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THE COLLEGE OF AERONAUTICS
CRANFIELD

TRENDS IN AIRCRAFT DESIGN

by

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SUMMARY

The improved performance of aircraft during the past decade has resulted in the need for new design and production techniques. Particular examples are integral construction and the use of sandwich panels. Although these processes are costly, especially when applied to titanium and steel construction, their use is likely to be necessary, at least to some extent, on many supersonic aircraft. The supersonic airliner is no exception to this and the paper discusses the design aspects of this type of aircraft which have a bearing on production problems. It is concluded that more research aimed at reducing the cost of sophisticated forms of construction is required.

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1. Introduction

The organisers of the Conference requested the lecturers to outline the trends in aircraft design which are anticipated in the near future, with special emphasis on the problems likely to face production engineers. Much has been written about possible developments in the next decade, but any forecasting must of necessity be conjectural. As far as the next generation of military aircraft is concerned the situation is very obscure, except for the fact that it is known that fewer types will be required. Developments in the civil field are rather easier to foresee, these being based on the anticipated travelling habits of the world's population.

The major emphasis in the realm of subsonic flight will involve the use of STOL or VTOL aircraft, together with greater utilisation of automatic flight and blind landing techniques. However, it does not appear that this will cause the production engineer any undue concern, apart from the normal developments aimed at achieving increased reliability by virtue of better detail design and diligence in meeting operational requirements. On the other hand the introduction of the supersonic airliner or a military aircraft of comparable performance will create many problems.

The paper will review some of the changes which have occurred in aircraft design in recent years and offer an explanation for them. Some of the problems associated with flight at two to three times the speed of sound, that is up to about 2,000 m.p.h., will then be discussed. The justification of high speed travel is outside the scope of this paper, but it seems reasonable to assume that the supersonic transport will be introduced into airline service during the 1970's. International competition in this field is already unusually keen and the industry will need to make active and urgent developments to be competitive in the world market for this particular type of aircraft.

2. The Development of Integral Construction

The tailoring and integration of structures to cater for strength, stiffness, fatigue and serviceability is now common on many military and civil aircraft. The introduction of the high speed, thin, swept wing military aeroplane brought this form of construction into being. The single or two spar configuration was impracticable for use in the thin wing aeroplane due to increased loading, stiffness and fuel storage requirements. It became necessary to distribute the wing bending material over as much of the cross-section as possible, taking into account the need to provide for flaps, ailerons, droop nose leading edges, undercarriage stowage and engine installations. These essential features of the aeroplane militate against an optimum structure made out of conventional constructional material built up of constant thickness plates.

Fig. 1 illustrates the design trends of one series of fighter aircraft, the North American F86A, D and H and the F100A and C⁽¹⁾. It is seen that the wings have reduced in thickness by 30%, the wing area has slightly increased and the aeroplane weight and wing bending moment have increased by about four times. This development took place from approximately 1946 to 1956. At the same time it was imperative to reduce relative structural weight. If structural design had not advanced in keeping with the increased performance of such aircraft, the weight

of a wing would be expected to be directly proportional to the loading and inversely proportional to the thickness. In fact the F86A had a wing root bending moment of 3,500,000 in. lb. , a thickness/chord ratio of 10% and a wing weight of 7 lb/ft². The wing root bending moment of the F100A is 8,100,000 in. lb. , the thickness/chord ratio is 7% but the wing weight is only 8.8 lb/ft², not 23 lb/ft² as would be expected by direct comparison. Fig. 2 illustrates in a simplified way the rise in average end load per linear inch from 4,500 lb on the P51 Mustang to 68,000 lb on the F100 and how this has necessitated a change of construction from simple skin and stringers to sculptured integral skins. Although the F100 skins at the root are 1.05" thick between spars and made from 75ST aluminium alloy, the technique of North American Aviation is to machine all skins from flat levelled stock to 0.01" tolerance and form the skins to contour after machining.

With civil aircraft the trend to integral construction was not brought about by excessively thin wing construction, because many of today's large civil transport aircraft still use sophisticated forms of skin-stringer construction. The aim of civil aircraft design is to achieve economy of production, ease of maintenance and inspection, and a long life consistent with safety. The two main enemies of the civil structure are fatigue and corrosion, both time dependent. Because of the fatigue phenomenon, the material must be chosen to have a low rate of crack propagation, the stress levels being such as to give a long crack-free life consistent always with the need for a low structure weight. To meet this requirement design philosophy has wavered from safe-life to fail-safe, and now a combination of the two. That is, the structure is designed so that no failure is anticipated within an acceptable period of operational time, but should it do so the result is not catastrophic. The accurate prediction of the probability of failure of a complex structure under all environmental conditions is exceedingly difficult, and the actual structural design will be influenced by the aircraft manufacturer's own operating experiences. Vickers-Armstrongs have progressed from the concentrated spar booms of the Viscount to the integral wing structures of the Vanguard and the V.C.10. Fig. 3 shows that although the wing root thickness/chord ratio has reduced successively from the Viking to the V.C.10, the wing root bending moment has increased by a factor of over 13, being 112,000,000 in. lb. on the Super V.C.10. Wing weight per square foot shows a slower rate of growth, the factor being approximately 3, even though over the same period the average end load in the wings has become 9 times as great. This is a rather unscientific way of presenting the information from the point of view of structural theory, but it does show the factual design trends which have brought about the need for integral construction. Whilst it is the task of the designer, the metallurgist and other scientific workers to make possible the advances required by new forms of construction, materials and safety, ultimately it is the production engineer who has the responsibility for converting the design into a successful accomplishment.

3. Comparison of Structures for Aircraft Designed to Fly in the High Subsonic and Supersonic Regimes - The Use of Sandwich Construction

The structure of the supersonic airliner can be very different from that of current large subsonic jet transports, because of the radical change of aerodynamic configuration necessary to achieve the desired speed economically. For speeds up to about 1,500 m.p.h. ($M = 2.3$) the use of aluminium alloys may be possible, with a reasonably small weight penalty as a result of the increased temperature. Fig. 4 illustrates the variation of temperature with speed and Mach No. , and its influence on the utilisation of various materials. A rapid reduction

in the strength of aluminium alloys occurs above $M = 2.3$ and it becomes necessary to substitute steel or titanium in many parts of the structure. At about $M = 2.7$ the use of high temperature resistant materials is required in all parts of the airframe structure and non-metals become a serious problem. Conventional hydrocarbon fuels require thermal insulation at cruise speeds above $M = 2$.

The optimum planform of a supersonic transport must provide the required stability with minimum drag at high speed. At low speeds the wing, in conjunction with the fuselage and stabiliser if fitted must possess adequate usable lift, good stability and reasonably low drag to minimise reserve fuel requirements. The delta and modified slender delta wing planforms offer satisfactory high speed cruise performance with reasonable low speed characteristics. An aircraft of this configuration must be carefully designed if the aerodynamic, landing and aeroelastic requirements are to be catered for with minimum structure weight. Fuel pressurisation may be necessary at high altitude, and when consideration is given to fuel insulation and acoustic effects, the use of honeycomb sandwich construction is indicated, at least in some areas of the structure. Honeycomb sandwich structure is well suited to low aspect ratio delta wing construction by virtue of its triaxial load carrying ability and its high efficiency at moderate load intensities. A further advantage is the good surface finish obtainable. As the temperature of the structure tends to increase, so also does the importance of emissivity. The need to endeavour to maintain laminar flow over the structure, and achieve a suitable surface finish to give high emissivity is of great interest to production engineers, although the former is likely to be out of the question on a slender delta configuration. Table 1 shows the effect of emissivity on equilibrium temperatures attained in sustained flight at $M = 2$, $M = 3$ and $M = 4$ at various altitudes⁽³⁾.

The possible implications of the structural design of a delta wing supersonic airliner have been stated, and it is therefore worth while to consider the construction of two delta winged aircraft. The two chosen are the Avro Vulcan and Convair B. 58 Hustler, which are both bombers, but differ in that whilst the former has a maximum speed of about $M = 1$, the latter is capable of travelling at about $M = 2$. Fig. 5 shows the planforms of the Vulcan and Hustler to the same scale⁽⁴⁾. Although little information about the Vulcan has been released officially, consideration of engine thrust indicates that the weight is of the same order as that of the Hustler. The volumes of these aircraft are vastly different since the Vulcan was originally designed to provide for internal stowage of the power plants, undercarriage, fuel and weapon store. The Hustler on the other hand has podded engines and integrated external weapon load in a special pod. The undercarriage cutout in the wing structure is large enough only for the bogie wheels, the drag strut remaining outside the wing section when retracted. These two aeroplanes might be considered as representative of different periods of aviation history, but in fact the Hustler became operational only three years after the Vulcan.

Fig. 6 shows a planform of the Vulcan wing structure which is built of light alloy along traditional lines, with virtually no integral stiffening or machined and tapered skinning. Bonded metal honeycomb, a form of construction which A. V. Roe pioneered in this country, is only to be found in localised areas and access doors on the aircraft. There are two principal spars, each conventionally built up from a plate web and machined upper and lower booms. Almost all of the rest of the airframe is manufactured from standard sheet and sections with a small

number of machined forgings, castings and extrusions. Fuel tanks are of the rigid variety, stowed on tank bearers in the wing.

