum suction rate and if a larger suction rate is used the overall drag reduction is decreased. To obtain wall shear stresses as low as those obtained if a laminar boundary layer is stabilised, the injection air mass flow is an order of magnitude greater than the corresponding suction quantity. The reduction in skin friction alone to be expected with air injection during the flight of this particular supersonic transport are given in Table 6. These figures are deduced from Rubesin's theory(3) and do not include the effect of pressure gradient. The experimental results of Rubesin, Pappas and Okuno(4), Tendeland and Okuno(5) and Mickley and Davis(14) indicate a slightly lower value of wall shear stress at the lower values of the injection parameter, but this does not affect subsequent deduction materially. It can be seen that increase in injection rate does not produce a proportional reduction in wall shear stress.

4.1. Injection air obtained from ram intakes or compressor bleed

Any system taking air from a ram intake or from the compressors of the installed engines is extremely wasteful of fuel as a result of the momentum drag penalty and the throttling necessary to reduce the large pressure to near-ambient pressure required at the surface. Table 7 sets out the net fuel penalties in providing the injection air at a value of $I = 0.0005$. As expected, the ram intake is the least wasteful; air bleed from the high pressure compressors is the most wasteful. At best the penalty is 2800 lb mass/hour in the cruise and at worst 10,500 lb mass/hour, even ignoring the losses of the system. Since increase of injection mass flow does not decrease wall shear stress proportionally it may be concluded that such methods of obtaining the injection air are of no practical value in this context. Before dismissing the ram intake completely it should be noted that, in the cruise, some 5000 H.P. is available if the air is passed through a turbine before being injected into the boundary layer. It is interesting to note that 11700 H.P. is needed to overcome the intake momentum drag.

4.2. The use of air from boundary layer bleed at the engine intake

The disadvantage of the injection systems previously described lies in the intake momentum drag which must be set against any skin friction reduction. Now it is normally necessary to remove some of the boundary layer just upstream of the engine intakes so that the intakes shall work as efficiently as possible. Removing only the very low speed part of the layer yields a small mass flow which is not sufficient in quantity or in pressure to supply an injection system. Usually an embarrassment, this air could perhaps be used profitably to vent a blunt trailing edge.

If, however, most or all of the boundary layer has to be removed for the efficient operation of the intake, this supply of air has a mean pressure considerably in excess of the pressure needed for injection. It can fairly be claimed that the momentum drag of this air is debitable to the propulsion system and not to the injection system. The characteristics of an injection system of this type applied to our basic aircraft are given in Table 8. A compressor efficiency of 65 per cent is assumed in the calculations of this section since the boundary layer air entering the compressor will have a very non-uniform velocity profile. The net reduction in the fuel consumed in the flight is 8260 lb. In addition to the fuel saving there is also considerable shaft power obtainable from a turbine which would be used to reduce the air pressure before injection. In mid-cruise 2700 H.P. could be derived in such a manner. A further advantage would be a reduction of approximately 20^{o}C in skin temperature in the cruise if adequate insulation could be provided.

The injection mass flow obtainable depends upon the position of the intakes and the thickness of the boundary layer to be removed. The aircraft studied here has the intakes in the centre of the rear fuselage where the boundary layer is thick. If the engines were located in two groups outboard the boundary layer at the intake lip would be thinner and the attractiveness of an injection system much reduced.

Alternatively, if most of the boundary layer is to be removed, the air so derived could be used to give thrust by ejecting it rearwards at free stream speed. Table 9 gives the details of such a procedure when the air is passed through compressors driven by the installed engines or through the outer part of the fan of a by-pass engine modified in the manner suggested in section 3.3.3. The fuel saving to be expected is given in the following table:-

		Net fuel saving (lb)	
1.	Compressor power from	in cruise	all flight
	Turbojet H.P. shaft	14000	20100
	Turbojet L.P. shaft	7410	12475
	By-pass H.P. shaft	9580	14900
	By-pass L.P. shaft	11980	17400
2.	Direct ingestion into fan of by-pass engine	18300	27550

It is immediately obvious that it is more profitable to eject the boundary layer air rearwards to give thrust than to inject it into a turbulent boundary layer to reduce the skin friction on this aircraft cruising at M = 2.2. Such a conclusion may not be valid at much higher Mach numbers where appreciable cooling may be required and where external combustion may be used for propulsion.

