Prospects for Improvement in Efficiency of Flight Propulsions Systems

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A broad survey of aircraft gas-turbine propulsion trends is attempted, identifying the critical performance characteristics and indicating probable future improvements. Particular categories of propulsion system including those for V/STOL and supersonic transport aircraft are considered in more detail. Some discussion of special and multiple function powerplants is also included. Desirable engine characteristics for types of aircraft considered are discussed and problem areas identified. The powerplants are considered from the viewpoints of thermodynamics, noise and installation. Specific engine projects relevant to the survey are discussed.

1. Introduction

THE subject implied in the title of this paper covers an enormous field of engineering activity which cannot be treated in great depth in a paper of this length. The field of view has deliberately been narrowed down to consideration of air-breathing gas-turbine systems and somewhat arbitrarily limited to a flight Mach number of 3.5. This is justified by the view held, at least in Europe, that the increasing cost of Research and Development involved in higher speeds has not so far been shown to be justified by the apparent advantages.

Within these limitations, the possible objectives of the engine designer appear however, both exciting and rewarding. The coming decade promises to consolidate some of the biggest advances in aeronautics and the achievement of improvements in both the basic component performance and over-all engine design which should at least match those of the previous decade.

2. The Over-All Scene

The gas turbine has now dominated military aviation for a quarter of a century and there has been 20 yr of commercial turbine operation. In the early years the success of the engine maker was judged largely by the two yardsticks of fuel consumption and engine weight. The second decade of civil operation saw the quest for ever increasing reliability and overhaul life where the latter increased from the 1000–2000 hr of the piston engine era to the value of 5000–10,000 hr now being achieved on long service gas turbines.

The increasing concern with environment conservation manifest in recent years makes it almost certain that the third decade will number among its prime concerns the additional factors of Engine Noise and Smoke Pollution. Increasing sophistication of Airline equipment is to be expected with the introduction of V/STOL and supersonic transports. A new feature of the scene which is anticipated is the emergence of powerplants performing new functions, e.g., the lift fan, or multifunction units providing both thrust and blowing air for high lift. The vectored thrust Pegasus engine in the Harrier is perhaps the first example of such systems. Military aviation progress which lost much of its impetus in the sixties may well regain some of it in this decade, particularly in the development of STOL and V/STOL high-performance combat and close support aircraft.

To achieve all these results major advances in mechanical design and aero-thermodynamics are required. This paper examines some of the fundamental parameters limiting progress and couples this with brief reviews of the major performance questions relating to particular powerplants. In particular much use has been made of the parameter specific thrust (thrust per pound of total engine airflow) which is a measure of propulsive efficiency and a powerful parameter in determining engine noise.

Component Performance

It is useful to distinguish between advances in component performance and advances associated with choice of thermodynamic cycle. Progress in improving the efficiency of the compression and expansion processes has not been spectacular and it may be said that, rather, the aim has been to achieve existing levels of efficiency with fewer stages of blading and lower weight. The scope for increasing small-stage efficiency above a value of 90% is limited by fundamental aerodynamic considerations while now the turbine designer faces the problem of maintaining his standards with blade profiles compromised by cooling geometry. As over-all pressure ratios have increased the achievement of the target design efficiency has become more vital to the matching of the more complex engine components.

The area where most progress has been achieved is in raising turbine entry temperature (TET). The statistical projection of this progress is set out in Fig. 1 which shows that it is now due almost entirely to improvement in air-cooled blade technology with little improvement in basic material properties. These higher temperatures have been employed in two ways: 1) to allow the effective use of higher pressure ratio gas generators without significantly altering the combustion temperature rise; and 2) to increase thrust at existing pressure ratios to give improved specific weight, as for example on the lift jet and the vectored thrust ducted fan.

A further very significant parameter which is now combining to control progress at the present time is air temperature at compressor delivery which is the major source of cooling air for high-temperature engine components. Limits are being reached set by stress/temperature relationships of the best high-

Presented as Paper 70–873 at the CASI/AIAA Meeting on the Prospects for Improvement in Efficiency of Flight, Toronto, Canada, July 9–10, 1970; submitted October 2, 1970; revision received June 28, 1971. The authors wish to acknowledge the help of their colleagues at Rolls Royce in the preparation of this document and in particular that given by T. Jordan. They wish to state that the views are their own and not necessarily those of their Company. Their thanks are due to the Directors of Rolls Royce (1971) Ltd. (Bristol Engine Div.) for permission to publish this lecture.