The plan view of the Hustler wing structure, which has about 4% thickness ratio, is likely to be as shown in Fig. 7. The skins consist of sandwich construction panels and take only approximately one third of the total end load. The wing is a fuel tank and is pressurised to 5 p. s. i. The honeycomb core is Hexcel 3/16" cell size fibre glass and was chosen because of its insulating properties. An epoxy phenolic resin bonds the core to the skins and is capable of withstanding temperatures of 260°C for a short time, or 126°C over a long period. The overall depth of the skin panels is approximately 5/8", the skins being 24ST aged light alloy. Aerodynamic and fuel system loads impose a lateral pressure of 30 p. s. i. on the panels which have a design compressive stress of 55,000 p. s. i. The spar booms, which are at 11" centres, and the rib booms are contained within the sandwich skins and are machined from solid plates, thus forming a continuous fretwork mesh extending to the panel boundaries. These members carry $\frac{2}{3}$ of the total end load. The corrugated spar webs have extruded caps incorporating bosses to receive the sandwich panels. Titanium bolts are used for the attachment.

It is an extremely complicated structure although predominately of light alloy, and for a supersonic transport designed to fly at $M = 2.2$ this is the sort of problem which may face production engineers. The criteria of design resolved themselves to insulation and pressurisation of fuel tanks, aerodynamic smoothness and panel flutter. It was necessary to make a compromise between internal member depth, spar spacing, sandwich thickness, web weight, end load per inch and internal fuel capacity to give adequate stiffness with minimum weight.

4. Sandwich Construction

The potentiality of sandwich construction as a structural means of carrying compressive and pressure loads has been illustrated. The separation and stabilisation of the two faces by the core permits stress levels to be achieved which are limited only by material properties. Thus over a wide range of the loading intensities found in supersonic aircraft the sandwich construction can be designed to give the lowest weight for a given strength. There are two basic forms of sandwich construction, one using a honeycomb and the other a corrugated core. Although the use of hexagonal cells results in slightly anisotropic properties, the loading may be triaxial in nature. The foil thickness used for the core and the cell shape and size may all be varied to give flexibility of application. The joining of the cores to the face-plates can be done by metal bonding, brazing or spot welding. On the other hand, the corrugated sandwich is anisotropic and consequently it is more efficient when subjected to unidirectional loading in its plane. In this case the core may be attached by bonding, brazing, spot welding, argon arc spot welding (puddle welding) or riveting.

The choice between the two is often difficult on structural grounds only and is influenced by production costs, repair and detail design considerations. A comparison of the structural efficiencies of the two forms over the temperature range of 150°C - 350°C is shown in Fig. 8⁽⁵⁾. The materials concerned are stainless steel FV 520 and titanium alloy, and it can be seen that the latter is preferable. However other considerations, such as formability, jointing, torsional stiffness and cost may make the use of stainless steel the better choice. It is significant that the use

of large quantities of stainless steel was proposed for the Avro 730, M = 3 bomber which was cancelled in 1957. At that time titanium sheet was not available in this country, but it was available in the U.S.A. when the North American B.70, M = 3 bomber came into being in the same year. This aircraft has a gross weight of around 500,000 lb. and it is estimated that 19,000 sq.ft. of stainless steel honeycomb sandwich is used in each aircraft, the largest panel being 8 ft. x 20 ft.⁽⁴⁾ As made today, steel sandwich construction is expensive, and it is used on the engine pylons, control surfaces and weapon pods on other American aircraft. Costs have been quoted as \$400 per sq.ft. or \$200 per lb. as against \$25 per lb. for conventional light alloy construction⁽⁶⁾.

There are various ways of making steel honeycomb and some are more expensive than others. A considerable amount of development was carried out in the early stages on the Avro 730 bomber, and it is a pity that the team engaged in this were not allowed to continue to produce hardware. Organic adhesives have been developed for bonding stainless steels for use below 250°C, but this does not exploit the full temperature capabilities of the material. Silver brazing techniques enable steel honeycomb to operate for long periods at 400°C - 450°C, but the process is costly. The U.S. Bureau of Naval Weapons⁽⁷⁾ has a development programme for a ceramic bonded stainless steel honeycomb having long service life at temperatures up to 425°C. Preliminary results indicate that a major advance in the art of low cost bonding may have been achieved. Although there may still be problems to be overcome, this work does show that it is worth while to conduct research in construction techniques without reference to a specific project.

4.1. Steel Honeycomb Sandwich Construction

In the complex cycle required for the manufacture of steel honeycomb sandwich, the 'hard' jiggling associated with the brazing process is perhaps of most interest to the production engineers. It is obvious that the strength and stiffness characteristics needed from this form of construction preclude subsequent working of the panels, and therefore the component must be made dimensionally accurate to size. Fig. 9 shows two types of brazing fixtures for simple flat panels which have been tried out in the U.S.A.⁽⁸⁾ Graphite forming blocks combine the advantages of physical stability with good thermal conductivity. The top weights in both methods are to hold the panel steady whilst the brazing cycle is in operation. It is also likely that the full heat treatment cycle of the panel is done "in situ". The type of heat treatment depends upon the face materials of the sandwich, usually 17-7 or 15-7 precipitation hardening stainless steels and the brazing alloys, which are more than 90% silver. It is believed that the A.V. Roe technique is a very much cheaper process⁽⁹⁾. Fig. 10 shows a typical brazing fixture for a flat honeycomb sandwich panel. The need for rapid heat transfer implies that the fitting must be light and yet it must retain sufficient stiffness to ensure dimensional stability at the brazing temperature. For flat panels mild steel fixtures can be used, but for curved panels with their thermal expansion problems, FV 448 (Firth-Vickers) 12% Cr stainless steel would be necessary.

Perhaps the most versatile steel for sandwich construction in this country is Firth-Vickers FV 520 (17% Cr 5% Ni 2% Mo 2% Cu.). Unfortunately small changes of brazing temperature affect the properties of FV 520, and also complicate the heat treatment cycle and jig design. A.V. Roe have concentrated mainly on two brazing temperatures, 650°C and 700°C. The effect on the material is roughly as shown in Table 2.

Both techniques make use of brazing alloys which are suitable for service temperatures of 300°C. Higher melting point brazing alloys for work at higher temperatures would require a new approach to the heat treatment. It is obvious that the designer would like the higher strength values obtained by brazing at 700°C rather than at 650°C.

Fig. 11 shows an early design of an FV 448 brazing fixture used by A. V. Roe. The working face of the fixture was a replica of the panel being produced and was made of 3/16" sheet. The necessary support was given by 1/4" thick grid members at 6" pitch. Pressure was applied to the sandwich panel by an inflatable, thin, stainless steel bag placed between the top platen and the panel. Made in 1957, the size of the panel was 8'6" by 4'0".

Core Development

Most American core material is spot welded together and it is expensive. A. V. Roe developed two new core methods. One is a flexible core and the other is capable of a high mass production rate for flat panels. The flexible core is ingenious because the attachment, cell to cell, is nothing more than a punched eyelet, making a mechanical connection and forming a vent to each cell to permit passage of purging and fluxing gases during the brazing process. As the attachment is not completely rigid it enables an appreciable amount of curvature to take place during assembly and it also permits accurate levelling of the ribbon width. Whilst this core does not meet the U.S.A. specification for core tension requirements before processing, it nevertheless competes very favourably after brazing.

It is hoped that such a detailed reference to the products of one firm will be forgiven, but it is considered that five years ago this country possessed the lead in this form of construction.

4.2. Secondary Structures

Primary structures have been dealt with at some length, but experience has shown that ingenuity is also needed in designing a high density material like steel into a low load carrying secondary structure. One development worthy of attention is a stainless steel corrugation called 'Spacemetal' developed by the Missile Division of North American Aviation, Fig. 12⁽¹⁰⁾. Based on the samples available, the surface finish may limit its application to internal structure, but the design is efficient. The material can be mass produced in 30" wide sheets at a rate of 50 square feet per minute. In all structural applications involving steel in compression, the method of jointing stiffeners to skins will need refinement for minimum weight. As a generalisation, on thin skins rivets result in earlier inter-pitch buckling failures than spot welds, because the spot welds can be more closely spaced. Argon-arc 'puddle welding', which can be used for blind attachment from the inside face of a panel, tends to give a lower strength than spot welds, due to the greater area of the local heat affected zone. Obviously just as there are many types of riveting for light alloy structures, the trend will be to employ many differing welding techniques for steel structures.