4.3. Foreign gas injection

If a light gas is injected into the turbulent boundary layer, a considerably reduced rate of mass flow is required to obtain a desired reduction in skin friction (see, for example, Rubesin and Pappas(15) and Pappas and Okuno(16)). If helium is used the injection parameter I would be half that for air and for hydrogen I is one fifth that for air. Table 10 shows the drag reduction to be expected when helium (I = 0.00035) and hydrogen (I = 0.00015) are injected. The required mass flow rates are also given. Although the fuel load for the Atlantic crossing could be reduced by 16,500 lb., this is only a small fraction of the weight of injected gas required; 282,000 lb of hydrogen or 658,000 lb of helium. Whatever value of injection parameter is used the weight of foreign gas is at least an order of magnitude greater than the fuel saving so that it may be deduced that foreign gas injection has no application to an M = 2.2 transport aircraft and it is very doubtful whether it has any attraction at M = 3.

5. Suggestions for Future Research

It has been assumed throughout this study that the results of small scale two-dimensional or axi-symmetric experiments at zero incidence can be extended to a large aircraft of slender delta configuration at incidence. While comparable unit Reynolds numbers are obtainable in tunnel tests, the lengths of suction surface and laminar flow obtained are two orders of magnitude less than required on the supersonic aircraft. The suction slots in the experiments were at approximately half-inch spacing.

Fundamental experiments are needed to find the proper spacing and location of the slots for larger surfaces and more complicated configurations. It is also necessary to determine the limit (if any) to which laminar flow can be maintained. Existing experimental and theoretical data refer to carefully prepared surfaces. Surface imperfections and radiated noise from any turbulent boundary layer present could result in failure to maintain laminar flow or in larger suction quantities being needed to preserve laminar flow and thus it is necessary to determine the suction quantities required for practical surfaces. Extensive experiment is also required to determine how valid the existing experimental data is for application to slender delta configurations.

The best savings are obtainable by use of a modified by-pass engine as a suction pump or by the use of a small compressor feeding the suction air to bleed slots in blunt trailing edges. The efficiency of the latter system is dependent upon the satisfactory operation of the controls with base bleed, confirmation of which must rely on experiment.

6. Conclusions

1. On the basis of the existing available data and the assumptions made, a reduction in direct operating costs of between 0.5 and 0.6 pence per short ton statute mile can be expected for the given configuration and a payload of 26,000 lb. when suction is applied at all altitudes above 20,000 ft. Applied in the cruise only, suction effects a reduction of 0.24 pence.

2. Alternatively the application of suction extends the range of the aircraft by 500 nautical miles.

3. If the theoretical maximum reduction in drag could be realised, the payload could be increased by 4750 lb. and the direct operating cost reduced to 10.63 pence per short ton statute mile.

4. Injection of air or a foreign gas into the turbulent boundary layer gives no reduction in direct operating cost.

7. Acknowledgements

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TABLE 1.

Effect of Suction on Drag

In subsonic flight C_Q has been assumed to be 0.00045. In supersonic flight C_Q has been taken as 0.00015. If C_Q has to be increased to 0.00020 to maintain boundary layer stability the figures in brackets apply.

