Power Units for Very High Speed Winged Vehicles

R. R. JAMISON

Chief Research Engineer, Bristol Siddeley Engines Ltd., Filton, Bristol, England

SUMMARY

The paper is a survey of the power units which are likely to be available in engineering form in the next ten to twenty years for winged vehicles able to fly within the atmosphere. Speeds in the band Mach 3 to Mach 8 have been considered in four fields:

(1) Long range high speed transports.
(2) Military combat aircraft.
(3) Guided Missiles.
(4) Space Launchers.

In the first two of these categories variants of duct burning turbofan engines, operating as ramjets above Mach 3, give the best solutions. Guided missiles may be served by rockets for short range interceptor roles while ramjets confer benefits at longer ranges. The hybrid air-augmented rockets may also have advantages.

For winged recoverable space boosters, air-breathing power units offer potential advantages, but their 'state of the art' is not yet advanced enough to displace rocket motors.

An analysis is given of the matching procedure for a turbofan-ramjet powerplant for a long range Mach 4 transport aircraft.

1. INTRODUCTION

The term 'Winged Vehicles' is used here to describe various forms of aircraft, either manned or unmanned which fly through the atmosphere and have wings to provide lift. The lift of the wings may be used to sustain the weight of the aircraft and also to provide lateral forces required to manoeuvre it. Such winged aircraft can, in some circumstances, pass beyond the effective atmosphere into a 'space' environment in which the wings would have no lift. However, it is flight within the atmosphere, with lifting wings, with which we are concerned here. In this setting we are looking at the problems of the propulsion of aircraft at high speeds. The phrase 'Very High Speed' serves to indicate broadly the field of speed into which engineering enquiry is moving, beyond the frontiers of existing experience. Manned aircraft are operating now at speeds up to Mach 3 and winged missiles at higher speeds, so for our present purpose we are concerned with propulsion in the atmosphere at speeds above Mach 3, about 1700 knots.

2. Fields of Application

If we look at the potential applications for high speed winged vehicles, we can identify four principal fields:

(1) Long range high speed transport, civil or military.
(2) Military combat aircraft.
(3) Guided missiles.
(4) Winged recoverable acceleration vehicles for space launching purposes.

In each case the application calls for a particular kind of duty from the powerplant which affects the general design philosophy and the engineering techniques which will be needed. Accordingly, it appears useful to survey each of these main fields to find what the general operational requirements are likely to be and the nature of the powerplants to match them.

2.1. *Long range high speed transport*

There is a generation of supersonic civil transports at present emerging to operate in the Mach 2 to Mach 3 band, while military aircraft are already operating at about Mach 3. The next significant step in speed would take us into the Mach 4 to 5 band (say, 2300 to 3000 knots). Aircraft operating at these speeds would, in general, use stage lengths of more than 2000 nautical miles in order to get the benefit of the speed capability.

In their civil form, such aircraft would be used to transport passengers and freight with adequate standards of economy, reliability, comfort and safety. In their military form, they would still basically be transports but, in addition to carrying passengers and stores, they may fly missions for reconnaissance or for the carriage of offensive weapons. From the powerplant designer's point of view, the requirements of the civil and military forms will generally be similar, but there will be variations in emphasis in the power specifications to take account of their different missions. By way of example the military aircraft on active operations will not be much concerned about noise limitation in the form of either jet noise or sonic bangs. As a result, they will be able to employ as much reheat as they wish for take-off and climb and follow a relatively low-altitude high-thrust trajectory during climb, with consequent benefits in powerplant weight. On the other hand, while the civil transport will be flown at heights and speeds to give the fastest or most economical journeys, the military machine may cultivate altitude for its own sake or require an emergency high speed capability.

Nonetheless, fundamentally they will be similar aircraft which will call for the same broad operating characteristics from their engines. In particular, despite the very high speed cruise requirement, it will still be necessary for the engines to be as fully effective at the slow speed end of the operational spectrum as the present-day subsonic transports. This means that in addition to facing the engineering tasks posed by the high-speed cruise conditions, it will be necessary to achieve great operating versatility in the engines. These must be able to reconcile the need for flexible, economical and effective operation during ground taxi-ing, take-off and subsonic flight conditions with the demand for high thrust during transonic acceleration and climb, and the ability to operate effectively under the arduous thermal loading met in high supersonic cruise flight.

This need for the powerplant to be efficient and effective at all flight speeds poses an increasingly severe problem as the top speed increases, which is additional to the structural and gas dynamic problems which are intensifying at the high speed conditions. We find that the matching of the characteristics of the components of the powerplant and their integration with the elements of the airframe and its operating spectrum is becoming an activity as important as any in the overall design process.

The kind of powerplant which gives these attributes of performance and flexibility is a ducted fan (or by-pass) jet engine with combustion in the by-pass duct (and possibly also in the gas generator exhaust duct). Such a duct-burning fan jet engine would be designed as an integral system with a variable geometry air intake and variable geometry exhaust nozzles. Provision is made to shut down and isolate the turbo-machinery during the high speed phase so that the powerplant operates then in the ramjet mode. Some typical layouts are shown in Fig. 1. An analysis of the engine design characteristics is given in a later section.

2.2. *Military combat aircraft*

This is a class of aircraft in which the emphasis on different flight phases is very different from those appropriate to transports. In the modern formula the military role calls for short take-off from unprepared fields, high speed low level strike (high subsonic or transonic) and high altitude supersonic combat or reconnaissance. In addition, the machine must have a high time endurance (loiter), high acceleration to combat and a long, preferably high

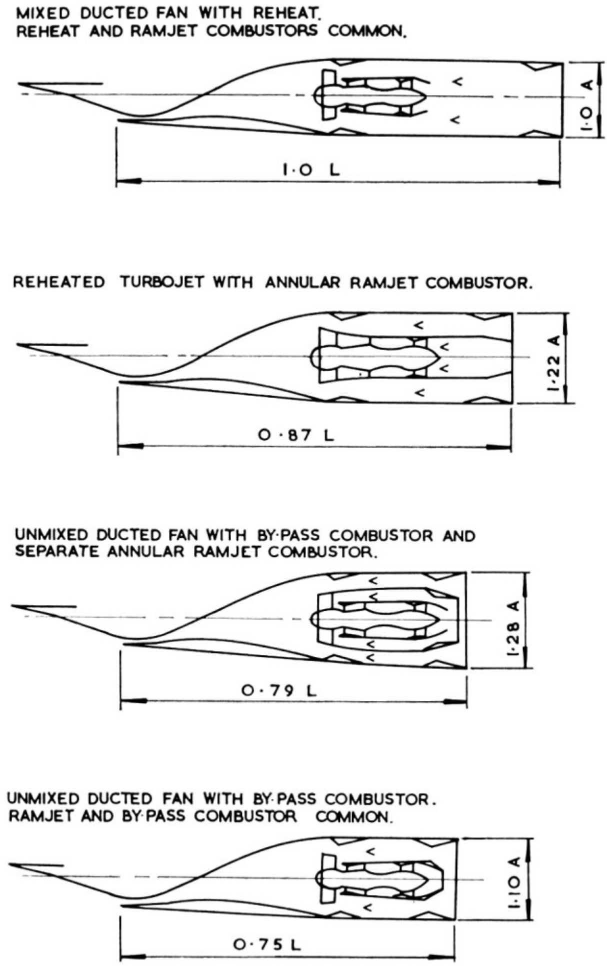

FIG. 1 — Typical layouts of duct burning turbofans (turboramjets) for Mach 4 operation

speed, ferry range. At present, aircraft of this type have a top speed around Mach 2·5. If this were pushed into the Mach 4 to 5 band it would probably be as a result of a change in role in which pursuit and inspection of high speed aircraft would figure, in cases where it would be important to have the service of a human crew. In other circumstances it might seem appropriate to complete the mission with a guided missile. This would react back on the powerplant specification. However, the optimum powerplant in these combat roles again crystallises in the form of a duct-burning turbofan, but the mix of components would be altered to suit the changed emphasis in the mission profile.

As an example, the use of variable sweep wings in an aircraft which is required to have long endurance at low speed, would call for a power unit able to preserve a low fuel consumption to very low thrusts. This is a difficult requirement when high performance at very high speeds is also called for. Low *specific* thrust would be needed to avoid installation drag, and it may well emerge that variable geometry will be needed in the engine components to match the variable geometry airframe. *See* Fig. 2.