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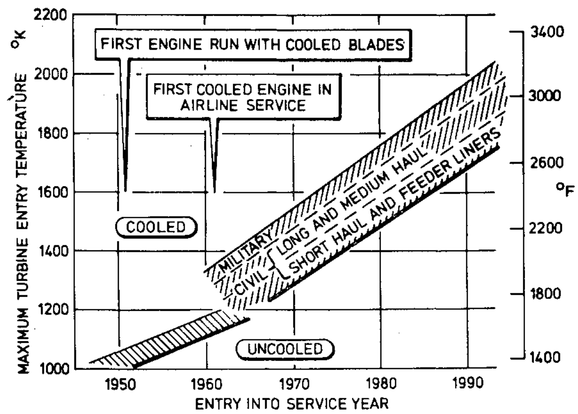

Fig. 1 Turbine entry temperature trends.

temperature alloy materials available for the design of compressor and turbine disks. Figure 2 illustrates the relationship between cruise cycle pressure ratio, Mach number and compressor delivery temperature. The same delivery temperature implies a pressure ratio of 35:1 for the subsonic engine, 10:1 for the Mach 2.0 engine and 3:1 for the Mach 3.0 engine. A further point to note on Fig. 2 is that below a flight Mach number of 1.4 the altitude cruise inlet temperature is below the test bed value which then limits the design.

Techniques for air cooling both turbine stator and rotor blades are advancing rapidly and the relative cooling efficiencies of differing methods are compared in Fig. 3 using a mean cooling effectiveness defined by

$$\bar{\eta}_M = (T^\circ \text{ hot gas} - T^\circ \text{ metal})/(T^\circ \text{ hot gas} - T^\circ \text{ cooling air})$$

The simple forced convection cooled blades are now giving way to improved techniques of film cooling in combination with convection cooling and will ultimately include transpiration methods. Film cooling may be regarded as a process halfway between these two extremes. For film and transpiration systems the cooling air pressure must be close to that of the hot gas since it has to flow out against the main gas stream. This tends to limit the cooling supply to compressor delivery bleed. It is however, possible to precool the cooling air in a subsidiary heat exchanger using, say, bypass air.

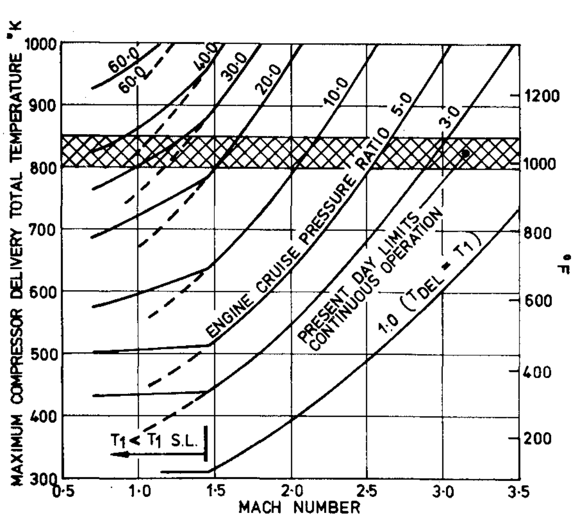

Fig. 2 Compressor delivery temperature variations with flight speed—ISA conditions.

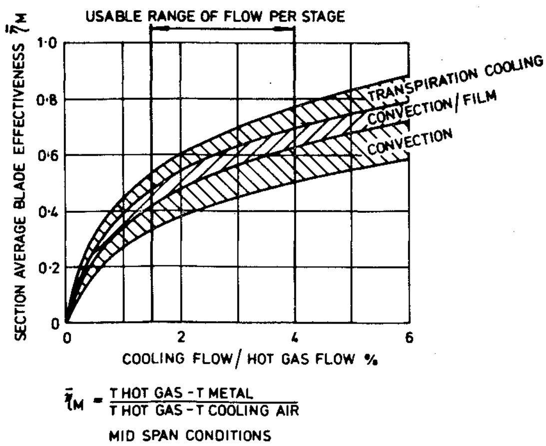

Fig. 3 Future cooling performance of HP turbine blades.

