Chapter 2. The general arrangement

SUMMARY

A sound choice of the general arrangement of a new aircraft design should be based on a proper investigation into and interpretation of the transport function and a translation of the most pertinent requirements into a suitable positioning of the major parts in relation to each other. The result of this synthetic exercise is of decisive importance to the success of the aircraft to be built. However, no clear-cut design procedure can be followed and the task of devising the configuration is therefore a highly challenging one to the resourceful designer.
Considerations, arguments and some background information are presented here in order to provide the reader with a reasonably complete picture of the possibilities. The differences between a high wing and a low wing layout, and the location of the engines either on the wing or fuselage or elsewhere, are discussed on the basis of various cases from actual practice. Examples of unconventional layouts and many references to relevant literature are given to stimulate further study and may possibly generate ideas for new conceptions.
The study of possible configurations should result in one or more sketches of feasible layouts. They serve as a basis for more detailed design efforts, to be discussed in later chapters, and they can therefore be regarded as a first design phase.

2.1. INTRODUCTION

Before a general arrangement drawing of a new design can be put on paper, a choice will have to be made as to the relative location of the main components: wings, fuselage, engines, tail surfaces and landing gear.

A specific configuration is often inspired by a trend or line of evolution which may have its origin somewhere in the past. It may be that previous experience with aircraft in a similar category has established a tradition which cannot be easily discarded. But even when a company tackles an entirely new type, it is generally found that designers fall back on research work done years before by the company's research department or aeronautical laboratories. One example is the Boeing 707 - or its immediate predecessor, the KC-135 Stratotanker - in which certain design features can be traced back as far as the 1945 Stratocruiser design, which itself was developed from the B-29 Superfortress (Fig. 2-1). At first sight the final version shows practically no similarity to any aircraft the Boeing company had previously built. Even so, the 367-60 and 367-64 preliminary designs have much in common with the Stratocruiser Model 377, particularly as regards the fuselage, while an obvious similarity also exists with the B-47 with respect to the location of the engines (Ref. 2-2). Although the Model 707 pioneered the new era of long-range high-subsonic transport aircraft with jet propulsion, its general shape still had its origin in previous designs. It follows that a sound evaluation of practical solutions incorporated in ex-

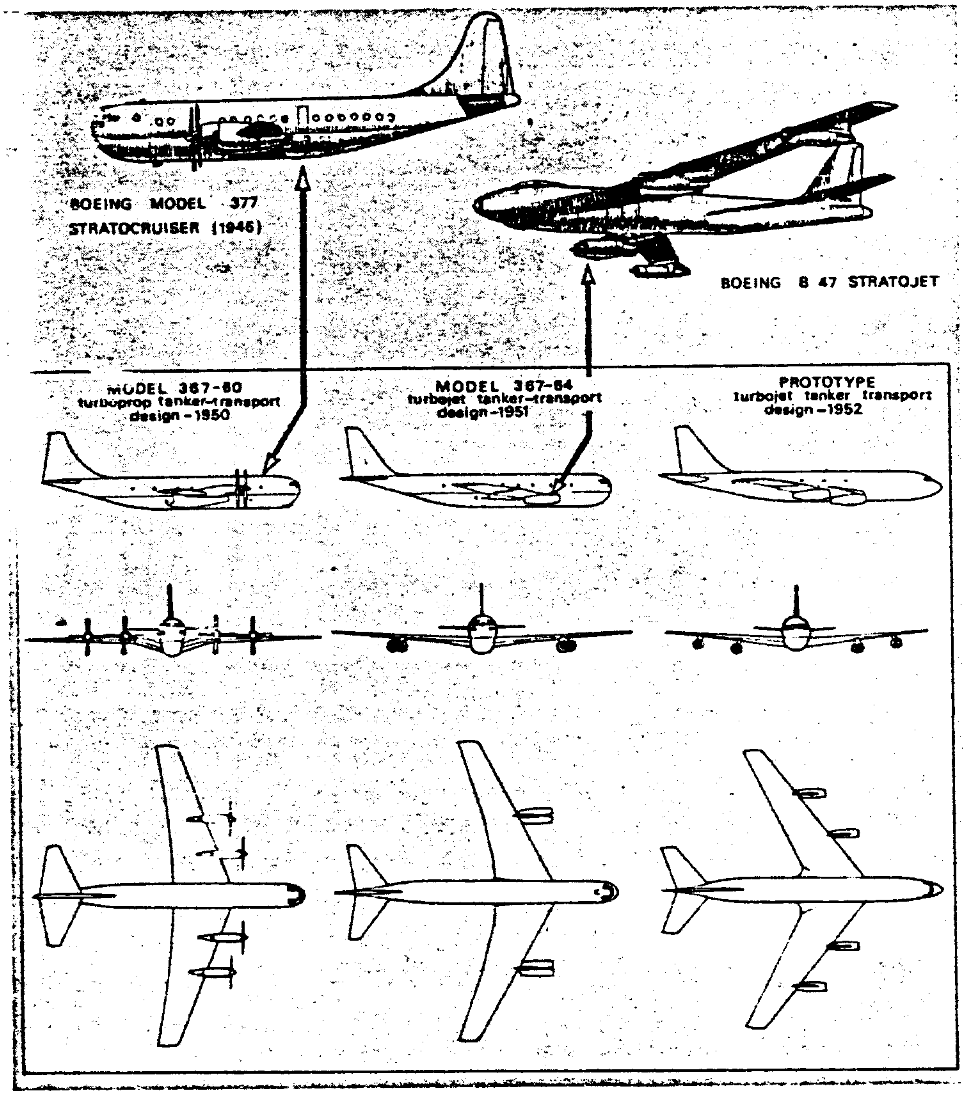


Fig. 2-1. Similarity between various designs by Boeing (Ref. 2-2).

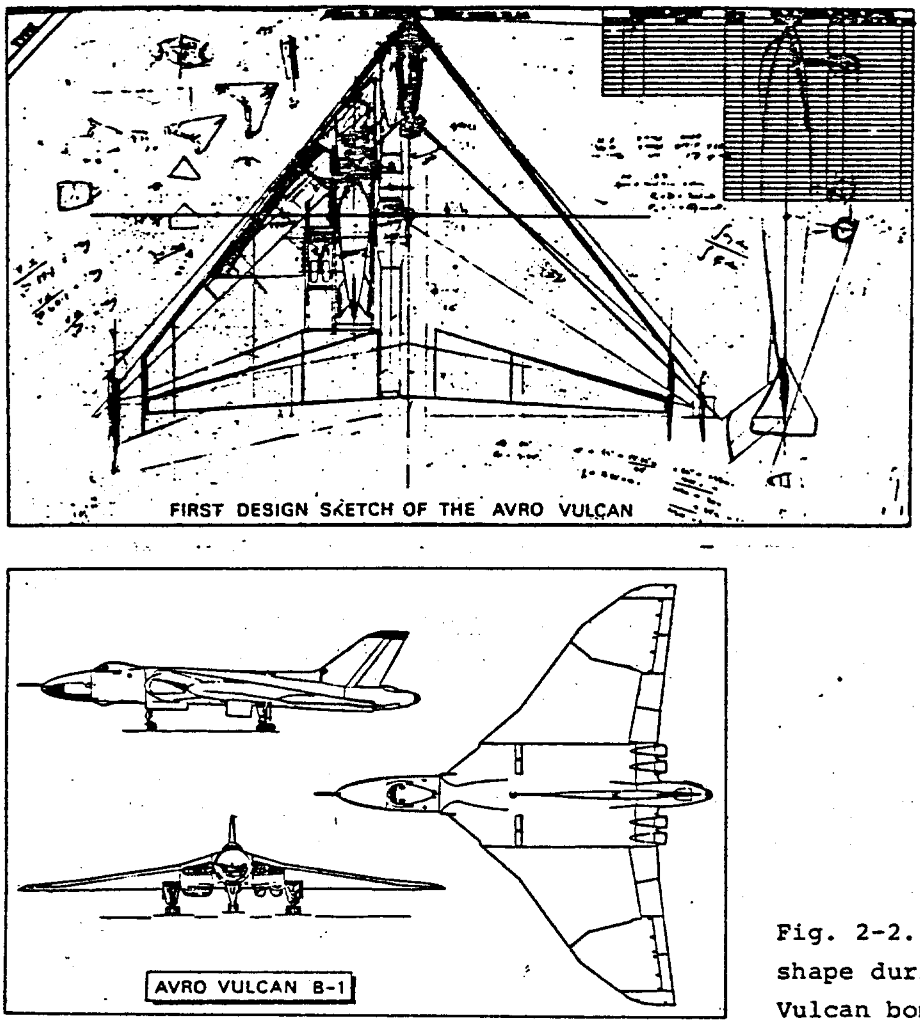


Fig. 2-2. Development of the external shape during the design of the Avro Vulcan bomber. (Ref.: Flight, 31 Jan. 1950)

isting successful designs should be the first step in the conceptual phase.

A successful first choice of the configuration does not mean that no major changes will be required as development proceeds. This is illustrated in Fig. 2-2 in which an early design sketch of the AVRO Model 698 is compared with the final layout of the B-1 Vulcan bomber (approximately 1945-1948). Though these versions exhibit considerable differences, a gradual evolution of the initial baseline configuration took place in the course of the project development (Ref. 2-7). If this design is compared with that of the Handley Page Victor and the Vickers Valiant, which were both based on the same specification, it can be concluded that various solutions, each with its own particular merits, are possible. This will be discussed in more detail in Section 2.3. Unfortunately, for various reasons few examples of design evolutions have been published, and it is therefore difficult to draw general conclusions from which recommendations can be deduced. The list of references includes one publication, Ref. 2-6, which is particularly interesting in this connection since it presents some very unusual arrangements dating from the introduction of jet propulsion.

The general arrangement adopted can, in fact, only be properly justified once the design has been finalized. A satisfactory comparison of two different solutions for the same specification will not always be possible, as many design details add up to determine the characteristics of an aircraft and the design considerations published by the manufacturers are as a rule insufficiently detailed.
Competition forces manufacturers to explore new solutions, which is one of the

reasons why competition has the long-term effect of advancing the technology. Excessively large departures from the existing state of the art may, however, lead to the taking of unwarranted commercial risks. Another restraining factor is the circumstance that all designs have to meet the existing or anticipated airworthiness requirements. Hawthorne's* definition of design may be aptly quoted in this context: "Design is the process of solving a problem by bringing together unlikely combinations of known principles, materials and processes". A typical example resulting from such a procedure is the Sud-Aviation Caravelle (Fig. 2-3), which successfully pioneered the location of the engine pods at the tail of the fuselage. The spiritual father of this design was Pierre Satre.

It is scarcely possible to give hard and fast rules for arriving at a sound configuration. Some relevant considerations will be presented in the sections which follow but these should be interpreted with caution, as it sometimes happens that even small dimensional differences between the designs may lead to completely different conclusions. Sketches that are reasonably accurate with respect to dimensions are indispensable in the design stage. Without a correct representation of the relative size of the major components, the design drawing might perhaps result in a good artist's impression of the designer's ideas but it is likely to be useless as a basis for further engineering. Engine dimensions, especially in the case of high bypass ratio engines, are often of particular importance in view of their relation to duct sizes, landing gear height, etc. Certain dimensions needed for these drawings may be deduced from data of similar aircraft, preferably using parameters such as wing loading, aspect ratio, relative airfoil thickness, etc. The statistical data presented in other chapters of this book may also be used as a source of information.

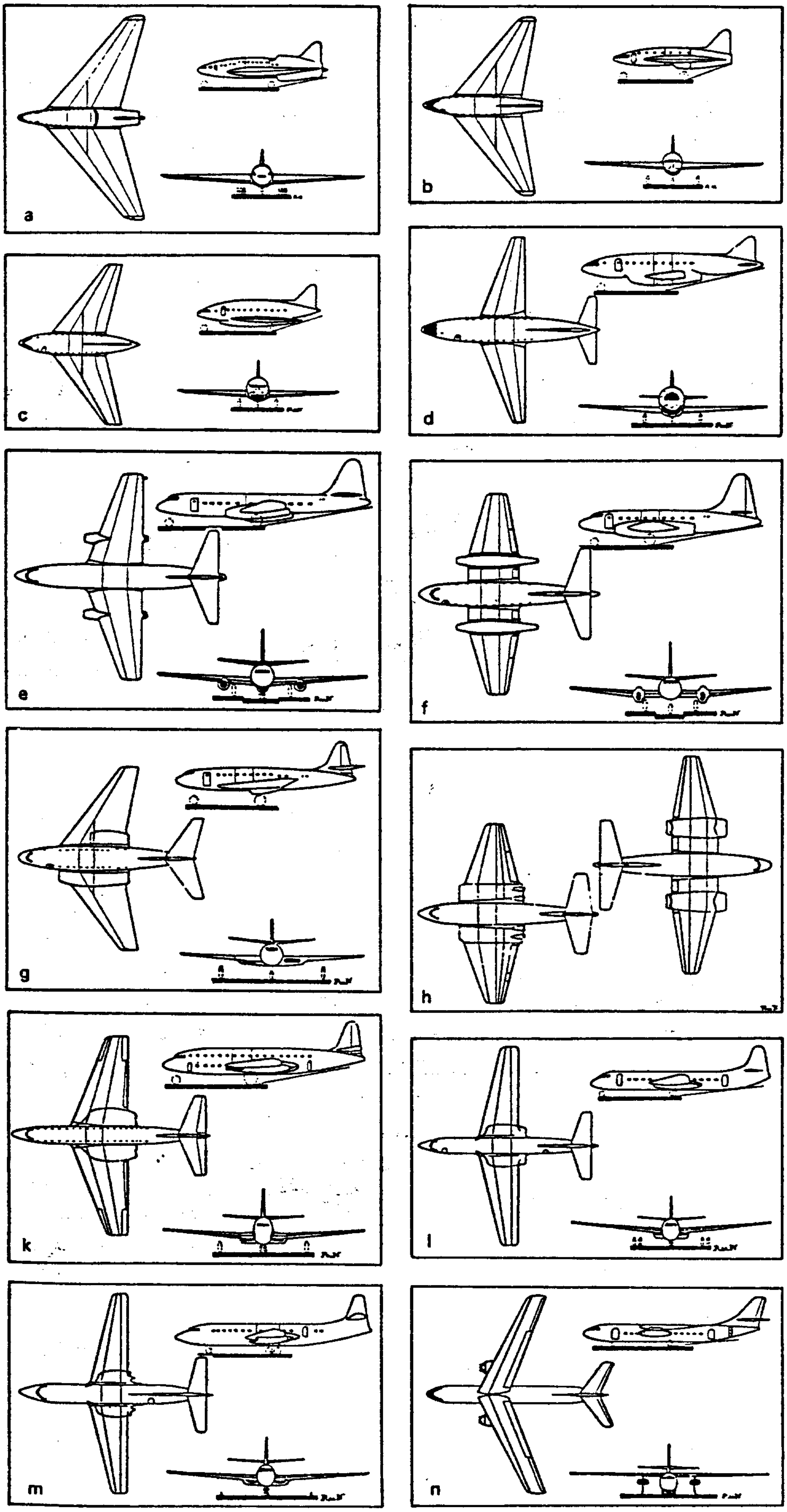
During the configuration study the designer should have a clear picture in his mind of the operational requirements of the aircraft and the environment, such as how it is to be loaded, the airport facilities, special requirements regarding visibility from the cockpit, the desirability of the aircraft carrying a very low price-tag, etc. Although the general design requirements will provide important pointers, the designer should develop a "design philisophy", determining priorities, indicating solutions, etc. In some cases the manufacturer's production facilities and capabilities affect the structural design and may thus influence the general concept. Every aircraft essentially is a very complicated entity; all superfluous complication will be costly both to the manufacturer and to the user and will lessen the design's chances of success.

The next few sections will be devoted to discussion of the general arrangement. This chapter will not deal with the fuselage layout, including the use of tailbooms, for which the reader is referred to Chapter 3, while the center of gravity limitations of the design and their influence on the general configuration will be discussed in Chapter 8. When engine location is dealt with (Para. 2.3), it will be assumed that the number and type of engines have already been decided. If this is not so, the reader should turn to Section 6.2 for more information.

2.2. HIGH, LOW OR MID WING?

The vertical location of the wing relative to the fuselage must be considered first. Fig. 2-4 shows three layouts of aircraft design projects in different categories. It will be obvious that the wing location relative to the fuselage is to a very large extent determined by the operational requirements. Although the aerodynamic and structural differences are not without importance, they can only be deciding factors when the choice between high, low and mid wing is not dictated by considerations of maximum operational flexibility.