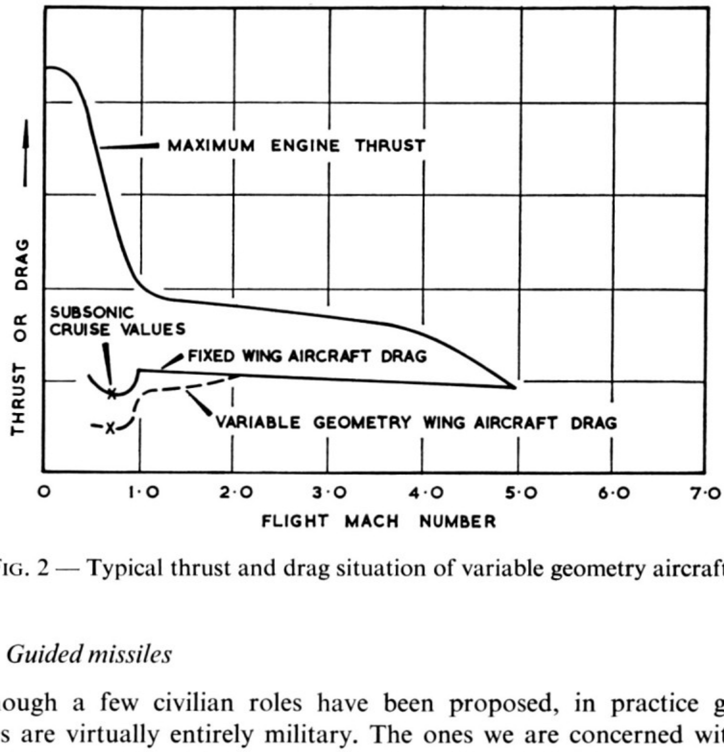

FIG. 2 — Typical thrust and drag situation of variable geometry aircraft

2.3. *Guided missiles*

Although a few civilian roles have been proposed, in practice guided missiles are virtually entirely military. The ones we are concerned with are those which use wings to manoeuvre in the atmosphere and, in particular, those operating at very high speeds. The duties are quite different compared with those of manned aircraft as the mission is usually highly specialised and there is little call for versatility in the power units. In reconnaissance or target missiles recovery and re-use are desirable but combat missiles are in general expendable. The two forms of power unit which are appropriate for these purposes are rockets and ramjets, singly or in combination. Rockets, especially solid fuelled rockets, are simple and can provide very high acceleration thrusts, but thrust control is difficult. Accordingly, in manoeuvring winged missiles, their use is most appropriate for relatively short ranges and high latitudes. Rocket motors, of themselves, have no speed limitation and so we find they can give a good performance in the Mach 4 to 7 band of speed in high altitude interception at moderate ranges.

The air-breathing ramjet engine, which needs a rocket to accelerate it to operating speed, has a much lower fuel consumption than a rocket, has a fully controllable thrust, and also has a thrust which automatically matches missile drag as speed and altitude vary. On a weight basis, a ramjet missile takes over from rocket propulsion at a range of about 10 nautical miles at sea level, increasing to roughly 25 nautical miles at 80,000 ft altitude. If the mission calls for a substantial cruise component or for a wide range of operational altitudes the ramjet confers definite performance advantages.

With present technology, ramjet engines for missile purposes can be designed to operate at speeds up to about Mach 7 (4000 knots). Figure 3

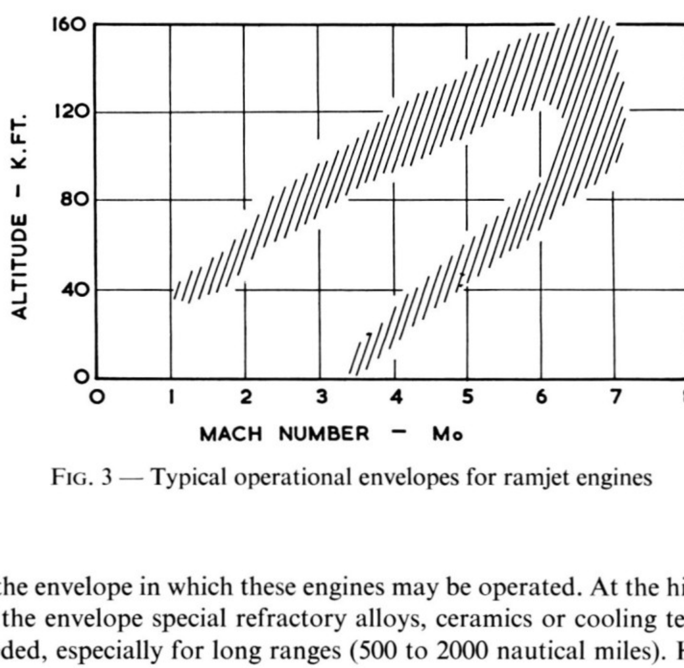

FIG. 3 — Typical operational envelopes for ramjet engines

shows the envelope in which these engines may be operated. At the high speed end of the envelope special refractory alloys, ceramics or cooling techniques are needed, especially for long ranges (500 to 2000 nautical miles). However, for the short duration interceptor type missions, ablation techniques are extremely effective for protecting the hot parts of the engines. The general configurations of a range of missile engines are shown in Fig. 4.

2.4. *Space launchers*

The present technique of space launching is simple and well established: vertical take-off by means of rocket motors in an unwinged multi-stage

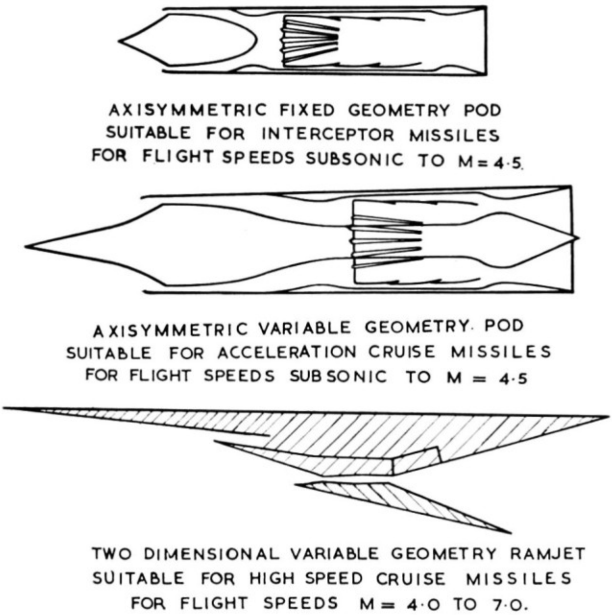

FIG. 4 — Examples of ramjet configurations

vehicle with the total loss of the booster stages and rudimentary recovery of the orbiting payload. If space missions become routine and, in particular, if manned orbiting space stations are to be constructed in space and maintained on a long term basis with a crew aboard, it will be necessary to have a regular ferry service between base stations on earth and the orbiting stations. This brings in the concept of the 'space transporter' as a vehicle which can make these journeys on a routine basis. In this context the present simple expendable boosters would have serious drawbacks. First, it would be economically highly desirable to recover these expensive vehicles for re-use and, second, it would be most important to limit the launch and re-entry accelerations to values which could be safely sustained by ordinary people. It would also be necessary to have a high degree of control and manoeuvrability to enable the stages to be guided accurately to their landing ground. These considerations point strongly to the need for the booster stages to have wings to generate lift in the atmosphere, especially for the first stage. After the re-entry phase the vehicle would fly as an aeroplane and land on a runway in the normal way, in a horizontal attitude. It would also be most desirable, in a ferry type vehicle like a space transporter, that it should be handled like a conventional aircraft in the take-off phase as well. This would enable it to taxi on the ground and take off from the runways of an airfield. This would be most convenient in comparison with the use of facilities for take-off in a vertical attitude with rocket propulsion in the current fashion.

However, the rocket motor has the clear advantage that it exists and is available for immediate application. On the other hand, air-breathing engines for very high speeds are still in the research and early development phases and one or two cycles of evolutionary application will be needed before they, in turn, become established as effective and reliable power units.

In these circumstances, the rocket propelled space transporter system, Project Mustard, of the British Aircraft Corporation[1], offers an excellent lead-in to this difficult field. *See* Figs. 5 and 6. Although, from the user's

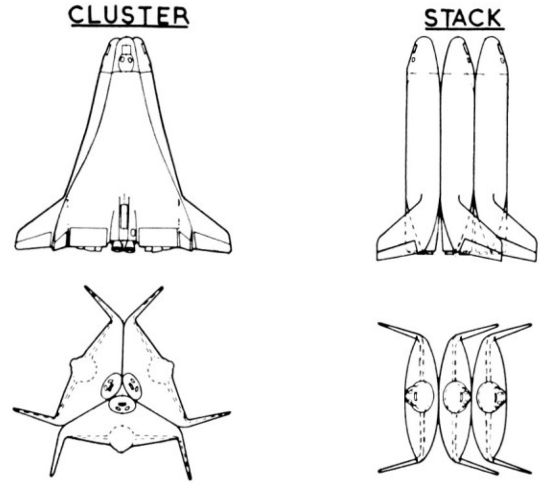

FIG. 5 — The space transporter proposal, Project Mustard, of the British Aircraft Corporation

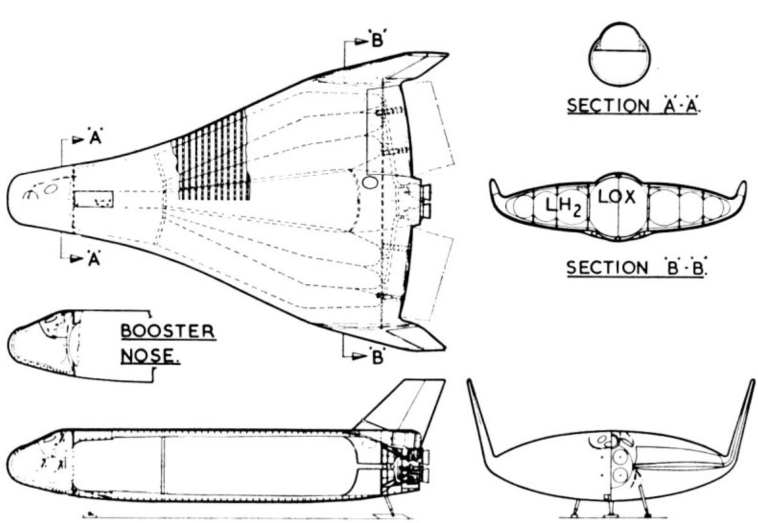

FIG. 6 — Layout of Project Mustard

viewpoint, it would suffer from the inflexibility and inconvenience inherent in the vertical launch technique, it nonetheless represents a practical attack on a first generation proposal for this class of vehicle.