Taking a limiting cruising blade metal temperature of 850°C (1562°F) the relationship between hot gas and cooling air temperature can be evaluated for given levels of cooling effectiveness. This is set out in Fig. 4. For a typical cooling flow of $2\frac{1}{2}$–3% of the hot gas flow, values of 0.4 and 0.7 represent the extremes of effectiveness envisaged, (Fig. 3). This shows that engines now in service which have cooling effectiveness levels of about 0.4, attain gas temperatures some 400°F (220°C) in excess of blade metal temperatures. An increase to 0.6 would raise the difference to around 900°F (500°C). As will be shown, such changes are the most significant open to the engine maker and their influence on engine design over a wide range of flight speed will be examined on a basis of similar levels of cooling technology. Also shown on Fig. 4 is the stoichiometric limit on TET, assuming cooling air temperature is equal to compressor delivery air temp. This illustrates the increasing difficulty of achieving near stoichiometric conditions, as over-all pressure ratio is increased, with conventional cooling systems.

Optimum Engine Cycles at Various Flight Speeds

Figures 2 and 4 have defined relationships between flight speed and cycle pressure ratio and between compressor delivery temperature and TET. If the assumption is made that both the highest pressure ratio and highest peak temperature are desirable aims then this defines the gas generator cycle Experience has shown that in general when this is combined with an optimum choice of bypass ratio then the best thermodynamic cycle is achieved. To compare engines designed to cruise at various speeds a common value of compressor delivery temperature of 850°C (1562°F) has been coupled with a value of cooling effectiveness of 0.62 which implies a cruise

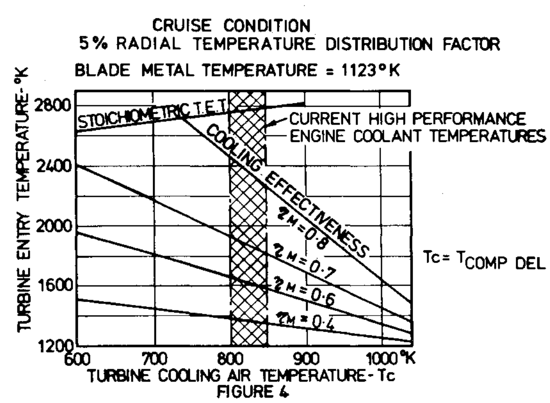

Fig. 4 Effect of cooling effectiveness and cooling temperature on turbine entry temperature.

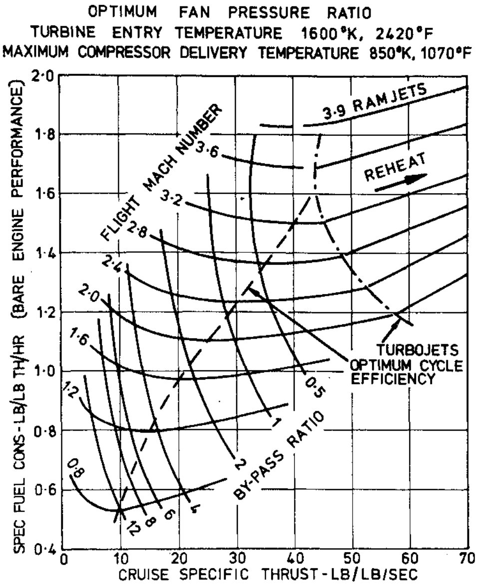

Fig. 5 Trends of specific fuel consumption with flight speed.

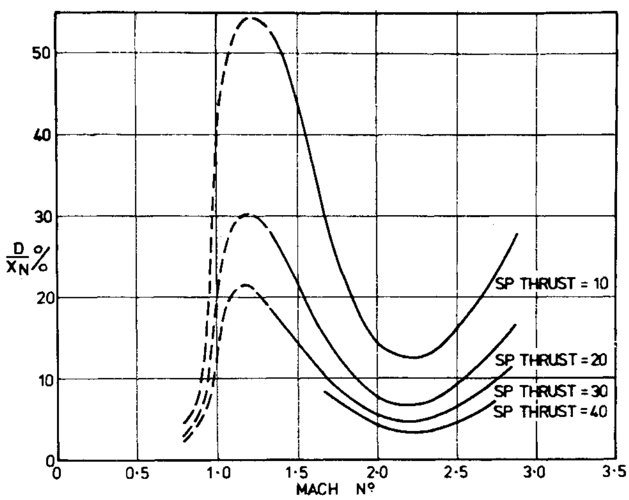

Fig. 6 Specific power plant drag.