5. The Supersonic Civil Air Transport

As stated previously, it appears probable that the supersonic airliner will be in service within ten years or so. The airline companies naturally view the prospect of this with some anxiety since these aircraft will bring with them vastly different operational, organisational and financial problems from those experienced with current types. As far as the United Kingdom is concerned the feasibility of such an aircraft was examined by a committee which first met in 1956 and reported its findings in 1959. Subsequently to this a design study contract worth £350,000 was awarded to the British Aircraft Corporation. Other countries have not been idle and various organisations in the United States have made proposals for supersonic airliners, although official interest has so far been largely confined to investigation of basic problems. Some £4 million has been granted towards the cost of this work. In the airline field Deutsche-Lufthansa have studied their requirements and concluded that they will be in a position to operate $M = 3$ supersonic airliners in 1972 - 4. However the only aircraft of which details are available and which seems likely to be built is the Sud-Aviation Super Caravelle⁽¹¹⁾. This aeroplane is illustrated in Fig. 13 and suggested dates for the first flight and airline service are 1965 and 1968 respectively. Sud-Aviation and the British Aircraft Corporation have discussed the design and production of this aircraft, which is intended to fly at about $M = 2$ over medium stage lengths. As the illustration shows, the wings and body are discrete aerodynamic units and there appears to have been no attempt to improve cruise performance by "area ruling". One problem of supersonic aircraft is the noise or "bang" at ground level caused by the passage of the aircraft overhead. The true extent of this problem is not yet known but it may restrict supersonic airline operation to flight over unpopulated areas. In view of this, the choice of medium ranges for the Super-Caravelle may prove to be unfortunate. The estimated cost for the development of the aircraft is at least £100 million, and this may be nearer £200 million by the time airline service is achieved. An expenditure of £8.75 million in 1962/3 has been budgeted for by the French Government. No doubt it is hoped that the United Kingdom Government will share development costs. Estimates reportedly indicate that a production of 80 aircraft would be profitable, but demand may be as high as 250. This is difficult to reconcile with American estimates of a maximum world wide requirement for 300 supersonic airliners of all types. Sale price of around £2.5 million per unit may be compared with U.S. estimates of £3.6 to £7.2 million for a $M = 3.0$ airliner. From a purely technical viewpoint the Super-Caravelle does not convincingly exhibit the characteristics of a successful supersonic airliner.

The $M = 2.2$ civil transport has been studied at the College since 1958. The transatlantic route has been concentrated upon and the designs produced have purposely differed from those receiving attention in the British industry. The basic aeroplane uses the so-called integrated shape and embodies unusual features of structural safety. The integrated layout enables high cruising efficiencies to be obtained, but makes it very difficult to incorporate cabin windows in the design. The psychological problem of a windowless passenger compartment is debatable. Airlines may find such an arrangement unacceptable, but supersonic flying is for the sophisticated, and internal decor plus closed circuit television could alleviate claustrophobic impressions. The absence of windows may reduce structure weight by as much as 2,000 lb and at the same time help to ensure the integrity of the pressure cabin. To be successful the structure of a supersonic transport must incorporate all, and indeed more, of the safe life and fail safe features

built into modern subsonic airliners. It is to be hoped that improvements will be achieved in safe life design and life prediction techniques before such a design is finalised. Coupled with this, proper attention must be paid to fail safe structural concepts, incorporating multiple load paths and crack propagation control. As the experience that can be gained through operation of large supersonic aircraft in this country is nonexistent, this is by no means easy to achieve. The effects of creep, fatigue and thermal stresses caused by the aerodynamic heating environment will need to be deduced by laboratory and theoretical work.

6. The Supersonic Airliner - Cranfield Project A-60

This airliner, shown in Fig. 14, is designed to cruise at $M = 2.2$ (1450 m. p. h) at altitudes between 57,000 - 65,000 ft⁽¹²⁾. The range of 3250 nautical miles with the necessary fuel reserves would cover most of the world airline routes, including the transatlantic service. The speed regime was chosen since for economic reasons the cruise should be as fast as possible, but flight above a Mach No. of 3 would require technological advances not thought to be possible in the time allowed before the aircraft becomes operational. Limitation to $M = 2.2$ within this regime enables extensive use of light alloy in the structure. The cruise altitude should avoid the worst weather conditions and help to minimise the ground level shock problem, as well as satisfying cruise speed and range requirements. Airline economic factors will dictate the passenger payload. The A-60 project can carry 108 passengers over maximum range with a seat pitch of 40 inches. A maximum of 126 passengers at 33 inches seat pitch carried over a somewhat reduced range is possible.

The tailless, slender, integrated layout was chosen for the aircraft. The planform is basically a 73° delta with a curved leading edge in the region of the tips and roots. Six turbojet engines, of approximately 18,000 lb sea level static thrust are mounted in the rear fuselage aft of the pressure cabin. This engine arrangement is not necessarily the optimum. In fact as a result of having faced the complications of this arrangement some form of underslung podded layout would be recommended, on the basis that the engines could be separately type tested and more readily installed and serviced. The all up weight of the aircraft is 325,000 lb and the maximum landing weight is 190,000 lb. Corresponding take off and approach speeds are 200 knots and 150 knots. The aeroplane should be able to take off and land on runways of 10,000 ft length at sea level, which is consistent with existing or planned runways at the world major airports.

6.1. Weight Breakdown

The component weights and locations on such an aeroplane are extremely critical. Fuel is the largest factor, with structure the second. Fig. 15 shows the weight breakdown in graphical form. The structure includes the integral wing-fuselage, fin and undercarriage, whilst the power plant covers the intakes, jet pipes and engine installations. Systems embrace power supplies, pressurisation, furnishings, flying controls, radio and radar and so on.

6.2. Layout

It is now proposed to discuss the layout of this particular integrated type of aircraft, although obviously a great deal more work is required to obtain the optimum performance. The wing planform has been chosen to meet the low and

high speed aerodynamic characteristics required. Aerodynamic drag considerations have dictated the smallest fuselage cross sectional area compatible with an adequate, although unorthodox, seating layout. It was decided that a triple-bubble inner shell should be used to withstand the full pressurised cabin stresses, the outer shell giving a reserve factor should the inner one fail in any way less than catastrophically. This is illustrated in Fig. 16. Careful design of plug-type doors, escape hatches and double glazing of the windscreen should ensure reliable supersonic flight up to the maximum operational altitude. The fuselage is 161 ft long but the maximum depth of the cabin is only 10.1 ft, about the same as on the Comet. The depth of the aircraft, and consequently the strength of fuselage, is of some concern particularly in the chordwise bending mode. In a slender tailless delta aircraft the inertia loads arising from aircraft manoeuvre are nearly balanced by the distributed aerodynamic loads. Consequently the undercarriage loads at take off and landing are critical, giving bending moments about 5 times as much as the flight cases. Although the location of the engines is questionable on grounds of accessibility, the use of submerged engines implies a deep fuselage and gives structural strength where the wing is thin, thus providing high stiffness to meet aeroelastic requirements.

6.3. Structure

The basic structure of the aeroplane is shown in Fig. 16. The wing section depth resulting from the slender layout is such that much of the construction envisaged is no different from that of subsonic aircraft. However it is suggested that light alloy honeycomb sandwich construction is desirable for the structure in some of the fuel tank regions. An idea of the magnitude of the production problem can be gathered by reference to Fig. 17, which compares the aircraft with the V.C.10, a subsonic airliner of similar weight. The Hustler and Super-Caravelle are included for comparison. The component breakdown of the structure is illustrated in Fig. 18. The major problem is concerned with the centre wing-fuselage unit, which ideally should be assembled as one component. Possible compromise solutions are indicated, but the components are still large.

The maximum temperature of the skins occurs at the leading edge of the wing and fin, and should not exceed 130°C . The most common material is likely to be light alloy RR 58. The engine intakes reach a somewhat higher temperature, and because of their rectangular shape and the high pressures, a steel or titanium construction is needed. The thick boundary layer which is associated with the semi-buried engine layout can cause considerable penalties in drag, and must be removed by ducting. It is thought that the surface contour and finish required will be no more difficult to achieve than on subsonic aircraft.

6.4. The Power Plant

Design trends of turbo-jet engines will be covered in the next lecture. Consequently it is not intended to dwell at length on this subject. However the engines have to operate efficiently in the cruise condition above $M = 2.0$, and they also have to be efficient in the take-off, climb, stand off and let down phase, because these regimes can consume almost half the total amount of fuel. Further, in the take-off and climb conditions the aeroplane will have to meet acceptable noise levels which may impose a restriction on exhaust velocities and the altitude of the transonic phase. To cater for the full speed range it is essential to match the air intake system to the engine requirements, this being one of the major

differences between a subsonic and supersonic propulsion system. The aeroplane employs movable two dimensional shock ramps which vary throat area, automatic operation throughout the flight being necessary. Fig. 19 shows the suggested air intake geometry. The combination of long, variable, rectangular air intakes with convergent-divergent nozzles implies the need for considerable design skill to achieve an acceptable installed power plant weight.

6.5. Systems

It is not proposed to describe all the systems, but it is envisaged that due to the speed of the aeroplane the function of the crew will largely be to monitor the aircraft and its equipment. Full autostabilisation, automatic throttle control, automatic landing and programmed fuel balancing and autopilot settings may be necessary. The flying control system must be fully powered and irreversible, since the pilot can develop only a small proportion of the hinge moment required to actuate each surface.

6.6. Pressurisation and Air-Conditioning

The difference between cabin air and stagnation temperature is much greater than that of subsonic transports, and the pressure level in the cabin is normally never more than an equivalent altitude of 6,000 ft. The control of the temperature must be fully automatic during flight and ground taxiing, the passenger and crew compartments being maintained between 15.5°C and 27.5°C under all ambient conditions. Walls, roof, and floor must have substantially the same temperature. Full conditioned air is supplied through ducting integral with the insulation, and louvres fitted under the light luggage rack and in the ceiling diffuse air into the cabin. Part of the cabin discharge air circulates behind the trim cloth and in addition to controlling the wall temperature also forms the recirculating air.