To look ahead we need to know something about the powerplants which may evolve and become serviceable in the next decade. In Fig. 7 and Fig. 8 are

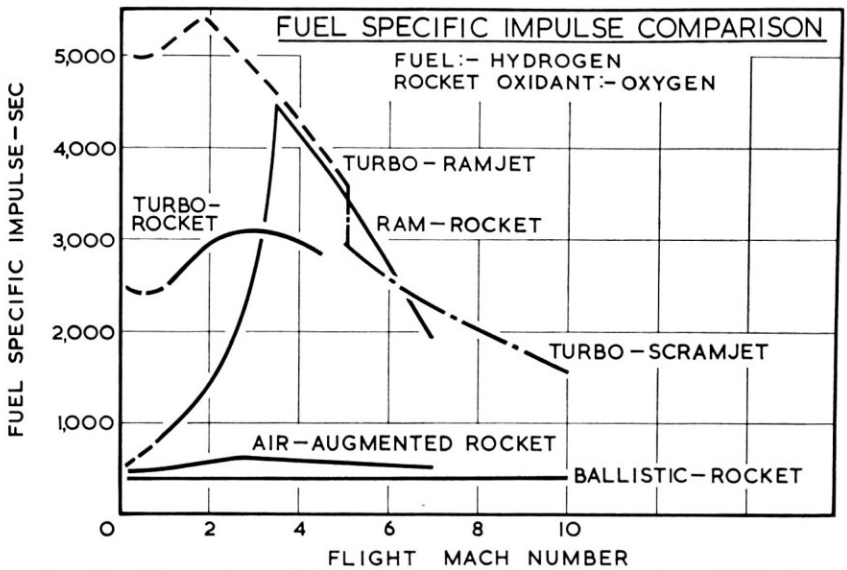

FIG. 7 — Comparison of the variation of fuel specific impulse with Mach number of a range of high speed power plants

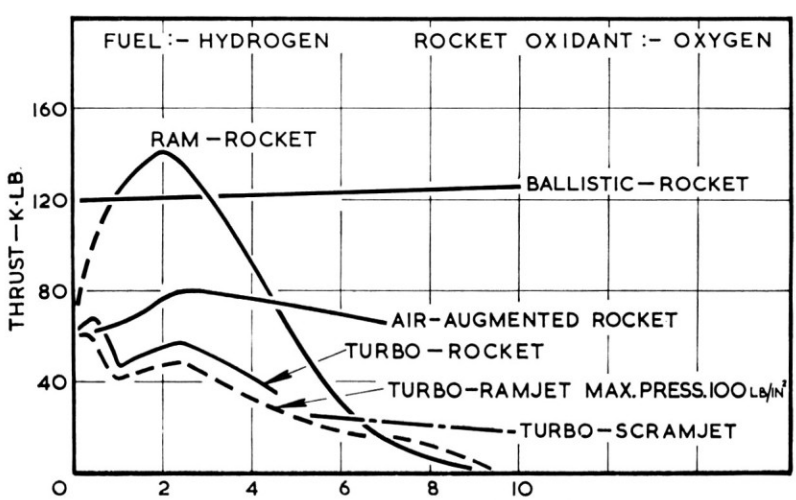

FIG. 8 — Comparison of the net thrust of different power units as a function of Mach number

plotted, against Mach number, respectively, the fuel specific impulse and the thrust of a group of alternative powerplants for a possible space transporter. The thrusts are based on a nominal all-up weight at take-off of 100,000 lb. Thus, for vertical take-off with rockets a thrust exceeding 100,000 lb is used but, for alternative power units for winged aircraft using a horizontal take-off, thrusts lower than this weight are permissible. This 100,000 lb all-up weight is arbitrary for comparison purposes. All the engines use hydrogen fuel and, in the rocket examples, liquid oxygen for the oxidant.

The powerplants compared are:

(1) *Turboramjet*

A turboramjet can be defined as a turbomachine and a ramjet so arranged as to share a common intake and nozzle. The turbomachine can be a pure turbojet or a ducted fan. A take-off thrust-to-vehicle weight ratio of approximately 0·6 is typical for acceleration to the lower hypersonic speeds — assuming horizontal take-off.

(2) *Turbo-scramjet*

A turbo-scramjet is a turboramjet where (by some means not yet determined) the ramjet mode of operation changes over from subsonic to supersonic combustion. It is hoped that the same common intake and nozzle will be used. The take-off thrust-to-weight ratio will be similar to that of the turboramjet.

(3) *Turborocket*

This is a hybrid powerplant system where a low-pressure compressor is driven by a small turbine supplied with fuel-rich combustion products from a rocket chamber. The air from the compressor is mixed and burnt with the fuel-rich efflux from the turbine.

The characteristics of this engine are such that a higher take-off thrust-to-weight ratio is necessary to reach hypersonic speeds, and would be approximately 0·7.

(4) *Vertical take-off rocket*

A multi-stage rocket is assumed with a take-off thrust-to-weight ratio of 1·2.

(5) *Air-augmented rocket and ram-rocket*

In this system the performance of a pure rocket is augmented by inducing and burning air with the fuel-rich rocket efflux. At low speeds, air is drawn in due to the pumping effect of the high-velocity rocket efflux. The actual increase in the level of performance at these speeds is difficult to estimate but it is doubtful if the increase would exceed 20%.

At the higher speeds, air is forced in due to the ramming effect ($M > 1{\cdot}0$).

The performance can then be assessed by considering the system to operate as a ramjet in parallel with a rocket.

The air-augmented rocket is defined as a combination of rocket and ramjet where the air/propellant flow ratio is up to about 3. The ram-rocket we have defined as a combination of rocket and ramjet where the air/propellant flow ratio is greater than that of the air-augmented rocket.

Figure 7 shows the gains in fuel consumption, especially at the lower flight speeds conferred by the air-breathing engines. This is illustrated also in Fig. 9 which shows that by using an air-breathing first stage a saving in the

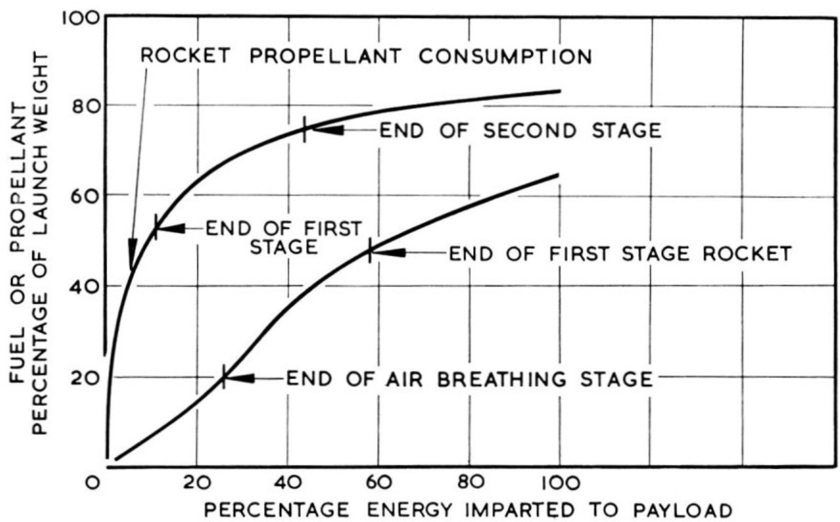

FIG. 9 — Comparison of the fuel consumption of boosters with rocket or air-breathing first stage engines

total fuel consumed during launch into orbit of about 20% of the launch weight would be realised and might be applied to increase the orbiting payload. These figures do not make comparisons of the cost of launching by the alternate means and, in fact, we do not have enough information to form accurate cost estimates. There is no doubt that, at the present time, rockets would have to be used for any space transporter which could be undertaken. On the other hand, it is clear that the potential rewards of air-breathing power units are very great, especially when the convenience and flexibility of operation which they confer on the aircraft are added to their performance advantages. It would seem that a likely path of evolution could be for the recoverable space transporter techniques to be developed with rocket propelled winged vehicles (such as Project Mustard) using vertical launch and conventional horizontal landing. Later versions might be considerably improved by using variations of the air-augmented rocket. On the other hand, the technology of the air-breathing hypersonic power unit is likely to evolve best in applications to long range very high speed transport aircraft. When sufficient progress has been made along these two channels, they may well be brought together in most effective combinations. First, a full understanding must be attained of the problems of providing very high speed air-breathing power units in the transport class (such as duct burning turbofans in combination with ramjets), then their further evolution into the high thrust versions needed for acceleration missions, with their greater thermal and pressure loadings (although of short duration) would be relatively straightforward.

However, an earlier opportunity for exploitation may open up for hybrid engines such as the augmented rocket or the ram-rocket. *See* Figs. 10 and 11. These units would adapt well to conventional rocket motor installations and may, if needed, be used with rocket propelled vertical launch procedure. The ram-rocket in particular would lend itself to the horizontal launch of a winged vehicle as its thrust builds up rapidly with forward speed. In any case, where air augmentation of rocket thrust is used, the trajectory would have to be adjusted to get the best total impulse from the air-breathing component which requires to stay within the atmosphere to deliver its contribution. Also, it must be remembered that the air augmentation of rocket thrust is effective only when the rocket is operating, or at very high speed. This means that its use is virtually confined to the acceleration phase and that it would not be helpful in the return cruise phase of a recovery mission.