TET of 1600°K (2912°F). This is a conceivable situation for the end of this decade. The results of such an optimum engine study are shown in Fig. 5 and are plotted in terms of the parameter specific thrust (net thrust per pound of airflow) which is a useful measure of the installation drag (and weight) and the sensitivity of performance to nozzle efficiency and duct loss. It can be seen that the level of specific thrust at which optimum SFC occurs rises with Mach number and that the SFC becomes less sensitive to specific thrust variation as speed rises. Installation drag considerations will therefore have increasing influence on the choice of specific thrust as speed increases. The variation of isolated pod drag with speed is given in Fig. 6 as a function of specific thrust. This can be combined with internal engine performance to give an installed performance variation shown on Fig. 7a and finally it can be combined with an assumed variation of basic airframe lift : drag ratio (Fig. 7b) to produce over-all specific air range (Fig. 7c).

It will be seen that the installed engine performance has reached an optimum at about $M = 2.5$. In applying the aircraft lift : drag ratio to obtain the variation of specific air range it has to be remembered that some further scope may exist for airframe optimization and minimization of powerplant drag by integration with the airframe.

Reduction of Noise

Even before noise certification legislation was contemplated the engine and airframe designers were making major efforts to reduce noise. Fortuitously for subsonic aircraft, the ducted

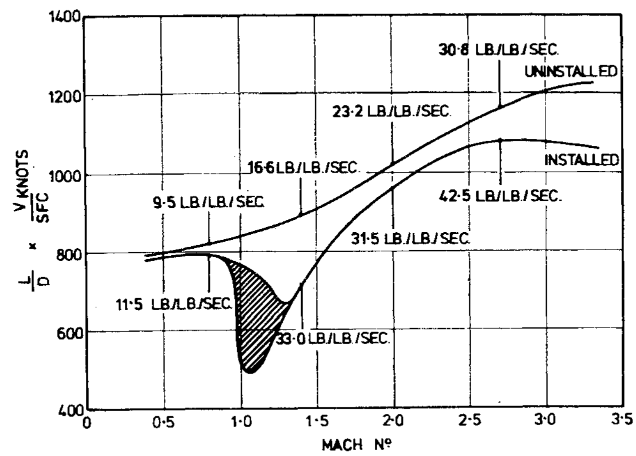

Fig. 7a Engine installation efficiency.

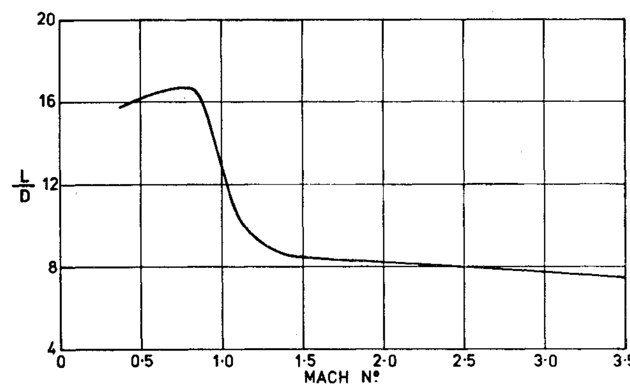

Fig. 7b Airframe aerodynamic efficiency.

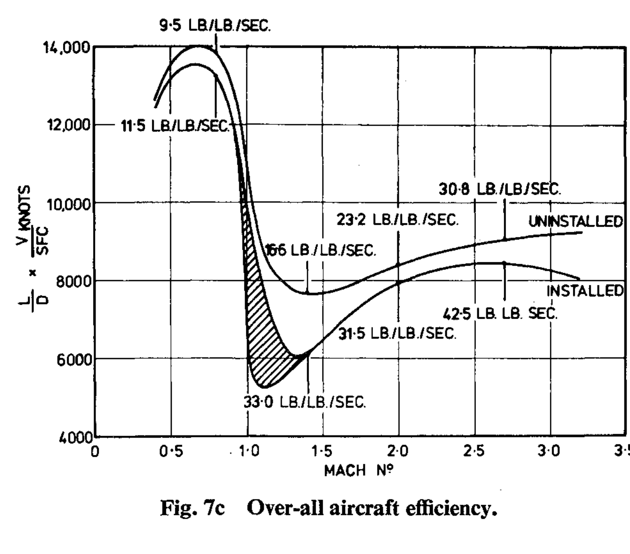

Fig. 7c Over-all aircraft efficiency.