A diagram of the air-conditioning system is shown in Fig. 20⁽¹³⁾. Air is tapped from the low pressure compressors of the main engines, three stages of cooling being employed before air is conditioned for supply to the cabin. Initial cooling is obtained by passage through a heat exchanger located in the air intake bleed, the second stage uses the fuel input to the engines as a coolant, and finally a Freon vapour system completes the process, using tank fuel as a heat sink. In the last stage of cooling recirculated air also mixes with the fresh air supply. The system is duplicated throughout, with provision for cross connection, and is made compatible with the operation of the fuel system. In addition a stored oxygen supply would be available as a short period emergency standby. Much of this system can be considered as a logical development from the subsonic aeroplane, with the exception of the fuel to air heat exchangers and the Freon system.

6.7. Fuel System

The fuel system presents new and varied problems to the designer, but the production engineer is more concerned to know how it affects the construction of the aeroplane. The fuel is disposed so that as it is used the centre of gravity of the aircraft remains within permissible limits. Since the fuel is distributed so widely over the aeroplane, pressure loads on the wing structure will arise from the fuel and the fuel system, these depending upon flight manoeuvres, crash loads and pressure fuelling. It therefore becomes necessary to compartment the

wing into a number of tanks, which must be small enough to minimise the pressure loads arising from the fuel head, and be sufficient in number to prevent aircraft unbalance should a feed blockage occur in any tank. The layout of the fuel tanks is shown in Fig. 21⁽¹⁴⁾. They are integral with the structure and because of the depth of the wing, the optimisation of tank bulkhead positions and pressure loading for minimum weight is not easy.

At flight speeds of $M = 2.2$, the average skin temperature exceeds 110°C and to use the fuel as a heat sink for the cabin conditioning and allied systems, it is necessary to insulate the skins. The insulation has been designed to limit the fuel temperature rise to 15°C during the cruise. The problem of fuel boiling is not serious providing Avtur is used, since this allows fuel tank temperatures greater than 90°C at 65,000 ft to be reached before boiling occurs. The insulation of the inside of the fuel tank surfaces is a problem because little information exists on the long-term behaviour of the most promising sealants. The insulant must be fuel resistant, withstand high temperatures and have good anti-peel characteristics, since accessibility for maintenance and repair is far from ideal. There are two likely ways of insulating the tanks. One is to coat the inside of the tank surface with a suitable light weight insulant, and the other to use sandwich construction for the basic skin structure. In the latter case the inspection of the inside tank surface is easy, and there is no insulation to lift off due to fuel penetration. The objection to sandwich construction is the high production cost, but on this aeroplane its inclusion can be justified on structural grounds.

7. Conclusions

Throughout this paper the authors have been extremely conscious of the honour afforded to Cranfield in your asking them to present this lecture. The supersonic airliner, which is but one aspect of the work in the Design Department, has been concentrated upon and it is to be hoped that it is in keeping with the theme of the Conference.

It is often claimed that the aircraft industry is in the vanguard of engineering progress, but from a production process point of view the only two firsts which can be claimed as British are the corrugated high tensile steel spar construction of 1928 onwards and the widespread use of metal-metal bonding. The same spirit of enterprise applied today could result in a breakthrough in the construction techniques of supersonic aircraft.

As the discussion has been concerned with design trends it is in order to end on a philosophical note. Integration has taken place in the British aircraft industry and it is now becoming associated with European firms. Amalgamation of industrial giants by itself does not necessarily lead to greater efficiency. The benefits of streamlining production, marketing and research can be cancelled out by the bureaucracy, frustration and lessened team spirit, which sometimes grows as industrial units expand. To be of the most use a design team must be associated with the production unit building its aircraft. Separate them, and the art of aircraft design may be quickly forgotten.

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TABLE 1
EFFECT OF SURFACE FINISH ON EQUILIBRIUM SKIN TEMPERATURE

Emissivity	Altitude ft.	Equilibrium Temperature °C					
		Laminar Flow			Turbulent Flow		
		M = 2	3	4	M = 2	3	4
0	Above 35,000	88	260	493	95	282	532
	50,000	50	170	295	90	245	430
0.9	75,000	5	100	196	70	205	355

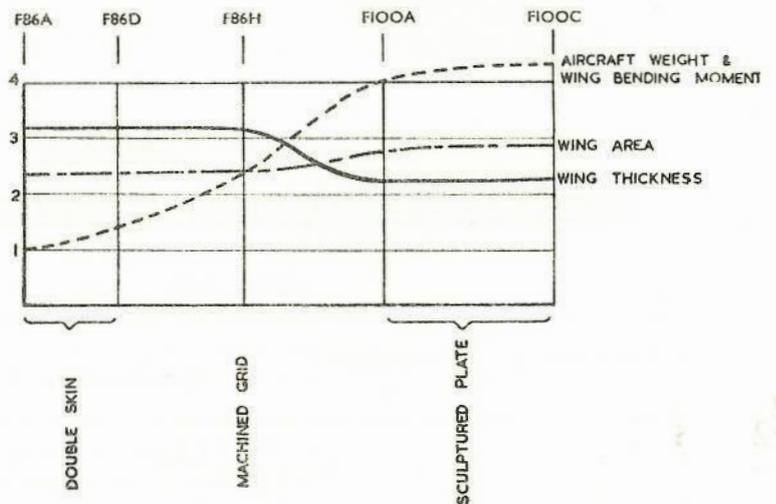
Values of Emissivity for above Temperature Range

Polished aluminium or steel 0.1
Carbonised or oxidised steel 0.6 to 0.8

TABLE 2
ROOM TEMPERATURE PROPERTIES OF FV520 STAINLESS STEEL

	0.1% Proof Stress Ton/in ²	0.2% Proof Stress Ton/in ²	Ultimate Tensile Stress Ton/in ²	Elongation on 2" Gauge length	Young's Modulus Ton/in ²
Normal Heat Treatment, no brazing	61.8	65.6	71.5	11%	12.5
After brazing at 650°C and Heat Treatment	47	51.8	63	13%	12.5
After brazing at 700°C and Heat Treatment	60.2	63.1	67.4	12%	12.6

Fig. 1. Fighter development over 10-year period—comparison of wing design



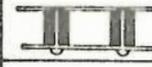
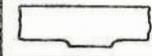
	TYPE OF CONSTRUCTION	LOAD PER INCH OF CHORD AT WING ROOT LBS.	ALLOWABLE COMP STRESS P.S.I.
	SKIN AND STRINGERS P-51	4500 (AVERAGE)	28000
	DOUBLE SKIN F86A, B.D.	14000 26000	35000
	MACHINED GRID F86 H	25000 35000	40000
	SCULPTURED PLATE F 100	88000 (MAX)	65000