There are further points to consider in the turboramjet class of powerplant. In acceleration vehicles there are special requirements in this kind of mission which will distinguish acceleration engines from those used in long range transports. The emphasis is on thrust to obtain a high total impulse during flight within the atmosphere with the least waste of energy spent on overcoming aerodynamic drag. High thrust comes from holding down the altitude-speed trajectory to keep high total pressure in the engine propelling nozzle flow. The relatively high static pressures and temperatures within the powerplant duct system resulting from this course call, in turn, for a heavy engine structure. This effect may be mitigated in two ways. First, by using a simple intake with relatively little geometry variation, intake losses are accepted which diminish the engine boiler pressures at low altitude without too great a penalty in thrust. The fuel consumption suffers, but if a high acceleration is obtained there is an overall gain in performance as well as a simplified and cheaper structure. A similar relief from internal pressure results from using supersonic combustion in the ramjet engine. The feasibility of supersonic combustion has now been established, but the techniques of using it in a flightworthy form are still being evolved[(2)].

Another practical point of difference between acceleration vehicles and

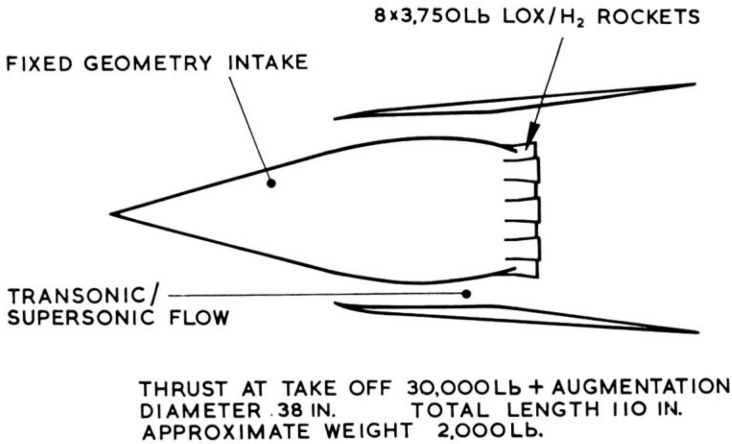

FIG. 10 — Diagram of an axisymmetric air-augmented rocket

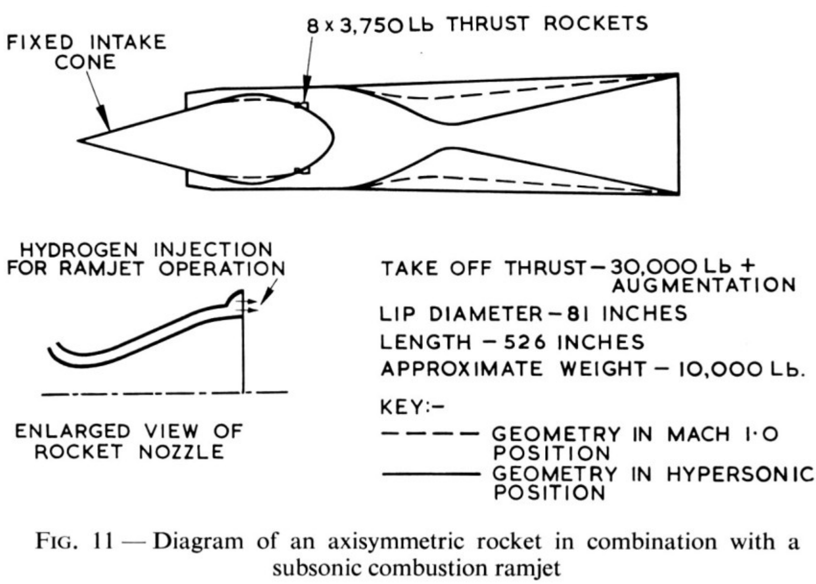

FIG. 11 — Diagram of an axisymmetric rocket in combination with a subsonic combustion ramjet

long range transports arises in the use of liquid hydrogen fuel. In the long range transport the benefit of the high calorific value of the fuel and its value as a heat sink may be largely offset by its large bulk. (Density about $\frac{1}{15}$th of that of kerosine.) High aerodynamic drag and structural problems result from the large volume needed for tankage. In acceleration vehicles, in which much less fuel is carried, these difficulties are removed.

3. Some Design Factors in a High Speed Power Unit

So far we have had a general survey of the applications for very high speed propulsion and of the kinds of power units which might be best suited to the tasks. The more advanced proposals still need a period of research and 'state of the art' improvement before serious design and development of operating systems may be undertaken. In the more immediate future is the class of powerplants where the existing engineering knowledge justifies serious studies and design proposals. There is coming into existence at the present time a class of military and civil 'transport aircraft' (in the wide sense of the term) to operate in the Mach 2 to 3 speed band. In the natural course of technical evolution it is sensible to be studying and acquiring the techniques for the next generationof high speed transports so that by systematic co-ordinated effort the necessary design data and engineering art may be assembled to meet the new requirements.

In this connection it is interesting to see the effect of operating speed on the reach of a transport aircraft. To illustrate this, Fig. 12, a plot has been made of the radius of action of aircraft travelling at different speeds from a chosen origin, in this case London. The plot has been made on a special map projection which has the property that radial distances from the origin are in true linear scale. What the map shows is the distance that an aircraft can reach in two hours flight (take-off to touch-down) at different operating cruise speeds with due allowance for terminal evolutions such as climb, acceleration, let down, approach and landing. Two hours was chosen as a period of reasonable comfort for civilian travel or as giving significant speed of reaction (in a global sense) for military transport purposes. The ratio of the cruise speeds represented by succeeding circles is approximately 1·5 (except that between the Mach 0·8, present subsonic, circle and the Mach 2·0 circle where the ratio is 2·5). The diagram shows the striking increase in the reach for a two hour journey which is conferred by the increasing speeds. This suggests that from the user's point of view an increase of speed from the present supersonic transport figure of around Mach 2·5 to around Mach 4 for a new generation would be extremely valuable. From the designer's point of view, also, this would represent a reasonable step to take to keep effectively within the scope of available technology. In particular, the most searching problems are likely to be those associated with the effect of the wight stagnation temperature on structures. At Mach 4 this temperature flould be about 600°C (1100°F), and this, which would represent a maximum structural temperature outside the combustion zones, would be within the capability of available alloys.

We can then look at some of the ways in which the principal design para-

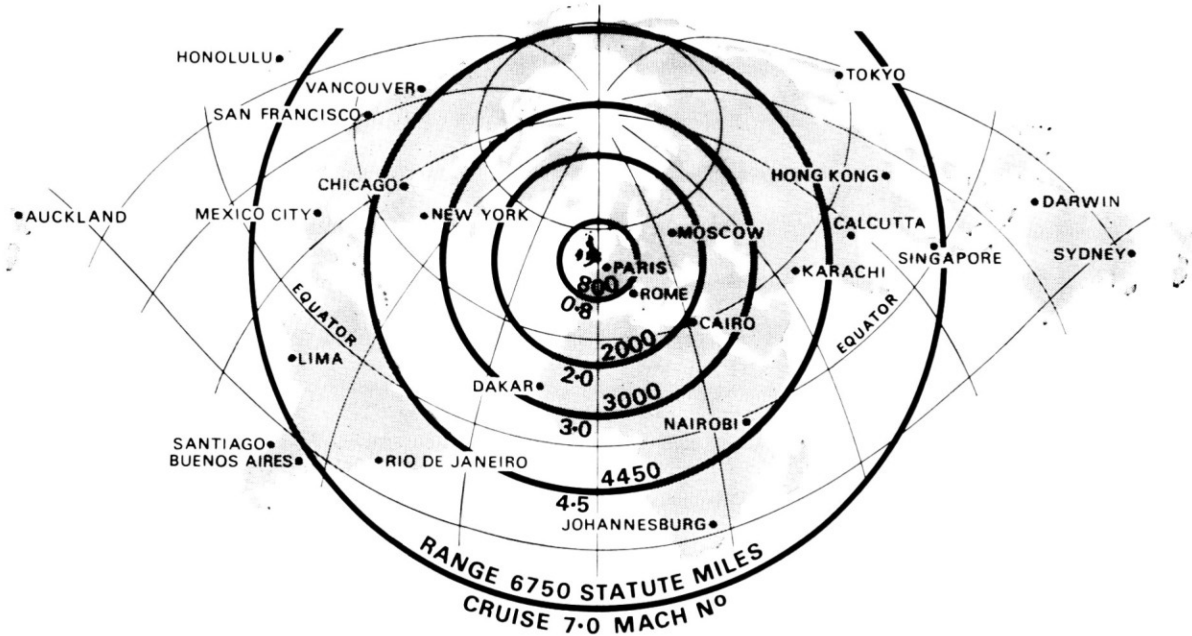

FIG. 12 — The effect of cruise Mach number on range for a two hour block time from London

meters of such a powerplant may be chosen. The aim is to match the mission requirements and obtain optimum performance with due attention to the reconciliation of the conflicting demands of the different phases of the mission profile.

The subject for study is the powerplant for a long range transport aircraft intended to operate a 3000 nautical mile stage length with reserves with a cruising speed of Mach 4, 2300 knots.

The following main airframe assumptions were made:

All-up weight at take-off — 400,000 lb.

Supersonic cruise Mach number 4, 2300 knots.

Subsonic cruise Mach number 0·75, 430 knots.

Range — 3000 nautical miles.

L/D at $M=4$ cruise 7·6 } *See* Fig. 13.
L/D at $M=0{\cdot}75$ cruise 14 }

Flight plan as per Fig. 14.