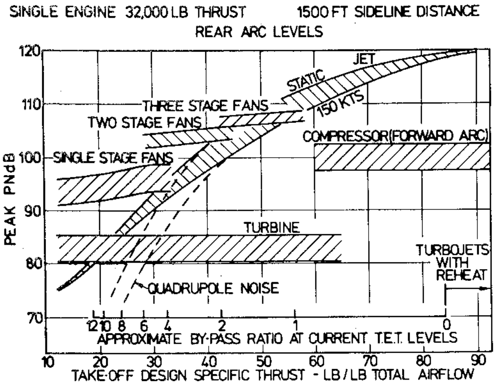

Fig. 8 Engine component noise—maximum thrust condition.

fan enabled this to be achieved in combination with major improvements in SFC. Noise control has now become an essential feature of commercial aircraft design to a degree where silencing is penalizing operating economics by increasing engine weight and worsening SFC.

The situation facing the large conventional transport aircraft is summarized on Figs. 8 and 9. Noise at maximum thrust, which defines the peak sideline noise, is shown on Fig. 8 as a function of design specific thrust at sea level static conditions. Specific thrust is equivalent to jet velocity and for the given design thrust chosen (32,000 lb) defines the compressor or fan entry airflow. These two numbers broadly define engine noise although the contribution of the fan is highly variable depending on its aerodynamic design and in particular whether it is a single or multistage unit. The single isolated fan stage tends to be roughly 10 PNdb quieter than a multistage unit of the same airflow and is a common feature of the new generation of large high-bypass engines, and JT9D, CF6 and RB 211 which all have specific thrusts of around 30.

It is anticipated that fan noise can be reduced with less difficulty than jet noise, and hence the scope for further noise reduction is increased as the gap between fan noise and jet noise widens at low specific thrusts. This gives some further incentive to increase bypass ratio and holds out the possibility of ultimate gains relative to todays new fan engines of between 5 and 10 PNdb. The noise on approach to landing (Fig. 9) is a far more difficult situation showing little fundamental variation in dominant noise with design specific thrust. However, the greater possibilities of attenuating blading noise again drive the designer towards lower specific thrusts.

The flyover case is not illustrated since it depends so dramatically on the height reached by the aircraft at a point 3½ naut miles from start of roll. This is controlled by the engine thrust level. The first generation SST aircraft with their high specific thrust (80–100) can use their high installed thrusts to advantage on flyover while Fig. 9 shows that they do not have a worse problem than other aircraft on approach. Their main difficulty is sideline noise which may well be reduced by silencer devices and which may not be as significant in terms of people affected as the approach and flyover cases.

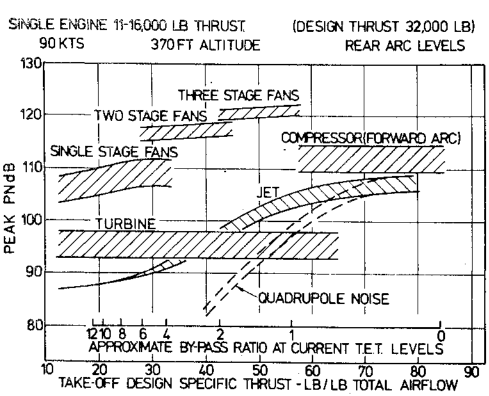

Fig. 9 Engine component noise—approach condition.

Reduction of Atmospheric Pollution

The obvious pollution caused by today's aircraft is undoubtedly the free carbon smoke. The reasons for the formation of this smoke are not completely understood although it appears to depend on the preparation which the fuel receives before arriving in the primary combustion zone and the conditions in the primary combustion zone itself. The problem is worsened with increase in gas generator pressure ratio and, subjectively, by increase in size, and together with the growth of traffic this has led to the situation around airports becoming acute. Rolls Royce experience with the annular vaporizer combustor over a long period and including recent experience at high-pressure ratios has shown it to be almost completely smoke-free and to offer a practical solution to this problem. A less obvious problem arises from the formation of toxic oxides of nitrogen. The incidence of this pollution increases with combustion intensity and hence will become more troublesome with advancing technology. Intensive research into this problem is in progress.

3. Particular Propulsion Systems

Viewing the role of aviation in the coming decade there are a number of specific roles for the gas turbines which warrant more detailed review. These are: 1) close support V/STOL (military), 2) air superiority combat (military), 3) short range V/STOL transport (civil and military), 4) subsonic transonic transports (predominately civil), and 5) supersonic transports (civil). It is only possible to touch broadly on the prime problems in this paper.

Close Support V/STOL

The Hawker Siddeley Harrier with the Rolls Royce Pegasus engine produced by the Bristol Engine Division seems likely to provide a step change in efficiency of support to ground forces, due to its unique V/STOL performance. This type of aircraft may well have a revolutionary influence on naval warfare also, both in defense and attack. The exchange rate between increased thrust or reduced SFC favors the former in this type of aircraft. Thus, the most effective method of development is by way of improved engine thrust/weight ratio.

