Some Aspects of Aircraft Evolution

M. B. MORGAN, C.B., M.A., C.ENG., F.R.AE.S.

1. INTRODUCTION

Those having the honoured task of preparing a lecture for this now well-established memorial series must inevitably think first of the Guggenheim family and of the encouragement given to world aeronautics by its far-sighted benefactions. Then, equally inevitably, we see Theodore von Kármán who was known so intimately by so many of us on both sides of the Atlantic and to whom the International Congress of the Aeronautical Sciences owes such an immeasurable debt. Maurice Roy, in a former Guggenheim Lecture, has paid a moving tribute to von Kármán — who, quite simply, was a great man. Not only great, but also great-hearted. In his own researches he did the work of five men; as a practical man of affairs, of incisive wit and judgment, he was outstanding; as a human being he was unique. He will always live in our hearts.

To people of my generation the names of von Kármán and Clark Millikan are inseparable. There they were together, for so many years, at Pasadena. It was a wonderful partnership. They made the California Institute of Technology not only a power house for the West Coast, but also for the whole of the United States and for the entire aeronautical world. Both were confirmed internationalists; both were intensely active; both had the gift of conveying their enthusiasms to others. Now, with Clark Millikan's death, the second of the two partners has been taken from us. We treasure the memories he has left behind; we mourn his passing.

The Council of the Aeronautical Sciences leaves to the author the choice of subject for this lecture. My intention in this paper is to outline some of the things which the present research scene might be suggesting in terms of future possibilities; to consider a few illustrative examples of intricate design areas of topical interest and to conclude with some remarks on the process of decision-taking when dealing with advanced aeronautical projects, more especially with the part of the scientist and engineer in such processes.

At this stage it might be as well to set the aeronautical scene. The aircraft

industry developed very extensively during the 1939–45 War and has continued
to expand. Nearly two million people are currently engaged in the world air-
craft industry. Of these about 650,000 are employed in the U.S.A., 250,000 in
the U.K., and 100,000 in France. A number of other West European countries,
together with Canada, Australia and Japan, have small aircraft industries. In
the Eastern Bloc the aviation scene is dominated by the U.S.S.R., with a size
of aircraft industry comparable with that of the U.S.A.

In those countries with advanced aeronautical industries, the employment
provided by the design and manufacture of aeronautical products is signifi-
cant to the overall economy. In the U.S.A. the aircraft industry absorbs some
4% of the total employment in manufacture; in the U.S.S.R. 3%; in the U.K.
3%; and in France 2%. It is roughly true to say that in the aircraft industries
the output per man, in financial terms, is similar to that for manufacturing
industries in general. The percentages quoted for employment can, therefore,
be taken as applying to output as well. The current annual sales output of the
world aircraft industry (and this takes in research, development and produc-
tion costs) now exceeds £7,000 million or 20,000 million dollars. Of this total,
defence accounts for 80%.

Of the £7,000 million world annual output, exports from one country to
another account for about £1,000 million. Exports from the U.S.A. make up
about 40% of this total, those from the Eastern Bloc about 30%, while the
figure for the U.K. is 15%.

From the figures quoted it is obvious that already the importing and export-
ing of aircraft can have a significant influence on the balance of payments
aspects of world economics, and that by any standards in dealing with aero-
planes we are dealing with really big business. When considering the future
scene it is well to remind ourselves how new this aircraft business all is, and
how rapidly it has expanded; the first powered aeroplane flew only a little
over half a century ago.

2. POINTERS TO THE FUTURE

2.1. *Exchange rates*

As a prelude to considering the impact of researches in the various tech-
nical areas — aerodynamics, structures, propulsion, materials, equipment
and so on — it is useful to look at exchange rates for project themes of
interest; that is, figures illustrating the overall influence on the all-up weight
of a project, when designing it from scratch, of given percentage improvements
in the various technical parameters whose values improve as we get cleverer
— such things as lift/drag ratio, percentage structure weight, engine specific
weight and consumption etc.

In Table I exchange rates are given for subsonic transports of ranges from

250 to 3,000 nautical miles; for a 3,000 mile supersonic transport; and — for comparison with the 250 mile transport — equivalent figures for a 250 mile vertical take-off transport suitable for civil use and for military use.

The absolute values of these exchange rates need not be taken over seriously, but their comparative values from project to project are of great interest and significance.

TABLE I

CHANGE IN ALL-UP WEIGHT FOR CONSTANT PAYLOAD

	Subsonic			S.S.T.
Design Range (n.m.)	250	1000	3000	3000
Payload percentage	22	19	13	7·5
10% reduction in total drag	1·4%	3·8%	10·5%	21·0%
10% reduction in s.f.c. throughout	2·7%	5·4%	10·5%	20·0%
10% reduction in specific structure wt.	6·5%	6·9%	7·0%	9·4%
10% reduction in powerplant wt.	2·3%	2·0%	2·0%	4·1%
1% improvement in supersonic intake pressure recovery (*e.g.* from 0·97 to 0·98)				0·6%
1% improvement in nozzle loss throughout (*e.g.* from 0·05 of net thrust to 0·04 of net thrust)				1·4%

	Subsonic		
Design Range (n.m.)	250 Civil conventional	250 Civil VTOL	250 Military† VTOL
Payload percentage	22	16·5	12
10% reduction in total drag	1·4%	1·6%	2·1%
10% reduction in s.f.c. throughout	2·7%	4·2%	6·3%
10% reduction in specific structure wt.	6·5%	6·9%	9·5%
10% reduction in powerplant wt.	2·3%	5·2%	7·3%

† Higher structure wt. due to low level flight and transport doors;
Higher engine wt. due to hot and high requirement;
Higher fuel wt. due to low-level and hover requirement.

It can be seen that supersonic transports and VTOL aircraft will benefit quite dramatically from relatively small advances in technology. One of the reasons why medium to long-haul supersonic transports can be advocated is the feeling that — faced with such exchange rates — provided we can get the first generation launched and into business, the supersonic machines should overhaul and pass the subsonic breed, size for size, as we get technically more clever. With the subsonic conventional transports, as we bring the range down we have to struggle harder for improvement. The subsonic short-haul civil transports are particularly obstinate in responding to technological advance; much depends on skill in choosing the specification to work on, giving the right aeroplane at the right time. A long time ago I made the point that on civil transports the golden rule for getting fares down was to make the aeroplane as big as you dare and then fill it. This applies as vigorously as ever today.

2.2. *Aerodynamics*

2.2.1. *Subsonic*. For aircraft designed to cruise efficiently at highish subsonic speeds it is difficult to see more than a gradual and limited improvement in the lift/drag ratio. The advent of high capacity computing machinery will increasingly enable the theoretical people to come up with workable solutions for the flows round complex wing shapes and wing body combinations, which should ease the designer's task in getting his aerodynamics more nearly right from the outset rather than after the lengthy *ad-hoc* development now sometimes needed. An important area for immediate drag improvement lies in the finer aerodynamic points of engine installations — more especially with the advent of higher by-pass ratio units.

It is interesting to speculate on whether — apart from truly supersonic medium and long haul aircraft — cruising speeds will stop short at about Mach 0·95. While opinion is divided on this, I myself have felt for some time that for the short to medium haul transports there is a possibility that we will learn how to generate an adequate lift/drag ratio at about Mach 1·15; a speed fast enough to give an appreciable economic advantage over 0·85 if we can hold our L/D, and slow enough to obviate any sonic bang problem from altitude — the bang never reaches the ground. Dealing with fuselage drag is the big problem here, and it may well be that this Mach 1·15 possibility will first be realised in fairly large machines approximating to all-wing layouts.

Laminarisation of the boundary layer has been the aerodynamicist's big prize for years in terms of spectacular drag reduction, but undoubtedly of late it has been running through a bad patch and even the enthusiasts are getting a little discouraged. It pays off with increasing vigour when range is increased, as illustrated in Fig. 1. But marked improvements of late in the efficiency of conventional aircraft — better L/D, better structure weight,
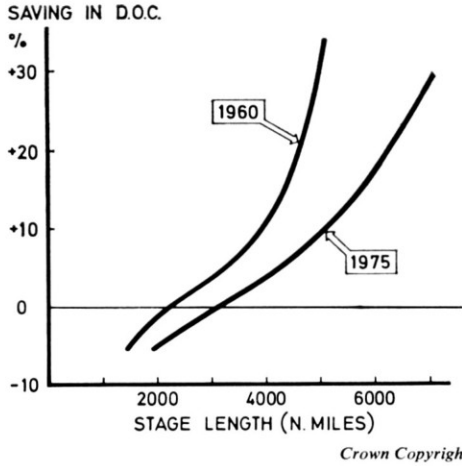
SAVING IN D.O.C.