* Engineering Laboratory, Cambridge University



a. SE X200, 200-tons all wing for transatlantic ranges
b. SE X202, Feb. 1947

c. SE X203, March 1947, 40 passengers
d. SE X204, two engines, 30 passengers

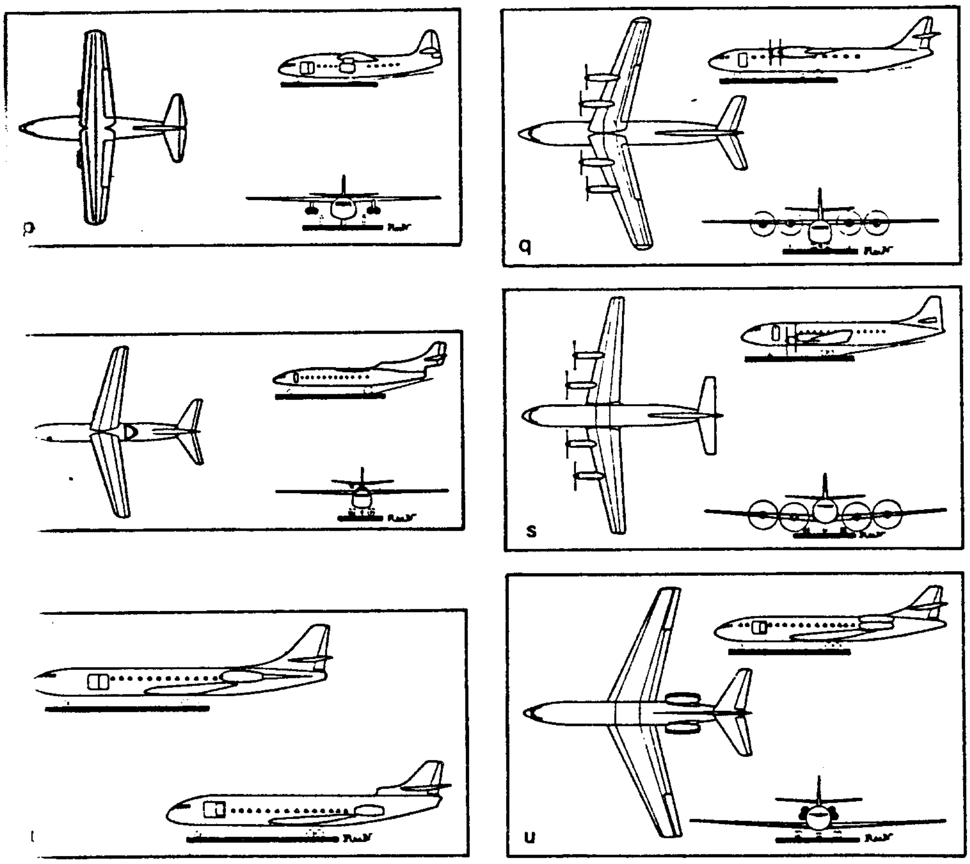
e. SE X205, July 1947, three engines
f. SE X206, four engines, 40 passengers

g. SE X206.02.03, different version from f.
h. SE X206.02.03, two other versions

k. SE X206.02.04, September 1947, four engines, two decks
l. SE X206.02.09, Jan. 1948, four engines, 40 passengers

m. SE X206-02-17, May 1948 four engines (Nene)
n. SE X206-02-21, June 1951, four engines (ATAR D), 48-60 passengers

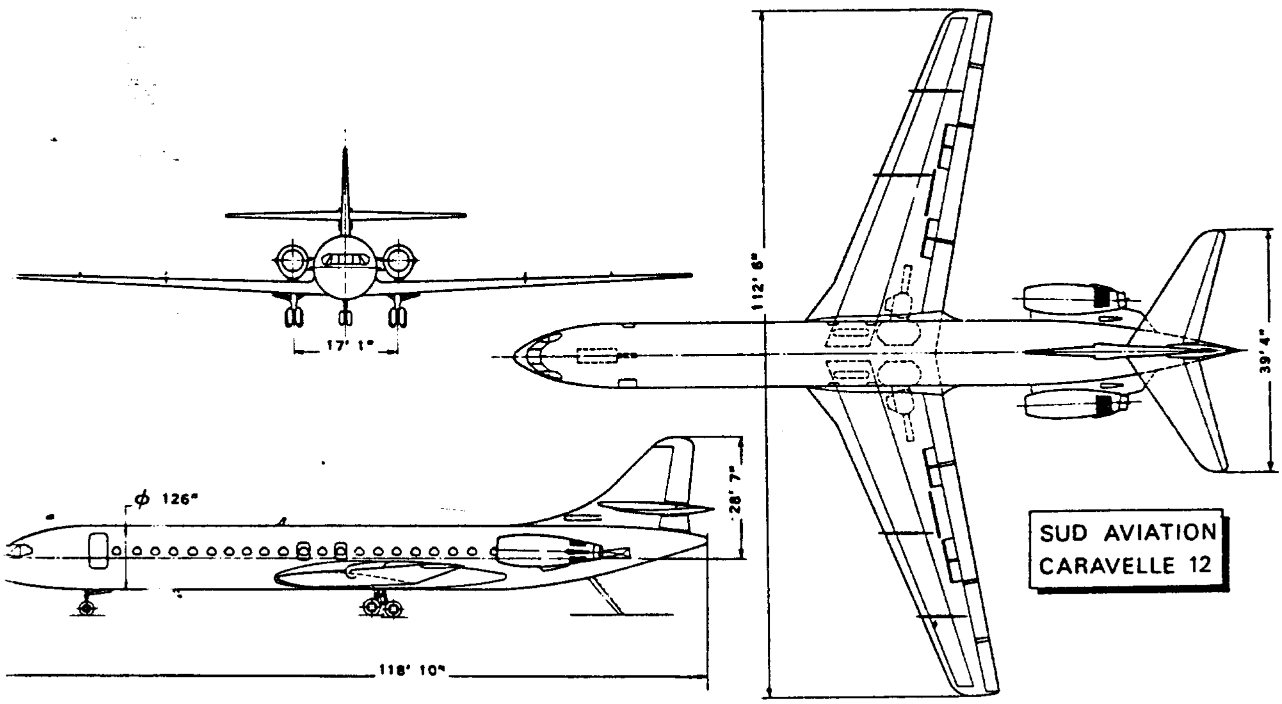
Fig. 2-3. Design projects by Sud-Aviation (Ref. ALATA, Febr. 1959)



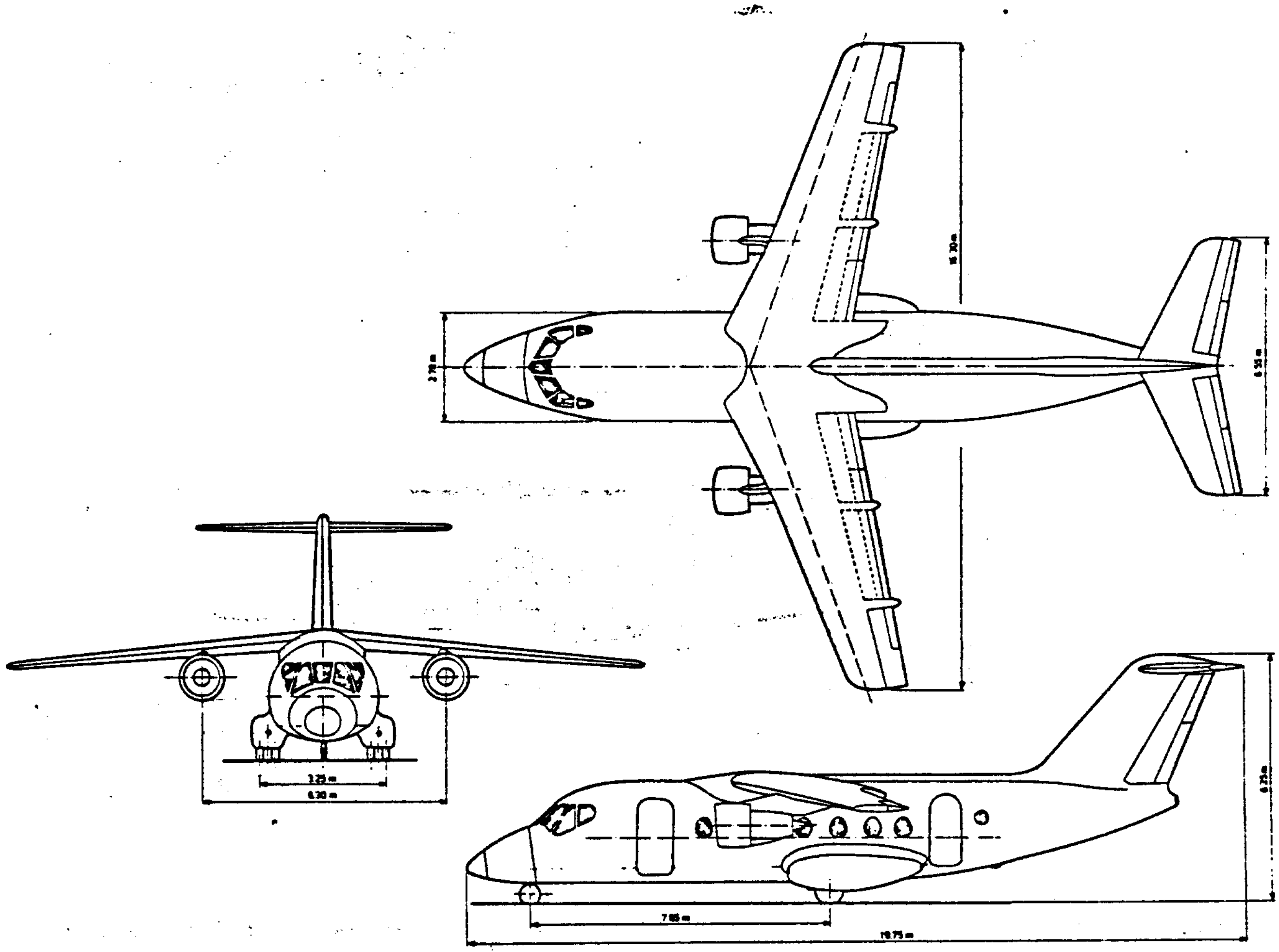
p. SE X210.02.01, four engines Turboméca "Tourmalet", 40-58 passengers
q. SE X210.02.09, July 1951, high wing, four turboprops

r. SE X210.02.10, July 1951, three engines derived from Grognard airplane, 48 pass.
s. SE X210.02.20, Jan. 1952, four turboprops

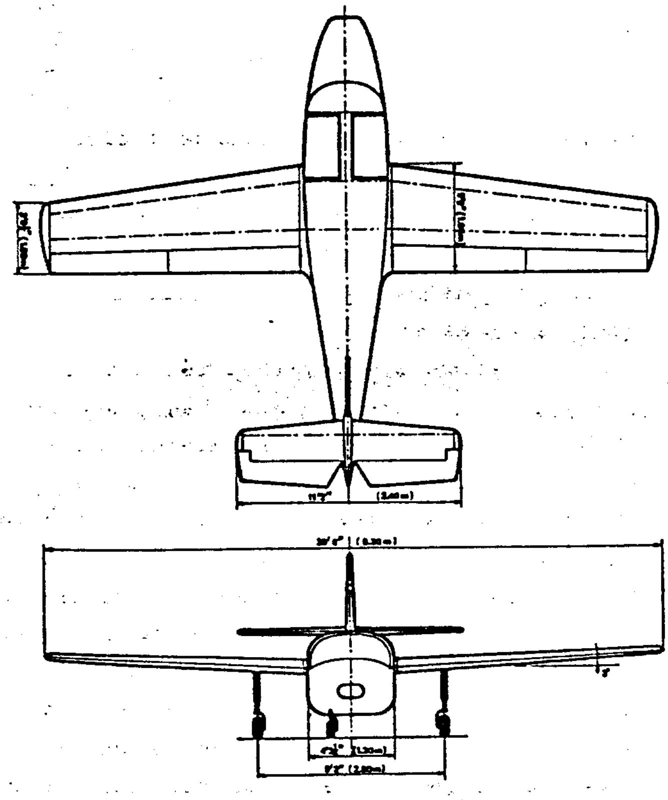
t. SE X210.02.10 and 14, December 1951, two versions with three engines
u. SE X210.02.24, March 1952. Final version, four engines later replaced by 2 Avons



'ig. 2-3. (continued)



HIGH - WING feederliner designed by the author



MID - WING light jet trainer designed by C.A. v.d. Eyk and J. v. Hattum

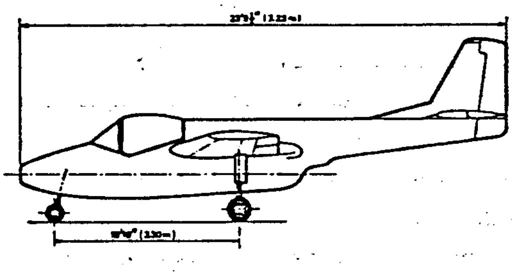
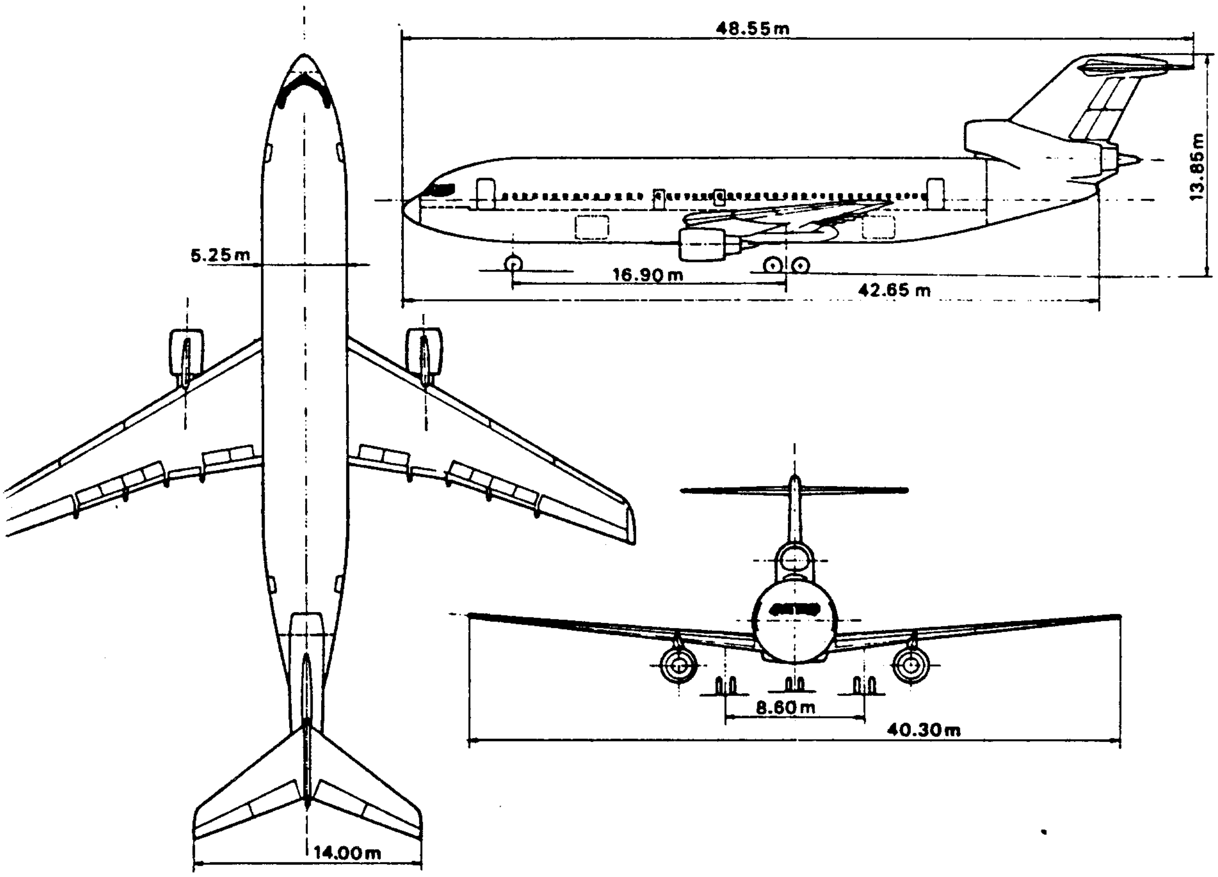


Fig. 2-4. Examples of high-wing, mid-wing and low-wing layouts (preliminary designs)



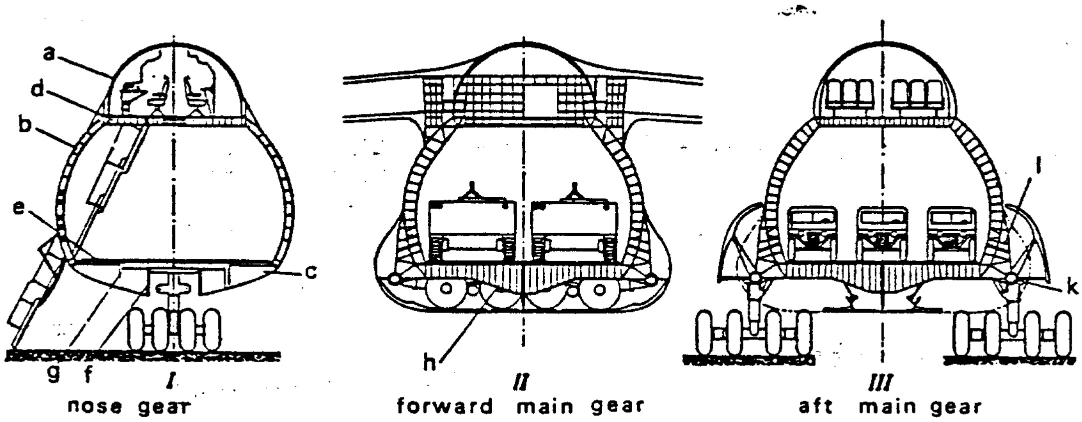
N - WING short-haul passenger transport designed by G.H. Berenschot and the author

g. 2-4. (concluded)

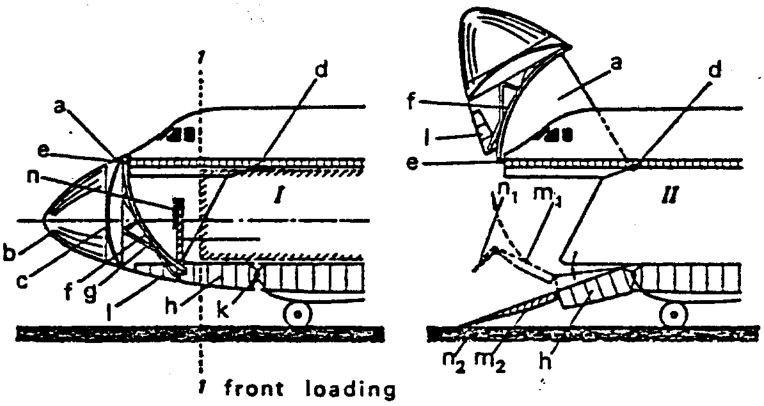
2.1. High wing

lesign requirement for the military trans-
t Lockheed C-5A was quick loading and un-
ding of infantry troops. The aircraft al-
had to carry a variety of cargo, such as
ton trucks, M-60 tanks and artillery ve-
cles, while space had to be provided for
rsonnel. Fig. 2-5 gives a number of cross-
ctions showing how this load is accommo-
ted in the fuselage. The floor is stressed
take a load of 740 lb/sq.ft (3600 kg/m^2)
d has an area of 2370 sq.ft (220 m^2),
ile it lies about 8¼ ft (2.5 m) above the
ron. The cockpit and the seats for trans-
rt of personnel are arranged in two sec-
ons, separated by the wing center-section.
ading and unloading take place through
se and tail doors and the sketch clearly
shows the importance of a low floor level
for this very large aircraft. In the case of
a low wing aircraft of comparable size, such as the Boeing 747, the main deck floor is about 16 to 17 ft (5 m) above the apron. This makes such an aircraft dependent on special loading and boarding equipment, which is unacceptable for a military aircraft such as the C-5A.