By applying the potential improvements in turbine entry temperature and work per stage, there is every reason to believe that still further significant improvements in engine thrust/weight ratio can be achieved. A second generation subsonic V/STOL close support aircraft which combined possible advances in engine and airframe technology might well have the sort of performance capability illustrated in Fig. 10, which also shows the effect of engine SFC and thrust/weight ratio on warload and radius of action.

Air Superiority Fighters

Substantial improvements in engine thrust/weight ratio can have a significant effect on the weight of this type of fighter, which, like the V/STOL aircraft, has a very high

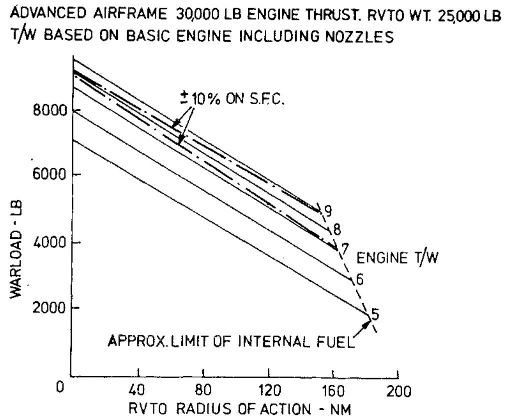

Fig. 10 V/STOL close support aircraft, influence of size and engine technology.

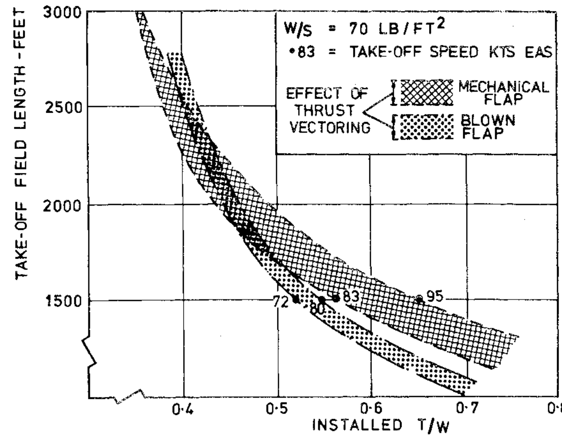

Fig. 12 Takeoff performance, STOL aircraft.

thrust/aircraft weight ratio. First-order effects of engine thrust/weight ratio on aircraft weight are shown in Fig. 11.

Because of the greater range requirement, engine SFC assumes a greater importance, so that higher pressure ratios are demanded. To give some measure of what we expect to achieve in the next 5 yr or so, improvements in engine thrust/weight ratio and specific fuel consumption will cause a reduction of nearly 25% in aircraft weight for the same job, compared with that possible with current engines. This type of engine with its greater development cost can be justified on the basis that the resulting reduction in aircraft size and hence over-all procurement cost substantially outweighs additional development costs. Apart from improvements in structural design, the source of weight reduction on this type of engine is likely to be found in increased TET.

Short Range V/STOL Transports

Although the long term solution to the short haul transport may well lie with a VTOL system, the immediate requirement, posed by major airport congestion in North America, is for a STOL solution. Present requirements indicate a market for aircraft capable of takeoff and landing in field lengths of 1500–2500 ft. These requirements also dictate that the maximum possible engine silencing is employed.

Consideration of the factors affecting short field performance is of interest. Figure 12 shows takeoff performance vs FAR field length, and indicates that thrust/weight ratios between 0.55 and 0.6 will be necessary to achieve 1500 ft. Figure 13 shows landing field length (assuming the $\frac{6}{10}$ factor) touch-down speed, and indicates that some form of engine augmented lift will be necessary in order to achieve under 2000 ft field length. Possible types of powerplant include the following: 1) separate propulsion and lift producing engines having a) an optimized low-noise propulsion unit, and b) either lift fans or separate wing blowing compressor engines for lift augmentation; and 2) multiple function powerplants providing propulsion thrust plus bleed air for wing blowing purposes. In this type of engine efficiency is compromised to some extent, but the advantage of a single engine type is achieved.