Acceleration required at Mach 1, 25,000 ft $=\frac{1}{3}\,g$.

Cruise thrust 27,500 lb at Mach 0·75 at 36,000 ft.

Six engines assumed.

Nominal payload, 5% = 20,000 lb.

Aircraft empty weight = 45% = 180,000 lb.

Total fuel load = 50% = 200,000 lb.

Note: The total allocated to aircraft empty weight and payload is 50%. Improvements in aircraft structure or powerplant weights would benefit the payload.

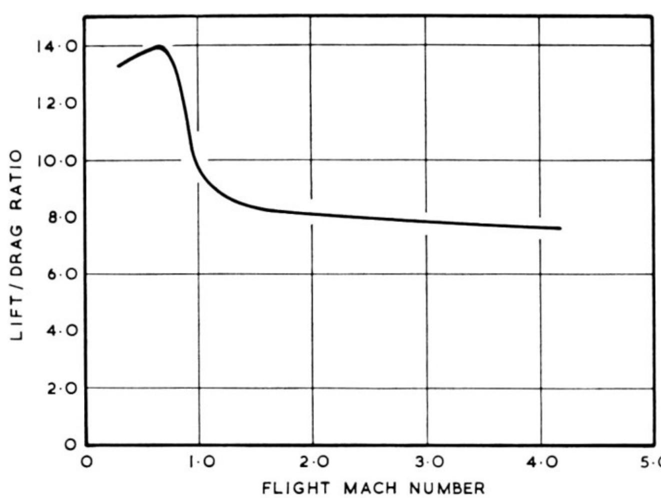

FIG. 13 — Assumed variation of lift/drag ratio with speed for a Mach 4 aircraft

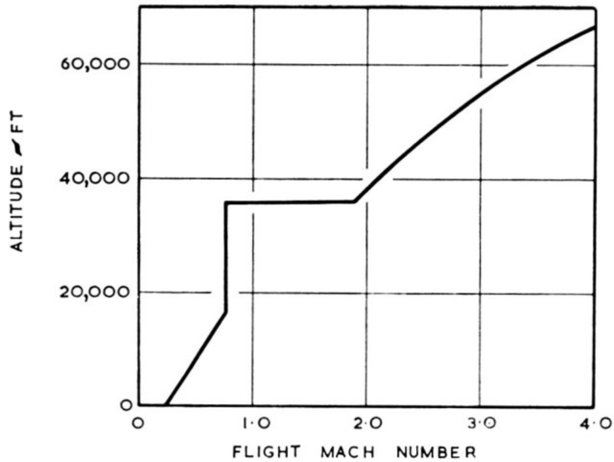

FIG. 14 — Typical flight plan for a Mach 4 transport

4. ENGINE ASSUMPTIONS

(1) A total installed thrust of 165,000 lb at Mach 1·0 at 36,000 ft.

(2) A turbofan layout is assumed, *see* Fig. 15, with thrust augmentation obtained by burning fuel in the fan duct.

(3) At high Mach numbers the airflow may be made to by-pass the turbofan. With combustion in the fan duct the engine would then run as a ramjet and the turbo-machinery would be isolated and insulated from the hot environment of the powerplant airflow.

(4) Pressure ratio, sea level static, 20:1.

(5) Maximum turbine entry temperature, 1500°K.

(6) A range of by-pass ratios is examined from 0 to 5.

(7) An 'unmixed' ducted fan layout. This is preferred to maintain good performance over a wide speed range.

The value of 20 :1 pressure ratio seems a good compromise for the mission assumed. A higher value might be appropriate if a high by-pass ratio were selected (with a correspondingly high turbine entry temperature) if the mission placed a great emphasis on subsonic performance. There would, however, be penalties in drag at high supersonic cruise conditions and in installation weight.

There are a great many ingredients in the 'mix' which goes to make a good powerplant for a high supersonic long range transport, not only in the make-up of the powerplant itself, but also in the concept of the airframe and its mission. Many iterations of the process of blending these 'ingredients', or design factors, have to be performed before a satisfactory solution is obtained.

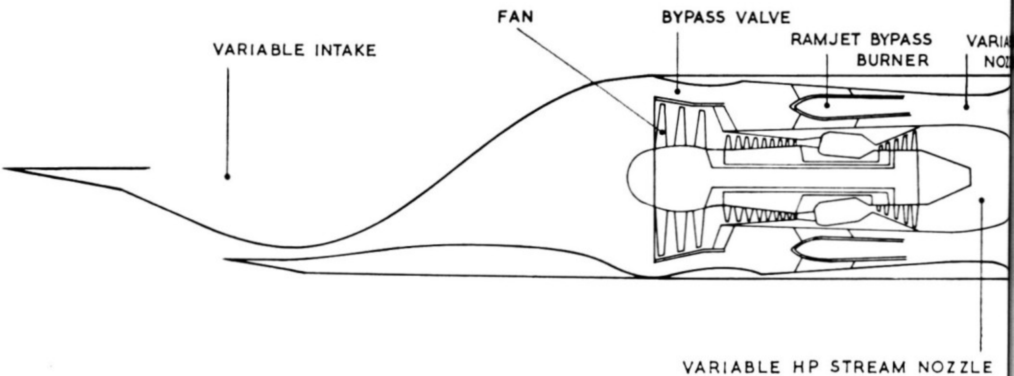

FIG. 15 — An example of a turboramjet engine for Mach 4–5 operation

For, in addition to the large number of design factors to reconcile, there are many conflicting operating conditions to meet as well.

One of the most important properties of the powerplant to consider is the by-pass ratio of the gas turbine and its relationship with the ramjet constituent used at high speed cruise conditions. Among possible arrangements are:

(*a*) Pure turbojet operating over the whole flight envelope.

(*b*) A pure turbojet in conjunction with separate ramjets.

(*c*) A ducted fan engine with fan duct combustion, passing over to a ramjet mode at high speed.

We can also distinguish in the fan engine between a 'mixed fan' and an 'unmixed fan'. In the 'mixed fan' the flow from the fan is mixed with that from the gas generator exhaust before the final nozzle. Reheat is then applied to the whole engine flow. In the 'unmixed fan' the two flows (from the fan and from the gas generator exhaust) are kept separate and are separately controlled by individual propelling nozzles. Combustion for thrust augmentation may be applied to either or both the streams. *See* Fig. 16. The unmixed fan, by permitting separate control of each stream by its own propelling nozzle system, allows better matching of the components and tends to give better performance, especially at high flight speeds. *See* Figs. 17, 18 and 19. In the present investigation unmixed fans are considered with the by-pass ratio at the sea level static rating point varying from 0 to 5. Thus, we are comparing a series of engines for the given duty, all of which are rated at the critical transonic flight condition to give 27,500 lb of thrust at Mach 1·0, 36,000 ft altitude, with a tailpipe temperature (duct burning or reheat) of 2000°K.

Now, in a civil transport, operating, for example, over the Atlantic, it is important from a safety aspect to be able to fly the whole journey at subsonic speed. This is to cater for a possible case in which the aircraft is at the mid-

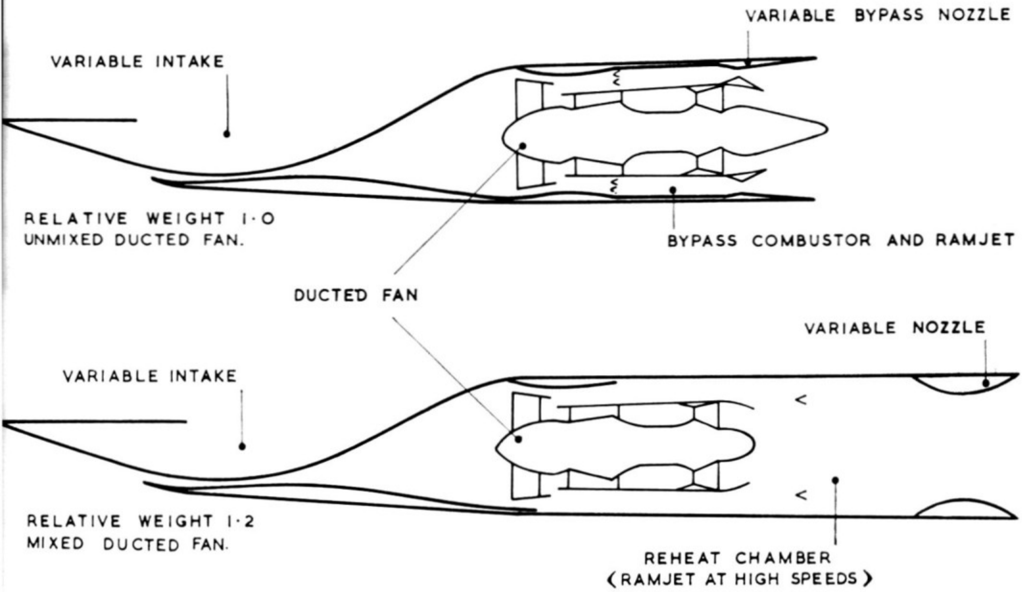

FIG. 16 — Diagrams showing the principle of turboramjets with (above) an unmixed ducted fan configuration and (below) a mixed configuration