Crown Copyright

FIG. 1 — Effect on costs of laminar flow wings

above all better engine specific weights and specific consumptions — has pushed the cross-over point a long way to the right. The question is then posed of the commercial or military justification for specialised very long range machines.

Short to medium haul aircraft can benefit markedly from improved high lift characteristics as well as from cruise drag reduction. Existing knowledge and current research work already point the way to better designs of flap and slat systems which should give optimum lift characteristics, at little expense in drag, for commercial airfields of 5,000 ft. or more. One can always design for shorter field lengths, but the economics of this are rarely attractive.

Serious thought has been given to large all-wing aircraft of 'ogee' planform for short haul civil work at subsonic speeds. On certain assumptions, using quite empirical tunnel data, a marginal case can be made for such a departure from the conventional swept wing/body combination. Wing flow at high incidence is dominated by the leading edge vortices on such shapes and in the years to come we should gain a better understanding of how to calculate the interaction of wing shape and vortex flow. Should such understanding lead to the conclusion that present tunnel *ad-hoc* results for lift and drag are not near the limiting values, there may well be a marked increase in interest in these unconventional shapes.

2.2.2. *Supersonic.* Here we are nothing like so advanced in refinement as with the now highly developed subsonic machines. Already it is clear that one of the areas most open to aerodynamic improvement is that in which engine and airframe interact — intake geometry, boundary layer diversion, nozzle variability, use of bleed air, external fairings to the power units and so on.

It is quite possible that proper handling of these problems could give us, in time, improvements in overall efficiency equivalent to more than 5 % increase in lift/drag ratio for aircraft in the Mach 2·0/3·0 range.

Ideas are evolving rapidly on the practical politics of large scale manned flight at still higher speeds up to, say, Mach 10·0 and the aerodynamicist is speaking much more confidently than he did five years ago. For example, it is already clear that lift/drag ratios in the Mach 5·0/10·0 region can be substantially higher than used to be imagined — the effect of this on Breguet range is well illustrated in Fig. 2, due to Küchemann. The closest integration of
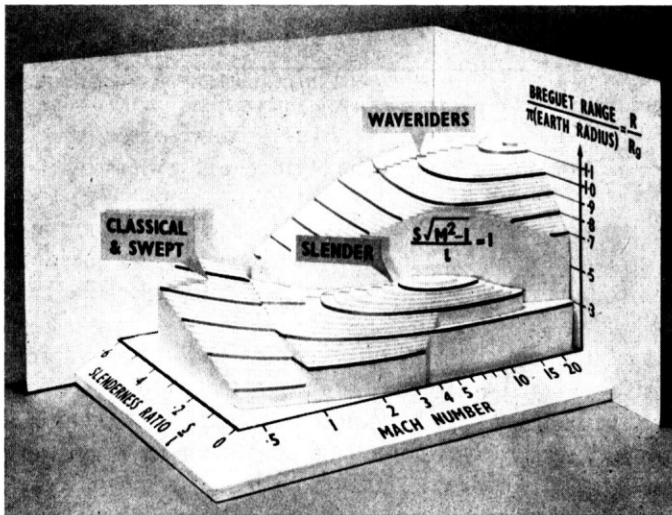
FIG. 2 — Range possibilities at various Mach numbers

engine and airframe will be the key to economic flight at these very high speeds; the use of supersonic combustion might be inescapable; hydrogen as a fuel needs close examination. While technical difficulties ahead of us remain formidable, and admitting that it is rather early to place before likely customers a series of considered projects, there is no doubt that the possibilities of exploiting this $M = 3·0/10·0$ speed band for civil or military purposes deserve keen attention.

2.2.3. *Vertical or Short Take-Off and Landing.* Quite apart from the helicopter story, V/STOL aircraft are now emerging from the phase of purely research aircraft, in a wide variety of guises and countries, to positive projects. We in the U K. are rather proud of our record in this field, both on the engine and airframe fronts, and as a follow up of the recent large scale tripartite exercise

on the P.1127 between the United States, Germany and Britain, I thought the audience might care to see a film recently taken at R.A.E. Bedford of the P.1127 operating experimentally and without difficulty into and out of a small hole in a large wood.

VTOL must be bought at a price. It may well be that large scale use of VTOL machines will first emerge from military needs, and that military and civil developments may drift apart in some respects owing to different emphasis on noise and on economics. The exchange rates already illustrated in Table I indicate that once we have established the first generation of military VTOL machines, marked improvements can be expected as basic aerodynamic, structural and engine techniques become more refined.

While the P.1127 may help to set a pattern for the smaller V/STOL military machines, considerable developments in the use of jet lift for larger military transport aircraft are on the technical horizon. While a variety of approaches to this are still being debated, I myself have a feeling that detachable lifting pods housing clusters of lightweight jet engines will, in due course, be found to have great merit; the type of arrangement illustrated in Fig. 3.

Crown Copyright

FIG. 3 — Example of the lifting pod theme for VTOL

The idea of removing nearly all your lifting machinery when not needed, thereby having a much more efficient aircraft for normal airfield use, is most attractive. The aerodynamic problems posed by such layouts, while formidable, already seem by no means intractable.

2.3. *Materials*

Aluminium alloys are the work-horses of aircraft designers; they have by no means reached the end of their evolution. As an example, the $Al - 5 Mg-$

4Zn – 1Mn alloy quite recently developed at Farnborough has been shown to have high ultimate strength in association with a fatigue strength significantly greater than is usual. This may have important repercussions, since in the past the fatigue performance of high ultimate strength zinc bearing alloys has held them back.

Titanium alloys will provide another significant avenue towards improved structural efficiency. Already they are available with values of specific proof, ultimate and fatigue strength twice as great as those for aluminium alloys. They offer appreciable weight saving in areas that are loaded predominantly in tension and for highly loaded compression structures. Their excellent weldability can give a saving of weight in joints and helps to exploit fully their good fatigue properties. The rate at which titanium comes in will depend on the rate at which raw material costs can be lowered, but it seems likely that in the coming years they could more than earn their keep for 15% or more of the total structure of aircraft operating up to say Mach 2·0. As we sweep through the Mach number range in the flight corridor up to satellite speeds, ideas are crystallising on likely materials for practicable flying machines (Fig. 4).
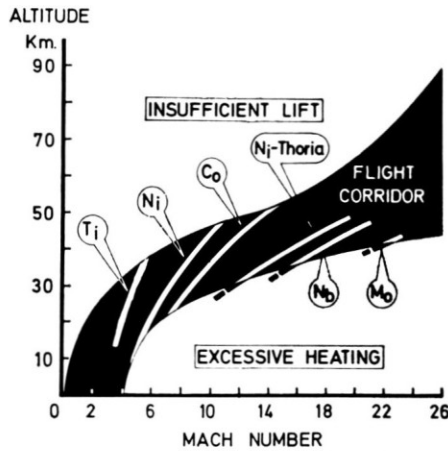
Crown Copyright

FIG. 4 — Materials for use in the flight corridor up to satellite speeds

Composite materials show signs of coming to life in a big way, and recent work in the U.K. suggests that they may well provide the most exciting advances on the materials front. Carbon fibres have been produced with specific strength comparable with glass fibres and with an elastic modulus twice that of steel. They show compatibility with a wide range of resins. In the past glass and asbestos reinforced plastics have given a specific elastic modulus (elastic modulus/specific gravity) only about half that of aluminium,

titanium or steel alloys. Now these carbon fibre composite materials are promising a specific stiffness not only equal to, but exceeding, that of the metals. This could have noteworthy consequences in the design not only of airframes but of engines.

Non-metallic materials — transparencies, tyres, seals etc. — can prove stumbling blocks to sustained high speed flight; development will have to be forced in order to match the primary structure in high temperature performance, but much progress has already been made. For example, recent research work on the mechanics of high-temperature ageing in synthetic rubbers, together with the invention of new polymeric anti-oxidants, has given us rubber capable of operating at higher temperatures, and for longer periods, than was thought possible a few years back.