Fig. 2. Wing bending material comparison

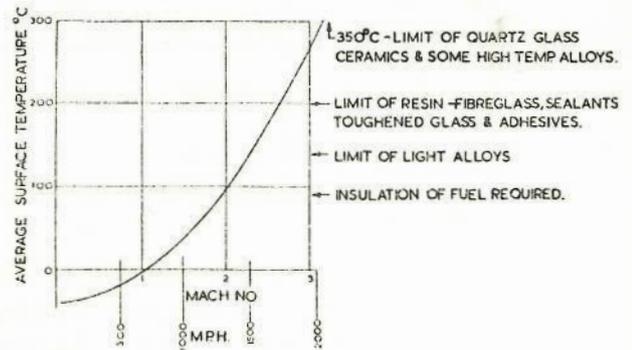


Fig. 4. Temperature limitations in long range cruise

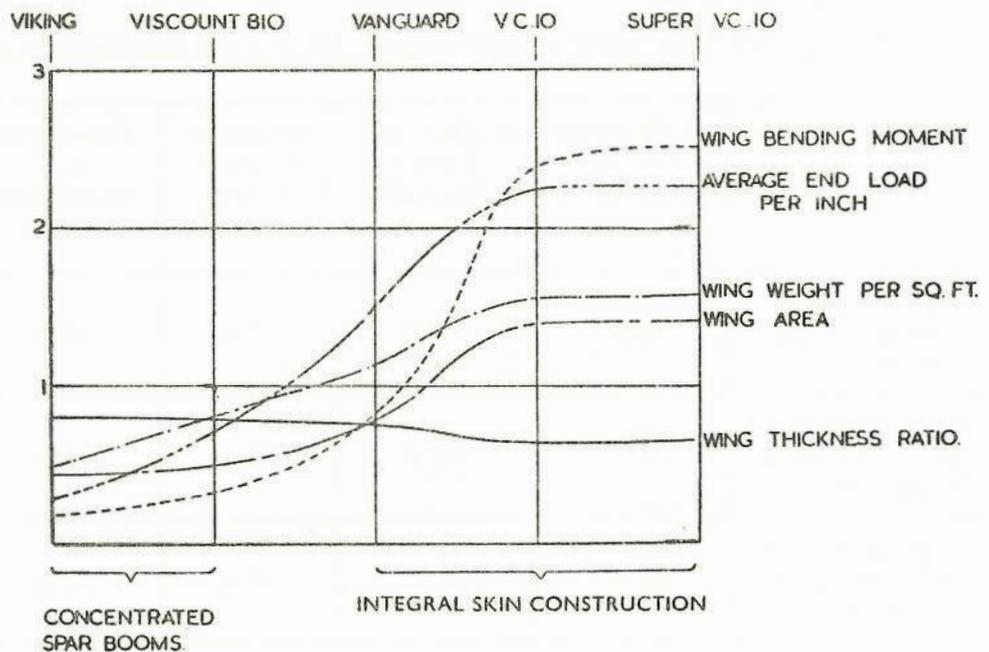


Fig. 3. Civil airliner development—comparison of wing design

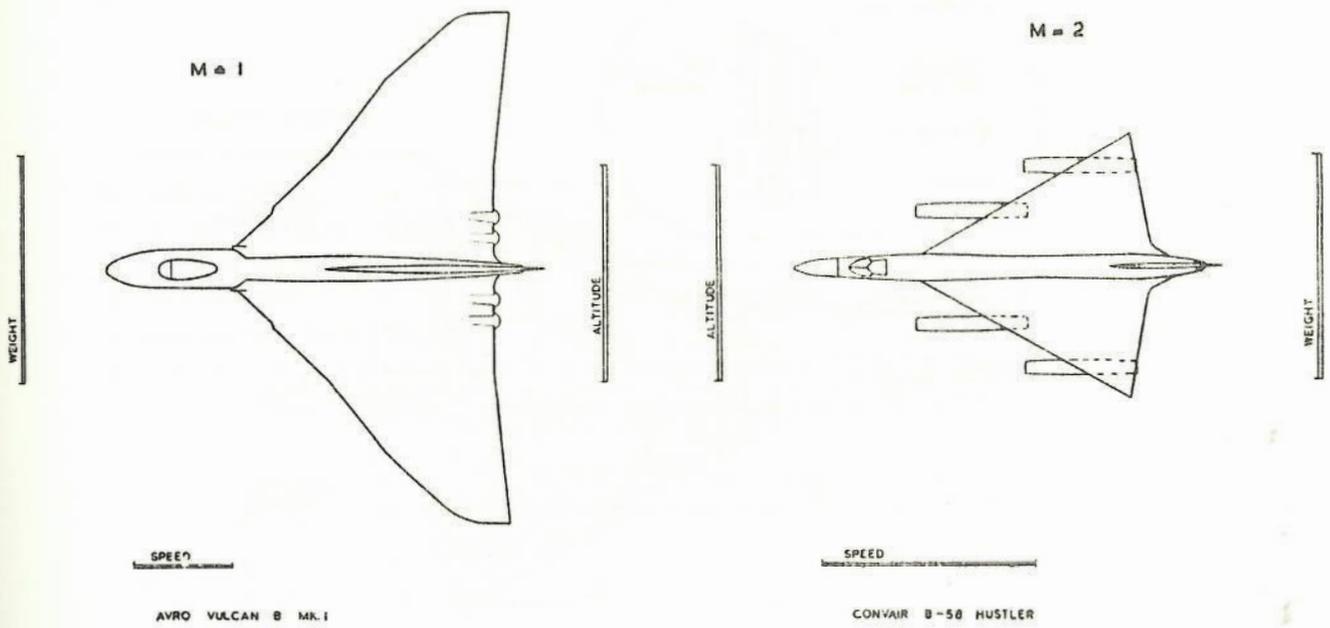


Fig. 5. Configuration of subsonic and supersonic bombers of comparable weight

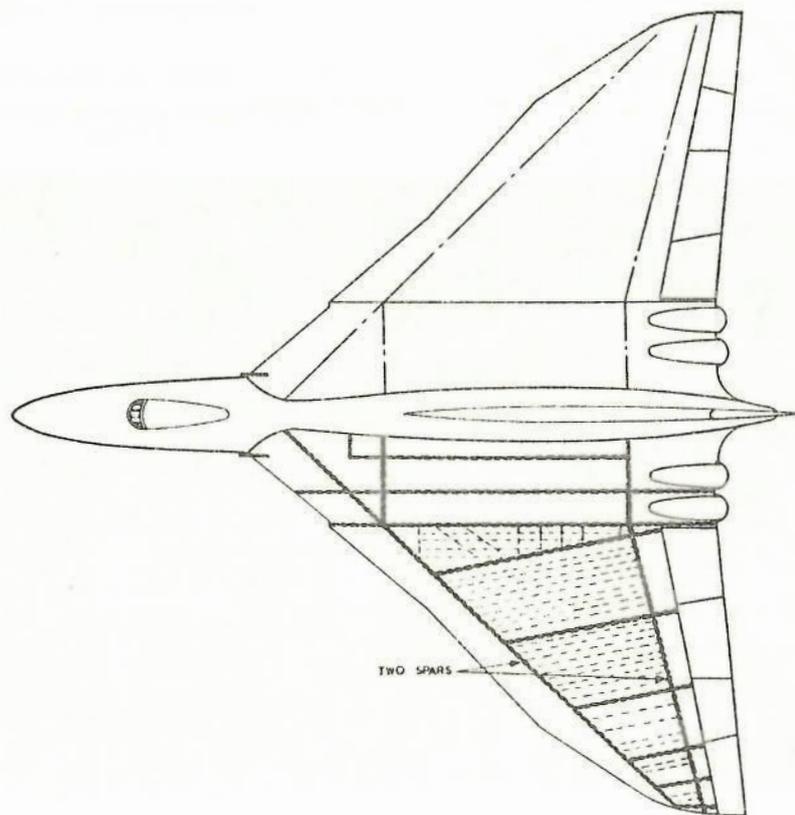


Fig. 6. Avro Vulcan B Mk I showing wing structural configuration

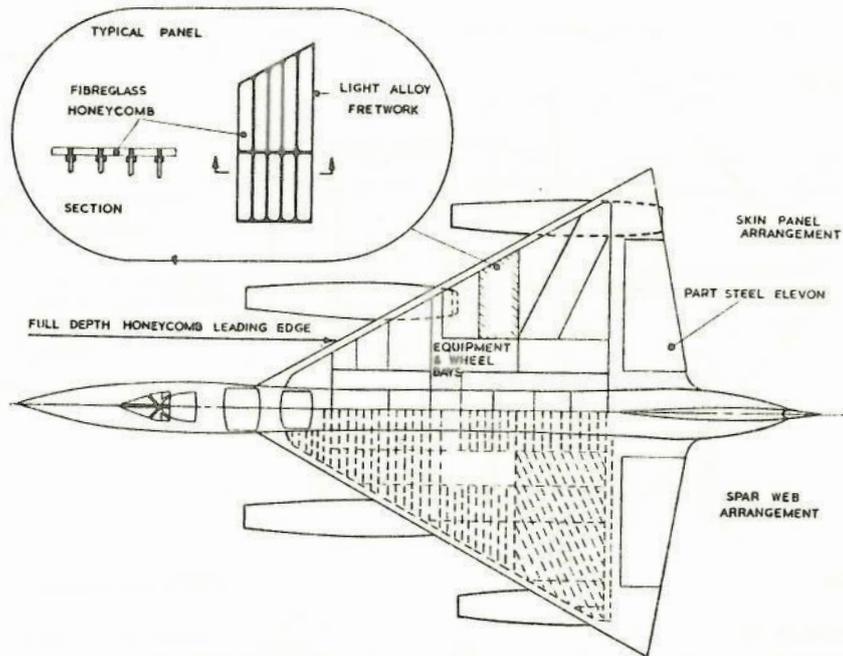


Fig. 7. Convair B-50 Hustler showing wing structural configuration

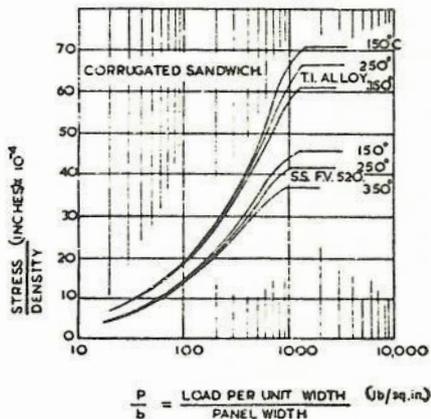
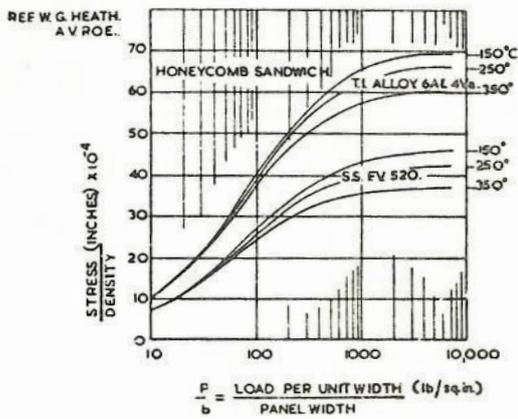


Fig. 8 Structural efficiency of honeycomb and corrugated sandwich panels

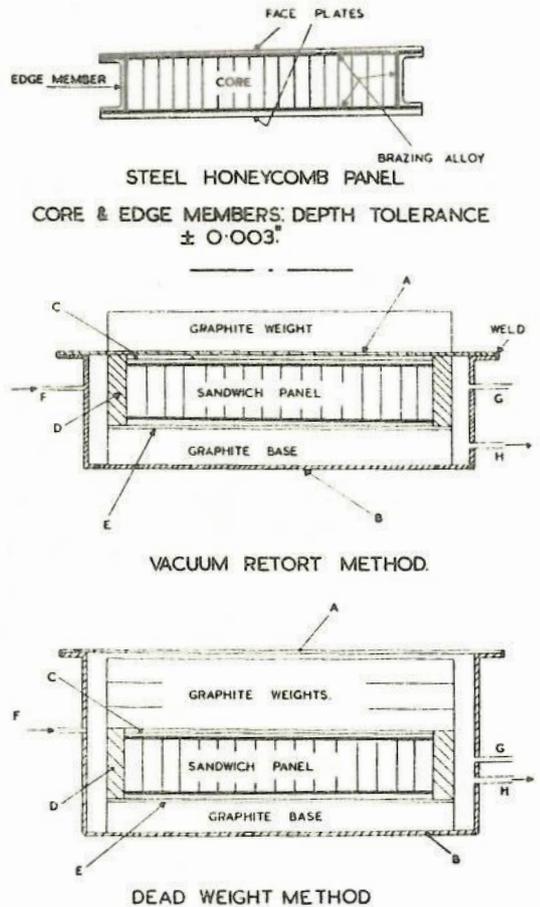


Fig. 9. Brazing fixtures: A thin cover skin of corrosion resistant steel; B stiff pan of corrosion resistant steel; C control sheet; D mild steel edge blocks; E slip plate; F argon gas inlet; G thermocouple; H vacuum line