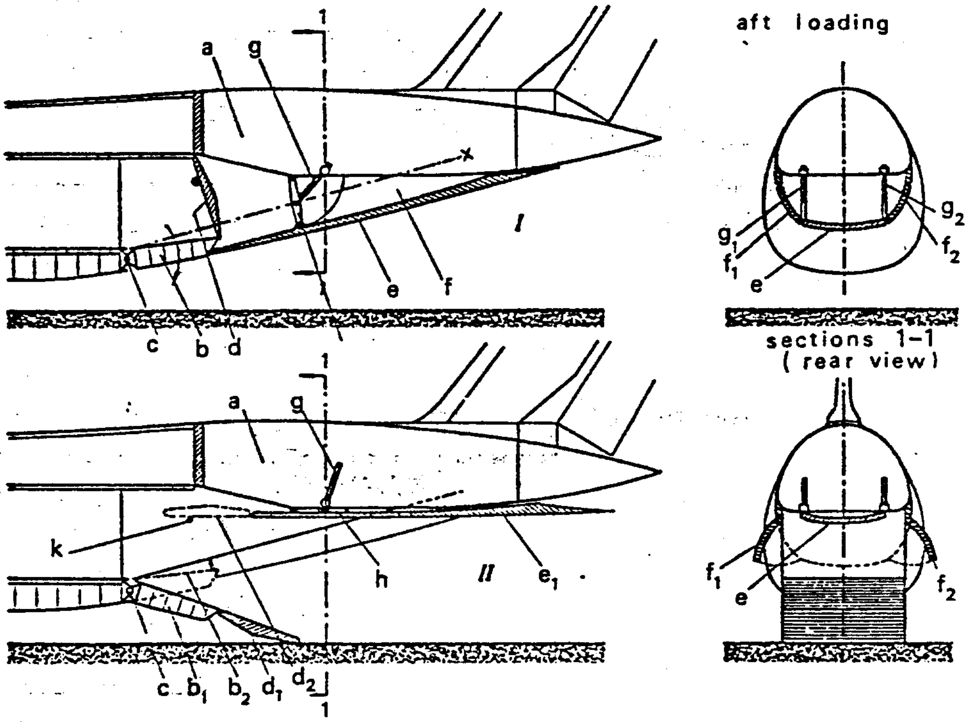
Fig. 2-5 shows clearly that retraction of the main undercarriage gear has posed special problems for the designers. In smaller high-wing propeller aircraft it may be possible to retract the main gear into the engine nacelles (Fokker F-27) or in the tail booms (Hawker Siddeley Argosy), but in the case of very large aircraft doing so would make it too tall and too heavy. This will unavoidably lead to mounting the gear to the fuselage, but the strengthening of the fuselage structure required for the transmission of the landing impact loads will result in a weight increase. This is only



a: upper lobe; b: central lobe; c: lower lobe; d: upper deck; e: main deck; f,g: longitudinal supports; h: main fuselage frames; k: main gear shock strut; l: external mounting frame

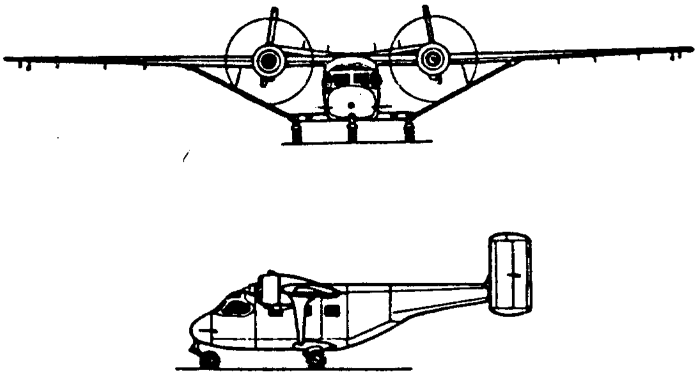


a: fuselage nose; b: radome; c: pressure bulkhead; d: door hinges; e: guide; f: slide; g: post; h: adjustable floor element; k: articulation; l: nose floor element; m: ramp; n: flap

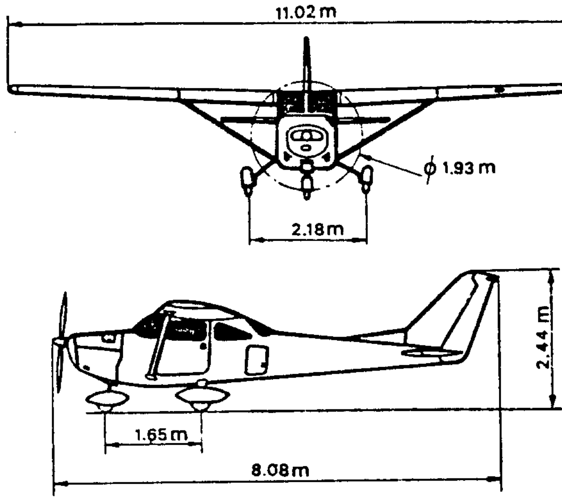


a: load-carrying structure; b: adjustable floor element; c: articulation; d,k: flap; e: central loading door; f_1,f_2: lateral doors; g_1,g_2: screwjacks; h: levers

Fig. 2-5. Loading provisions and undercarriages supports for the Lockheed C-5A (Ref.: DOC-AIR-ESPACE No 113 - Nov. 1968)



Antonov An-14 Pchelka



Cessna 172

Fig. 2-6. Examples of airplane types with braced wings

artially offset by the saving in weight in comparison with a low-wing design, due to the shorter landing gear struts. Moreover, with a fuselage-mounted main undercarriage it is difficult to obtain a sufficiently wide track. These considerations may be regarded as having favored the use of low-wing monoplanes.

raced-wing monoplanes (Fig. 2-6) are nowadays generally high-wing designs. Bracing struts cause little interference when attached to the lower side of the wing, while hey usually can be lighter than in other positions since in this case the critical strut loads are likely to be tension loads.

In the case of STOL aircraft close proximity of the wing to the ground in takeoff and landing may cause pronounced and generally undesirable ground effects. Moreover, if a low wing was adopted, the required ground clearance of the large, fully deflected trailing-edge flaps and - in the case of propeller-driven STOL aircraft - of the large propellers, would entail a very tall and heavy landing gear. In this case a high-wing design generally has more to recommend it.

2.2.2. Mid wing

This layout is generally chosen when minimum drag in high-speed flight is of paramount importance. With a fuselage of roughly circular cross-section, the surfaces at the wing-fuselage junction meet at practically right angles so that interference between the boundary layers at small angles of attack will be minimized. In most cases the fuselage section at the location where the wing is mounted to it is roughly cylindrical. The divergence of the airflow over the wing root at high angles of attack is thus minimized. Wing root fairings of only very modest size will therefore be required. For these reasons many mid-wing layouts are found in fighter and trainer aircraft, where it is an acceptable arrangement, provided the space required for the useful load is small in relation to the total internal fuselage volume and can be divided into separate sections. The wing may be continuous through the fuselage because the transfer of the loads from the wing may take place via almost "solid" bulkheads to which each winghalf is attached. It is generally not feasible to adopt such a scheme for transport aircraft, and very few mid-wing monoplanes are to be found in this category. However, it is worth noting that on large transport aircraft the wing arrangement adopted approaches the mid-wing position, the reason being that the cabin floor, which is located just above the wing center section, is positioned relatively high in the fuselage cross section. Another exception is the HFB 320 Hansa (Fig. 2-7), which features a negative angle

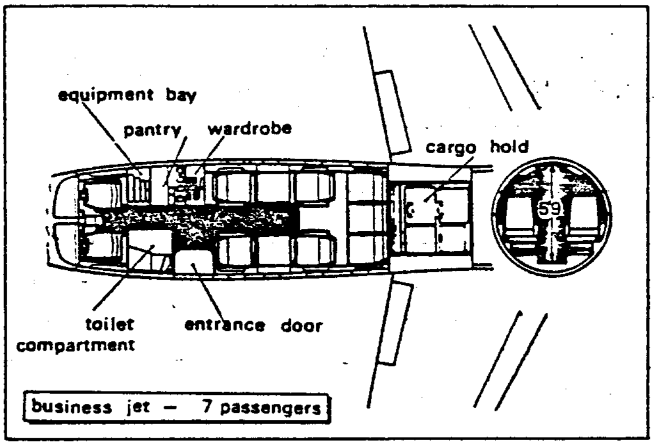


Fig. 2-7. Fuselage layout of the HFB Hansa jet

of sweep, with the engines at the tail balancing the cabin ahead of the wing center section. However, with this layout it is difficult to avoid considerable shift of the center of gravity for different loading conditions unless serious loading restrictions are accepted.* The swept-forward wing presents certain aeroelastic problems which are difficult to solve without the use of tip tanks. Although the manufacturer claims that the aircraft possesses low drag characteristics, maximum cabin height for a given fuselage diameter, and a good view for all the occupants, it remains doubtful whether these outweigh the disadvantages.

2.2.3. Low wing

The low wing position frequently offers many advantages. It is true that light aircraft still account for a fair number of high-wing monoplanes, but this may be more a matter of company tradition than an obvious technical advantage. The low cargo floor height is of benefit to small freighters designed for operating into secondary airports and from airfields and airstrips where special loading equipment is not available. In the case of most passenger aircraft, the height of the cabin floor above the ground is of lesser importance as use can be made of steps of loading bridges.

Efficient use of the underfloor space in the fuselage for the stowage of cargo is possible only if the fuselage is at a suitable height above the apron. Without resorting to a tall undercarriage, this is more easily achieved in a low-wing design. The generally larger fuselage height above ground level on a low-wing configuration may also offer advantages when, after a fuselage stretch, the tail angle available is still sufficiently large to allow for optimum rotation during the takeoff, without creating an unacceptable geometrical pitch angle limitation (Fig. 2-8).

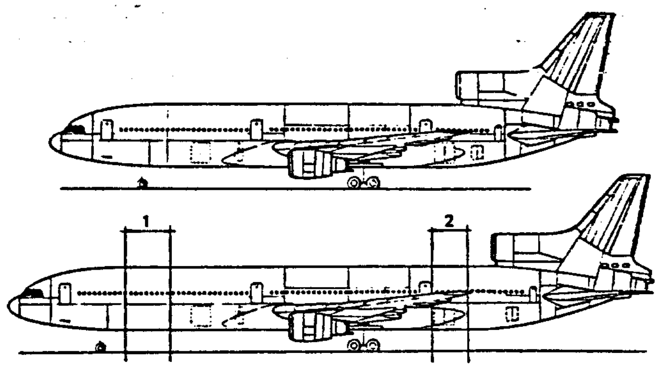


Fig. 2-8. A stretched version of the Lockheed Tristar is envisaged in the design stage. The fuselage will be stretched by 3.56 m (1) and 4.57 m (2) in front of and behind the wing resp. The undercarriage is sufficiently long to allow rotation over 12° after stretching (Ref.: Aviation Mag. No. 550, 30 Nov. 1970)

2.2.4. Effect of the wing location on the general arrangement

a. Interior arrangement.

On a high-wing aircraft the fuselage section below the floor is generally flattened in order to reduce the undercarriage height and to keep the floor at the desired level

*See Section 8.5.4

above the ground, truckbed height being generally 4 to 4½ ft (1.20 to 1.40 m). A lat fuselage belly leaves little or no oom to carry underfloor cargo and this may ecessitate a longer cargo hold in the cab- n, as compared to aircraft with a circular uselage cross-section. This in turn may engthen the fuselage, particularly when, n addition, most equipment and services ill have to be located above the floor. A arge center of gravity travel may result. n low-wing aircraft the landing gear may e retracted into (propeller) engine na- elles or into the fuselage just behind the enter-section of a swept-back wing. Re- raction of the main undercarriage between he main wing spars is more easily achieved ith a non-stressed lightly loaded skin han with a stressed-skin structure.
n small high-wing transports the aisle is ometimes sunk in relation to the rest of he cabin floor to provide adequate stand- ng room. The most critical point is at the ing-fuselage intersection where a slightly owered cabin ceiling may be unavoidable. t may be worthwile investigating whether his space can be used for stowage or a loakroom, or whether lavatories can be xtended into this area.
ow-wing aircraft sometimes have the wing rotruding slightly below the fuselage, ecessitating extensive fairings (e.g. awker Siddeley 125). In some small touring ircraft the front seats may be mounted irectly on the wing box, thus saving space.

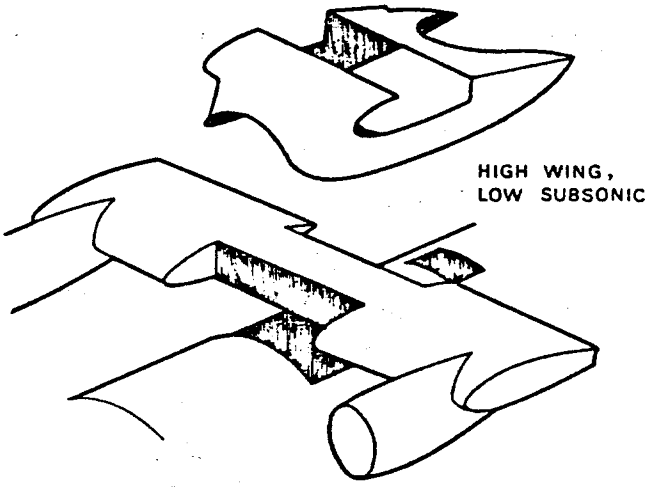
. Safety.

he low wing and possibly the engines will orm a large energy-absorbing mass during forced landing, although they also present otential fire hazards upon contact with he ground. The wing generally contains uel and the tanks are likely to be damaged, articularly if they are of the integral type. If the impact is not too heavy, dam- ge and fire risk in a high-wing aircraft may be limited. When an aircraft is forced down on water, the fuselage of a high-wing monoplane will be submerged; provisions must therefore be made for escape through the cabin roof. It should be noted, how- ever, that not all aircraft have to be cer- tificated for overwater operation.

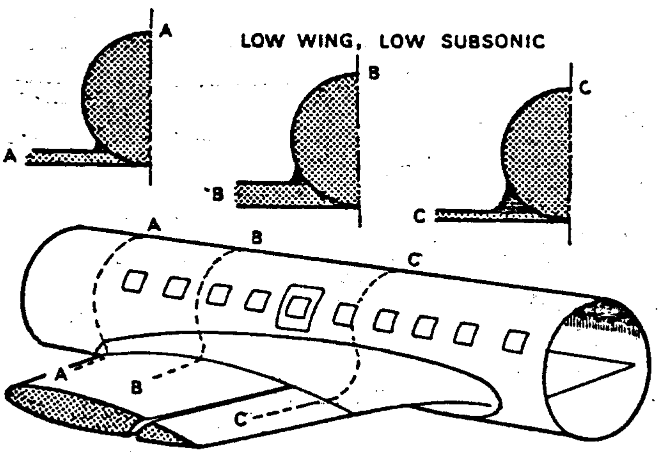
c. Performance and flying qualities.