Metal-to-metal adhesive bonding shows signs of surging forward with the advent of new thermosetting resins, such as the polyimides and polybenzimadazoles. The possibility of joining steel or titanium by relatively simple techniques for extended use at 250°C cannot now be dismissed.

2.4. *Engines*

The advent of the jet engine has already revolutionised civil and military aviation, but researches indicate that much development still lies ahead in the propulsion field. In the early days the air went in through a simple pitot intake in the front and came out of a simple nozzle at the back; the overall pressure ratio was about 4. Now, looking at the pressure/volume indicator diagram for a Mach 2·2 powerplant, as illustrated in Fig. 5, we think in terms of an overall pressure ratio as high as 94. When jet propulsion started, ram
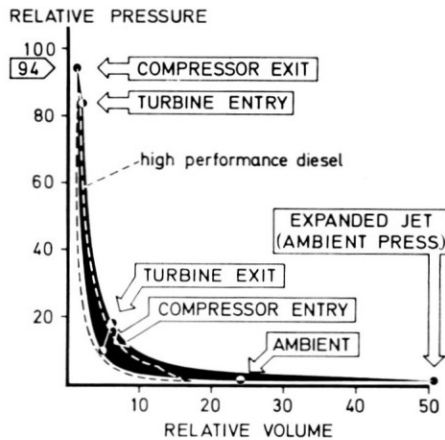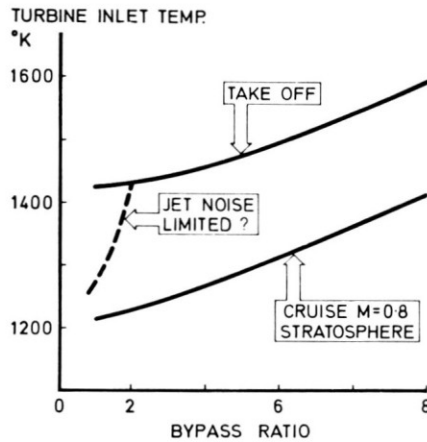

Crown Copyright

FIG. 5 — Mach 2·2 powerplant — pressure/volume diagram

F

effect contributed little. In the Mach 2·2 case of Fig. 5 more than half of the work done thermodynamically is associated not with the engine itself but with the compression and expansion processes in the aircraft intake and exhaust system.

This tendency for the intake and exhaust systems to form an increasingly important and functionally integrated part of the thrust producing apparatus is by no means confined to supersonic operation. With the development of fan engines of high by-pass ratios the same trend is evident in long haul subsonic aircraft. More and more, propulsion research is concerned just as much with intakes and nozzles, and with marrying internal and external flows, as with the gas producer itself. Three lines of research are worthy of particular mention:

(*i*)   The search for still better high temperature materials, and for techniques of turbine cooling, to allow us to take full thermodynamic advantage of the increased pressure ratios becoming available (*see* Fig. 6).

FIG. 6 — Influence of by-pass ratio on TET

(*ii*) The evolution of lighter and more efficient intake and exhaust arrangements for realising in practice the gains that should be available from first class aerodynamic design.

(*iii*) Possibly as important a field as any, the understanding of how best to evolve really sophisticated control systems, fully automatic and featuring elaborate computational processes, for managing the whole intake–engine–exhaust system with the many degress of freedom necessitated by large scale variable geometry. Getting the best out of an aeroplane in all the wide variety of flight conditions covered by an

operational sortie — taxying, take-off, climb, cruise, let down, stand-off and landing — is a major undertaking; big prizes can be won by doing it properly, automatically and reliably.

Many of the above points are good for aircraft exploiting the speed ranges we are used to today — from VTOL aircraft to high subsonic machines and supersonic transports. Once we start travelling at speeds well beyond Mach 3·0, as illustrated in Fig. 7, ram temperature will subject the intake components

RAM TEMP.
°K

AMBIENT TEMP.
216·5°K

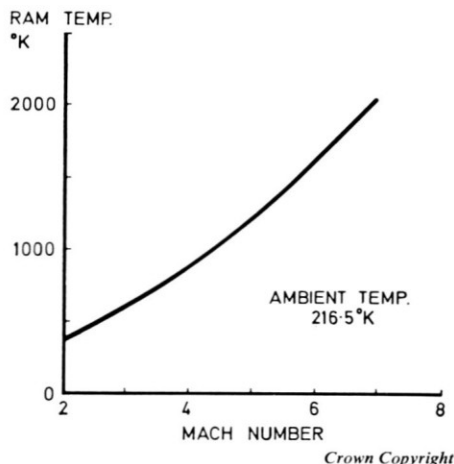MACH NUMBER

Crown Copyright

Fig. 7 — Ram temperatures versus Mach number

to an environment now only met with in the gas turbine itself; new cooling techniques will be needed since the atmosphere can no longer be used as a simple heat sink. These heat problems will be even more acute at the exhaust end. A significant proportion of the gases in the propelling nozzle will be in a dissociated condition. Use of shock tubes and gun tunnel types of apparatus will be necessary to gain a proper understanding of these dissociated flows and thence to design for maximum overall efficiency.

2.5. *Equipment*

From being a poor relation when compared with the airframe and engine fields, aircraft equipment on the military side has now attained a position — if not of dominance — at least of parity. Since military equipment in general poses rather more severe problems than civil — essentially because in war one operates in an unco-operative and actively hostile environment — it might be useful to paint briefly the offensive/defensive picture which so strongly colours aircraft equipment research and development.

The development of the ground-to-air guided missile forced strike aircraft away from high altitudes — which from the aerodynamics and propulsion angles is their natural region — when in the neighbourhood of defended targets; from this sprang the stand-off bomb and the low altitude strike aircraft.

The stand-off bomb in its turn forced defences to expand from pin-point to area; area defence made the fighter armed with air-to-air guided weapons more fashionable. Air-to-air weapons can give a fighter the ability to make 'snap up' attacks in the forward hemisphere against targets of superior speed and height.

All in all this adds up to a strong inducement for the attacker to come in really low — in spite of the sacrifice in range — for as long as possible. At a few hundred feet he can use the ground as a cover. The situation calls for very advanced work on the equipment front. The bomber must be able to fly consistently low by day or night, at the same time navigating and bombing accurately. The opposing fighter would like early warning and this is made difficult by his opponent flying below the normal ground-based radar horizon; and quite apart from early warning, the fighter itself must finally be able to pick out the low altitude bomber quite accurately against ground clutter in order to mount and press home an attack; and so the offence/defence technical battle continues. The general picture is one of much more emphasis being placed on equipment finesse, and possibly less emphasis on the last ounce of aircraft performance.

Aircraft equipment can be considered under two headings — sensors and data handling. Sensors concerned with picking up something going on in the aircraft itself have benefited immensely from the stimulus given to transducer design by the guided weapon and its associated telemetry. Of particular interest to weapon systems are sensors, active or passive, operating over a wide variety of frequency bands, designed to probe the external environment — artificial eyes enabling the aircraft to detect the presence of airborne or surface objects. While the direction of sensor research is spurred by operational need, break-throughs are difficult to anticipate. The world-wide technical battle between low altitude offence and defence has provided, and will continue to provide, a powerful stimulus and already dramatic progress has been made on both the offensive and defensive fronts. The laser might well turn out to have triggered another burst of sensor development, since it offers very accurate ranging from a high density source of extremely narrow beam width.

Data handling equipment has developed very fast of late and will continue to prove an exciting research area with the advent of digital computers and micro-miniaturisation. The digital computer is far more attractive than the analogue when very high capacity is required, and allows the designer to be much more bold in the scope it gives him for intricate and automatic computa-

tions in flight, for storage, and for self-checking. In principle it will be possible to give the the air crew much more information, for monitoring or for action, and the problem of how to get this information to the crew — how to display it within a very limited cockpit space — will become increasingly interesting and important. Some of this information is needed throughout the flight; other parameters may only be wanted for a very brief period, say at some stage of an attack. It becomes increasingly attractive to use a single display for several alternative functions. The head-up display already promises a revolution in giving the pilot easily assimilated instructions. Display techniques are promising to become so flexible as greatly to ease the design problems of the multi-role aircraft — a single display and computational system will be able to deal with a wide variety of roles and the problem of changing from role to role will lie in the sensor and weapon components rather than with computation and display.