BRAZING SEQUENCE

1. PURGE FIXTURE WITH NITROGEN
2. LOAD IN FURNACE.
3. AT 300°C PRESSURIZE CHAMBER WITH NITROGEN.
4. AT 500°C BF_3 REPLACES NITROGEN FLOW TO FIXTURE.
5. HOLD AT 700°C.
6. WITHDRAW FROM FURNACE AND COOL.
7. AT 500°C NITROGEN REPLACES BF_3
8. AT 300°C RELEASE PRESSURE.

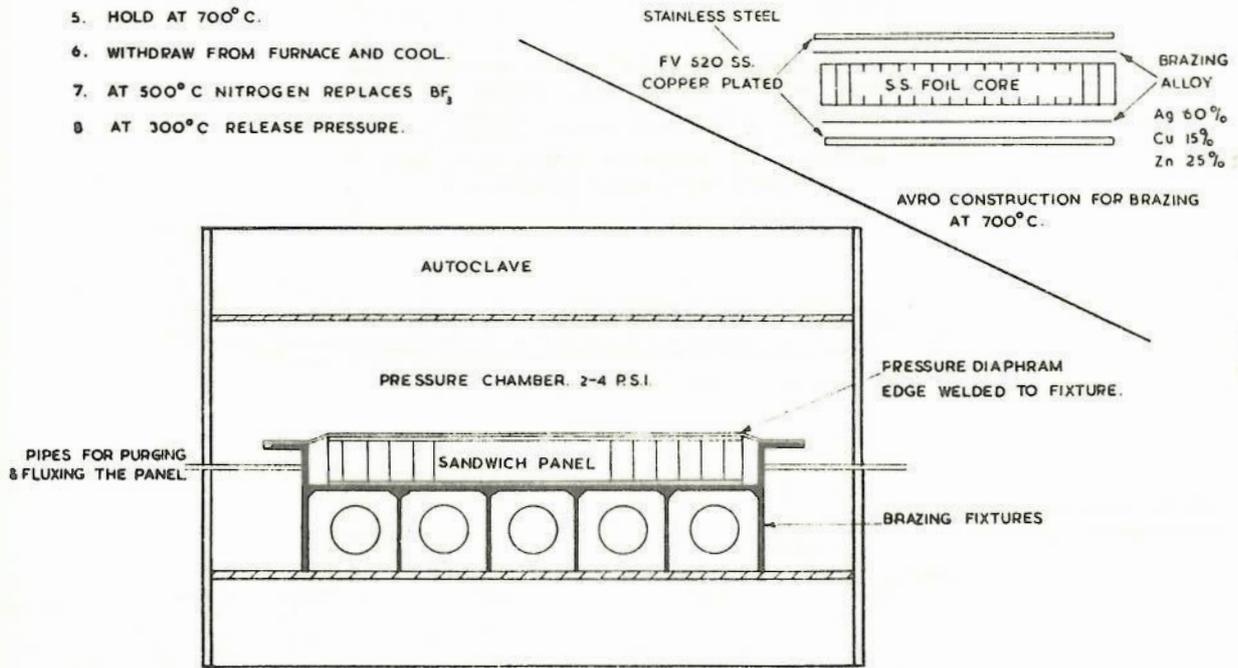


Fig. 10. Autoclave type brazing fixture

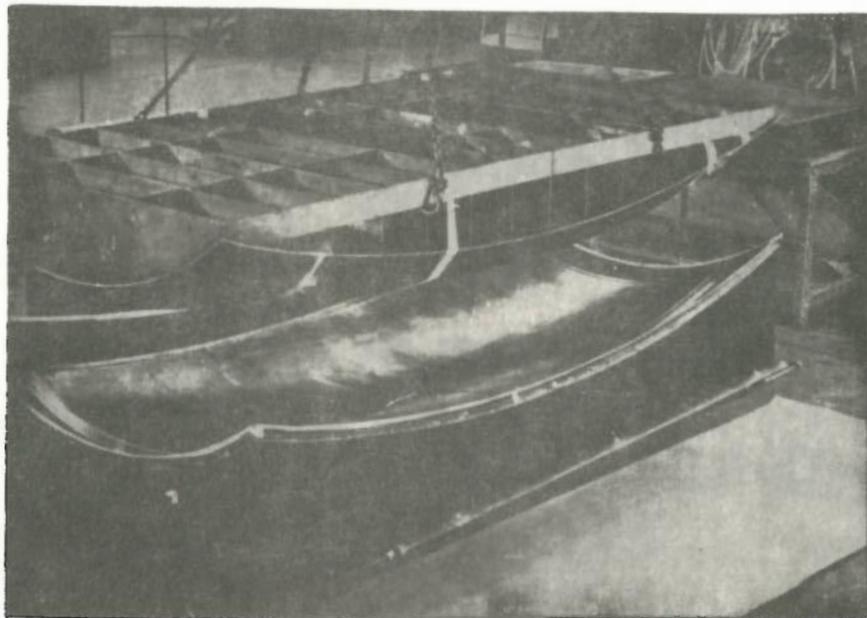


Fig. 11. Steel honeycomb panel

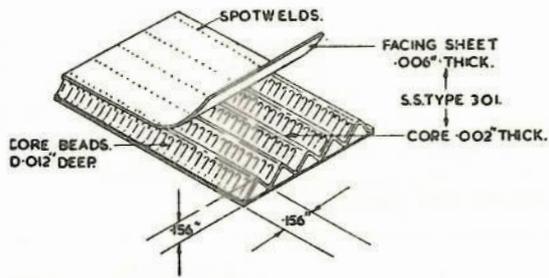


Fig. 12. Typical "spacemetal" features: solid sheet having equal weight = 0.0166 in. thick; moment of inertia "spacemetal" = 235; section modulus "spacemetal" = 23.3; solid sheet longitudinal comp. strength R.T. 80,000 lb./sq. in.; 260° H = 66,000 lb./sq. in.; 360° C = 64,000 lb./sq. in

Fig. 13. Sud-Aviation Super-Caravelle airliner

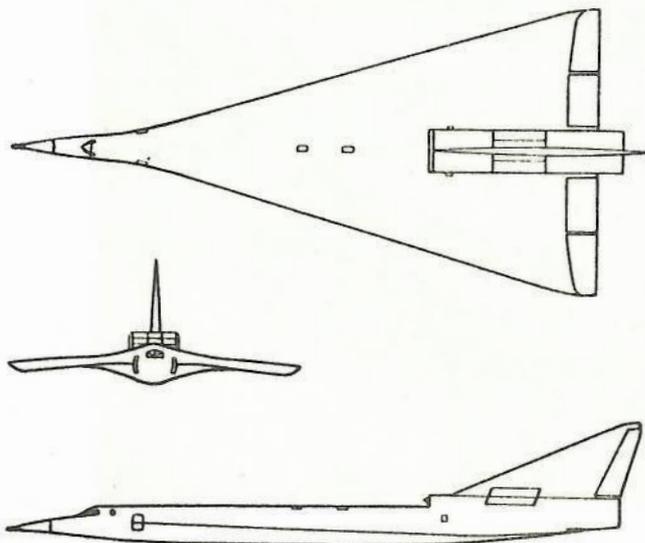
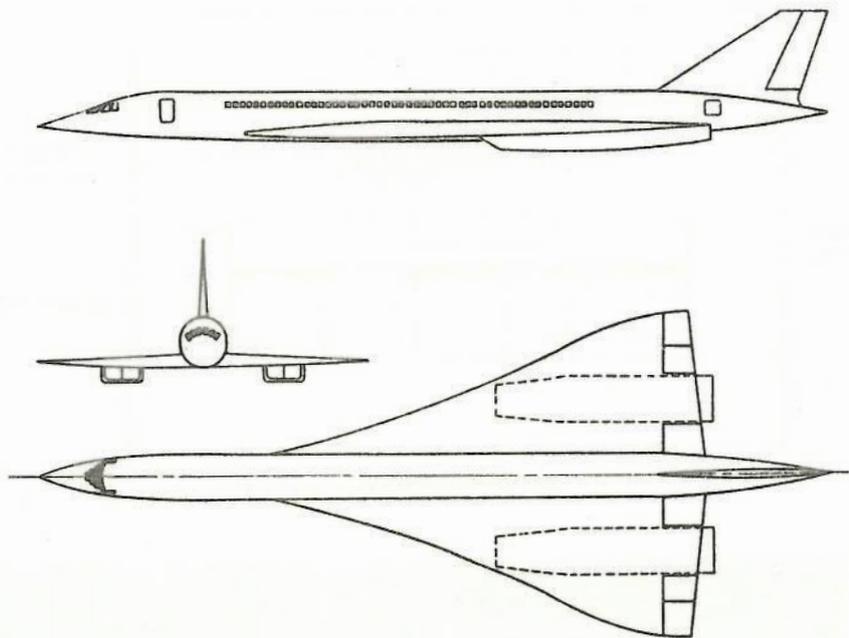


Fig. 14. Integrated layout $M = 2.2$ supersonic airliner — project A-60: length, 164 ft.; span, 77 ft.; maximum weight 325,000 lb.