Altitude (ft)	Drag Reduction (lb)	Suction mass flow (lb/sec)	Thrust from suction air (lb)
Subsonic climb			
20000	7930	184	5400
25000	6655	169	4800
30000	6125	137	3810
35000	5420	114	3100
40000	4800	88.3	2390
Supersonic climb			
40000	6620(5730)	49.1(65.4)	2210(2950)
45000	6500(5620)	43.5(58.0)	2210(2950)
50000	6200(5360)	38.6(51.4)	2210(2950)
55000	5870(5080)	34.2(45.6)	2210(2950)
Supersonic cruise			
56000	5840(5040)	33.3(44.4)	2200(2930)
60000	4830(4150)	27.5(36.6)	1815(2410)
65000	3720(3170)	21.8(29.0)	1445(1925)
Supersonic descent			
60000	3120(2640)	23.0(30.6)	1280(1710)
55000	3120(2640)	26.2(34.9)	1290(1720)
50000	3170(2680)	29.5(39.3)	1290(1720)
45000	3340(2730)	33.3(44.4)	1290(1720)
40000	3410(2690)	37.7(50.0)	1300(1730)
Subsonic descent			
35000	2510	78.0	1480
30000	2490	86.1	1480
25000	2465	93.0	1475
20000	2440	90.6	1475

TABLE 2.

Fuel saving as a result of suction
(Suction air ejected at low velocity)

Altitude (ft)	Horsepower	Fuel saving (lb/hr) Turbojet engine H. P. shaft	Turbojet engine L. P. shaft	By-pass engine H. P. shaft	By-pass engine L. P. shaft
Subsonic climb					
20000	797	7000	6810	6445	6500
25000	705	5900	5725	5400	5430
30000	546	5430	5430	5015	5075
35000	435	4810	4810	4470	4460
40000	333	4260	4260	3975	3960
Supersonic climb					
40000	186(247)	8450(7300)	8410(7250)	8855(7615)	8900(7675)
45000	164(219)	8295(7165)	8255(7110)	8680(7450)	8725(7555)
50000	146(194)	7915(6840)	7880(6795)	8285(7140)	8330(7200)
55000	129(172)	7490(6475)	7455(6430)	7845(6760)	7895(6830)
Supersonic cruise					
56000	126(168)	7460(6425)	7420(6375)	7815(6715)	7880(6800)
60000	104(138)	6175(5290)	6145(5250)	6455(5370)	6510(5600)
65000	82(109)	4745(4040)	4725(4015)	4975(4220)	5020(4280)
Supersonic descent					
60000	87(116)	3985(3360)	3970(3340)	4165(3370)	4195(3410)
55000	99(132)	3985(3360)	3965(3335)	4160(3360)	4195(3410)
50000	112(149)	4040(3405)	4025(3385)	4210(3540)	4255(3605)
45000	126(168)	4250(3475)	4240(3460)	4425(3600)	4500(3700)
40000	143(189)	4335(3420)	4335(3415)	4515(3515)	4600(3630)
Subsonic descent					
35000	298	2205	2200	3235	3380
30000	335	2190	2190	3200	3360
25000	388	2160	2160	3140	3330
20000	397	2140	2135	3095	3290

TABLE 3.

Fuel saving as a result of suction
(Suction air ejected as flight speed)

Altitude (ft)	Horsepower	Fuel saving (lb/hr) Turbojet engine H. P. shaft	L. P. shaft	By-pass engine H. P. shaft	L. P. shaft
Subsonic climb					
20000	7030	12980	11180	8980	9610
25000	6160	11700	10140	7830	8390
30000	4830	10200	8970	7130	7570
35000	3850	8390	7410	6320	6670
40000	2910	7030	6280	5490	5750
Supersonic climb					
40000	6120(8170)	10410(9930)	8420(7270)	9960(9100)	10270(9510)
45000	8100(10800)	9970(9400)	7100(5570)	9080(8000)	9490(8540)
50000	11200(15000)	9140(8460)	4830(2680)	7540(6120)	8100(6870)
55000	15580(20840)	8380(7250)	1620(-1400)	5220(3230)	6070(4380)
Supersonic cruise					
56000	16500(21975)	7900(7010)	3390(-2210)	3680(2630)	5570(3730)
60000	13650(18070)	6540(5780)	2570(-2260)	3680(1810)	4440(2820)
65000	10630(14180)	5070(4460)	1720(-2130)	2610(1060)	3140(1770)
Supersonic descent					
60000	6140(8175)	4740(4380)	3280(1310)	3790(3010)	4100(3420)
55000	4710(6275)	4960(4670)	3960(2500)	4350(3750)	4580(4060)
50000	3900(5170)	5140(4880)	4350(3200)	4730(4230)	4930(4490)
45000	2880(3480)	5510(5010)	4940(3840)	5340(4640)	5500(4870)
40000	2320(3100)	5690(5210)	5250(4330)	5660(5040)	5800(5220)
Subsonic descent					
35000	1325	3800	3460	3170	3290
30000	1220	3870	3550	3150	3280
25000	1130	3970	3620	3180	3250
20000	1090	3940	3600	3130	3200