Any remarks about the future of the equipment scene would be incomplete without vigorous stress being placed on reliability. Wings falling off or engines stopping are sufficiently dramatic for everyone to see the point that these primary components must be extremely reliable, and large sums of money and immense technical effort are devoted to these ends on the airframe and engine sides. The same must be true on the equipment front, both for the individual articles of equipment and for the methods of hooking them up. When we strip off the immense weight of statistical theory in which reliability discussions tend to be shrouded, at the bottom what is needed is good sound detailed engineering.

2.6. *Project themes*

From the knowledge already amassed as a result of current researches, and of extensive design and operational experience, the aeronautical world is poised for many advances in the relatively short term. For any individual country such an expanding field of possibilities has to be looked at within the framework of a budget governed by the size of its resources. All countries have to be selective in their aeronautical activities, and for medium and small sized aeronautical nations international co-operation will increasingly become the order of the day if their scientists and engineers are to keep abreast of the developing art. Looking at the world aviation scene the following points can be made.

In the transport field the first generation of supersonic transports will give answers to the open question of the future balance between subsonic and supersonic machines for the medium and long hauls. Meanwhile research will undoubtedly give a clear lead to a second generation of supersonic machines more refined in aerodynamics, in powerplant and in structure.

At the same time as supersonic transports are winning their spurs the

second and third generations of subsonic long range jet transports will be making their presence felt, keeping up the pattern of improved economics primarily by exploiting larger overall size and better engine characteristics. The shorter haul subsonic civil machines will continue to come in a variety of sizes; the rate at which aircraft size grows with time — as grow it will — will be determined by the battle between the attractions of high frequency as a means of appealing to the public and large size as a means of getting costs down if load factors are sustained. Growth of traffic and of aircraft size will accelerate demand for improved passenger handling arrangements at the airports.

Military aircraft projects will tend to fall into two groups. First, special types designed for specific tasks — these are the aircraft which will force top speed steadily up the Mach number scale, well beyond the Mach 2·0/3·0 region which is becoming familiar to us. Second, more versatile types — which may well become increasingly popular — where stress is laid on multi-role characteristics and flexibility in operation. Variable geometry and mini-aturised equipment will help in giving flexibility.

Quite apart from the traditional roles covered by trainers, reconnaissance machines, fighters and bombers, air transport must continue to play an important role in any Service needing quick reaction time. There will be the usual resulting interplay and cross-fertilisation between Civil and Military transports. With the advent of electronic techniques for detecting low fliers, special purpose long endurance aircraft capable of multiple target detection and multiple fighter or guided weapon control may become a more familiar part of the military pattern.

Helicopter development will give steadily improved performance for the duties to which these machines are already adapted, by general cleaning up from the drag angle, by refining blade characteristics, by greater attention to engine optimisation, and by increased emphasis on reliability. Dramatic increase of speed is unlikely — although a step forward can be taken if needed by a compound layout such as that of the Rotodyne — until tech-niques are established for (*i*) stopping and possibly stowing the rotor on the cruise or (*ii*) converting it to a propeller on the cruise.

Many alternative approaches to VTOL are now before us; we have already mentioned the vectored thrust P.1127, and the possibility of lifting pods for VTOL transports. For smallish fighter/strike VTOL machines radius of action is likely to be measured in some hundreds of miles initially, and there will be a place for subsonic and supersonic designs. The lifting pod scheme — rendered practicable by the development of ultra light weight jet engines — has attractions for military transports, especially if emphasis is laid upon readily removing the lifting apparatus — as can be done with pods. Should one be content with permanently built-in VTOL arrangements, a wide variety of tilt wing or tilting propeller schemes can be considered. The next

decade will witness an increasingly sharp tussle between conflicting VTOL themes for military application.

Mention must be made of one other new concept — the Hovercraft — which is likely to find a niche both in civil and in military roles. Development in size has been steady, and there seems no technical reason why sea-going craft of 500 tons weight should not be within our grasp. Such craft would have obvious military applications in anti-submarine warfare and as transports; smaller sizes of Hovercraft can well be imagined as fast patrol boats mounting a useful guided weapon armament.

3. ILLUSTRATIVE EXAMPLES OF TECHNICAL AREAS DEMANDING HIGH EXPERTISE AND OF TOPICAL INTEREST

3.1. *Intakes and nozzles for economical supersonic flight*

The word economical has been used above to distinguish those machines where the primary objective is to cruise a long way at minimum cost at supersonic speeds — the supersonic transports, from those needing adequate supersonic performance as part of their role but which are content to achieve extreme ranges by subsonic cruising — military aircraft with a supersonic dash capability.

Supersonic transports demand enormous aerodynamic care in fixing their general external shape to match adequately the demands of airfield performance, stand-off performance and extreme efficiency on the cruise. Equal care is needed in intake and nozzle design; some of the problems facing the designer and his specialist advisers at speeds round about Mach 2·0 will now be described.

When supersonic transports began to be taken seriously, the essential aerodynamic requirements for the engine installation were seen crudely as provision of high pressure recovery in the intake combined with a low installed drag. From military work a fair background of research on the internal aerodynamics of supersonic intakes was available, and it seemed that a fairly high pressure recovery could be obtained from a variety of approaches. The crucial question then became one of external drag. Lift/drag ratio on the cruise was so difficult to get up that it tended to dominate people's thoughts.

On a subsonic aircraft with discrete underwing engine pods, the cruising skin friction and form drag of the pods alone usually amounts to about 5% of the engine thrust, increasing to, say, 7% when allowance is made for the drag of the supporting struts. Initial calculations suggested that at speeds round about Mach 2·0 to 2·5 discrete pods designed to take a suitable engine would have a percentage drag very much — indeed horrifyingly — higher than this; about three times as much. This is well illustrated in Fig. 8.

Percentage wise, skin friction drag is higher than at subsonic speeds because

a longer nacelle is needed to give a good supersonic shape; a roughly equal amount of drag comes from supersonic wave drag associated with the forebody taper and the boat-tail; further wave drag comes from the shaping of the forward lip of the cowl needed to match the type of intake selected — in this context a mixed compression design (at least one oblique shock and the
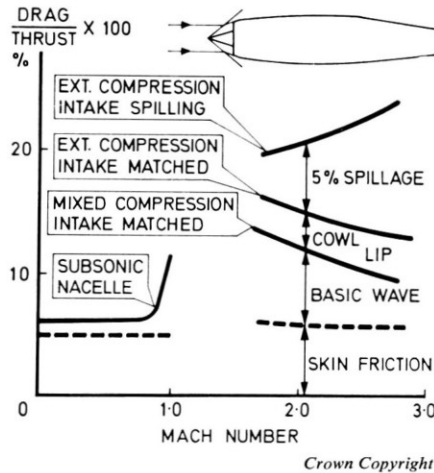
FIG. 8 — Drag of isolated supersonic nacelle

terminal shock located inside the cowl) shows up better than an external compression design (terminal shock effectively in the entry plane); finally, an alarmingly high drag penalty comes from any mismatch of intake and engine flow requirements, as indicated in the 5% spillage case of Fig. 8. The word finally is misleading, since so far we have been talking about the isolated pod. Adding on such components as the supporting pylon drag and intake bleed can easily bring us up to a figure for installation drag of between 20% and 25% of the net thrust. At this stage the aerodynamicists tended to throw up the sponge and to search for a new approach. They found it in the integrated installation wherein discrete pods are abandoned and the engines merged into the wing body shape; this approach fitted in well with a slender wing design.

The idea now is to house the engines close to the wing undersurface in such a manner that:

(*i*) increase of wetted surface area is kept to a minimum;

(*ii*) some airframe volume is utilised to part bury the engines, so reducing wave drag.

Such a theme is illustrated in Fig. 9. This has been somewhat idealised, and in the form shown the increase in skin friction drag over the basic wing

is limited to the shallow side walls of the combined duct, giving only a 1% decrease in net thrust. The partial burying of the engines allows an optimum cowl profile to be used between intake and exit nozzle; since these do not differ greatly in area, the basic wave drag is reduced to quite a small value, again about 1% of the net thrust.