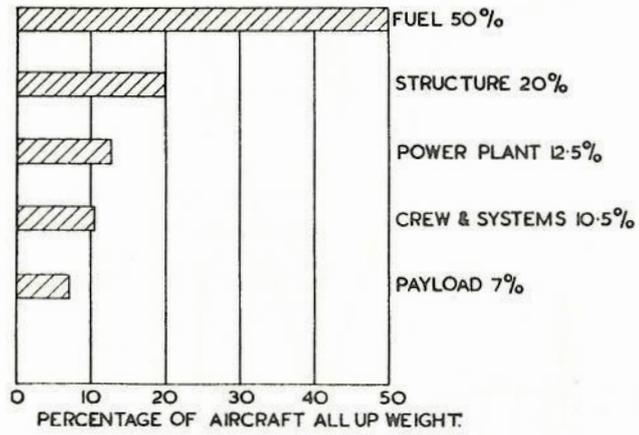


Fig. 15. Weight breakdown of M = 2.2 airliner A-60

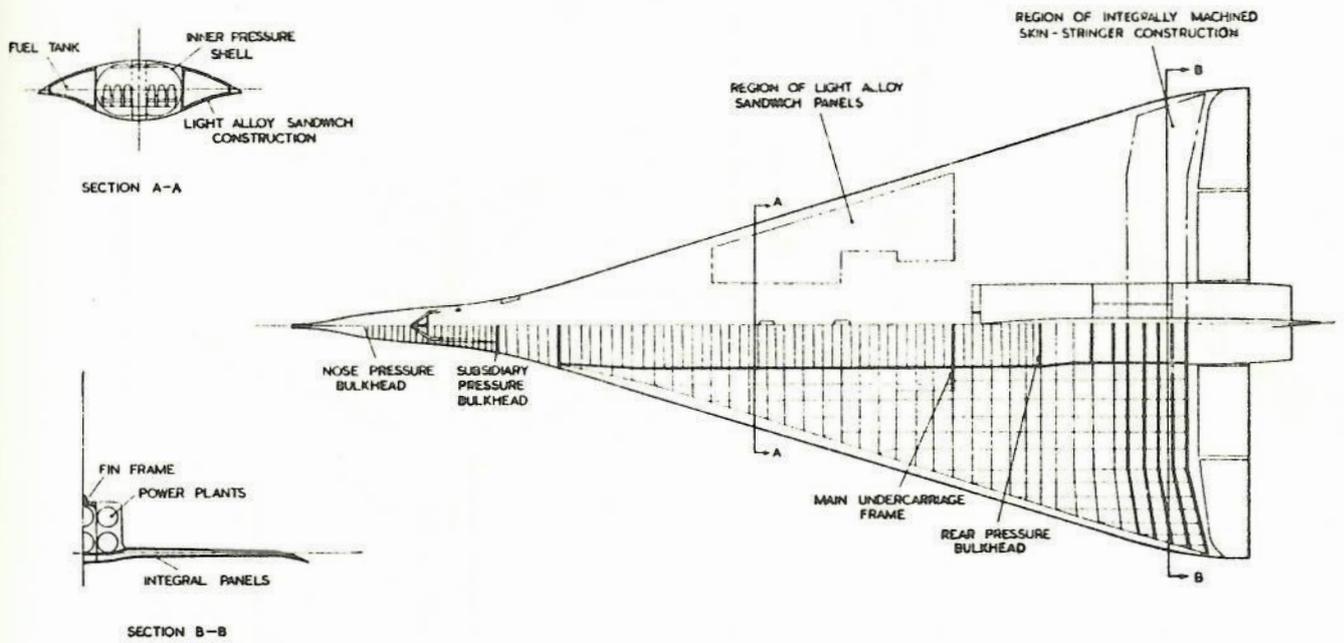


Fig. 16. Construction of integrated layout — supersonic airliner A-60

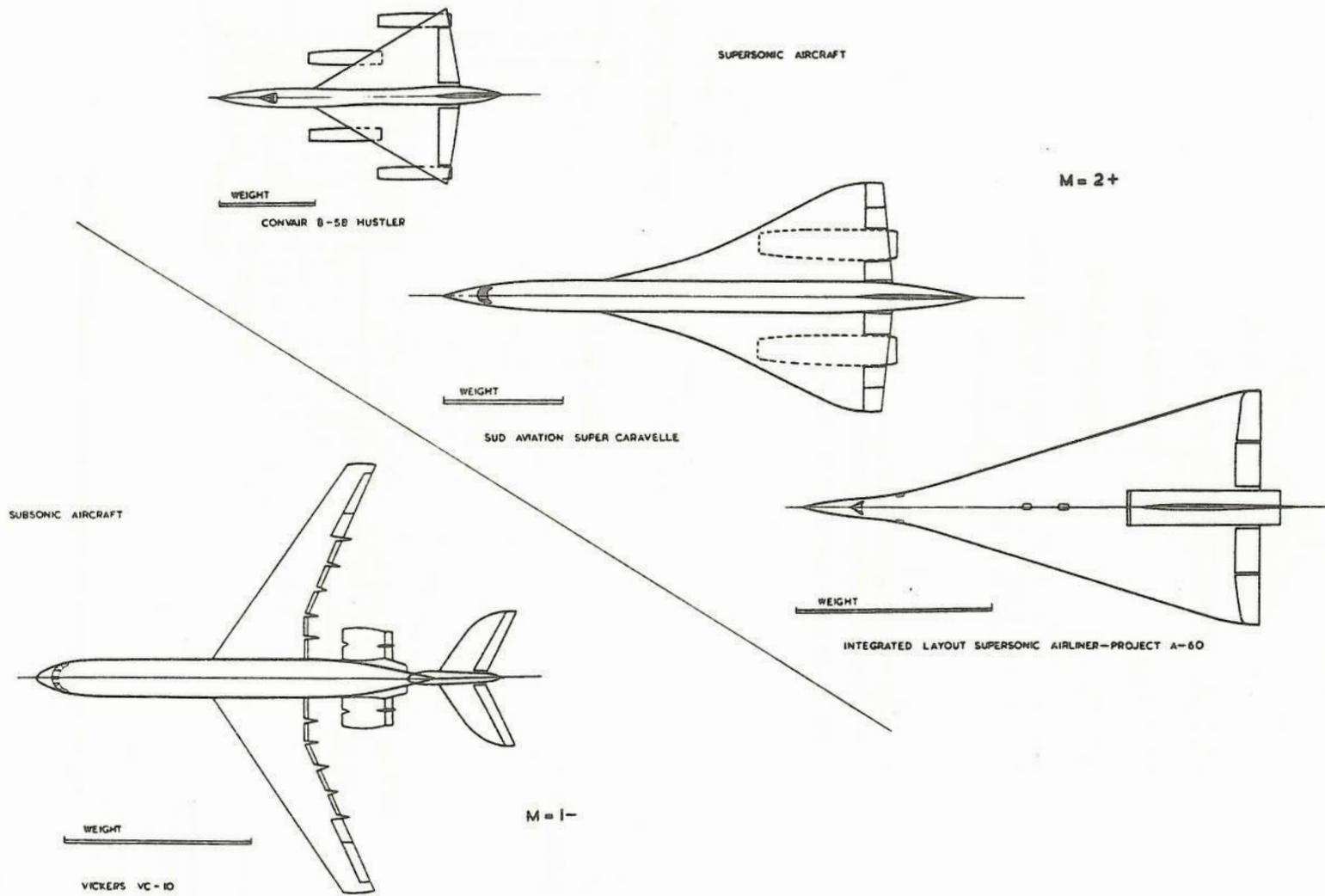
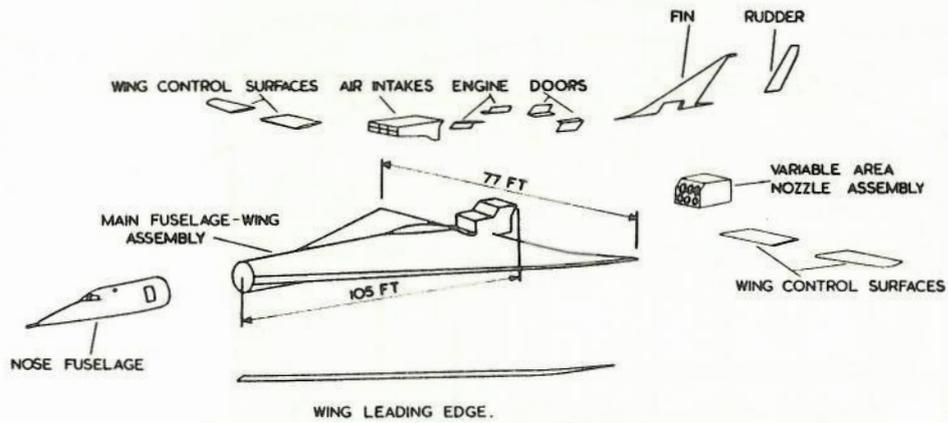
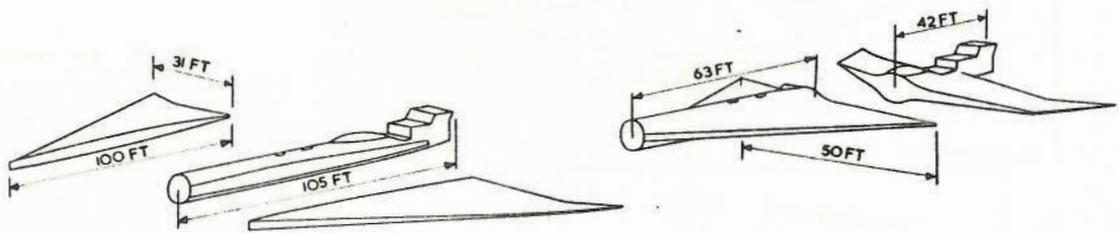