The principal difference between the char- acteristics of high- and low-wing layouts during takeoff and landing is the ground effect, which decreases with increasing wing height above the ground. Ground effect will generally cause a reduction in vortex- induced drag, resulting in a decreased takeoff distance and an increased landing distance. Sometimes, however, it leads to premature breakaway of the airflow and even reversed flow below the wing flaps, re- sulting in an increase in the Minimum Un- stick Speed* and consequently a longer takeoff run.
Probably more important is the decrease in downwash at the horizontal tail, leading to a nose-down pitching moment. This will require greater elevator deflection for the takeoff rotation and the landing flare-out and this may be a determining factor for the elevator power required. The proximity of the ground may have an opposite effect, causing the aircraft "to land itself". This means that after a properly executed final approach little or no elevator movement is requirement for the flare-out. This can be the case when the wing is placed in such a low position that ground effect causes a marked lift increment, while the nose-down pitching moment mentioned above is approx- imately compensated by a nose-up pitching moment due to the wing lift. Though this characteristic may in itself be advanta- geous, it is practically impossible to de- sign the aircraft from the outset in such a way as to achieve it.
With respect to maximum lift and minimum drag, there are admittedly differences be- tween the high and low wing locations, but these may be minimized by proper use of fillets and fairings (Fig. 2-9). Even so, the high wing is superior in this respect to the low wing, particularly where induced

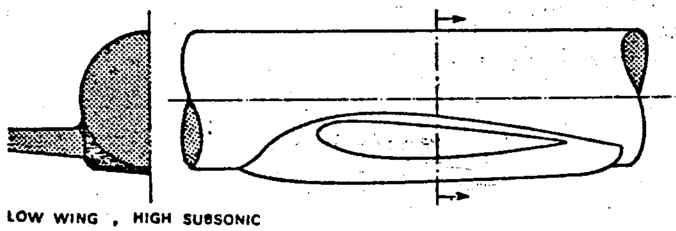
*See Appendix K, Section K-2



a. fillets mainly on lower wing surface



b. fillets mainly on upper wing surface



c. fillets act to obey the area rule and to house the main landing gear

Fig. 2-9. Several types of fillets to reduce unfavorable wing-fuselage interference

drag at high lift is concerned. The potential differences in damping the Dutch roll may be largely suppressed by good design, particularly proper choice of the wing dihedral angle and fin area. Negative wing dihedral, desirable on swept-back wings, can easily be incorporated in a high-wing design without resorting to a tall undercarriage. However, both configurations may possess comparable flying qualities, except for fast maneuvers in aerobatics, which are favored by the mid- and low-wing layout. High-wing aircraft will generally require roughly 20 percent more vertical tail area than low wing types.

d. Structural aspects.

The Lockheed C-5A has already been cited as an example of the difficulties encountered when designing the undercarriage of a high-wing aircraft. Although the weight penalty in the fuselage structure is partly offset by a lighter wing and a shorter and lighter nosewheel gear, on balance the high-wing layout will be at a disadvantage with respect to empty weight and complication of the structural design.

2.3. LOCATION OF THE ENGINES

2.3.1. Propeller aircraft

Aircraft powered by piston engines are generally seen in two layouts: the single tractor engine type with the powerplant in the fuselage nose and the twin tractor type with both engines fitted to the wing. New aircraft types with four piston engines are not being built any more since any rating over, say, 500 hp is produced more efficiently by the turboprop engine, and piston engines in that class are practically obsolete. Configurations are occasionally observed which differ from the generally accepted solutions described above, but in such cases the choice must have been influenced by special considerations, such as the desirability of creating a high thrust-line (amphibians) or avoiding asymmetry in

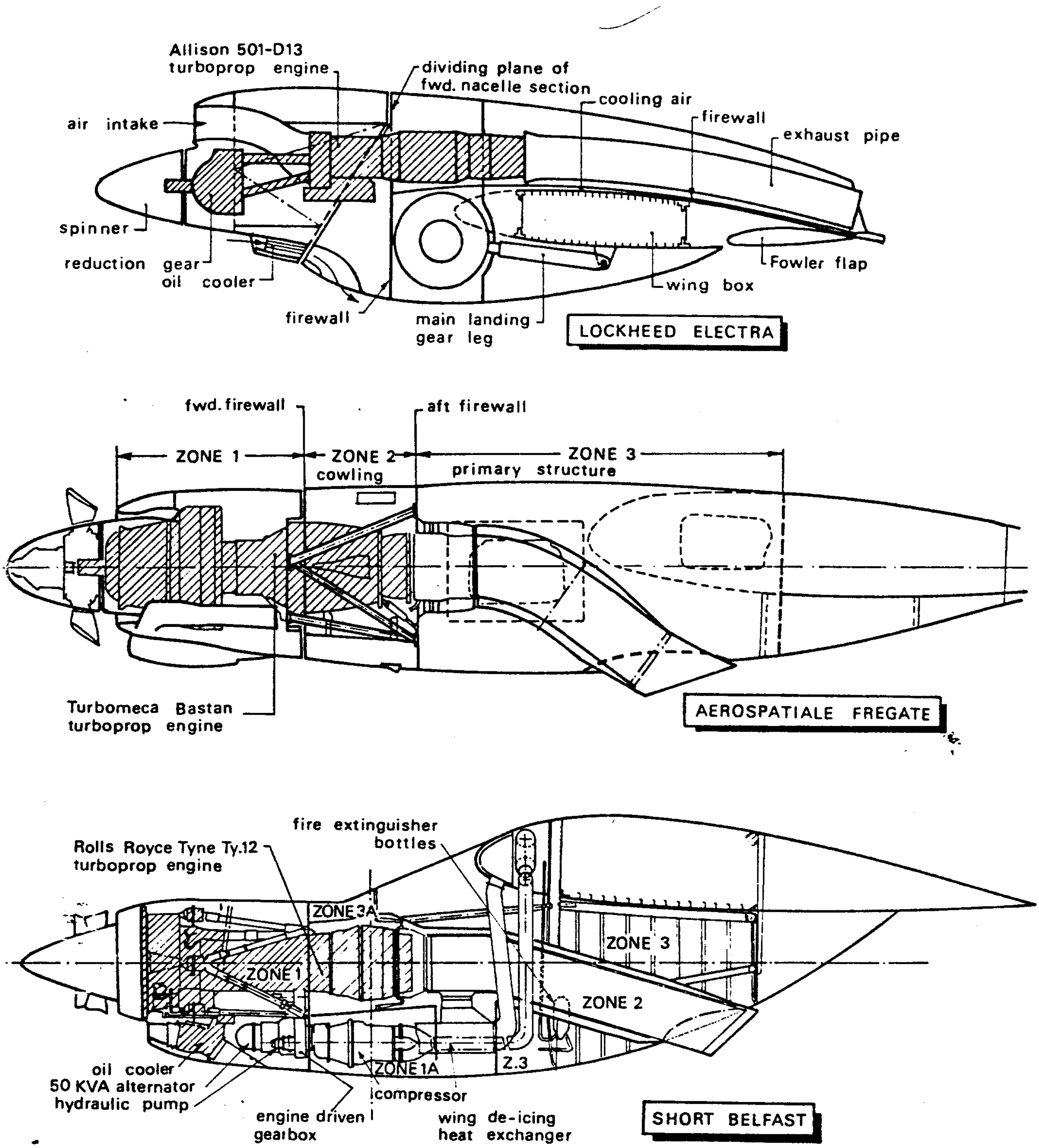


Fig. 2-10. Three types of turbopropeller engine installation

the event of engine failure by using one tractor and one pusher engine in the plane of symmetry (e.g. Cessna Skymaster).

Positioning the propeller engines in front of the wing generally results in the most attractive configuration from the aerodynamic and structural point of view. The propeller slipstream of operating engines generally has a favorable effect on the stall and increases the wing lift, in particular when trailing-edge flaps are extended, thus forming a kind of built-in safeguard against stalling. On the other hand, an engine failure may cause considerable windmilling drag before the propeller is feathered and while the flow over the wing is still disturbed. The yawing and rolling moments induced by engine failure present control problems and downgrade the flight performance, in particular when the engine fails in the takeoff. Variation of the engine power will change the downwash behind the wing and this is of particular influence on the stabilizing contribution of the tail surfaces (Section 2.4.2).

The location and installation of the engines in nacelles mounted to the wing leading edge is illustrated in Fig. 2-10 for several aircraft types. As will be shown in Chapter 6, the engine configuration and the propeller design have considerable influence on this. In the case of a high-wing layout there is generally more freedom with respect to the vertical position of the engines relative to the airfoil as compared to low-wing aircraft, since propeller clearance over the ground is relatively easily provided.

When turboprop engines are used, an engine nacelle which is placed low relative to the wing is to be favored, both for its light supporting structure and for effective discharge of the hot gases, requiring only a short exhaust pipe. On a low-wing aircraft designers are often forced to adopt a relatively high position for the engine nacelles in order to ensure sufficient propeller to ground clearance. This may lead to unfavorable interference effects between the nacelle and the wing, causing premature breakaway of the airflow and additional induced drag.

2.3.2. Jet-propelled transport aircraft

When the jet engine became an acceptable prime mover for both transport and large military aircraft (about 1947-1950), the traditional piston engine layout was discarded and a new configuration was sought which would suit the specific characteristics and demands of the jet engine. Smaller jet aircraft were generally designed for military purposes and had a single engine in the fuselage; in the case of transport

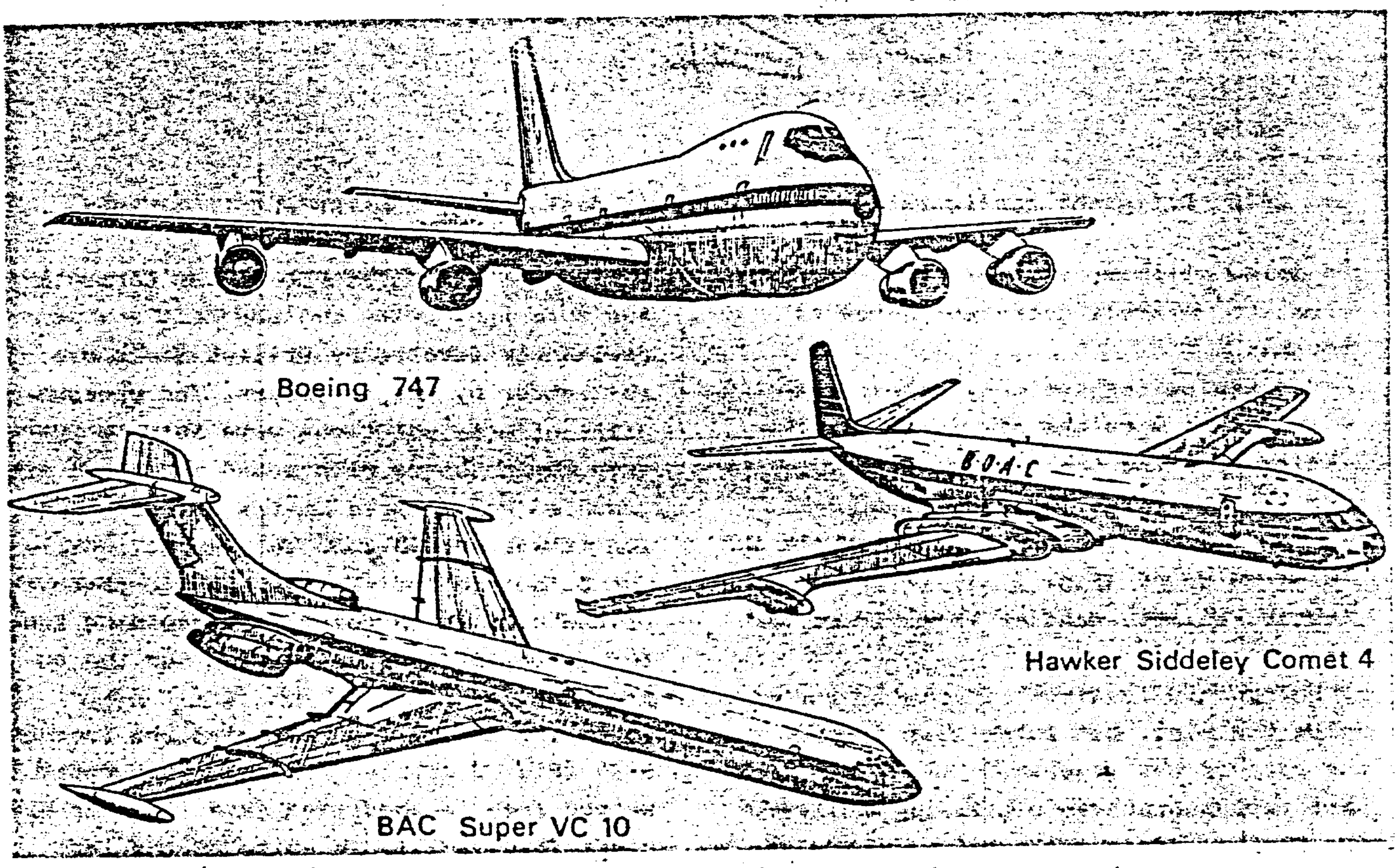
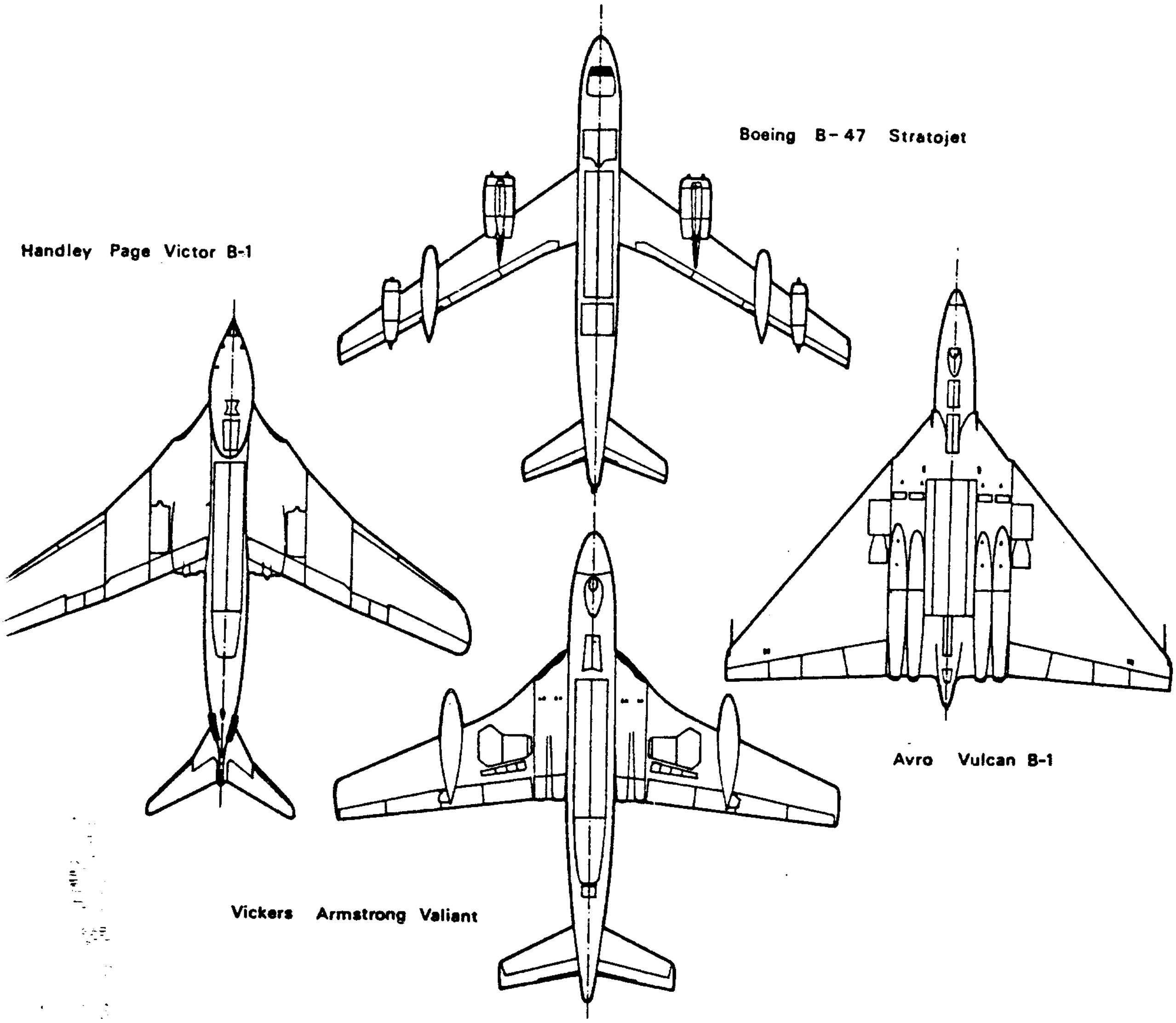


Fig. 2-11. Examples of powerplant installation on subsonic jet transports



g. 2-12. Different configurations for aircraft designed to similar specifications

d large military aircraft there appeared be two entirely different lines of .ought:

. Engines buried entirely within the root the wing, with the air intake in the .ading edge and the exhaust at the trailing ge, close to the fuselage. Examples of ach an arrangement may be seen in the De avilland Comet (Fig. 2-11), Avro Vulcan, ickers Valiant, Handley Page Victor and upolev 104.

). Pod-mounted engines, initially suspended elow the wing, but later also fitted to the rear of the fuselage. The first important representatives of this school were the Boeing models B-47, B-52 and KC-135 (Fig. 2-1), while Sud-Aviation originated the rear-mounted engines in the Caravelle.