Mitigating against these gains, however, is the fact that the wing boundary layer ahead of the intake has to be dealt with by bleeding. This was thought to result in a drag of roughly 4% of the net thrust. Even so, adding it all up, and taking into account also the 1% net thrust loss associated with intake compression surface bleeding, target figures for installation drag of 8% for a mixed compression intake or 11% with an all-external compression intake seemed reasonable. These seemed so much nearer the subsonic values that, with a sigh of relief, the aerodynamicist felt that he had done a good job and that detailed working up was possible.

Intake pressure recovery was good — say 92% for an external-compression design, or 89% for a mixed-compression layout with its associated lower drag — with the possibility of still further increase asssociated with the slightly reduced Mach number at the underwing intake relative to free stream. It soon became apparent that the idealised central position of the engine cluster illustrated in Fig. 9 would have to give way to two symmetrical

PART-BURYING LEADS TO NEAR ZERO WAVE DRAG

FRICTION DRAG LIMITED TO SHORT SIDEWALLS
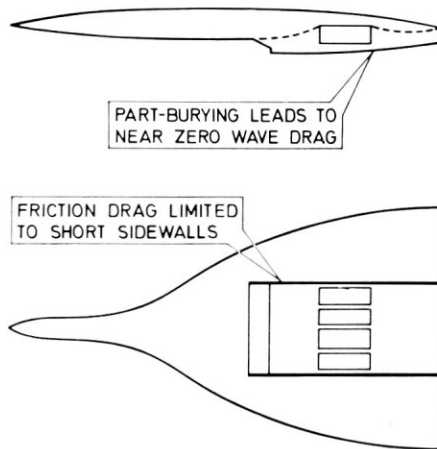
Crown Copyright

FIG. 9 — Low drag installation for moderate supersonic speed (idealised)

clusters, one each side of the centre line. While this increased the friction drag and the wave drag, such an increase was partially balanced by a decrease in boundary layer bleed drag since each intake was dealing with a thinner boundary layer.

Choice between mixed compression and external compression for the two-

F2

dimensional intakes demands much work and very fine judgment. Of equal importance to the aerodynamic arguments, and possibly less frequently aired, are the sheer engineering difficulties of providing an adequate control system. On this score the external compression intake has much to recommend it, and it can be argued now — after a great deal of experimental work — that for an aeroplane designed to cruise at about Mach 2·0 the overall balance of advantage lies with the external compression arrangement. Models of the type illustrated in Fig. 10 have demonstrated a pressure recovery of 94% with a
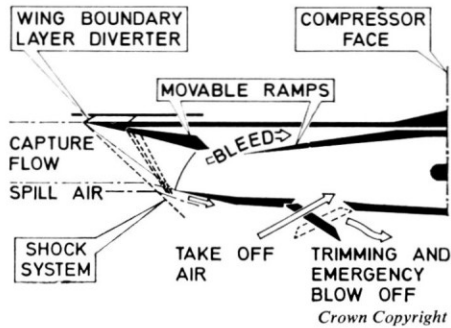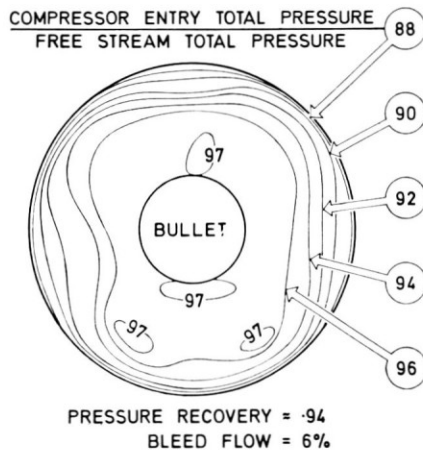

Crown Copyright

Fig. 10 — External compression intake

bleed flow of about 6%. Flow distortions at the compressor entry can give — and have given — untold trouble to the engine man; in this context the two-dimensional external compression intake can be made to give results as encouraging as those indicated in Fig. 11.

PRESSURE RECOVERY = ·94
BLEED FLOW = 6%

Crown Copyright

Fig. 11 — Example of flow distortion at the compressor face

Turning to the nozzles, again we enter a tender area demanding difficult judgments since a very small change in nozzle efficiency can give a much larger proportional change in aircraft payload for a given task. Many arrangements are possible. The preferred exit section differs both in area and shape from the maximum nacelle cross-section; for the Mach 2·0 aeroplane the nozzle exhaust area for correct expansion is noticeably less than the area of the nacelle. After much work it looks as though it is wise to retain circular exhausts, and to keep boat-tailing to a minimum.

The off-design case now rears its head. For expansion ratios of about 15 at cruise the ideal nozzle is of convergent-divergent form, whether it is single or two-stream; the expansion of a secondary flow from intake bleed etc. must be accommodated. It is well known that these forms of nozzles with fixed exhaust areas show very poor thrust characteristics at pressure ratios well below design. This cannot be tolerated if good fuel economy is to be achieved for diversion and stand-off — as is essential.

Two basic solutions are available. The first concentrates on techniques aimed at preventing serious over-expansion in an all-internal expansion nozzle, using a combination of aerodynamic and mechanical devices. A nozzle of this form is often labelled a 'blow-in door' type, a name derived from the mechanism which allows entry of free-stream air at low speeds of flight — with the aim of suppressing primary jet expansion and hence minimising the extent of the negative pressures on the divergent walls; the downstream portions of the latter are also moved inwards to reduce exit area, a dominant parameter. A second approach — often labelled the 'plug' nozzle — concentrates on having at least part of the supersonic expansion taking place externally, so that away from the design point the nozzle flow can accommodate itself to the applied pressure ratio far more readily. In practical terms such an arrangement demands a central 'plug' used in conjunction with a parallel outer shroud.

Choice between these two radically different approaches is peculiarly difficult, since much detailed design work is essential to get a 'feel' for the balance between factors such as weight, complexity, cost and time-scale. At the moment the 'blow-in door' is in the ascendant, although advocates of the 'plug' feel that in the course of time this alternative approach might come into its own.

3.2. *Variable geometry*

'Variable geometry' is rather an unsatisfactory term since an alteration of part of the aircraft shape in order to deal with changing conditions has been with us for years, but is rarely referred to by this name. We are all familiar with the variable pitch airscrew, with the retractable undercarriage, or with trailing-edge flap arrangements, some of which give a very sizeable increase

in wing plan area when the flaps are extended. However, 'variable geometry' has come to mean pivoting the wings in some way so that they can be swept backwards or forwards to suit flight conditions — back for high speeds and forward for low speeds. By using such a device interesting possibilities are opened up and a whole area of formidable aerodynamic problems is exposed.

The first point to be made is that variable geometry is not a heaven-sent gift to designers whereby good aeroplanes are automatically made better. On the contrary, for many single role specifications it can be shown quite conclusively that anything a variable geometry aeroplane can do, a fixed geometry aeroplane can do better. Unless the aircraft specification is chosen with care, variable geometry may well add to the cost and the complexity of the machine.

However, provided we have a suitable specification — essentially one demanding a fairly long endurance on the subsonic cruise combined with supersonic capability and good airfield performance — variable geometry can become very attractive and considerable thought has, over the years, been given to variable sweep in a number of countries.

The reason why care has to be taken in choosing variable geometry is that breaking the wing can introduce weight and drag penalties. Structure weight is increased because loads from the outer wing have to be concentrated in the hinge region; there is a loss in stowage volume because of the necessity for parts of the outer wing to retract into the inner wing as sweepback is changed; there are additional mechanical and weight complications associated with the sweep mechanism and with sealing the gaps which occur between the two parts of the wing — or the wing and fuselage — at some sweep angles.

To counteract these disadvantages, the high aspect ratio in the unswept wing position allows the use of efficient leading and trailing edge devices for landing, and gives a good lift/drag ratio when cruising subsonic, while the low aspect ratio and low thickness/chord ratio with wings swept back limits the transonic variation of aerodynamic characteristics and allows good supersonic performance to be achieved — although possibly not as good as a fixed geometry shape designed specifically for good aerodynamics when cruising supersonic.