Fig. 17. Comparison of supersonic and subsonic aircraft

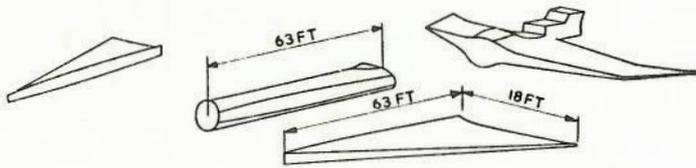


BREAKDOWN OF STRUCTURE - PROJECT A-60



A. SEPARATE WING UNITS - STRUCTURALLY HEAVY

B. SEPARATE FORE AND AFT UNITS - DIFFICULT JIGGING PROBLEM



C. FOUR UNIT BREAKDOWN - COMPARABLE WITH B.

Fig. 18. Possible breakdowns of wing-fuselage unit

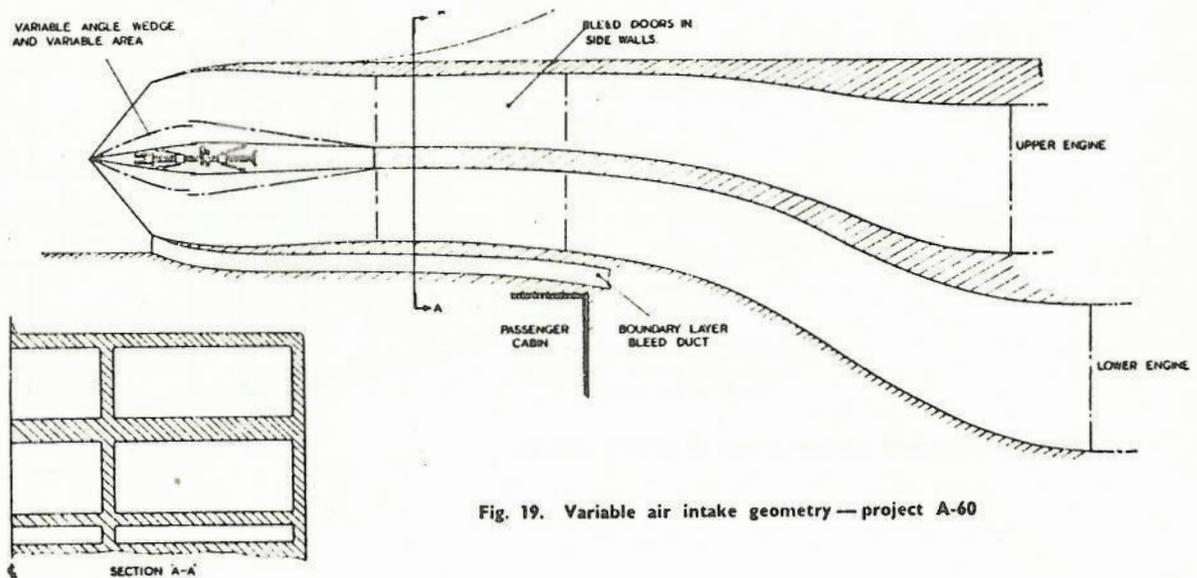


Fig. 19. Variable air intake geometry - project A-60

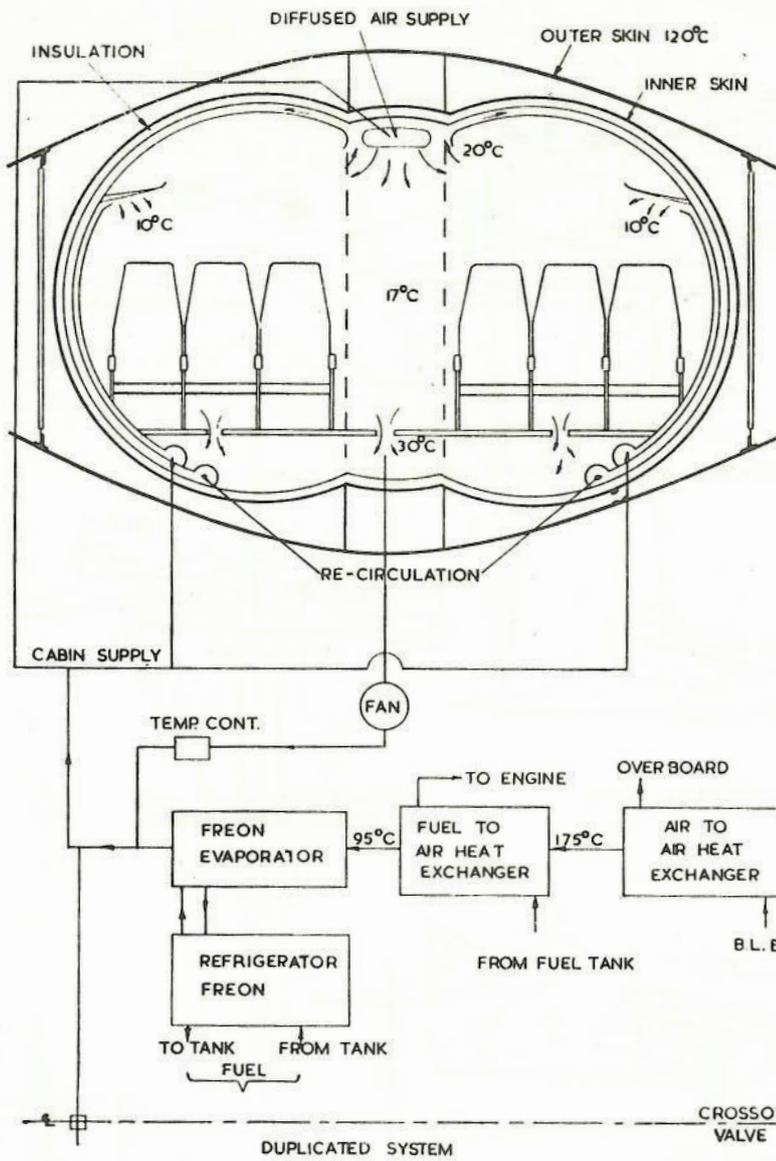


Fig. 20. Air conditioning system

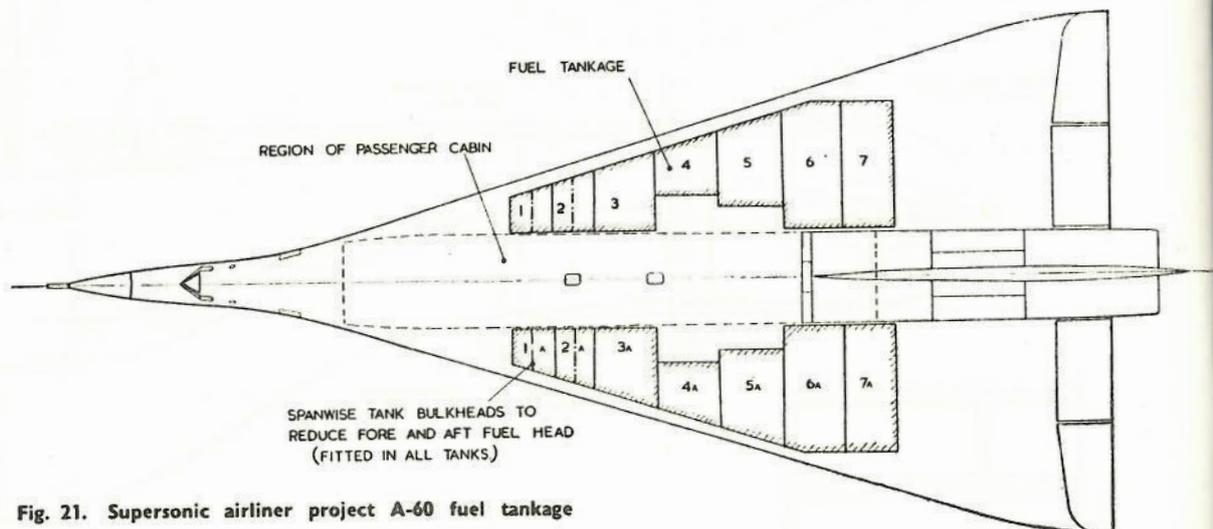


Fig. 21. Supersonic airliner project A-60 fuel tankage