The former of these two concepts was predominantly favored by British designers, the latter by the Americans. The protagonists of both solutions were able to justify their choice with sound technical arguments (Ref. 2-11). In the author's opinion it was not so much the engine installation but rather the aerodynamic concept of the wing which formed the deciding factor in the difference between the two approaches.

Comparing the Avro Vulcan with the Boeing B-47 (Fig. 2-12), we find that the total wetted area is about the same for both aircraft (Fig. 2-13), in spite of the fact that the wing area of the Vulcan is nearly

	BOEING B-47	AVRO VULCAN
GROSS WING AREA ~ ft^2 (m^2)	1430 (133)	3448 (320)
TOTAL WETTED AREA ~ ft^2 (m^2)	11300 (1050)	9500 (885)
SPAN ~ ft (m)	116 (35.4)	99 (30.2)
MAX. WING LOADING ~ lb/ft^2 (kg/m^2)	140 (690)	43.5 (212)
MAX. SPAN LOADING ~ lb/ft (kg/m)	1750 (2590)	1520 (2250)
ASPECT RATIO	9.43	2.84
C_{D_o} (ESTIMATED)	.0198	.0069
$1/\pi Ae$ (e = OSWALD FACTOR)	.0425 (.8)	.125 (.9)
L/D_{max} ; $C_{L_{opt}}$	17.25 ; .882	17.0 ; .235

Fig. 2-13. Similarity in max. lift/drag ratios for two widely different configurations

three times that of the B-47 (wing area*). In contrast to this, there is the difference between the aspect ratios**, namely a figure in excess of 3. However, both aircraft have nearly the same span loading (weight/span). The remarkable conclusion can be drawn that for a given dynamic pressure both the profile and vortex-induced drag*** will be roughly equal for these aircraft. Although the comparison shown in Fig. 2-13 is based on estimated values, it clearly shows that it is possible to achieve a comparable range performance with both wing layouts. There are, all the same, considerable differences between the two types:

a. The maximum lift/drag ratio occurs at C_L = .235 for the Vulcan and at C_L = .68 for the B-47. When cruising at high altitude the Vulcan had more freedom to maneuver without experiencing serious buffeting due to compressibility.

b. The structural height at the wing root of the Vulcan, namely about 6 feet 8 inches (2 meters), proved ample to house the engines internally; in the case of the B-47 the height available was only about 26 inches (.66 m).

* The gross wing area used in Fig. 2-13 is as defined in Appendix A Section A-3.1.

** Aspect ratio = $span^2$/area = span/geometric mean chord. See Appendix A.

*** Definitions in Section 11.2.

In a sense this means that the design philosophy with regard to the engine installation was mainly decided by the shape of the wing. Although this example is predominantly of historical interest, it shows that there is a close connection with decisions in other fields.

The protagonists of podded engines attached to the wings by means of pylons use the following arguments to support their views:

a. Separately spaced engines are well placed from the safety point of view. In the event of fire in one of the pods the likelihood that fire will spread to the fuel in the wing is limited. In fact this was the main argument for the choice of the B-47 configuration.

b. The short intake and exhaust ducts enable the engine to run under optimal conditions.

c. The mass of the engines and the pylons lead to a reduction in the bending moment of the inner wing, thus lightening part of the wing structure. When they are located ahead of the flexural axis, they constitute a mass balance against flutter.

d. The engines can be made easily accessible at the cost of very little increase in structure weight since the pods do not form part of the stressed structure. Access to engines buried in the wing roots has to be provided by detachable skin panels at a location where the wing is highly stressed.

e. The engine pylons appear to have a favorable effect on the airflow at large angles of attack and tend to counteract pitch-up of sweptback wings (Fig. 2-14). The pylons act in a manner similar to

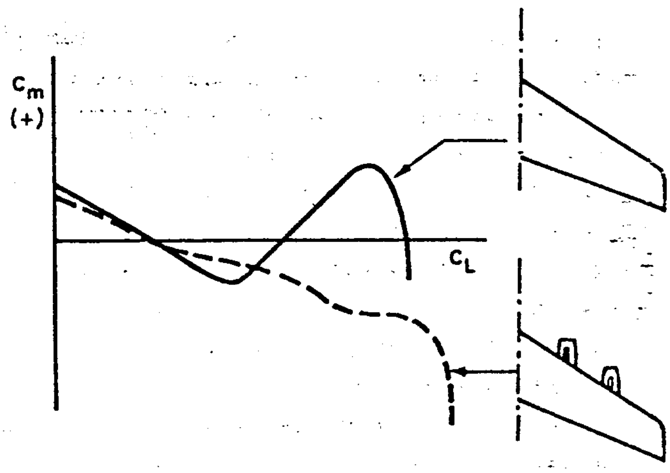


Fig. 2-14. Effect of wing-mounted pods on longitudinal stability (Ref. 2-11)

fences, which are often used on "clean" wings. Against this the protagonists of completely buried ngines list the following arguments:

. The extra drag resulting from the buried engine nstallation is only a few percent as against about 5% of the total drag in the case of a configura- on similar to the B-47. Incidentally, the current neration of turbofans show a value of about 8 to 0%.

. As a result of the low wing loading and low alue of C_L in cruising flight, maneuvering is ssible without compressibility problems such s buffeting.

. The pitch-up problem of swept wings is less ignificant for low aspect ratio wings.

. As a result of the low wing loading, the low- peed performance will be better.

. The relatively low aspect ratio wing box struc- ure will lead to greater stiffness and aeroelas- icity will be less of a problem.

ny of these arguments are only valid up to a oint, and in particular the progress in engine echnology towards high bypass ratio engines, to- ether with the development of more efficient high- ift devices in 1950-1970, has settled the case in avor of high wing loadings and pod-mounted engines. his does not mean that buried engines will not re- urn to favor again in the future. For example, the pplication of laminar flow control by suction of he boundary layer to reduce drag might eventually ead to a totally different design approach, such s a combination of low wing loading and engines f relatively low thrust in cruising flight, inte- rated into the wing or fuselage.

interesting example of configuration udies is shown in Fig. 2-3 for the Sud iation Caravelle. The maiden flight of his airplane, with its engines at the rear f the fuselage, took place in 1955. Thus a ew configuration was added to that intro- uced by the B-47 with the engines in pods elow the wing, a layout also adopted by Douglas (DC-8) and Convair (880 and 990). When this engine location had proved a success in the Caravelle, various new types were designed to practically the same for- mula: the BAC 1-11, Vickers VC.10, Hawker Siddeley Trident, Douglas DC-9, Boeing 727, Fokker F-28 and all executive turbojet air- craft. Though this layout has the obvious advantages of a "clean" wing, low door sill height and little asymmetric thrust after engine failure, it also has a large center of gravity variation with variation in loading condition and it has to be care- fully designed to avoid the superstall problem. Therefore, after 1965, a new trend towards engines on the wings occurred (Boeing 737, Lockheed L-1011, Douglas DC-10, Dassault Mercure).

It would serve little purpose to express a general verdict in favor of either of these two configurations. Each specification, as well as every new type of engine, will re- quire renewed study to support a particular choice and the outcome can only be properly assessed when various configurations have been designed according to the same ground rules. This procedure was followed by the Boeing Company for the development of their Model 737 (Fig. 2-15), when two competing

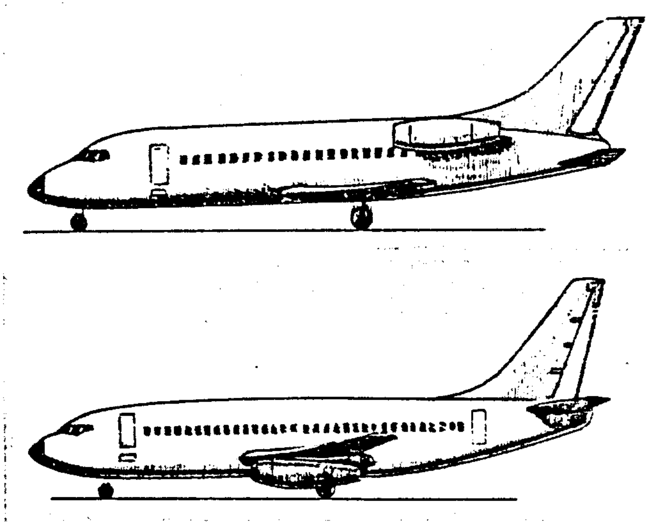


Fig. 2-15. Two configurations of the Boeing Model 737, resulting from a competition of two design teams

design teams were put on the same exercise. Factors which should be investigated in the case of a transport aircraft are indicated in Fig. 2-16. The principal differences be- tween the Caravelle and the Boeing 737 en- gine location will be briefly discussed with reference to that list.

• EMPTY WEIGHT	• FLYING QUALITIES
• ENGINE MAINTENANCE	stalling
• FOREIGN OBJECTS INGESTION	engine-out control
• SYSTEMS	go around
fuel	cruise dutch roll
anti-icing	• NOISE
air conditioning	• PERFORMANCE
• CARGO LOADABILITY	drag
	max. lift
	second segment climb

Fig. 2-16. Engine location factors (Ref.: ATA Engng and Maint. Conf., Oct. 27, 1964)

a. Empty weight.
The following factors have to be considered:
- A wing structure weight saving is possible with wing-mounted engines due to the mass relief effect on the bending moment on the inner wing.
- Engines placed too far outboard increase the landing impact loads and necessitate a large vertical tailplane.
- Engines at the rear of the fuselage require local "beef-up" and lead to loss of useful space in the tail, resulting in added structure weight and a larger fuselage for the same payload.
- Differences in weight of the tail surfaces depend on various factors which do not permit a general conclusion.
Summing up, we may say without too much emphasis that the empty weight of a Caravelle-type layout will typically be 2 to 4% more than that of a comparable design with the engines on the wing.

b. Engine maintenance.
Although the size of the aircraft comes into it, engines below the wings are generally better accessible from the ground than in any other layout.

c. Flexibility of loading.
This depends primarily on the location of the load relative to the center of gravity of the empty aircraft, a subject that is treated more fully in Chapter 9. Both configurations may be designed for good loading characteristics, although a greater c.g. travel must be catered for in the case of rear-mounted engines. At full payload the download on the tail, with consequent loss in the lift to drag ratio, will be considerable with engines mounted to the rear fuselage. Besides, the layout with wing-mounted engines will have a larger underfloor cargo-hold behind the wing, which is generally more easily used.

d. Performance.
Regarding drag in cruising flight there is little to choose between the two layouts, assuming that both have been well designed aerodynamically. Douglas, however, claims that in the case of the DC-9 the drag of the wing plus nacelles at high subsonic speeds is reduced as a result of favorable aerodynamic interference, (Ref. 2-30). Generally speaking, a layout with wing-mounted engines will lead to an increase in induced drag and a slight reduction in the drag-critical Mach number. The drag resulting from the asymmetrical flight condition following engine failure, rapidly increases with the lateral distance of the failed engine to the aircraft centerline and will, therefore, be greater with engines mounted on the wing. The protagonists of the Caravelle layout claim that their clean wing gives a gain of 20% in maximum lift. The Boeing Cy. does not agree, basing its opinion on test data and arguing that in the case of the clean wing the useful lift is reduced by gadgetry to ensure a favorable pitching behaviour at the stall. And indeed, looking at maximum C_L values for a number of aircraft with different layouts, it is not possible to discern a clear-cut tendency either way.

e. Flying qualities.
Engines mounted to the rear of the fuselage are often combined with a tailplane on top of the fin (T-tail). This particular layout has a potential problem in the high incidence range, namely the "deep stall"*

*Also referred to as "superstall" or "locked-in stall"; see Section 2.4.2

(Section 2.4.2). In the case of engines on the wings, the yawing moment resulting from engine failure will be more pronounced.

f. Mounting of a central engine.
Three-engined aircraft generally have one engine mounted centrally at the rear of the fuselage. The problem which will have to be faced here is whether to bury this engine in the fuselage, which will require a fairly long and curved inlet (Boeing 727, Hawker Siddeley Trident, Lockheed L-1011) with consequent loss of intake efficiency and extra weight. Alternatively, the engine can be installed in a pod on top of the fuselage, but in that case the vertical tail surface forms an obstruction. Fig. 2-17 depicts some possible solutions, all

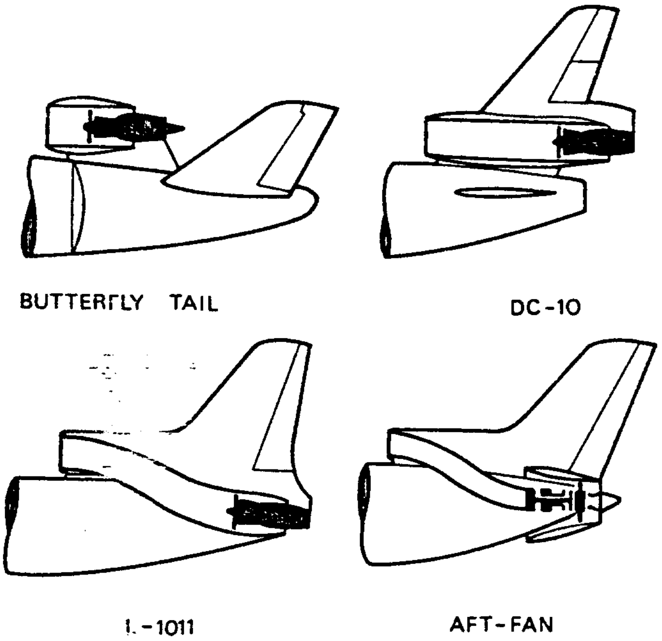


Fig. 2-17. Installation of the central engine on a three-engined jet aircraft

of which present particular design problems. The thing to do here is to optimize the chosen solution in such a way that the disadvantages will be limited. Ref. 2-23 shows that a purely objective comparison of two solutions is very difficult. Manufacturers' data for structure weight, fuel consumption and economy for both the L-1011 and the DC-10 are used to show that both solutions are best.

2.3.3. Single-engined subsonic jet aircraft

Aircraft of this type have the engine mounted inside the fuselage and the intake and exhaust ducts often present a problem. The inlet duct has to supply a constant flow of air at different operational engine settings and in different flight conditions. Flow distortion and turbulence at the compressor face must remain within the limits

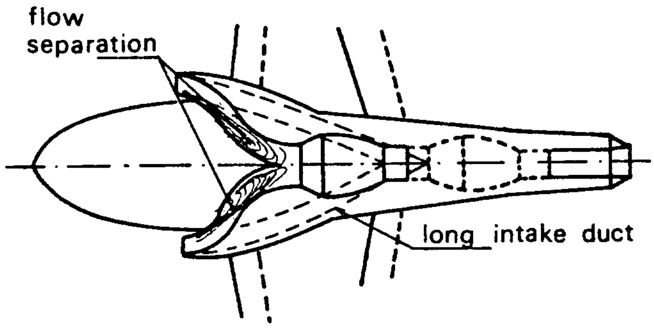


Fig. 2-18. Intake problem on a stubby fuselage with side intakes

laid down by the engine manufacturer. Pronounced curvature in the inlet duct should therefore be avoided. This is not very easy to comply with in the case of a fuselage which is relatively wide at the location of the air inlets unless a long inlet duct is acceptable (Fig. 2-18). The latter is generally undesirable for reasons of space or balancing. It also costs weight and results in inlet pressure loss.
At different angles of attack variations in the direction of the incoming air should

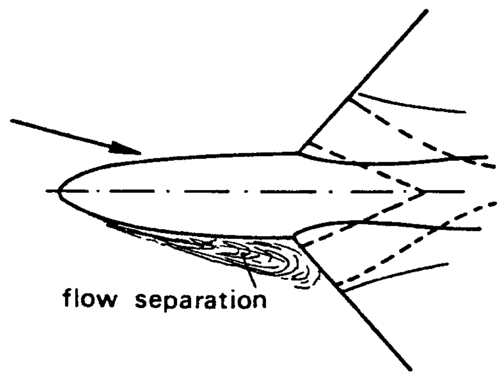


Fig. 2-19. Asymmetric intake condition in a sideslip

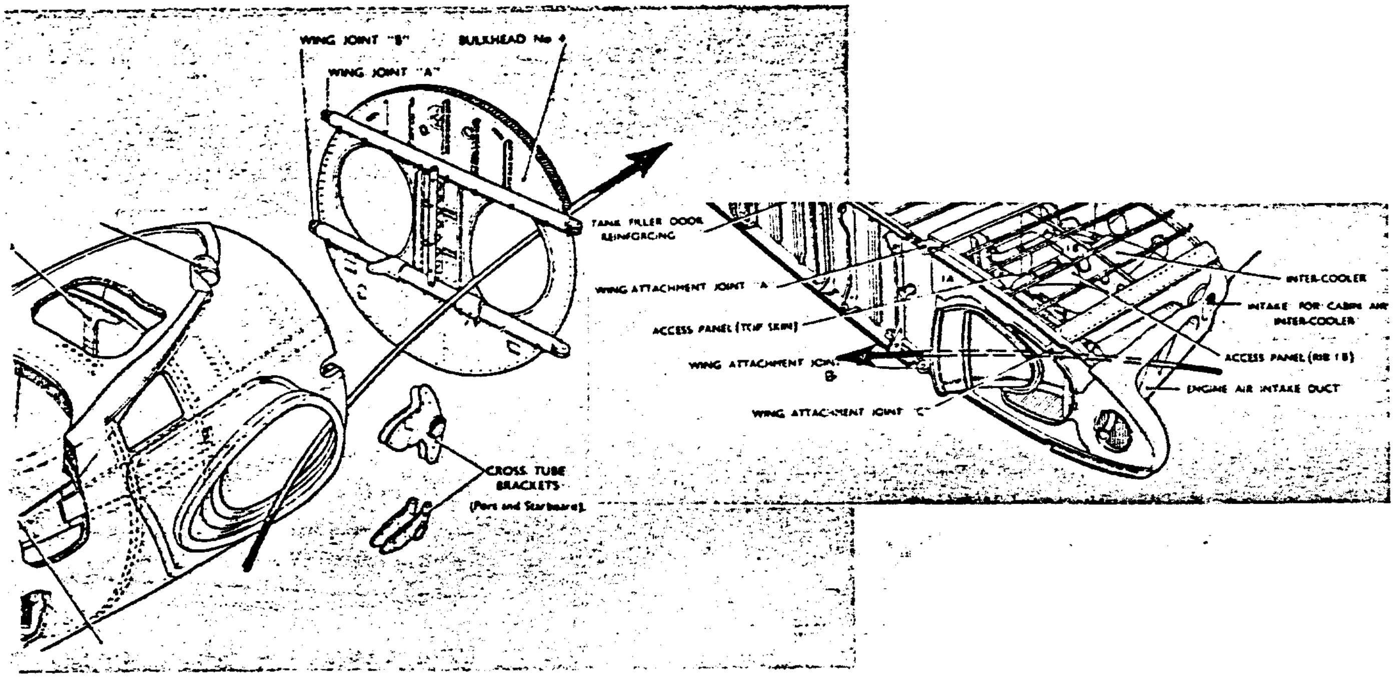


Fig. 2-20. Structural arrangement of wing-root air intake (De Havilland Vampire)