Choice of wing loading is all important. If the main requirement is for good airfield performance and for long range on the subsonic cruise, a relatively low wing loading is desirable. If, however, a lengthily sustained high Mach number at low level is demanded, combined with ability to accelerate rapidly to supersonic combat conditions at high altitude, then a much higher wing loading emerges. For a multi-role fighter/strike aircraft a relatively high wing loading is found to be the best compromise. This implies equipping the wing with fairly advanced and sophisticated high lift devices if good airfield performance is to be maintained, while to preserve subsonic manoeuvrability

the basic wing section must have a high critical Mach number at incidence.

In many variable geometry studies a hinge position well outboard of the fuselage has been chosen to minimise the variation of aerodynamic centre relative to the centre of gravity as sweep is altered. This means that a highly swept inboard section of the wing stays put while the outboard section changes its sweep, and brings with it a number of disadvantages. High lift devices have to be restricted to the outboard portion of the wing only. At high incidence the vortex shed from the highly swept inboard portion of the wing can give a violent pitch-up unless a very large tailplane is used; such a vortex also induces a strong spanwise boundary layer drift over the rear of the wing which can result in tip separation — again giving pitch-up — and can also reduce markedly the effectiveness of trailing-edge flaps.

If all this catalogue of trouble drives one to a large tailplane, one begins to query the virtue of an outboard hinge position chosen essentially to keep down aerodynamic centre movements.

Considerable aerodynamic advantages spring from moving the hinge inboard to the fuselage side. High lift devices can now be used over the whole span, and high C_L's can be achieved with little pitch-up; under these conditions the centre of gravity of the aeroplane can be kept behind the aerodynamic centre of the wing, and hence the large tailplane still needed to deal with the trim changes associated with wing movement can contribute significantly to overall lift. At the stall the wing lift is ahead of the centre of gravity and so one gets a beneficial nose-down pitch rather than self-stalling. One final aerodynamic virtue of an inboard hinge position is that, because of the simpler geometry of the exposed wing both when swept and unswept, advantage can be taken of theoretical design methods now available for achieving good lift/drag ratios at high subsonic speeds; flow conditions at supersonic speeds with wings swept back are also more responsive to theoretical treatment, thereby reducing the amount of wind tunnel testing needed when evolving the precise shapes.

While aerodynamic problems bulk large in variable geometry layouts, variable sweep introduces an intriguing range of problems on the structural and powerplant sides. Choice of pivot design — the single pivot versus the pivot and track — is by no means obvious; stiffness and flutter characteristics need careful watching. The impact of variable sweep on powerplant choice can come from the wide flexibility in role offered by variable geometry. This introduces, for example, still further difficulties in assessing the optimum by-pass ratio — a task which is quite complicated on a fixed geometry machine.

All in all it can be said that, given the right specification variable geometry is of great significance; it provides one more weapon in the designers' armoury. It demands a high standard of expertise and sophistication from the supporting specialist groups, a standard which has been attained as a result of lengthy

and patient spade work in the aeronautical laboratories of industry and of the research establishments.

3.3. *Terrain following*

This has been chosen to illustrate a complex problem in the aircraft equipment area, demanding the application of a wide variety of disciplines, and judgments involving safety, reliability and operational utility. The case for evolving a system allowing a military aircraft to fly consistently and fast within a few hundred feet of the ground is well indicated by Fig. 12. The
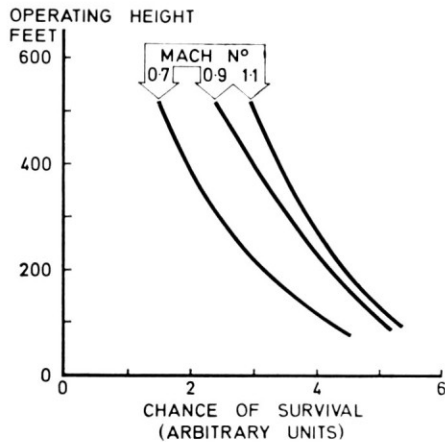
Crown Copyright

FIG. 12 — Influence of height on chance of survival

lower the aircraft flies, the less warning time available for the defences. Ground defences are forced to a very rapid reaction time. In hilly country defence installations may be sited on top of the local eminences to maximise warning time; this, to some extent, can be offset if the aircraft can take advantage of the screening of intervening terrain. Fig. 12 illustrates the chance of survival against an arbitrary guided weapon defence pattern. The virtue of coming down really low is readily apparent — we are talking in terms of a few hundred feet rather than thousands. The limited value of increasing speed from Mach 0·9 to Mach 1·1 is also well brought out — the gain in chance of survival can equally be obtained by dropping the height a few tens of feet.
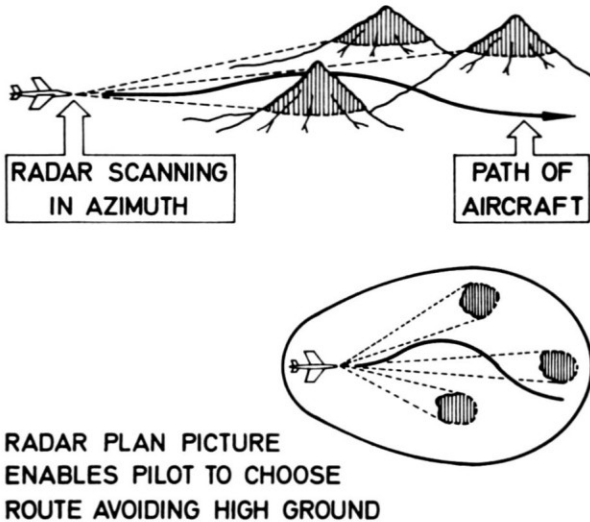
A pilot can fly really low at quite high speeds just using his eyes, provided that visibility is better than about 6 miles and that duration is sufficiently short to avoid mental fatigue. However, when duration is long or the visibility is poor, a radar must be used in conjunction with an automatic flight control

system to allow the aircraft to be flown safely and consistently at the altitudes of interest to us.

This problem of blind and automatic navigation in three dimensions involves the integration of aircraft sensors, references, navigational facilities and a radar which provides range/angle data for the profile of the ground as seen from the aircraft.

Two types of terrain-sensing systems are of operational interest:

(*i*) *Terrain avoidance* (plan systems). An Azimuth scanning radar is used to display in map form the distance along any bearing of the nearest ground for a selected height relative to the flight level of the aircraft. This allows the crew to take horizontal evasion and to plan a route which offers maximum screening — they can choose to fly along shallow valleys — as illustrated in Fig. 13. However, such weaving in azimuth makes it difficult to attain a good ground hugging performance in elevation.


RADAR SCANNING IN AZIMUTH

PATH OF AIRCRAFT

RADAR PLAN PICTURE ENABLES PILOT TO CHOOSE ROUTE AVOIDING HIGH GROUND

Crown Copyright

FIG. 13 — Terrain avoidance

(*ii*) *Terrain following* (elevation system). Here the radar is pointed along the flight path in azimuth and scans in elevation. In this way ground profile straight ahead is determined and it is possible to display on a flight director instructions which enable the pilot to hug the ground closely; alternatively, the radar information is fed into an autopilot which does the pilot's job for him — simultaneously keeping the flight director information displayed to the human pilot so that he can

monitor what is going on. By suitable refinement a system of this sort can be adapted to deal not only with the aeroplane flying straight, but also with controlled turns (Fig. 14).