TABLE 4.

Fuel saving as a result of suction
(Suction air ingested by a by-pass engine)

Altitude (ft)	Reduction of fuel consumption (lb/hr)
Subsonic climb	
20000	10350
25000	8750
30000	7665
35000	6560
40000	5540
Supersonic climb	
40000	8860(8280)
45000	8475(7885)
50000	9135(8545)
55000	9040(8505)
Supersonic cruise	
56000	8890(8360)
60000	7375(6865)
65000	5750(5335)
Supersonic descent	
60000	3815(3345)
55000	4515(4180)
50000	4505(4145)
45000	4760(4080)
40000	4820(4130)
Subsonic descent	
35000	3235
30000	3245
25000	3400
20000	3330

TABLE 5

Fuel saving as a result of suction
(suction air as base bleed)

Altitude (ft)	Drag reduction due to blunting and bleed (lb) C_Q=0.00015	0.00020	Total Drag Reduction (lb)	Fuel saving (lb/hr) Turbojet engine L.P. shaft	Turbojet engine H.P. shaft	By-pass engine L.P. shaft	By-pass engine H.P. shaft
Subsonic climb							
20000	-3660	-4800	4270(3100)	3600(2550)	3755(2700)	3455(2455)	3375(2375)
25000	-2970	-3890	3685(2765)	3100(2280)	3235(2415)	2975(2195)	2905(2125)
30000	-2360	-3120	3765(3005)	3195(2510)	3320(2635)	3055(2410)	2990(2350)
35000	-1880	-2460	3540(2960)	3155(2530)	3135(2610)	2915(2420)	2870(2380)
40000	-1470	-1950	3300(2850)	2870(2460)	2930(2520)	2725(2345)	2695(2310)
Supersonic climb							
40000	495	630	7115(6360)	9020(8050)	9070(8110)	9540(8530)	9520(8495)
45000	490	630	6990(6250)	8870(7910)	8925(7970)	9390(8375)	9365(8345)
50000	490	630	6690(5990)	8510(7580)	8550(7630)	8975(8035)	8955(8010)
55000	520	665	6390(5745)	8130(7280)	8170(7325)	8585(7700)	8565(7675)
Supersonic cruise							
56000	540	660	6380(5700)	8050(7125)	8170(7225)	8530(7580)	8510(7540)
60000	440	550	5270(4700)	6630(5885)	6710(5970)	7040(6260)	7020(6230)
65000	330	415	4050(3585)	5100(4490)	5160(4555)	5415(4780)	5385(4745)
Supersonic descent							
60000	290	370	3410(3010)	4325(3810)	4345(3840)	4570(4025)	4560(4010)
55000	290	370	3410(3010)	4320(3805)	4345(3840)	4570(4020)	4555(4005)
50000	290	365	3460(3040)	4380(3830)	4410(3865)	4635(4060)	4620(4035)
45000	270	340	3610(2970)	4065(3730)	4600(3775)	4830(3960)	4810(3935)
40000	210	295	3620(2985)	4080(3740)	4620(3790)	4845(3985)	4825(3960)
Subsonic descent							
35000	-590	-785	1915(1720)	1635(1460)	1690(1520)	1560(1400)	1530(1370)
30000	-600	-800	1890(1690)	1595(1420)	1660(1480)	1530(1360)	1495(1330)
25000	-615	-820	1855(1650)	1555(1370)	1625(1440)	1490(1315)	1450(1275)
20000	-635	-840	1805(1600)	1510(1320)	1580(1395)	1450(1270)	1410(1235)

TABLE 6

Effect of air injection on drag

The figures given are the direct reduction in drag and do not include the drag equivalent of the pump power. The values in brackets for small values of injection parameter I are derived from experiment.