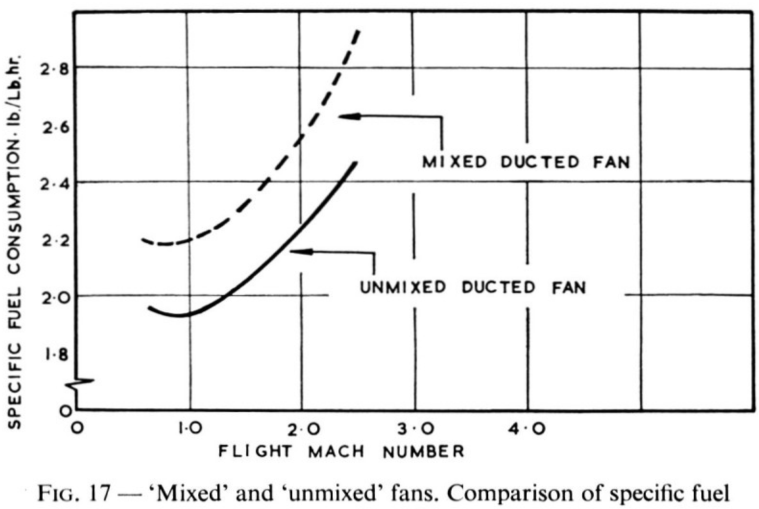

FIG. 17 — 'Mixed' and 'unmixed' fans. Comparison of specific fuel consumption

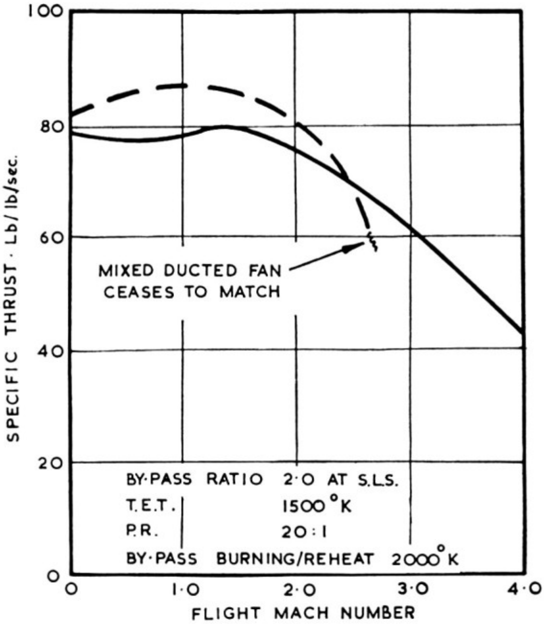

FIG. 18 — 'Mixed' and 'unmixed' fans. Specific thrust as a function of Mach number

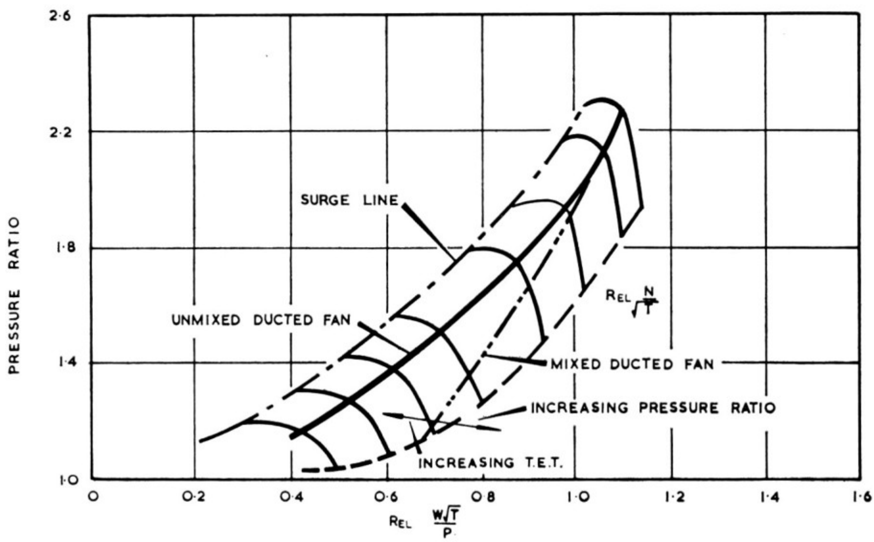

FIG. 19 — 'Mixed' and 'unmixed' fans. Comparison of the running lines plotted on the fan characteristics

way point and has some failure or malfunction in its structure or systems which force a deceleration to subsonic speed and the completion of the flight at this speed. The subsonic performance of the powerplant is then a critical design factor. This is sensitive to by-pass ratio so an examination has been made of the effect of this on the cross-sectional area of the nacelle, Fig. 20, and on the total weight of the powerplant, Fig. 21. The subsonic cruise specific fuel consumption on Fig. 22 shows the net internal s.f.c. and the 'installed s.f.c.' which allows for the intake spill and the base drags. These results are combined in Fig. 23 to give the total weight of the powerplant plus the fuel consumed in a 3000 nautical miles subsonic cruise phase. Now the cross-sectional area of powerplant needed in the ramjet phase for supersonic cruise is close to the minimum for the turbofan corresponding to a by-

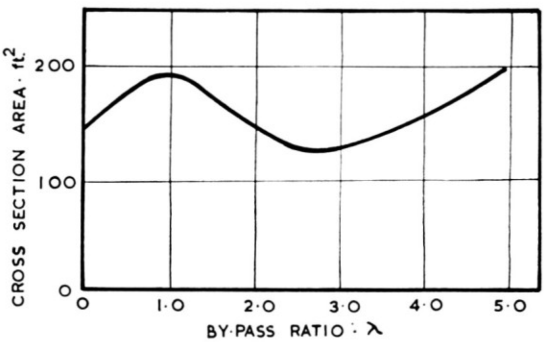

FIG. 20 — Mach 4 transport aircraft. The effect of by-pass ratio on the powerplant cross-sectional area

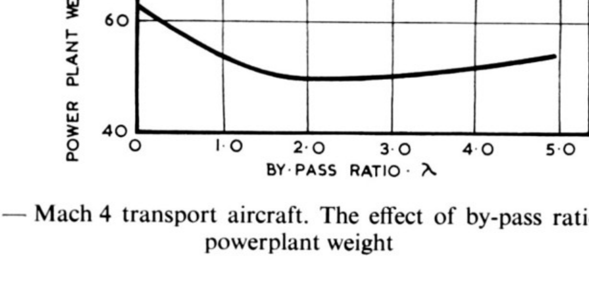

FIG. 21 — Mach 4 transport aircraft. The effect of by-pass ratio on the powerplant weight

pass ratio of 3 (Fig. 20). As the minimum weight of powerplant plus fuel also comes between by-pass ratios of (λ) of 3 and 5, and as with increasing λ excess supersonic drag would be caused, it looks as if we should choose $\lambda = 3$ as the best compromise on this iteration.

There would also be the problem (with high by-pass ratio engines) of finding ground clearance for the underwing aft-mounted powerplants

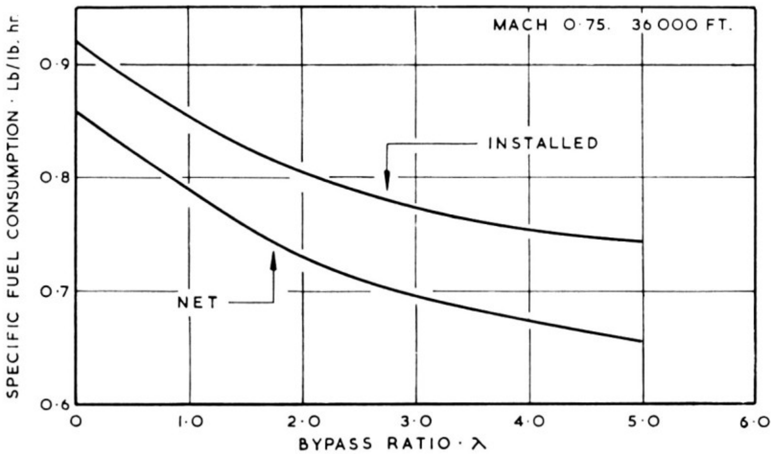

FIG. 22 — Mach 4 transport aircraft. The variation of the powerplant specific fuel consumption with by-pass ratio; Mach 0·75 at 36,000 ft

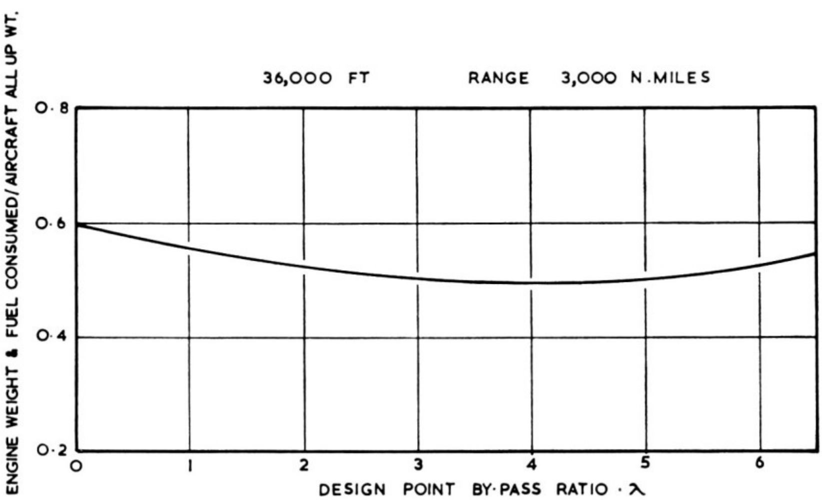

FIG. 23 — Mach 4 transport aircraft. The variation of 'engine-plus-fuel' weight with by-pass ratio for 3,000 nautical miles cruise at Mach 0·75 at 36,000 ft

favoured in supersonic aircraft layouts. In this context Fig. 24 is interesting as it shows how, rather surprisingly, the specific impulse, thrust per unit of air mass flow, is virtually unaffected by the by-pass ratio at transonic speed when the tailpipe temperature is kept at 2000°K. The corresponding s.f.c. curves are in Fig. 25.