The optimized propulsion unit must meet the severe noise requirements and must provide a high ratio of takeoff to cruise thrust for optimum thrust matching. Figure 14 gives the variation of this ratio with engine bypass ratio for a typical gas generator design for short haul operation. This indicates that a bypass ratio of 10 is not unrealistic for cruise speeds between 0.7 and 0.8. The advantages of high bypass ratio include additional scope for noise reduction. Because fuel weight is a relatively small percentage of aircraft weight in a typical STOL design (being very similar to powerplant weight) engine pressure ratios will tend to be modest.

The STOL aircraft landing requirement is perhaps the most critical and will undoubtedly demand a thrust reversal system

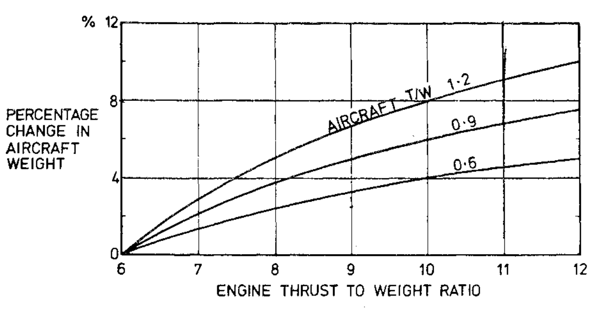

Fig. 11 Effect of engine thrust to weight ratio on aircraft take-off weight, air superiority fighters.

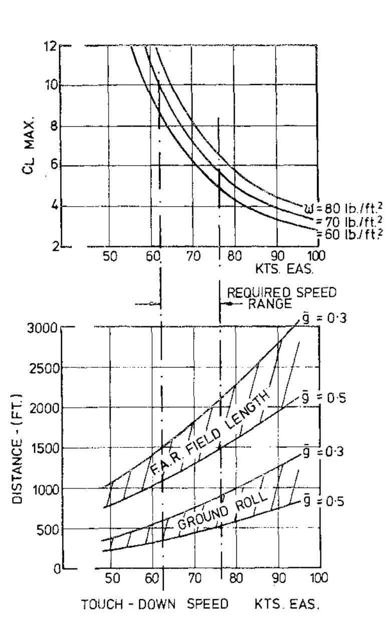

Fig. 13 Landing performance, STOL aircraft.

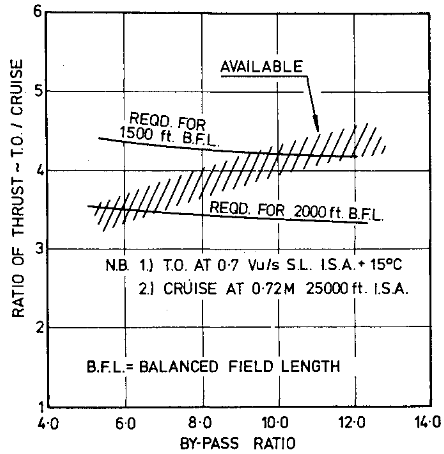

Fig. 14 Effect of bypass ratio on thrust matching.

free from undesirable ingestion and erosion problems down to zero forward speed. Combining this with the noise and thrust requirements previously stated leads to a solution which has a high bypass ratio (10:1) obtained by a gear driven fan with variable pitch blades providing a modest fan pressure ratio (Fig. 15). The reverse thrust mode does not involve any jet impingement on the aircraft or ground and is a step back towards the turbo-prop although the disk loadings are still some 10–15 times greater.

The self-contained lift fan unit as typified by the RB 202 has been designed against the background of lightweight lift engine technology. It is designed for high thrust/weight ratio, and minimum noise and SFC. Because of the dominant importance of weight, the engine is of low-pressure ratio and achieves low SFC and noise through high bypass ratio.

The alternative separate air supply unit to provide wing blowing air has very similar requirements to the lift engine in terms of minimum weight SFC and noise. Schemes are currently proposed in which the background of Rolls Royce lightweight lift engine technology is used to provide suitable blowing units based on use of existing lift engine components.

The second category of STOL powerplants has additional constraints imposed by its multiple functions. Against this must be set the advantages of having only one type of powerplant. These engines must supply air to the wing to increase lift and at the same time provide varying amounts of propulsive thrust for takeoff and landing.

Figure 16 shows the choices open to the designer in abstracting blowing air at varying pressure ratios while maintaining a hot jet velocity of 1000 fps. This figure indicates how the blowing thrust of a plain fan engine may be reduced at a given jet velocity by extracting energy via an additional propulsion fan, at the same time improving the specific fuel consumption. It may be seen that at low-percentage blowing-thrust specific fuel consumption is less sensitive to blowing pressure ratio than for the situation where all the bypass air is used for blowing.