Altitude (ft)	Injection Mass Flow (I=0.001) (lb/sec)	Drag reduction (lb) I = 0.0005	0.001	0.002	0.003
Subsonic climb					
5000	292.5	3060(3190)	6000(6320)	8700	9200
10000	272.5	3420(3560)	6500(6850)	9200	9400
15000	250.5	3450(3590)	6320(6650)	8900	9500
20000	230	3300(3440)	6300(6630)	8900	9300
25000	208	2720(2840)	4800(5050)	8500	9050
30000	189	2000(2080)	3900(4100)	6580	7200
35000	124	1600(1680)	3140(3300)	5140	5650
40000	98	1270(1320)	2550(2680)	3920	4400
Supersonic climb					
40000	163.5	3800(3920)	7350(7900)	10300	11500
45000	145	3750(3860)	7250(7800)	10650	12000
50000	128	3600(3710)	7100(7640)	10200	11100
55000	110.5	3440(3540)	6860(7380)	10100	10500
Supersonic cruise					
56000	110.5	3920(4040)	6730(7250)	10140	10910
60000	91.5	3190(3280)	5335(5740)	8110	8790
65000	71.5	2540(2620)	4330(4650)	6670	7330
Supersonic descent					
60000	62.5	2060(2120)	3840(4130)	5900	6340
55000	74	2030(2090)	3820(4110)	5860	6300
50000	87	2040(2100)	3860(4150)	5940	6350
45000	102.5	2090(2150)	3990(4290)	6160	6550
40000	125	2120(2180)	4030(4340)	6220	6680
Subsonic descent					
35000	86.5	850(875)	1629(1710)	2020	2260
30000	94.5	845(870)	1600(1690)	2020	2180
25000	104	830(855)	1600(1690)	1970	2090
20000	113.5	815(840)	1570(1655)	1950	2080
15000	123	800(825)	1550(1635)	1900	2050
10000	133.5	790(815)	1540(1625)	1890	2000
5000	136	775(800)	1520(1600)	1850	2000

TABLE 7

Fuel penalties as a result of air injection
(Air bleed from installed engines or ram intake)

The penalties are expressed as increased fuel consumption (lb/hr) for the case when the injection parameter is 0.0005.

Altitude (ft)	Ram intake	Turbojet engine L.P. compressor	Turbojet engine H.P. compressor	By-pass engine Fan delivery	By-pass engine H.P. compressor
Subsonic climb					
5000	4740	21170	27590	15280	23360
10000	4480	19020	25180	14320	21270
15000	4420	20450	22900	13870	19230
20000	4540	15600	20880	12150	17300
25000	4140	14130	19130	10980	16060
30000	2310	8180	11420	6270	9450
40000	1810	6360	9030	4980	7370
Supersonic climb					
40000	4580	11120	14410	8760	12890
45000	4720	9790	13070	6980	11330
50000	4760	8610	11630	6200	9850
55000	4540	7380	10180	5160	7830
Supersonic cruise					
56000	4240	7430	10460	5610	8520
60000	3180	5990	8590	4860	7610
65000	2800	4570	5480	3910	5180
Supersonic descent					
60000	970	3250	4540	2060	3530
55000	1380	3950	5560	2500	4320
50000	1750	4650	6430	3060	5140
45000	2060	5390	6960	4230	6010
40000	2840	6680	8290	4990	7050
Subsonic descent					
35000	1065	4180	5370	2780	4350
30000	1050	4720	6070	3310	4830
25000	1070	5350	6890	3720	5510
20000	1080	5680	7740	4060	6310
15000	1100	6680	8630	4870	7040
10000	1110	7410	9580	5480	7840
5000	920	7700	9900	5760	8150