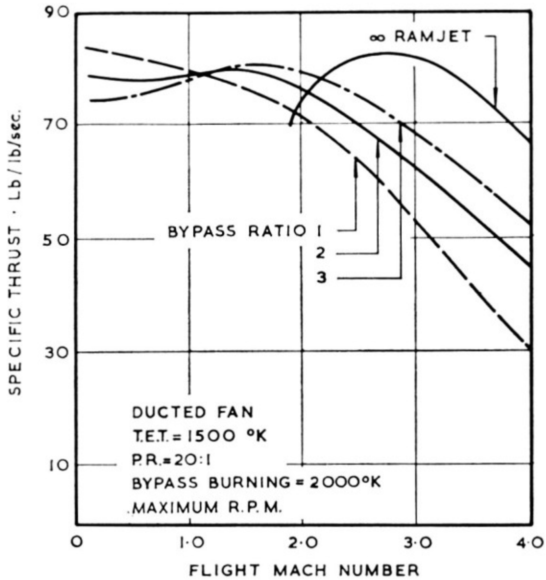

FIG. 24 — Unmixed ducted fans. The variation of specific thrust with by-pass ratio and Mach number

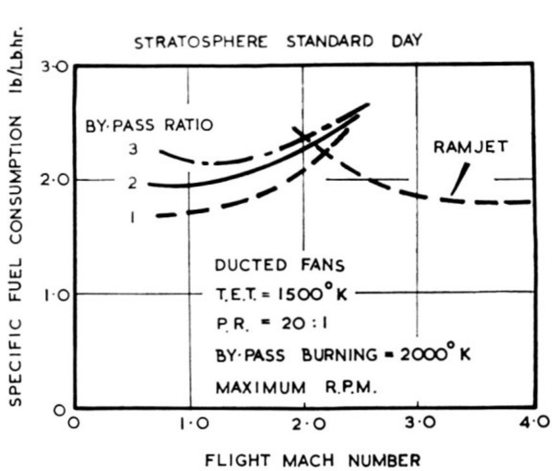

FIG. 25 — Unmixed ducted fans. The variation of specific fuel consumption with by-pass ratio and Mach number

5. Engine Matching for Low Speed Cruise

We have seen how the high supersonic cruise requirement in the ramjet mode is reconciled to a high subsonic duty by choosing the fan by-pass ratio. However, further refinement can be applied. This is especially important where a low subsonic operating speed is a significant part of the mission profile and calling for good economy. This may be sought in military applications where there is need for a long time endurance (loiter) or patrol at low speeds. The problem is essentially due to the fact that the lip area needed to pass the engine air at supersonic speed is considerably larger than is needed for the airflow at the low subsonic cruise conditions. The unwanted air is spilled round the intake lip and causes an increase in the 'installed drag'. A similar drag penalty is incurred in the propelling nozzle base area. The remedy for this low speed low thrust condition is a considerably increased by-pass ratio. In this way the duct area needed for the supersonic condition could be filled with a large flow of low energy air which would eliminate, or greatly diminish, the spill and base drags. If the turbofan is merely throttled back its airflow falls and it moves to an uneconomic, high s.f.c., running condition. Some gain can be made by opening the fan final nozzle to increase

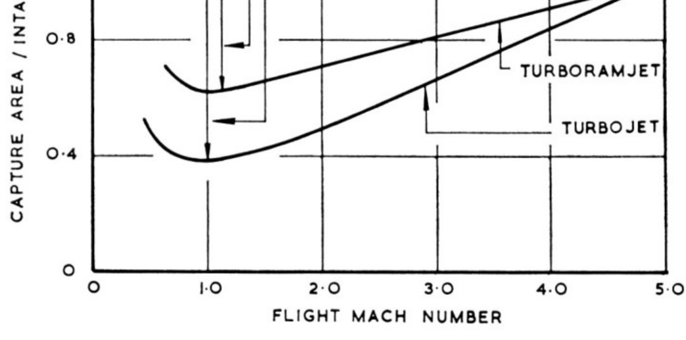

Fig. 26 — The variation of capture area with flight Mach number for different engine configurations

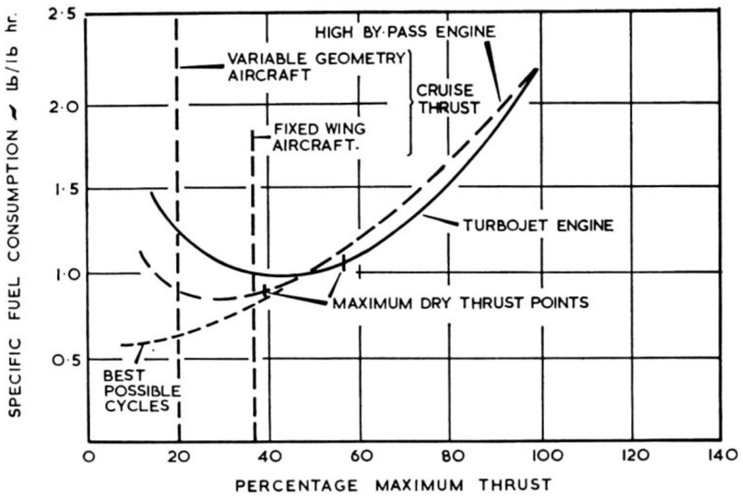

FIG. 27 — The effect of engine and aircraft types on the relationship between thrust and fuel consumption at low speeds

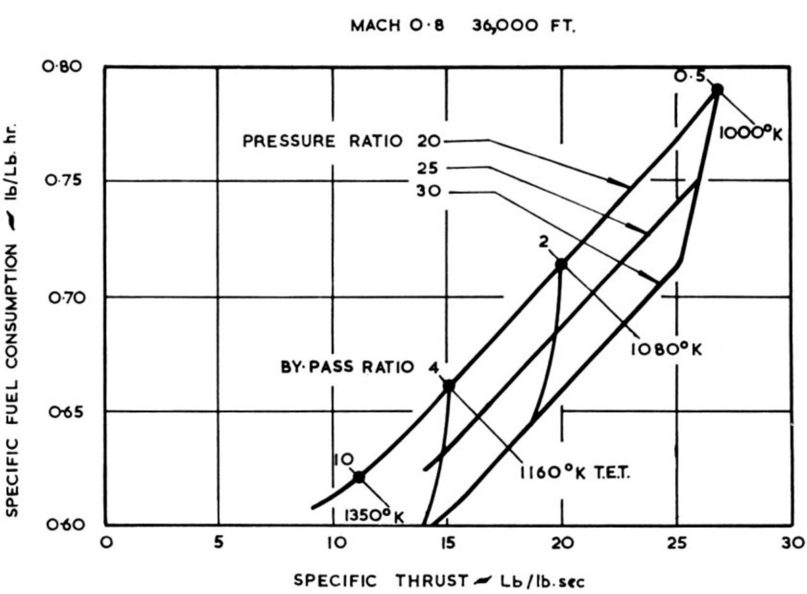

FIG. 28 — Unmixed ducted fans operating at Mach 0·8, 36,000 ft. The effect of the main operating parameters on thrust and fuel consumption

the mass flow while lowering the jet velocity, but this causes the fan efficiency to fall and may undo the benefit of the increased mass flow. The problem is, of course, aggravated in an aircraft with variable geometry wings. *See* Figs. 2, 26, 27, 28, 29 and 30.

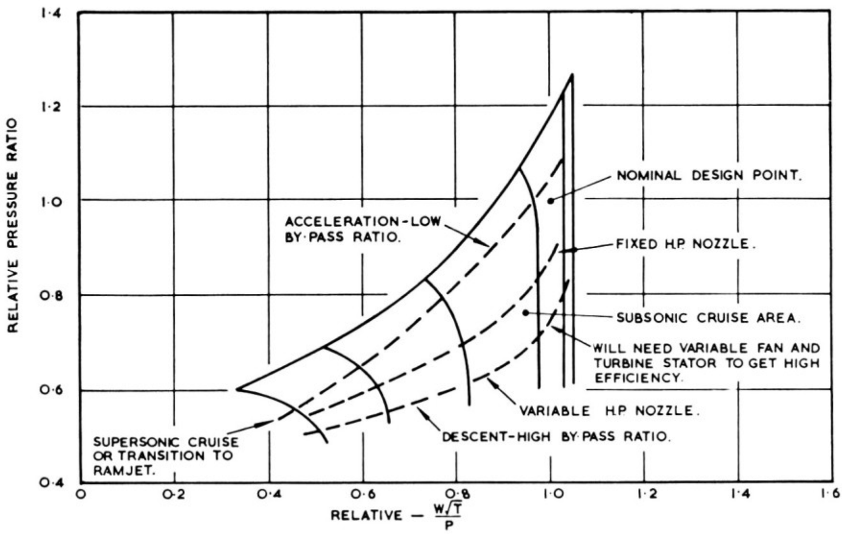

FIG. 29 — Unmixed ducted fan. Operating lines for different flight regimes on the fan characteristics