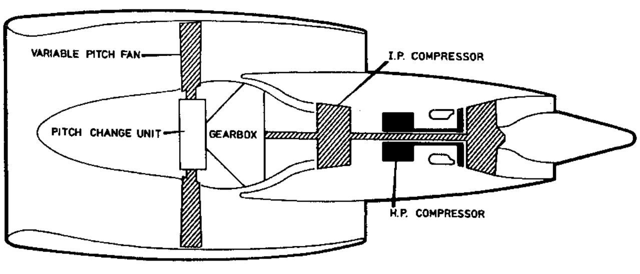

Fig. 15 Variable pitch geared ducted fan.

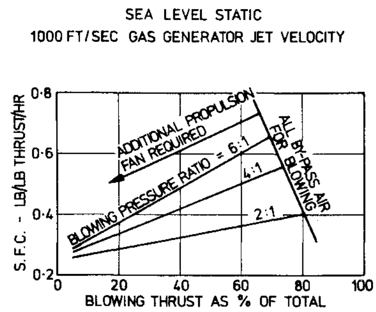

Fig. 16 Multifunction blowing/propulsion engines.

Subsonic/Transonic Transport Engine

These two types of engine have been coupled together because the case for flying at $M = 1.15$ over land, the fastest speed where no sonic boom would arise, rather than increasing the speed of the essentially subsonic design to as close to $M = 1.0$ as possible, has not been satisfactorily resolved as yet.

Figure 5 does show that there are some changes in optimum cycle relationship occuring between $M = 0.8$ and 1.2. It is perhaps sufficient to say that if flight at $M = 1.15$ is found to be desirable then the engine designer will be faced with the difficult task of either producing a low-noise single-stage fan engine of bypass ratio around 4:1 which will have too low a fan pressure ratio, or a noisier multistage fan engine of around bypass 2:1 which will require a large amount of duct acoustic treatment.

Turning to the subsonic engine, it is evident that major progress in both economy and low noise is being made at the present time with the introduction of large bypass (5:1) engines for a new generation of subsonic transports. These engines have cycle pressure ratios of 25–30:1 and cruising TET levels of 1300–1400°K giving SFC values of about 0.6 at $M = 0.8$. The low-noise single-stage fan of about 1.6 pressure ratio used, implies a value of about 18:1 for the pressure ratio of the additional gas generator compressor(s). Development of this type of engine is likely to be concentrated on further reducing fan noise coupled in addition with the possibility of modest improvements in performance.

The Supersonic Transport Engine

The engine problem posed by the SST is that, as shown in Fig. 5, there is only a minor change in SFC for a doubling of specific thrust or halving of the airflow in the $M = 2.0$ to 3.0 speed range. Hence powerplant drag and weight considerations almost certainly outweigh SFC and bias choice towards the highest specific thrust. The takeoff airflow is directly proportional to the airflow installed at cruise. Hence for a given takeoff thrust requirement, the jet velocity is proportional to the cruise specific thrust. A cruise specific thrust of 40 for Concorde produces a takeoff specific thrust of 80.

It can be seen from Fig. 5 that when TET is raised to 1600°K a cruise specific thrust of 40 is obtained with a bypass ratio of just below 0.5 at $M = 2.0$ rather than the turbo-jet cycle of the Olympus 593. If for noise reasons, specific thrust were reduced to say 32 then bypass ratio would rise to 1.0. This is in fact the optimum installed specific thrust shown on Fig. 7.

There are more significant subsonic SFC benefits for increasing bypass ratio. The future development of this type of engine is therefore likely to be in the direction of higher TET and hence lower-gas generator weight while at the same time reducing specific thrust for noise reasons as far as is practicable.

For higher-cruise Mach numbers the permissible engine pressure ratios reduce rapidly and this is reflected in a progressive deterioration in off-design subsonic performance due to reduced over-all pressure ratio. At $M = 3.9$ the extreme case is reached where the ramjet is the only airbreathing solution allowed by the material temperature limits assumed and separate powerplants are necessary for takeoff and lower-speed operation.

4. Conclusions

The broad conclusion from this study is that significant advances likely to be achieved in the coming decade will be based largely on higher turbine entry temperatures with perhaps modest increases in cycle pressure ratio, limited in many cases by delivery temperature conditions set by material properities. New specialized powerplants for V/STOL will provide scope for the ingenuity of the aerodynamicist and engine designer.