Tendency to fly from peak to peak

TERRAIN FOLLOWING

Follows terrain more closely
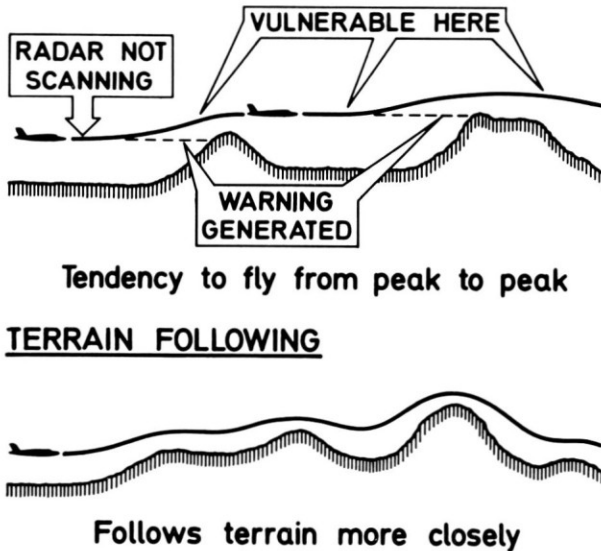
Crown Copyright

Fɪɢ. 14 — Terrain clearance

Radar design demands a number of compromises — for example, the more complex the scan the lower the data rate and the less accurate the information for each look. Safety provides quite intricate problems — possibly more testing than those of automatic blind landing. If anything is malfunctioning, even slightly, the aeroplane must automatically switch to some alternative component and carry on or veer away from the ground to enable the pilot to take over and get things sorted out. As an example, if a Doppler system is used to provide a drift and speed datum, its output can be automatically monitored; in the event of loss of signal lock the Doppler information can be ignored and replaced by inertially derived velocity or airspeed. If radar returns are temporarily lost by, for instance, flying over a patch of very calm sea, a radio altimeter can act as the source of accurate height information. The combination of immense basic technical difficulty with the obvious need for the most stringent fail-safe precautions, when flying automatically at near sonic speed a few hundred feet from undulating terrain, makes this problem peculiarly fascinating. It illustrates the advanced state of the military aircraft equipment art that it has, in fact, been tackled successfully.

4. BASE LOAD

I am introducing a few short paragraphs under this heading to make the point that design offices are rarely monopolised by exciting new projects — important though these are for future health. An immense amount of high quality scientific and technical work — possibly less glamorous and certainly less publicised — must go into taking existing projects, shaking them up, and selling more of the modified versions.

Any initially successful aeroplane should subsequently be developed further to increase its capabilities. This may take the form of design refinement to improve performance in terms of speed or range or payload capacity. It can involve aerodynamic refinement, structural alterations or re-equipment. Uprated engine variants or a change to a completely different engine sometimes dominate this scene.

Statistics for a number of British aircraft indicate that in later versions the take-off weight has increased by up to 50% above the take-off weight at which the aircraft entered service.

Re-equipment is often consequent on a change of role. Particularly in military machines such changes are commonplace — being dictated by current thoughts on the identity of potential enemies and on what such likely enemies may be up to. A classic example is the conversion of the V-bomber role from high altitude to mixed high/low operation. Quite apart from equipment changes, such alterations in role can generate much work on the basic aircraft design. Taking again the V-bomber story, once low level operation is demanded the influence of gusts on fatigue life is sharply accentuated.

Looking at experience in Britain — which is parallelled by that of other major aeronautical design countries — we can say that design and development may well extend for 10 years or more beyond the first introduction of an aeroplane into service. During this period the level of effort can be as great — and sometimes greater — than the manpower employed in the original basic aircraft design. For many years past, on average, manpower on design has been divided in the rough ratio 40% on new projects, and 60% on the developments of existing designs. This is not generally appreciated, and can provide a useful element of stability in the rather turbulent fluctuations of the aircraft project scene which, from time to time, afflict the aeronautical countries.

5. THE HANDLING OF INDIVIDUAL PROJECTS

From the formal angle most major aeronautical countries have felt impelled to evolve elaborate processes for establishing the need for new aero-
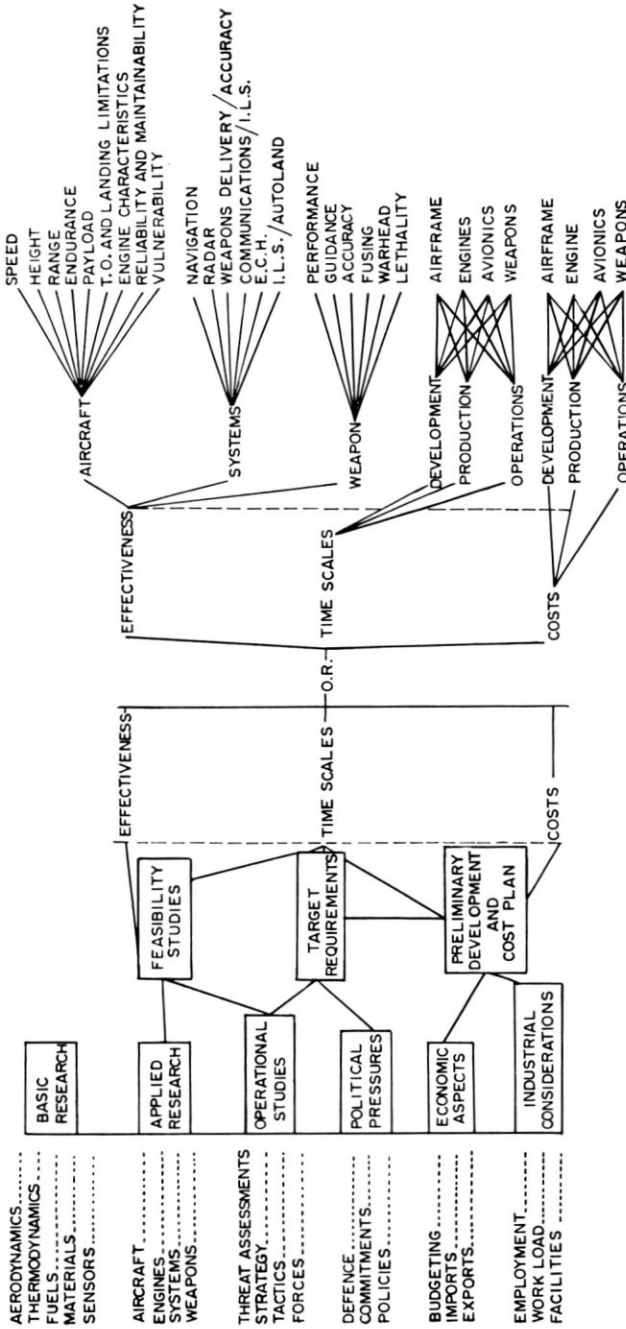
Crown Copyright

Fig. 15 — The operational requirement scene

nautical military equipment, and for the subsequent design and procurement of the relevant hardware. For obvious reasons the civil picture has been less formalised in the Western world, since more private money is involved and, in general, less reliance can be placed on large scale sales to a single customer.

In the United Kingdom the broad procedure is intended to run as follows. In the context of an established defence policy, the individual Services — closely held together by the Ministry of Defence — keep a continuous watch on their future project needs. The operational requirement staffs work under a wide variety of pressures — domestic and foreign. The dominating foreign pressure obviously springs from information on the posture, plans and technical status of potential enemies. The primary domestic pressure results from the need to replace blocks of equipment within certain date brackets — because they will by these dates either be worn out or rendered obsolete by technical advance. The various inputs involved in firmly establishing an aircraft operational requirement — involving advice, work and decisions by Research Establishments and Industry as well as the Whitehall machine — are illustrated in Fig. 15. Feasibility studies will have been done by Industry, based on Staff Targets coloured by state-of-the-art advice from the research people. Very preliminary cost-effectiveness appreciations will have been prepared. Very preliminary long term forward costings will have been looked at to see whether likely spend over the years fits in with possible future budget allocations. All this takes time and it may be a year or so, rather than months, between the first glimmerings of a new requirement and its final formalisation, with a specification written and industry working on it as a positive project.

Initially the Operational Target is written in fairly broad terms to illustrate the sort of jobs the Service staffs envisage for the new aeroplane and its environment. During feasibility studies this Target is related to the technical state-of-the-art and many solutions are explored, each of which will have advantages and compensating disadvantages; the overall effectiveness of each solution has to be assessed.

Let us take as an example the problem of a strike aircraft whose main function is to support intervention operations. Possible solutions could range from aircraft of well over 100,000 lb. all-up weight, operating from major bases and carrying bomb loads over long distances, to much smaller aircraft operating with lesser loads from more primitive bases much nearer the centre of operations. These smaller aircraft might need V/STOL capability because of restrictions in likely landing area size or in aid of dispersion. Very preliminary aircraft studies would cover this ground and would present, for a family of aircraft, curves illustrating the influence of payload, range and take-off characteristics on all-up weight — the latter being a dominant factor in determining costs.

Complexes of enemy targets can then be assumed related to distances from known or projected friendly bases. The airfield characteristics of these bases

can be postulated. Force levels required to inflict arbitrary degrees of damage can be calculated, and loss rates due to various assumptions on the strength of enemy reaction estimated.