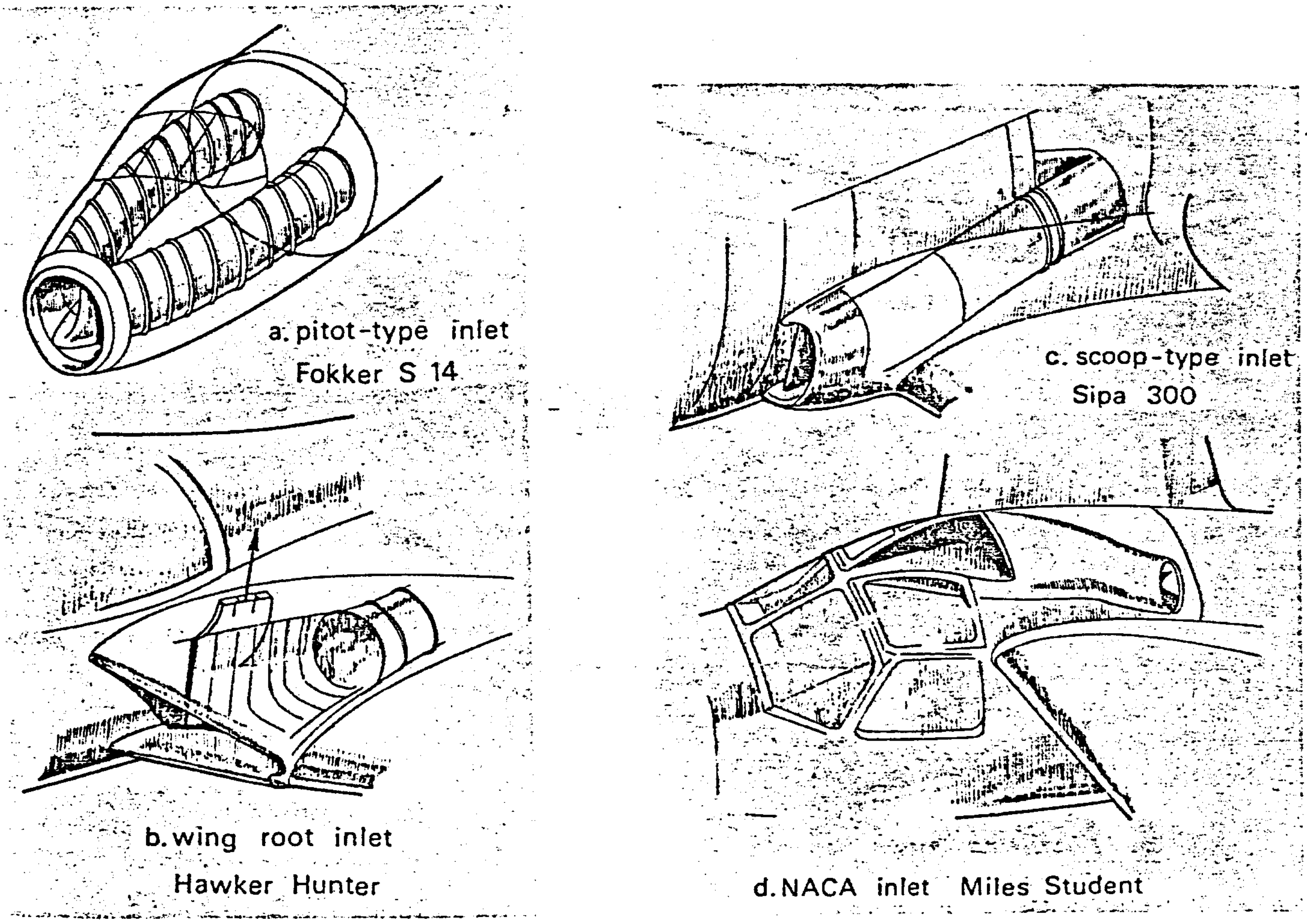
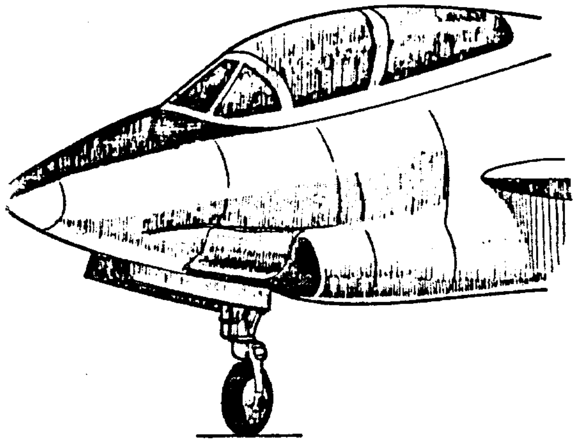
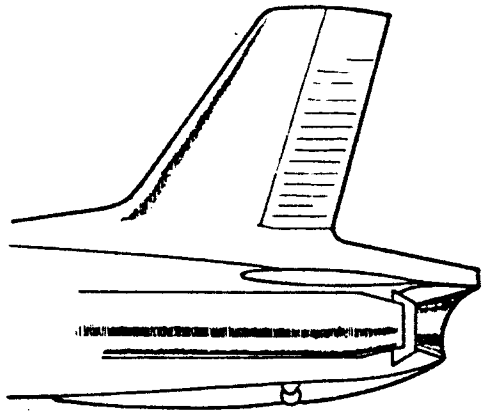


Fig. 2-21. Intakes on subsonic aircraft with engine(s) buried in the fuseIage

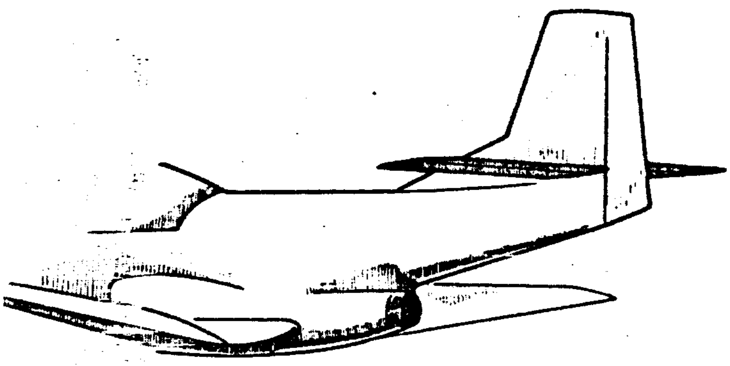


e. split scoop-type inlet
North American Rockwell
Buckeye

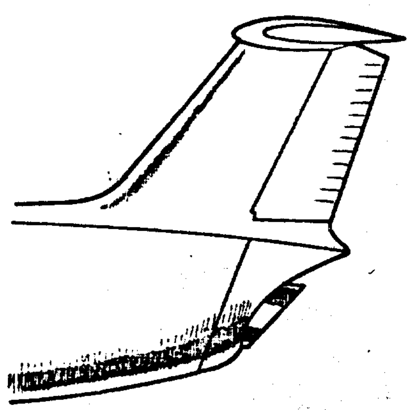
'ig. 2-21. (Concluded)



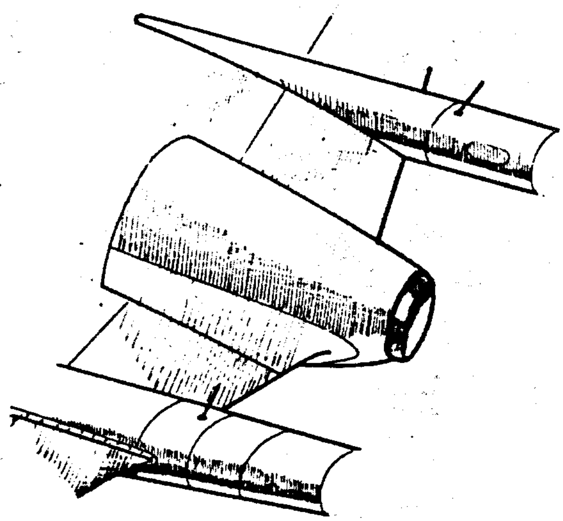
LONG EXHAUST – AERMACCHI MB 326



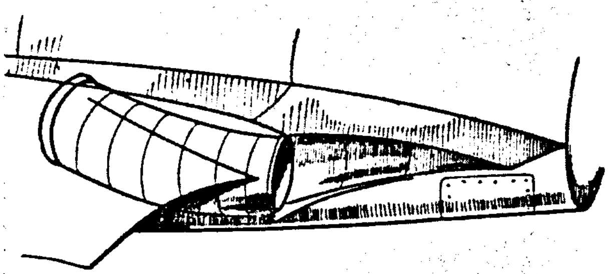
OW EXHAUST, SINGLE TAIL BOOM – SIPA 300



SHORTENED EXHAUST – L 29 DELFIN



SHORT EXHAUST PIPE
DE HAVILLAND VAMPIRE



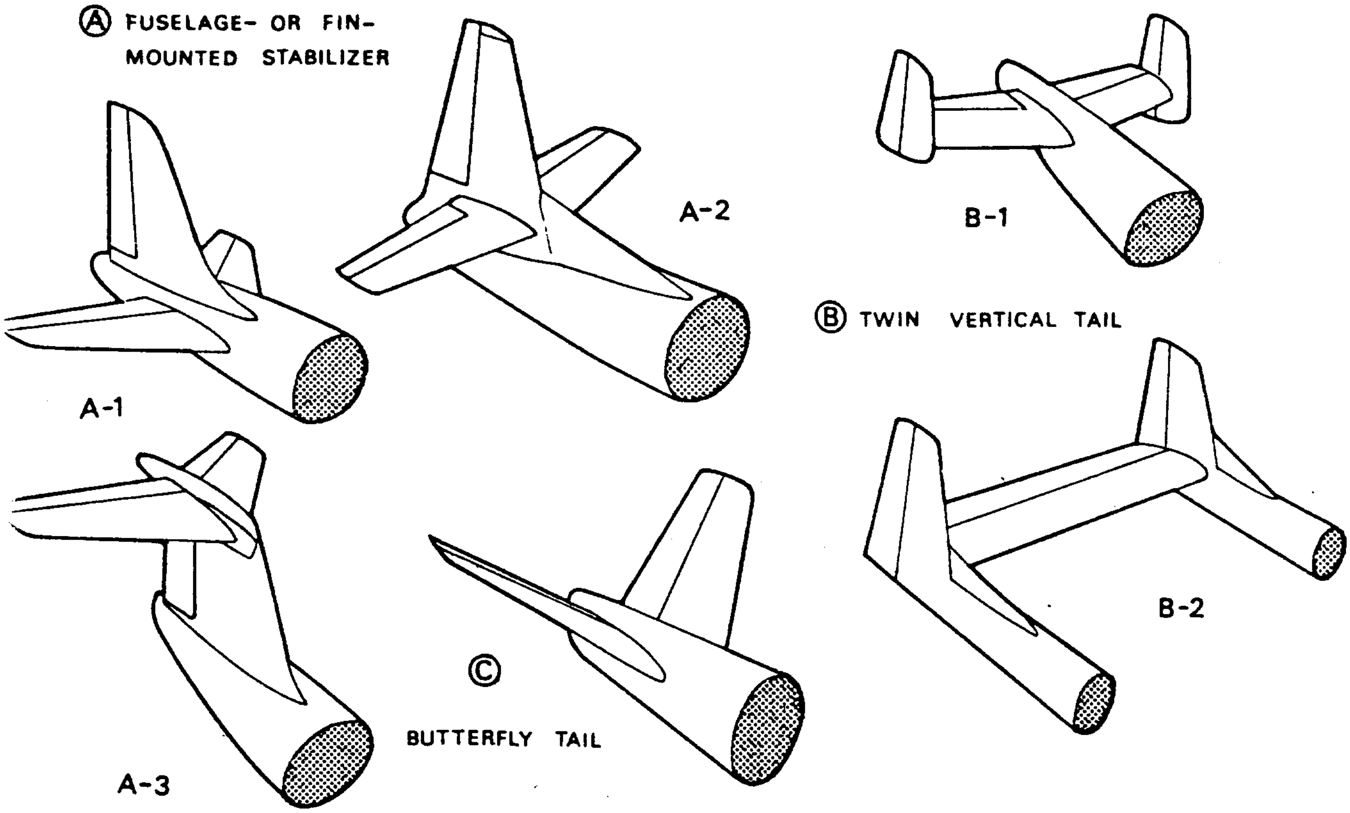
SPLIT EXHAUST – HAWKER SEA HAWK

Fig. 2-22. Exhaust locations of single-engined subsonic jet aircraft

not be excessive. The wake of the partly stalled wing must not enter the inlet duct, which means that the leading edge of the wing would be an unsuitable location unless special measures were taken. When split intakes are used, a sideslipping condition will cause dissimilar flow patterns, which may lead to unstable flow and even to air oscillating instead of entering the duct as shown in Fig. 2-19.
When the engine is installed in the fuselage, the designer has to decide whether it is desirable to continue the wing structure through the fuselage without interruption. On a highly maneuverable aircraft, designed for high normal load factors, such a continuous structure is very attractive. It will then depend upon the relative proportions of the inlet duct and the thickness of the wing whether it is feasible to lead the inlet ducts through the spar webs. Fig. 2-20 shows that this was possible in the case of the De Havilland Vampire, but in other cases it may prove desirable to lead the inlet either over or under the wing.
Fig. 2-21 shows different types of inlet which will be briefly discussed here.
The pitot type (a) provides the engine with undisturbed airflow for all flight conditions. It requires a long inlet duct, which generally will have to be divided at the level of the cockpit, and intake efficiency is low. This type is now rarely used on subsonic aircraft.
An intake in the wing-root (b) is difficult to realize as the intake opening must be able to supply the required airflow at different intake velocities and also cope with changes in the angle of attack and angle of sideslip. At the same time the local airfoil shape must not be modified more than is strictly necessary.
Side inlets on either side of the fuselage form scoops and thus cause additional drag. To keep this drag low, the airscoops must not be kept too short and must be well faired. A divertor is needed to prevent the fuselage boundary layer from entering the duct but this also adds to the drag. The inlet opening should be located sufficiently far ahead of the wing in order to avoid interference with the wing and excessive variations in the intake conditions.
An air inlet on top of the fuselage has sometimes been used in experimental aircraft and was adopted for the Miles Student. The opening has to be raised sufficiently far above the fuselage to avoid boundary layer and wake ingestion at large angles of incidence.
A split inlet at the bottom of the fuselage may be regarded in some ways as a compromise between the pitot inlet and side inlets. When measures are taken to avoid the ingestion of debris during takeoff and taxying, this layout may be particularly attractive for mid-wing and high-wing aircraft.

The exhaust nozzles should be so positioned and directed that the (hot) jet efflux will not impinge on the structure. At subsonic speeds in a parallel flow, the expanding gases of a pure jet may be assumed to expand within a cone with half the top angle equal to 6 degrees. Exhaust nozzles are manufactured from stainless steel sheet and are fairly heavy; on pure jet engines they will weigh from 1 to 1.5% of the engine weight per foot of length (3 to 5% per meter). The weight will be even greater in the case of bypass engines. Moreover, exhaust nozzles cause a thrust loss of about .3% per foot (1% per meter). They should therefore be kept as short as possible. Some examples shown in Fig. 2-22 will be discussed.

When the exhaust nozzle is located in the rear end of the fuselage, it is possible to keep the efflux away from the aircraft without having to take any special precaution. A single tail boom is sometimes adopted in order to shorten the exhaust. Another solution consists of a split exhaust with two openings on either side of the fuselage. Unfortunately, both configurations lead to structural problems, while complicated fairings must be used around the exhausts. Another way to shorten the length of the e



ig. 2-23. Classification of tailplane configurations

aust pipe is to use two tail booms. This as the added advantage that it provides xcell[illegible] accessibility to the engine.