TABLE 8

Effect of air injection
(Air derived from boundary layer bleed)

Altitude (ft)	Mass flow available (lb/sec)	Net Drag Reduction (lb)	Fuel saving (lb/hr)	Horsepower available
Subsonic climb				
5000	452	3400	3030	1400
10000	415	3720	3390	1540
15000	371	3350	3080	1730
20000	332	3220	2980	1820
25000	276	2100	1970	1450
30000	224	1560	1480	1120
35000	182	1210	1170	860
40000	148	1070	1060	710
Supersonic climb				
40000	222	3710	4600	3280
45000	195	3650	4550	3300
50000	173	3600	4540	3240
55000	151	3580	4540	3220
Supersonic cruise				
56000	146	3820	4890	3200
60000	124	2550	3260	2710
65000	101	2000	2560	2200
Supersonic descent				
60000	110	2380	3040	2370
55000	126	2150	2750	2140
50000	141	1920	2460	2030
45000	160	1770	2210	2020
40000	180	1450	1560	2020
Subsonic descent				
35000	140	450	420	260
30000	155	450	420	125
25000	171	465	435	120
20000	195	480	440	40
15000	211	460	420	0
10000	230	450	410	0
5000	242	430	390	0

TABLE 9

Boundary layer bleed at intake lip

Fuel saving as a result of using boundary layer bleed air to give thrust.

Altitude (ft)	Compressors driven by installed engines						Ingestion by by-pass engine	
			Net fuel saving (lb/hr)					
	Thrust (lb)	Compressor H.P.	H.P. shaft (turbo - jet)	L.P. shaft (turbo - jet)	H.P. shaft (by-pass)	L.P. shaft (by-pass)	"Cold" thrust (lb)	Net fuel saving (lb/hr)
Subsonic climb								
5000	10350	2060	7740	6770	6990	6690	5460	12060
10000	10150	2155	7705	6685	6870	6540	5210	11250
15000	9990	2150	7775	6770	6775	6440	4875	10360
20000	9640	2310	7345	6260	6455	6080	4410	8850
25000	7860	1860	5920	5055	5020	4700	3505	7020
30000	6240	1445	4410	3730	3840	3555	2730	5655
35000	4950	1125	3295	2780	2850	2590	2125	4435
40000	4000	905	2470	2055	2120	1900	1790	3580
Supersomic climb								
40000	10000	5875	9950	8645	9840	10235	5040	10900
45000	9950	6260	9190	7635	8770	9360	4420	10065
50000	9950	9790	9410	7010	8120	9210	5200	11355
55000	9780	12900	8780	5520	6460	7990	4770	11165
Cruise								
56000	9660	13790	8460	4550	6150	7340	4350	10870
60000	8210	11690	6995	3690	4950	6180	3910	9385
65000	6690	9510	6470	3020	3640	4840	3400	7690
Supersonic descent								
60000	6130	5500	5170	4135	4520	5240	2420	5585
56000	6200	4290	5375	4825	5080	5795	3380	6700
50000	6200	3620	5455	5000	5280	5995	3490	6715
45000	6220	3040	5560	5350	5490	6290	3740	6825
40000	6230	2295	5675	5625	5775	6485	3815	6970
Subsonic descent								
35000	2650	420	1320	1200	1070	1095	1570	2635
30000	1670	385	1345	1230	1100	1125	1360	2695
25000	2700	355	1375	1270	1135	1160	1230	2890
20000	2820	340	1490	1390	1240	1265	1225	3155
15000	2815	320	1480	1290	1240	1265	1220	3500
10000	2830	275	1510	1425	1275	1300	1200	3520
5000	2600	255	1300	1220	1085	1105	1200	3555