From such assessments many of the aircraft in the range of sizes and characteristics covered can be rejected out of hand as being obviously over-costly ways of doing the set job. It is rare, however, that a sharp and clear optimum appears. This preliminary work gives the 'feel' of the problem, but the final decision on the precise wording of the Operational Requirement often comes from considering the importance attached to secondary roles and to judgments on how much technical risk can be taken during the development cycle.

In the early year or so of industry's subsequent design activities much firmer information can be built up on all aspects of the project, as illustrated in the second half of Fig. 15, culminating in a considered cost-development plan which will form the framework for future work. At this stage the project is reviewed, and should the up-to-date information conflict markedly with the very early feasibility study work — either in terms of increased cost, later dates, or decreased operational promise — the question will be raised and debated of whether or not it should continue. With a small and inexpensive piece of gear a cold-blooded decision to stop at this stage is straightforward if the facts are clear enough. It is much more difficult when dealing with a major and very expensive item — such as an advanced modern military aeroplane and all its systems — since by this time it will have acquired a large momentum with quite major issues arising should plans need changing. This highlights the importance of very thorough preparatory work in selecting the appropriate variant for detailed project definition.

From the moment an operational requirement is firm to the moment the aeroplane can get into service in appreciable numbers, some five to ten years will go by; it will remain in service for another five to ten years. Over a decade even the most passionate advocates of stability and ordered progress would find it difficult to argue that — looked at historically in terms of what has happened each decade over the past 50 years in the military aircraft and aerospace world — major and unexpected changes will not occur, and will occur frequently. Some changes — alteration in ideas on costs, timing and effectiveness of individual projects — can partially be guarded against by tighter detailed control, closer early technical and financial appreciation, use of the most modern management techniques and so on; but even here, on any advanced project, some hideous combination of technical difficulties is liable to throw plans out at a late stage. Much more difficult to cope with on a ten year cycle are changes in the international scene, changes in the economic situation and still — in aeronautics — dramatic changes in the technical climate owing to the rapid exploitation of quite random break-throughs.

We have all — looking at the world picture in military aeronautics and not

solely at our own local experience in the United Kingdom — seen ideas on supersonic bombers alter drastically with the advent of more efficient high altitude missiles and the perfection of surface-to-surface ballistic missiles; we have seen elaborate surface-to-air missile systems and special purpose fighters optimised for dealing with mass raids of high flying aircraft — systems which, when developed, had a radically altered threat to face; we have seen highly sophisticated equipment designed for use against technically advanced opponents having to be used in a very different environment. Looking to the future, he would be a bold man who would predict with any pretence at precision the course of the struggle between ballistic missiles and anti-missiles; or the impact of new aeronautical materials — and new miniaturised electronic techniques — on what is and is not possible in military aviation; or the effect on air warfare of the new V/STOL techniques now burgeoning.

The lessons for military aircraft evolution which I myself would draw from the foregoing paragraphs are these:

(*i*) Those drafting operational requirements should have the likelihood of a changing future scene in front of their minds; they should not operate too rigidly in terms of an optimised solution to a limited and rigid scenario.

(*ii*) Fortunately techniques are available whereby flexibility can be introduced into military aircraft specifications — when dealing with the fighter, strike, reconnaissance and even transport roles.

(*iii*) The most important of these techniques is to leave plenty of stretch in the basic design — ability to accommodate large increases in engine power without a major airframe rework; ability to accommo-date a variety of equipment fits; and so on. All past experience suggests that such stretch is invaluable, is invariably taken up and can be taken up in a variety of ways to suit the circumstances of the time many years after the original operational requirement was evolved.

(*iv*) For military aircraft, the full blooded 'weapon system' concept can undoubtedly be overdone. Of course any particular mark of aeroplane must have airframe, engine, armament and equipment integrated in a sensible way. The central position of the aircraft designer, and the resulting suspicion of the assessment world that armament and equipment were considered vulgar necessities to be pushed in almost as an after-thought, resulted in the pendulum swinging too far towards masses of optimised new components being developed simultaneously with an optimised new airframe and an optimised new engine to form a system optimised for a task which — as mentioned earlier — might well have changed when the whole thing was in production.

(*v*) There is much to be said — again in terms of preserving flexibility —

for the 'building block' approach. What this means is developing advanced aircraft components — not just computers, navigators, radars, weapons etc. but also engines — in their own right rather than as parts of a specific overall project. All aircraft designers would like to design round a tried engine or a variant of a tried engine. Development of a new engine in a new airframe is technically awkward since the timing of the key points in the development cycle rarely match. Once an engine has been established, usually as a result of being tied to a project, almost invariably it finds other outlets. The same is true of many other pieces of important equipment. The whole subject bristles with difficulty — particularly for large components such as engines where development costs can be formidable. The key to a steady extension of the 'building block' concept is obviously the ability to operate within an adequately large market.

It may be appropriate to return at this stage to the question of procedures for obtaining very preliminary estimates of money and time well before a cost-development plan has been established for a major project; and for subsequently managing wisely development through to production, not only technically but also financially. The world aeronautical fraternity has undoubtedly generated an unsatisfactory image in these areas, although as has already been indicated management of an isolated project is but part of a larger whole. Much has been written on these matters, and I have no wish to add to an already well established literature. Two points, however, are well worth making.

First, if asked a question about the time and cost of a possible future ambitious project while it is still just a gleam in someone's eye, the technical man's answer should be: 'I don't know, and it will cost so much to find out.' If he is anxious to please, and quotes numbers surrounded by hosts of guarding clauses, the guarding clauses will soon be forgotten; the numbers never.

Second, the technical discipline involved in dealing with such intricate design areas as were described in section 3 of this lecture are very real and quite formidable. The scientist and engineer on research extends our knowledge continually. The designer works on the fringe of existing knowledge, usually with convincing and sometimes with spectacular technical success. In this risks must be taken, but he knows that he must hold within fairly fine tolerances, his weights, his aerodynamic efficiencies, his engine characteristics, to avoid technical disaster; and he succeeds.

It can be argued that equally powerful feed-backs into the core of the design and production teams are desirable, in terms of man-hours, time and money as we already have on weight, lift and drag. They exist, of course, already in large measure. Their strengthening, however, might well result in an earlier and more forceful approach to the customer for a slight relaxation in his

demands should it begin to appear that the last 1 % of technical excellence was being bought at too great a cost. Contractual and administrative devices designed to smooth the way for such adjustments will undoubtedly add strength to the aeronautical scene.

6. Concluding Remarks

I would like in conclusion to make a few remarks about the place of the scientist or engineer in the aeronautical scheme of things. Quite simply, I believe he is undervalued by some of those concerned with the policy and financial aspects of the aviation scene, and that this is not their fault — it is his.

The whole business of grappling with the quite fascinating research, design and development problems thrown up by modern aeroplanes is so absorbing, and keeps those concerned so much on their toes, that too many of them tend to regard any departure from the pure milk of science and engineering as a fringe activity of doubtful decency. Market research, financial control, management techniques, economics, are admittedly important; of course they can think about these things intelligently; but how are they going to deal with a quite unexpected kink in the C_L curve — that, in their judgment, is the proper sort of thing to tackle.

In the face of such professionalism it is not surprising if — to exaggerate wildly — some of those outside the technical circle equate the aeronautical engineer to the plumber hired to mend a leaky tap — if the tap stops leaking he is a good plumber; if the technical people hired to design and build a good aeroplane in fact produce just that, they are good engineers, no more.

There is undoubtedly a need for a loosening up of specialist professional attitudes. Much of the detailed expertise and judgment exercised in severely technical work can be paralleled by that needed on the administrative, financial and marketing sides. When operating in these spheres a thorough appreciation of the design processes is of immeasurable value. Aeronautics would gain if first class scientists and engineers were encouraged to spread their wings at an earlier age to embrace more general problems of forward policy, management and financial manipulation, taking the lessons of their own speciality with them and applying them vigorously. The future has never been more exciting; we can see a wide range of new technical possibilities. To keep forging ahead in good order more scientists and engineers must leave the engine room for the bridge and contribute to command, navigation, tactics and strategy.

Acknowledgments