.4. ARRANGEMENT OF THE TAILPLANE

ne design of the tail surfaces probably epends more on the general arrangement and ne detail layout of the aircraft than any ther major part. Because of their loca- ion, their effectiveness is influenced by ne wing and the operation of the engines, rticularly in the case of propeller- iven aircraft. The way in which the em- nnage is mounted to the fuselage, or pos- bly to tail booms, affects the structural yout of the tail surfaces and that of the iselage. General instructions applicable the preliminary design stage are there- re very difficult to lay down.

.4.1. Classification of tail surface con- igurations

Examples are given in Fig. 2-23 of the principal configurations seen in practice. Although there are many intermediate solutions, these will not be discussed here.

Group A: A single fin with the stabilizer mounted either on the fuselage or on the fin represents the most common current layout. It also ensures structural simplicity and stiffness, although in the case of the T-tail (A-3) attention must be devoted to preventing tailplane flutter. Aerodynamic considerations leading to this choice are discussed in Section 2.4.2.

Group B: The considerable height of a large fin will cause a rolling moment due to rudder deflection as a consequence of the large distance of the fin aerodynamic center from the longitudinal axis of the aircraft. If this is considered to be objectionable, a twin fin may be well worth investigating as a means of minimizing this effect. When twin tail booms are used (group B-2), such a layout is the fairly obvious choice.

Group C: The V- or butterfly tail is often adopted for sailplanes, with the object of avoiding damage to the tail when landing on overgrown terrain. The V-tail is sometimes also used on powered aircraft, e.g. the Fouga Magister where it served to keep the tail surface clear of the jet efflux of the engines, without having to resort to a T-tail. Another classical example is the Beechcraft Bonanza. The V-tail has never become popular, mainly because the moving surfaces have to serve both as rudders (differential deflection) and as elevators (simultaneous deflection), which leads to a complication in the control system design.

2.4.2. The location of tail surfaces

a. Jet efflux effects.

The tail surfaces must never be in the jet efflux. Assuming that the efflux of a pure jet spreads out conewise with half the top angle equal to 6 degrees, this defines a region which may be regarded as "out of bounds" so far as the tail surfaces are concerned. If necessary, the centerline of the jet efflux may be diverted a few degrees in any desired direction. Another possibility is to apply a moderate dihedral to the horizontal tailplane. It is advisable to have as great a distance as possible between the noise generating regions and the tail surfaces, since otherwise the very high intensity of the engine noise may cause acoustic fatigue in the relatively flat skin panels of the tail. Any special measures to prevent this will entail a weight penalty. A jet efflux close to the stabilizer will affect the direction of the airflow and diminish its stabilizing contribution due to the jet pumping effect.

b. Slipstream effects.

In symmetrical flight, the lift distribution of the wing with deflected flaps depends on the engine speed. The same applies to the downwash and the local velocity distribution at the tail. When the airspeed and the angle of attack are changed, the stabilizer moves in a vertical direction relative to the slipstream, which causes variations in the longitudinal stability. These depend partly on the location of the stabilizer, measured in the vertical direction. Fig. 2-24 shows

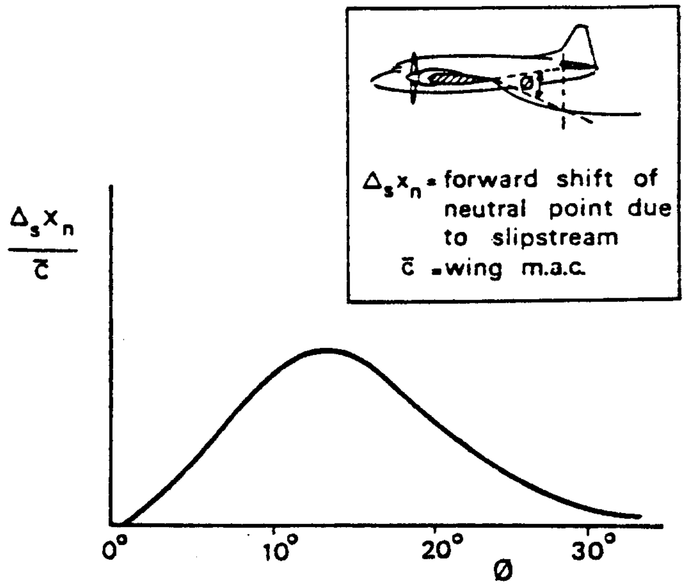


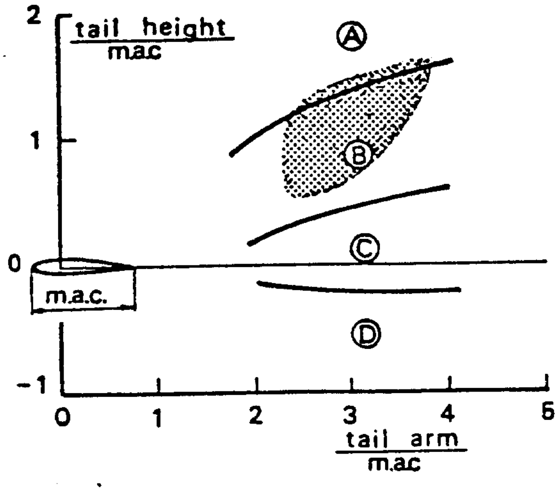
Fig. 2-24. Forward shift of the neutral point due to slipstream (Ref.: ARC R & M 2701)

that loss of static stability is small with the stabilizer placed very high or very low, but this cannot always be realised in practice. As the power to weight ratio and the maximum lift coefficient increase, the slipstream effects will also become more pronounced and generally the tail size will have to be increased.

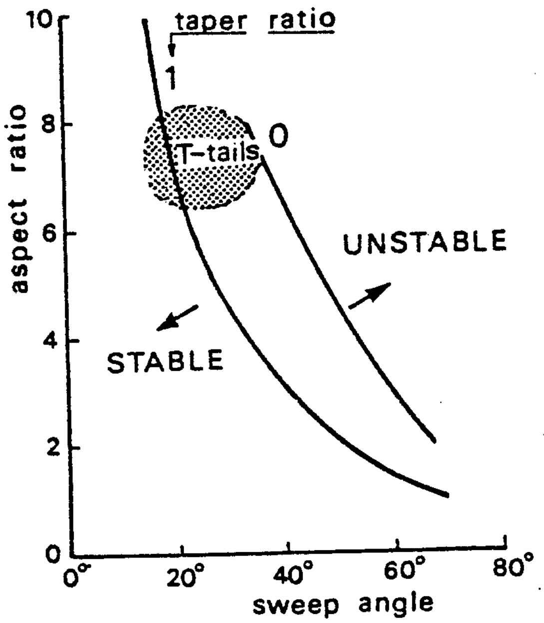
In flight with one engine inoperative there will be a yawing moment which has to be counteracted mainly by rudder deflection. There will also be a non-symmetrical lift distribution over the wing and this will cause a sidewash at the fin, effectively resulting in an increase in the yawing moment. This condition of flight provides a criterion for the size of the fin and rudder in the case where the engines are mounted on the wing.

c. Stability and control in the stall and post-stall condition.

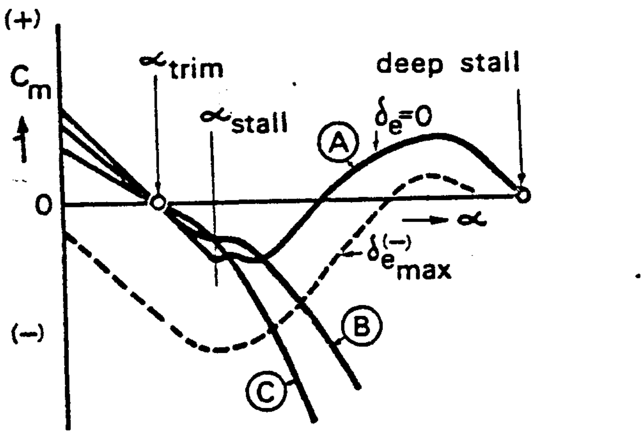
Although in normal operating conditions a wing stall is avoided by applying adequate safety margins relative to the minimum fly-



a. Regions of tailplane location, characterizing post-stall behaviour



b. Stability boundary for the wing alone



c. Post stall stability for the complete airplane

Fig. 2-25. Static stability at high angles of attack as affected by wing shape and tailplane location (Ref.: NASA TM-X-26)

able speed, a stall may be encountered occasionally. The stall speeds must be demonstrated during certification testing as they form the baseline for most performance figures in takeoff and landing. Safe recovery from a stall is therefore a requirement. The longitudinal flight characteristics are affected primarily by the "stiffness in pitch", represented by the slope of the C_m-α curve (Fig. 2-25c). A negative slope corresponds to positive static stability, while the trimmed condition is equivalent to $C_m = 0$, to be obtained by elevator and/or stabilizer deflection. The wing and horizontal tailplane are the main contributing components, the tailplane location being of prime importance. Fig. 2-25b shows combinations of wing sweep angles and aspect ratios which ensure a stable wing pitching moment slope at the stall. The stable region marked is only approximate and may be influenced by airfoil variation, wing twist, boundary layer fences, engine pylons and leading edge high-lift devices. The boundary of the stable region, as derived from windtunnel tests, indicates a reason why highly swept wings generally are of low aspect ratio. A slightly unstable wing pitch-up may be acceptable, provided the horizontal stabilizer is sufficiently effective. The effect of the vertical location of the stabilizer is illustrated in Fig. 2-25c for several cases, defined in Fig. 2-25a. In region A, which covers most T-tails, instability at large angles of incidence is generally preceded by a less pronounced instability at the stall. In region B the stabilizer only enters the wake of the wing when the latter becomes unstable. Region C does not show these phenomena at low speeds, but pitch-up may occur on maneuvering flight at high subsonic speeds. Region D is a location which may be regarded as satisfactory for all angles of incidence. This arrangement may sometimes be possible in the case of high-wing aircraft, but attention should be paid to the location of the wake, particularly whe flaps are deflected.

Most tailplanes designed for normal opera-

ting conditions will be sufficiently effective to provide stability at high angles of attack as well. However, if the wing wake is augmented by the wake of a wide fuselage and pod-mounted engines on either side of the rear fuselage tail, conditions may exist such that a T-tail aircraft encounters extended regions of post-stall instability. At very high angles of attack the tailplane contribution to longitudinal stability will be reduced to 10-20% of its normal value. At angles of attack between 30 and 40 degrees the tailplane itself stalls and the slope of the C_m-α curve is once more reversed into a stable one. At $C_m = 0$ the aircraft is trimmed in a "deep stall". In that condition the pitching moment due to elevator deflection may be insufficient to restore the normal attitude and the airplane is locked in this condition. A very fast descent at low forward speed is unavoidable and recovery from it is very doubtful. There are various methods of curing such unacceptable behavior, e.g. increasing the tailplane span and modifying the wing shape. For added safety a stick shaker can be installed to warn the pilot at a preset angle of attack, while a stick pusher is frequently used to force the steering column forward when the stalling angle of attack is approached.
Adoption of a T-tail does not necessarily face the designer with disadvantages only.

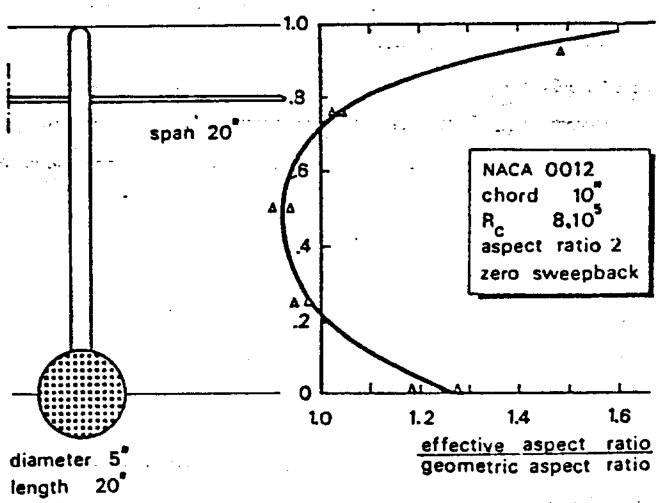


Fig. 2-26. Effective aspect ratio of the fin in combination with a horizontal tailplane (Ref.: NACA TN 2907)

Fig. 2-26 shows that placing one tail surface at the tip of another leads to an increase of about 50 percent in the aerodynamic aspect ratio, so that the stabilizer may increase the lift curve slope of the fin by roughly 15 percent. A similar improvement in the effectiveness of the horizontal stabilizer may be obtained by the use of two fins at the tips. Another point is that the downwash at moderate angles of incidence decreases with increased verticality of the stabilizer, which in the case of a T-tail may sometimes justify reducing the area. The same effect is achieved by placing the stabilizer on top of a sweptback fin, thus increasing its moment arm.

d. Recovery from spins.

In the case of aircraft designed for aerobatics (e.g. trainers), recovery from a spin must be possible. In small aircraft this involves use of the rudder, which must therefore be effective even at very large angles of incidence. It will be seen from Fig. 2-27 that the indicated location of

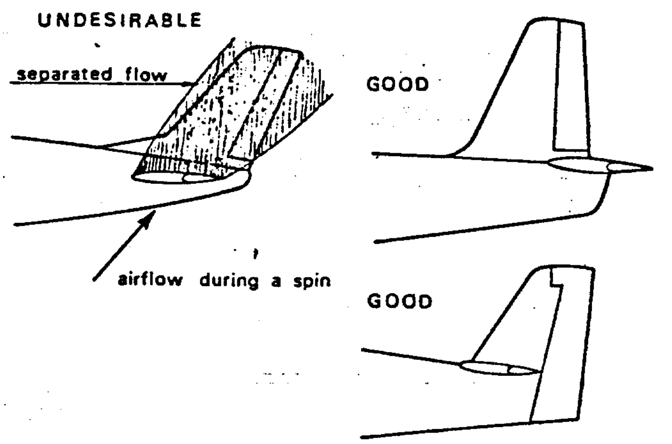
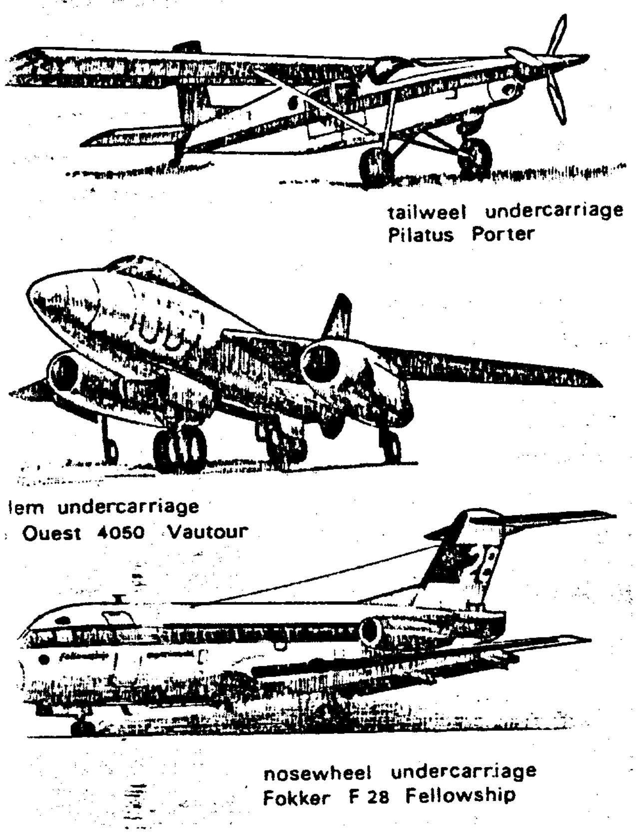


Fig. 2-27. Effectiveness of the rudder during a spin

the stabilizer will cause the greater part of the rudder to be shielded. Some layouts for avoiding this are indicated. V-tails and fins at the tips of the stabilizer are favorable in this respect.

2.5. ARRANGEMENT OF THE UNDERCARRIAGE

arious configurations for the undercar-iage have been adopted in the past, but any of them were designed for special pur-ɔses. Only three of these need be dis-ıssed in the present context. The discus-on is further amplified by Fig. 2-28 and fs. 2-35 through 2-38.



g. 2-28. Undercarriage configurations

5.1. Tailwheel undercarriage

though this type of undercarriage was in ıeral use during the first three decades aviation, it must now be regarded as ob-ete for most designs. Its advantages ould nevertheless be mentioned:
The tailwheel is small, light and simple design.
The location of the main gear legs makes achment to the wings an easy matter.
A three-point landing can be carried out bringing the aircraft to a stalled con-tion. The aerodynamic drag will provide a etarding force, which is particularly needed when the airfield is unsuitable for full application of brakes (e.g. wet grass).
d. When brakes are applied the vertical load on the main gear will increase, thereby reducing the risk of skidding.

The reason why the tailwheel undercarriage has been almost completely superseded by the nosewheel or tricycle gear is that it also possesses the following drawbacks:
a. Violent braking tends to tip the aircraft onto its nose.
b. The braking force acts ahead of the center of gravity and thus has a destabilising effect when the aircraft is moving at an angle of yaw relative to its track. This may cause a ground loop.
c. In a two-point landing a tail-down moment will be created by the impact force on the main landing gear, resulting in an increase in lift which makes the aircraft bounce.
d. The attitude of the wing makes taxying difficult in a strong wind.
e. In the case of transport aircraft the inclined cabin floor will be uncomfortable for the passengers and inconvenient for loading and unloading.
f. In the tail-down attitude the inclination of the fuselage will limit the pilot's view over the nose of the aircraft.
g. During the initial takeoff run drag is high until the tail can be raised.
In some designs it is possible to circumvent some of these disadvantages at least partly. Interconnection of the tailwheel and the rudder control provides a simple means to control the aircraft on the ground.