TABLE 10

Foreign gas injection

Altitude (ft)	Drag reduction (lb)	Fuel saving(lb/hr) Turbojet engine	By-pass engine	Hydrogen Mass flow (lb/sec)	Helium Mass flow (lb/sec)
Subsonic climb					
5000	4920	4330	4030	87.3	203.7
10000	5035	4520	4130	81	189.0
15000	5095	4580	4170	74.4	173.6
20000	5185	4660	4250	67.8	158.2
25000	4245	3810	3480	56.1	130.9
30000	3430	3090	2810	45.9	107.1
35000	2740	2460	2245	37.2	86.8
40000	2180	1960	1785	29.4	68.6
Supersonic climb					
40000	5880	7540	7450	48.9	114.1
45000	5795	7410	7540	41.1	95.9
50000	5625	7200	7300	38.1	88.9
55000	5420	6940	7180	33.9	79.1
Cruise					
56000	5390	6900	7220	33.0	77.0
60000	4590	5880	6250	27.3	63.7
65000	3645	4660	4960	21.6	50.4
Supersonic descent					
60000	3160	4050	4300	23.1	53.9
55000	3170	4060	4240	25.8	60.4
50000	3175	4065	4170	29.1	67.9
45000	3295	4220	4310	33.0	77.0
40000	3325	4260	4230	37.5	87.5
Subsonic descent					
35000	1450	1310	1190	25.8	60.4
30000	1430	1290	1170	28.2	65.8
25000	1410	1270	1155	30.9	72.1
20000	1390	1250	1140	33.9	79.1
15000	1380	1240	1130	36.9	86.1
10000	1360	1225	1115	39.9	93.1
5000	1340	1205	1100	40.2	93.8