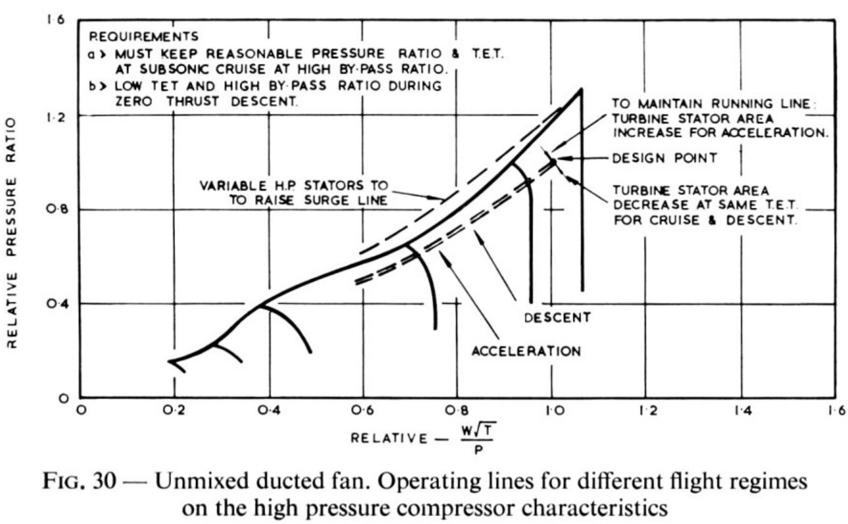

FIG. 30 — Unmixed ducted fan. Operating lines for different flight regimes on the high pressure compressor characteristics

In fact, it appears that if we wish to reap the full benefit of a variable geometry aircraft it will be necessary to have variable geometry in the engine as well, applied in the fan blades (equivalent to a variable pitch airscrew) and in the turbine nozzles. There is scope for a great deal of study in this field which is only now becoming significant because of recent design advances in engines and aircraft. The work will be complex as it will involve the mission profile, the aircraft design and its variable geometry characteristics, the thermodynamic and aerodynamic design of the turbo-machinery, the mechanical design and development of engine variable geometry devices, and the evolution of matching control systems. The engine intake and exhaust nozzles will also have to be considered, together with their control systems, in the overall objective of a fully integrated airframe-powerplant combination.

6. Conclusion

We have seen that the field of application for powerplants for very high speed winged vehicles is indeed a wide one and that there are many propulsion techniques either available or evolving to take their place in it. The scope for rockets in this context is rather limited but, with air augmentation, it does look as if the hybrid will be useful for application to acceleration vehicles such as the space transporter. We have seen, also, that our advancing knowledge in the design of powerplants for high supersonic flight puts us in a position seriously to undertake their study and evolution at the present time to provide a follow-up to the supersonic generation now materialising. The task will be a complex one, but the basic techniques are available so that a methodical and well co-ordinated programme could lead to effective powerplants being available to enter service in the next decade.

Powerplants for hypersonic flight still require a period of research to provide basic data and techniques adequate for the launching of a similar engineering programme. It seems likely that they will first find use in the first stage of a space transporter for launching space satellites and maintaining a ferry service for manned orbital space stations. Later on, with the growth of knowledge of heat transfer, materials and structures, we may expect to produce powerplants for long range hypersonic winged vehicles for terrestial journeys.

Acknowledgments

The author wishes to acknowledge his indebtedness to Bristol Siddeley Engines Ltd. for permission to publish this paper and to his colleagues in the

Advanced Propulsion Research Group for providing technical material, advice and help.

He would also like to thank Mr. T. W. Smith of the British Aircraft Corporation for permission to reproduce Figs. 5 and 6.

References

(1) Smith, T. W., 'An Approach to Economic Space Transportation.' *J.R.Ae.S.* August 1966.

(2) Ferri, A., 'A Review of Problems in the Application of Supersonic Combustion.' *J.R.Ae.S.* September 1964.

Discussion

T. W. Smith (British Aircraft Corporation, Preston Division): In our work on the Space Transporter, which is briefly covered in your ref. 1, we considered a great many different types of vehicle. These included vehicles with air-breathing first and second stages and H.T.O. and V.T.O. rockets. To the best of our ability we applied the criteria of cost effectiveness to the various alternatives. Data which we collected showed that manufactured weight had a powerful influence on both the development and manufacturing cost of any vehicle.

A vehicle with air-breathing engines obviously requires to be supported within the atmosphere. It is for this reason, and the fact that its engine is complicated and heavy, that we find that it has a very much higher manufactured weight to payload ratio than the equivalent rocket vehicle. The materials used in vehicles of the lifting body re-entry type are largely nickel alloys similar to those used in present-day gas turbines. For the air-breather operating at $M=4$ to $M=7$ within the atmosphere we have to resort to increasing amounts of refractory metals which are costly and difficult to work. The cost per lb of manufactured weight for the air-breathing vehicle is likely to exceed that for the rocket vehicle; thus further increasing the overall difference in cost.

It would therefore appear that the air-breathing booster will be more costly to design, develop and manufacture than a recoverable rocket vehicle such as the B.A.C. Mustard concept. In exchange it is said to have the following advantages.

(1) Low fuel consumption.
(2) Capability for horizontal take-off.
(3) Flexibility.

The advantage of low fuel consumption is easily over-rated. It is now well known that propellant costs are a small part of the total operation. There is, then, little point in greatly increasing the cost of a vehicle to achieve a reduction.

It can clearly be shown that there is a heavy penalty, in designing for horizontal take-off either in a rocket or air-breathing vehicle. Lifting surfaces have to be provided to sustain the vehicle aerodynamically. Higher '*g*' loadings, dynamic pressures and ram temperatures are experienced and for much longer periods. In exchange, passengers can sit in a normal position instead of reclining in couches in the V.T.O. vehicle.

It is said that H.T.O. vehicles will be able to use existing runways. Some of them may, but proposals have been made, admittedly for rocket vehicles, for schemes employing a self-propelled trolley travelling along several km of track. Such installations would involve comparable expenditure to a vertical launching pad. The fact that an air-breathing vehicle could use an existing runway would not greatly reduce the launch costs. All the usual refuelling, handling, check out, tracking and control facilities would have to be provided. The upper stages and possibly the lower stages would use hydrogen fuel and it is inconceivable that such operations could be carried out from an aerodrome which was used for any other purpose. Indeed, safety requirements would probably demand that the launching site should be quite some distance from any habitation. The capital cost of the vertical launching tower would be avoided but this is really quite small when compared with the total cost. Allowance has been made for this in the cost effectiveness studies summarised in your ref. 1.

Flexibility can include a number of factors. First, consider the capability of ferrying the device from point to point on the earth's surface. It must be remembered that no Aerospace Transporter of any type can operate without extensive support facilities. The concept of flying to any airfield and operating from there is not realistic. However, some ferry capability is useful but then the ferry range of a Mustard module as a boost glide vehicle is considerable.

A second aspect of flexibility which is often quoted is the fact that an air-breathing first stage can first carry out a cruise before launching, thus effecting a plane change. This cannot be achieved however, without penalty. To carry the extra fuel a larger machine is required with consequent cost increases. Thus if a high degree of plane change were incorporated, the vehicle would be compromised for its more usual mission involving a small plane change. In any case our calculations show that incorporating a higher velocity capability into a recoverable rocket vehicle is a more economical way of obtaining plane change. An even cheaper method is to construct and maintain a launching site at a point on the earth from which a co-planer launch is possible.

We were also extremely interested to read of the engine suggested by Dr. Jamison incorporating the variable pitch fan. B.A.C. Preston Division have for some time been working on the concept of an aircraft embodying a variable by-pass engine. This is a by-product of our work on variable pitch fans for V.T.O. concepts and we have been granted a number of provisional patents in this field.

Dr. Jamison: I am well aware of the work which Mr T. W. Smith and his colleagues have done in this field of space transporters, and, in fact, have cited it in ref. 1 of my paper, and have been grateful to reproduce a drawing of the most interesting 'Mustard' project.

To some extent, my reply to Mr. Smith must be that we are not yet in a position to assess with accuracy what the cost of a hypersonic powerplant or aircraft would be. From our own work, and that which has been done in the U.S., there appears to be a very plausible case that this advanced high speed aircraft could be made successfully in the future. However, as I said in my paper, it would appear to be reasonable to expect that a generation of high speed, long range cruise aircraft and launchers of the 'Mustard' category, should be achieved before we shall be in a position really to tackle the more advanced hypersonic version with air-breathing engines. In the meantime research work into the techniques involved would put us in a much better position, say in about ten years' time, to deal with the problems.

My paper, of course, is of a general nature and is not confined to space launchers and I believe that it is not unreasonable to favour horizontal take-off from runways which, after all, is almost universal practice at the present time in both civil and military operations. There are extremely important advantages in this procedure compared with vertical take-off from prepared launchers.

On the use of hydrogen fuel, I do not share Mr. Smith's extreme pessimism. I believe that it would be quite practical to arrange for this fuel to be used on commercial aircraft if necessary. It is now a common operation in the U.S. to transport hydrogen fuel in large road tankers from coast to coast and no special precautions are considered necessary. It is true that techniques will have to be worked out for the use of this fuel, but on our own experience of handling it in experimental work, and from consultations we have had with manufacturers, there do not seem to be any definite reasons why routine operation should not become acceptable. Recent work has indicated that liquid methane might be better for high speed aircraft, in some circumstances, than hydrogen, and in this connection, of course, it is well known that liquid methane in great tonnages is transported from the Mediterranean to the Thames Estuary, and then is put into our domestic gas supply. This is a routine operation which is not considered to be specially hazardous.