2.5.2. Nosewheel undercarriage

The merits and drawbacks of the nosewheel gear are roughly the opposite of those of the tailwheel type. The principal advantages are:
a. The braking forces act behind the c.g. and have a stabilizing effect, thus enabling the pilot to make full use of the brakes.
b. With the aircraft on the ground, the

fuselage and consequently the cabin floor are practically level.

c. The pilot's view is good.

d. The nosewheel is a safeguard against the aircraft turning over and so protects the propeller(s) when used.

e. During the initial part of the takeoff the drag is low.

f. In a two-point landing the main gear creates a nosedown pitching moment.

The steady increase in landing speeds of modern aircraft has accentuated these advantages, so that they carry more weight than the following disadvantages:

a. The nose unit must take 20 to 30% of the aircraft's weight in a steady braked condition and it is therefore relatively heavy.

b. The landing gear will probably have to be fitted at a location where special structural provisions will be required. In the case of a retractable nosegear on light aircraft it may also prove difficult to find stowage space inside the external contours of the aircraft.

Although there is still a measure of choice during the preliminary design stage, this constitutes one of the most difficult problems to be solved.

Summing up, we may state that the nosewheel undercarriage has gained favor because it greatly facilitates the landing maneuver and enables the brakes to be used more efficiently.

2.5.3. Tandem undercarriage

Here the main wheels are arranged practically in the plane of symmetry of the aircraft and the front and rear wheels absorb landing impact forces of the same magnitude. Use of the tandem gear is justified when much emphasis has to be placed on the following advantages:

a. Both main legs are placed at nearly equal distances ahead of and behind the center of gravity, thus locally creating space for payload close to it.

b. The wheels may be retracted inside the fuselage without interrupting the wing structure. The increase if any in fuselage weight will depend on other factors.

Against these we have to set the following disadvantages:

a. Outrigger wheels will be required to stabilize the aircraft on the ground and these may increase the all-up weight by approximately 1%. However, by using two pairs of main legs instead of single ones, a certain amount of track may be obtained, resulting in a reduction of the load on the outriggers (Boeing B-52).

b. The pilot must carefully maintain the proper touchdown attitude in order to avoid overstraining the gear. Care has also to be taken to limit the angle of bank during the landing to avoid overstraining the outriggers. It may sometimes be possible to locate the rear legs close to the center of gravity of the aircraft, and so reduce this disadvantage, but that also means losing the opportunity to have an unobstructed space.

c. A large tail download is required to rotate the aircraft. It will therefore be desirable to chose the attitude of the aircraft at rest so that it will fly itself off, but this may lead either to an increase in drag during the takeoff roll or to a high liftoff speed.

Generally speaking, the arguments against the tandem gear are of such a nature that its adoption should only be considered when no other solution meets the case.

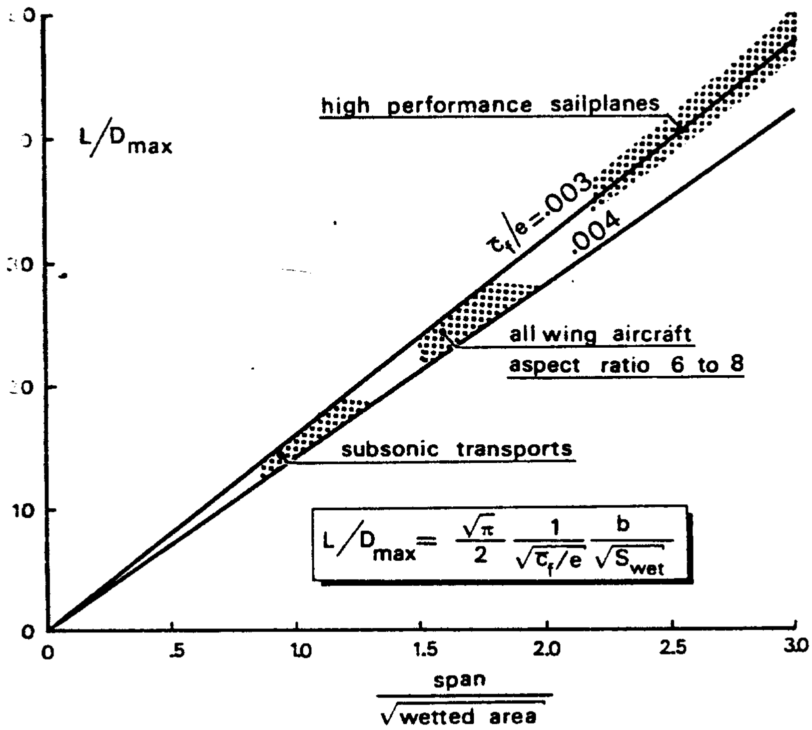
2.6. SOME UNCONVENTIONAL AIRCRAFT CONFIGURATIONS

The characteristics of different general arrangements discussed in the preceding sections mainly apply to the classic airplane layout for which a clear distinction can be made between lifting, nonlifting and stabilizing major components. It was assumed that the tailplane was mounted at the rear of the aircraft. The payload is carried inside the fuselage while the fuel is mainly stored in the wings and, if

necessary, the fuselage. The fuselage is basically designed for optimum transport and rapid loading and unloading, and contributes little to the lift.
ᐠ radical departure from the classic lay-ut is the integrated configuration of hich the flying wing is the purest repreentative. The wing is designed to produce ift as well as to contain the entire payoad while it also provides stability and ontrol. Less radical is the tailless airaft which does have a fuselage but no orizontal tail surfaces. A third unusual ayout is the tail-first or canard.
hen the choice of one of these types is onsidered, there have to be obvious points hich indicate that materially better perormance, a considerably lighter structure r improved flying qualities will be ahieved. For example, the flying wing layut would most probably be considered only n the case of a sailplane or a long-range ircraft, both of which make full use of he potential improvement in lift drag raio. Practical experience with this type ndicates that a new design will require tensive research before a reliable prodct can be put on the market. Many examples llustrating this point are known in the istory of aviation.

2.6.1. The flying wing

During the period around the Second World War, several designers in various countries regarded the flying wing as the ideal layout, promising large reductions in drag and structure weight. They included A. Lippisch and the Horten brothers in Germany, J.K. Northrop in the U.S.A. and G.H. Lee in Great Britain. Round about 1965 Lee attempted to draw attention to a flying wing design for a short-haul airliner (Fig. 2-30, Ref. 2-45).
Since a pure flying wing possesses no fuselage and no horizontal tail surface, it may be possible to achieve a very low zero-lift drag coefficient. This may be of the order of .008 to .011 as compared to .015 to .020 for conventional aircraft. The maximum lift/drag ratio being inversely proportional to the square root of this figure, a theoretical improvement of about 40% may be obtained for a given aspect ratio (Fig. 2-29). Assuming similar fuel weights, takeoff weights and cruising speeds, the same improvement applies to the range. Alternatively, this gain may be taken in the form of a reduction in fuel consumption, engine power and takeoff weight for a specified payload and range.



b = wing span
$\bar{c}_f$ = mean skin friction coefficient, based on S_{wet}
e = Oswald's span efficiency factor
S_{wet} = total airplane wetted area
D = drag
L = lift

Fig. 2-29. Maximum lift/drag ratio at subsonic speeds

The empty weight of the flying wing could be less, mainly as a result of the favorable mass distribution within the wing, which reduces the bending moment at the root. Supposing the mass to be distributed along the span in a similar manner to the lift, it would even be theoretically possible to reduce the bending moment to zero in 1-g flight. Hence the bending moment will predominate in the landing and the torsion moments in flight and a large part of the wing structure will be designed on the basis of stiffness requirements. By and large, a reduction in structure weight relative to the conventional layout is likely to be possible. To ensure stability in a trimmed condition, the following requirements must be fulfilled:

a. The aerodynamic pitching moment at zero lift and zero control deflection must be positive (i.e. nose-up). This condition can be met by using a special wing section with a bent-up trailing edge or a sweptback wing with washout at the tip, or aileron deflection. Both measures tend to increase the vortex-induced drag.

b. The center of gravity must be ahead of the aerodynamic center, but this condition is difficult to fulfill in the case of a straight wing, as it implies that the entire load must be concentrated in the forward part of the wing. With a sweptback wing there is less trouble, first because the aerodynamic center is situated further back and second because more space is available in the plane of symmetry ahead of it.

A high aspect ratio sweptback wing is longitudinally unstable at large angles of incidence (Fig. 2-25b). In the case of a flying wing this instability cannot be corrected by means of a horizontal tailplane and a high aspect ratio is therefore detrimental to stability. Consequently, part of the aerodynamic gain is lost and in the case of Lee's flying wing (Fig. 2-30) its aerodynamic superiority over the conventional layout has largely disappeared.

A low aspect ratio wing enables the design-

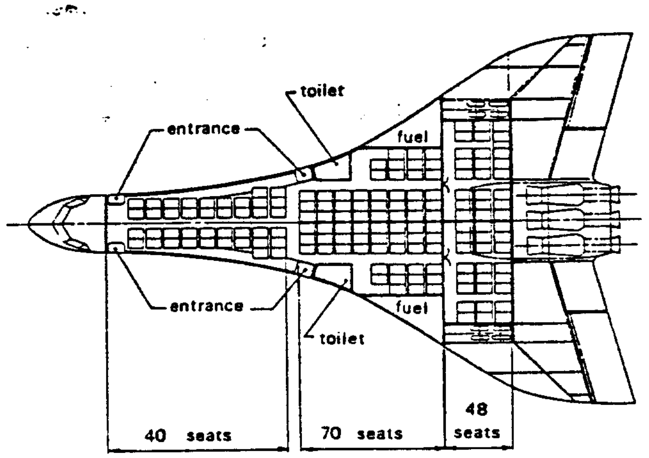


Fig. 2-30. Proposal for a short-range all-wing aircraft

er to get a sufficiently thick wing to accommodate the load to be carried. In addition to comparing a conventional aircraft and a flying wing on the basis of equal aspect ratios, we can also do so on that of equal volumes. With a given payload density an optimum design will generally be one in which the space within the external contours is fully utilized. For equal volumes both configurations have roughly the same wetted area and the flying wing can only gain through a greater span and the use of buried engines, creating less drag. Another drawback of the flying wing is that it is incapable of achieving a high maximum lift coefficient. Effective flaps at the trailing edge cause a nose-down pitching moment which cannot be trimmed. A low wing loading is not just a secondary effect here but an absolute must. However, high load factors in turbulent air will be the inevitable result; these will be objectionable less from the structural viewpoint than from that of the occupant's comfort and the pilot's workload. The flying wing can be made longitudinally stable but its response to control surfaces deflections and bumps will always be accompanied by a poorly damped phugoid and an oscillatory short period motion, both annoying characteristics to the pilot, although this might be improved by some form of artificial stability augmentation.

It should finally be pointed out that the loading flexibility of the flying wing is not very good, particularly in the case of a low-density payload. Loading restrictions will be necessary with respect to both the longitudinal and the lateral position, which is an undesirable factor in the operation of transport aircraft. Moreover, the shape of the flying wing is far from that of an efficient pressure vessel and incorporation of a pressure cabin might well lead to a considerable increase in structure weight. Further development to increase the payload is not feasible as the stretch potential of the flying wing is almost nil.

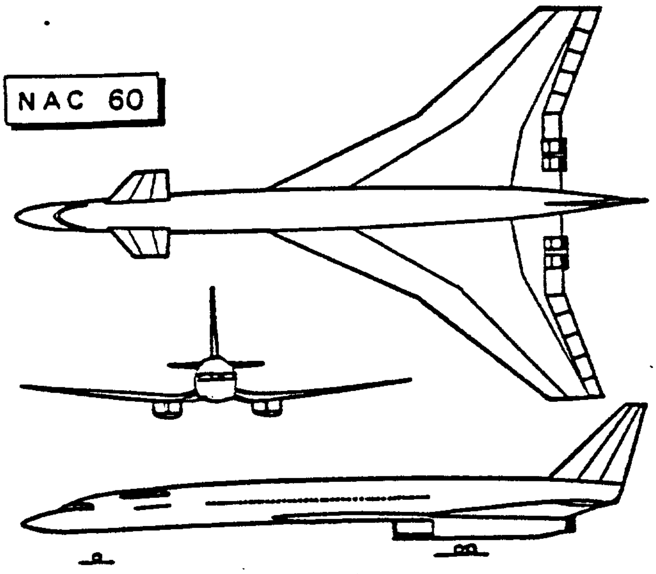
Summing up the case for the flying wing, we may say that this configuration is potentially capable of reaching a high lift to drag ratio with a low structure weight but the flying and operational characteristics are troublemakers. Since the control function is integrated in the wing, there will be additional trim drag. As a passenger transport aircraft the flying wing does not appear to be a suitable proposition but it may be considered for special purposes, such as sailplanes, long-distance reconnaissance or very large, special-purpose cargo aircraft.

2.6.2. Tailless aircraft

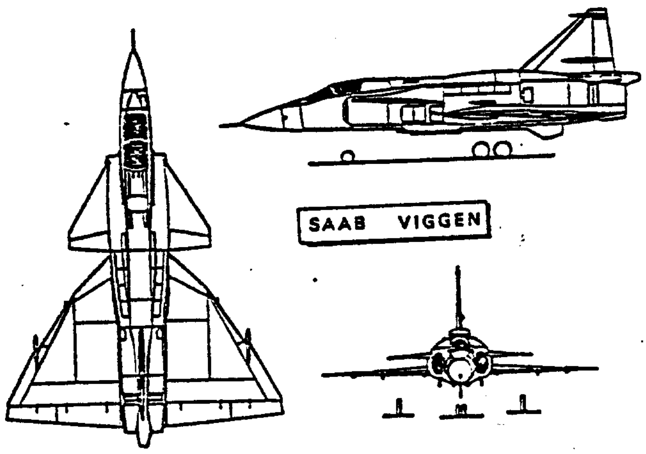
Although the flying wing and the tailless aircraft share the characteristic of not possessing a horizontal tailplane, the latter type has a conventional fuselage which carries a large part of the load. The tail of the fuselage is relatively short and carries only a vertical tail surface. The tailless aircraft is generally designed for supersonic speeds and utilises a slender delta wing. The movable parts at the trailing edge act as elevators when deflected in the same direction and as ailerons when deflected in different directions. Like the flying wing the tailless aircraft is unable to carry effective landing flaps and sufficient lift for landing is obtained by choosing a low aspect ratio wing of large area, resulting in large approach angles. Some of the disadvantages mentioned in connection with the flying wing also apply to this type, although they generally weigh less heavily on account of the lower aspect ratio and larger mean chord.
Since the tailless delta is of a much less radical nature than the flying wing, various successful aircraft have been built to this formula and have reached series production. The best known are: Avro Vulcan (almost a flying wing, Fig. 2-12), Convair B-58, Convair F-102, Lockheed YF-12A, Douglas F-4D, Dassault Mirage, SAAB Draken and the BAC-SUD Concorde. These aircraft all operate in the transonic or supersonic speed region, the tailless delta being one of the best configurations for supersonic cruise. Ref. 2-44 gives general information concerning the design of such aircraft.

2.6.3. Tail-first or canard aircraft

Canard aircraft have attracted the interest of designers from time to time on account of several particular characteristics. After all, the Wright brothers' aircraft was a canard and it appears an attractive idea to place the longitudinal control surface in front of the wing and out of the wing downwash to where it can never be in its wake. The aircraft's equilibrium is preserved by means of an upward force on the forward plane, which contributes to the lift in a positive sense. In contrast to the conventional layout, this will increase maximum lift and reduce the trim drag, a characteristic which is of particular advantage in the case of high-speed, highly maneuverable aircraft.
A distinction can be made between a long-coupled and a close-coupled canard (Fig. 2-31). In the former category emphasis is laid on the reduction of drag in cruising flight, which is obtained by placing the forward plane far ahead of the wing, thereby reducing the mutual interference. Dynamic stability may be assured by keeping the area of the forward plane below 10% of that of the mainplane. Design problems re-



a. Long-coupled canard (North American design for an SST, 1964)



b. Short-coupled canard

Fig. 2-31. Tail-first airplane configurations

lating to this configuration are:

a. To achieve an acceptable range for the center of gravity, the forward plane has to be capable of producing a higher maximum lift coefficient than the main wing. Generally speaking, this can only be achieved when the main wing possesses a low aspect ratio. The forward plane has to be provided with a sophisticated flap system.

b. The trailing vortices of the forward plane affect the flow over the wing and will set up a rolling moment in a sideslip. The vortices may also strike the fin.

In the case of the short-coupled canard the mutual interference between the two planes is deliberately used to achieve a high maximum lift. This effect is obtained at large angles of attack on surfaces of low aspect ratio with sharply sweptback leading edges. The large drag which now occurs will only be acceptable for aircraft with sufficiently powerful engines.

In short, the canard layout appears to be suitable for transonic or supersonic and highly maneuverable aircraft, in the latter case if sufficient thrust reserve is available.