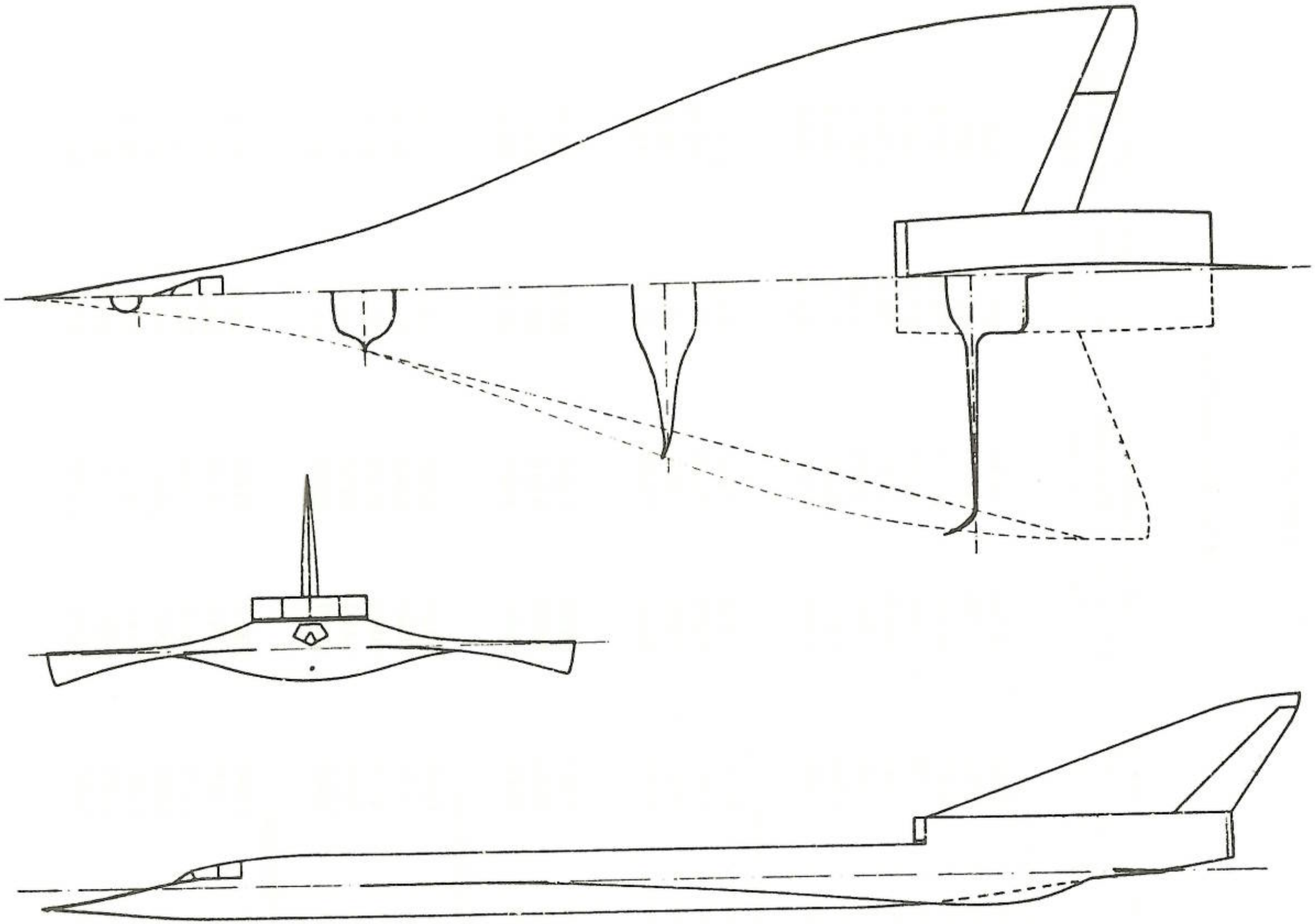
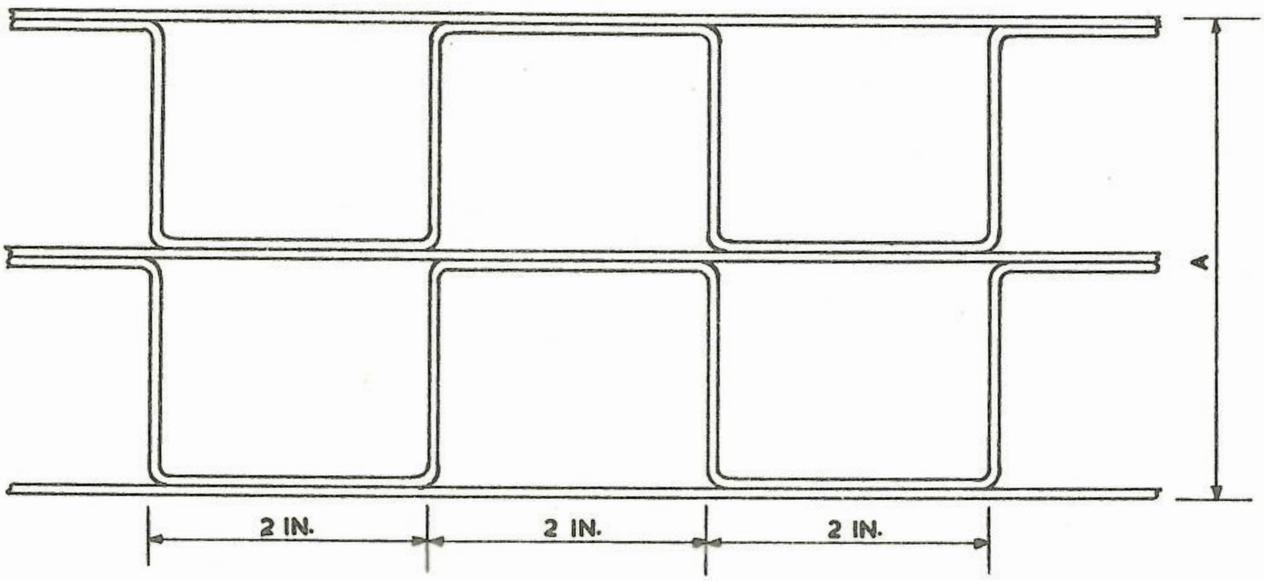


FIG 1. THE BASIC AIRCRAFT

Scale:- 24 ft. to 1 in. (1 : 288)



$A = 4.14$ in. for $C_Q = 0.0002$

$A = 3.24$ in. for $C_Q = 0.00015$

Fabricated from 0.060 in. thick sheet

FIG. 2. THE BLEED LAYOUT