HIGH PERFORMANCE SUPERSONIC AIRCRAFT INTAKE DESIGN

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Summary.

The intake of a supersonic passenger aircraft is one of the key components affecting both performance and economy. This paper discusses problems encountered by designers in optimising an intake, which is required to supply the correct amount of air mass flow to the face of the compressor with desired velocity for a wide range of speeds, altitudes and aircraft thrust requirements. This includes the sizing for the cruise and the system adopted to enable stable operation, including the provision of auxiliary doors and moveable ramps.

Engine location is of importance since it has implication for aircraft safety. Under some circumstances an engine shut down may influence the stability of the shock wave pattern at the intake of an adjacent engine. This could lead to shut down of the adjacent engine.

Future generation supersonic passenger aircraft will need to be very fuel efficient and will have to demonstrate an extremely good safety record. The intake design plays an important role in achieving these objectives.

1.0 Introduction.

The intake is an integral component of the propulsion system, by means of which the gas turbine engine is supplied with air taken from the atmosphere. The intake is designed to capture the correct amount of air mass flow required by the engine, also to supply the flow to the face of the compressor with the desired velocity, and to ensure that the air approaches the face of the compressor uniformly at the appropriate angle of incidence. All this has to be accomplished for a wide range of speeds, altitudes and aircraft thrust requirements. A supersonic power plant generates the thrust required to take-off from sea level, subsonic climb, subsonic and transonic acceleration and to sustain supersonic cruise. The engine can only produce desired thrust if the intake is correctly matched to the engine needs.

The air mass flow requirement varies across the entire flight spectrum. Therefore, the intake must be able to adjust the airflow accordingly. An intake needs to be able to handle air over a range of velocities, altitudes and the aircraft thrust requirements. Early supersonic intakes were of fixed geometry. These were unable to give a stable operation outside a limited flight envelope, not always able to cope with for example excessive incidence as in a high g manoeuvre. For that reason high performance as discussed in this paper is taken to mean that the intake incorporates some mechanical features such as variable geometry, which extend its operational flight envelope, ie forward speeds, altitudes and incidence.

The above is true for both civil and military aircraft. However the civil designer has a priority to ensure most economic operation and is therefore seeking fuel efficiency. The military designer in addition to the fuel economy demands a much larger flight envelope and high agility. See figure 8 on page 11.

For optimum operation, airflow leaving the intake is required to reach the engine face with optimum level of pressure, temperature and velocity. These properties are essential for good performance and stability of the engine operation.

Disturbance in the airflow upstream of the intake may have a significant influence on the ability of the intake to achieve this. Care is needed to be taken in siting the intake in relation to those parts of the fuselage which may be ahead of the intake or in relation to a fore plane if fitted. At take-off the proximity of the runway may be needed to be of significance.

The designer's task is to provide an intake which satisfies the engine requirements for all operational needs, taking into account all constraints.

2.0 Design.

The actual design decision for supersonic aircraft is taken from the aircraft design specification. Military aircraft are designed normally with one or two engines and which are normally integrated within the airframe. Combat Aircraft are designed with a high angle of attack compatibility and should have high manoeuvrability. They are normally sized for high subsonic speed and to give maximum acceleration during the transonic phase. Combat Aircraft are designed with a larger flight envelope than the civil aircraft. For the purpose of civil use, aircraft are normally designed with four engines, but it may be reduced to two engines in future. High manoeuvrability and high angles of attack are not needed and the intakes are normally sized for the supersonic cruise condition. The flight envelope is much more restricted than for military aircraft. This is because the aircraft must operate with maximum economy.

The principal aspects of high performance intake design are its size, shape, compression ramps, sharp lips for shock wave stabilisation and control of the aircraft boundary layers. Many other components have to be carefully designed so the correct amount of air mass flow is delivered to the face of the compressor with the desired velocity over a wide range of aircraft speeds, altitudes and the aircraft thrust requirements.

Figure 3 on page 8 clearly illustrates the intake and its component parts for a typical civil supersonic aircraft.

2.1 Intake Size. Normally supersonic intakes are sized for the cruise condition, but with emphasis on the maximum acceleration during the take-off from sea level and subsonic climbs. A supersonic intake has to cope with the engine airflow demand over the required flight envelop, see figure 8 on page 11. All supersonic aircraft have to fly at subsonic speed, therefore the intake must be able to handle flow at subsonic speed, this includes take-off from sea level, subsonic climb, subsonic cruise, descent, land and taxi. In addition to sizing the intake for engine demand allowance should be made for boundary layer control, environmental control and the engine cooling system.

An intake sized for subsonic operation will be too large for the cruise condition and therefore will generate excess drag. The designers therefore have to seek a compromise which balances the needs to provide the airflow without a large drag penalty. For high performance it is essential that a variable geometry solution is employed to handle a wide variation in air mass flow requirements and variation in flight speed.

The final design is a compromise taking into account these requirements.

2.2 Intake Shape. Apart from specialist

aircraft, the modern supersonic intake has a two-dimensional configuration. Probably the most important devolvement of Two-dimensional intake shape is incorporation of horizontally mounted compression ramps. This offers very good performance with high efficiency, because of the variable geometry. After extensive research, designers came to the conclusion that it is the best shape for a supersonic civil jet. This is because it can be mounted externally to the airframe, which makes it easier to access the propulsion system for the purpose of maintenance. It can also generate a greater number of inclined shock waves, followed by a normal shock, boundary layers can easily be controlled and it offers variable geometry. See figure 1 on page 7.

2.3 Auxiliary Doors. A typical supersonic civil jet is designed for the cruise condition. During the take-off from the sea level and subsonic climb the engine demands a higher air mass flow than the cruise, to meet this requirement, auxiliary doors are provided which in effect increase the intake capture area. These doors are opened inwards to admit part of the engine airflow demand, during take-off from sea level and acceleration to a supersonic cruise. The air is required to be sucked in when the pressure within the inlet is less than the outside pressure. The pressure within the inlet is low when the aircraft is flying at low speed, which occurs at take-off, landing and subsonic acceleration. During these manoeuvres the auxiliary doors are opened inwards to admit the extra air mass flow. The auxiliary doors are usually mounted at the side or bottom of the intake structure and do not affect the thickness of the intake walls. For a typical civil aircraft the auxiliary doors are operated by the hydraulic system. In the use of the Concorde these doors are fully opened up at Mach 0.35 and progressively close to the fully shut position at Mach 0.7. At the speed above Mach 0.7 the pressure within the intake is higher than the external pressure. The auxiliary doors remain closed until the external pressure is less than the internal pressure.

Figure 4, 5 & 6 on page 9 clearly illustrates the application and use of auxiliary doors.

2.4 Variable Geometry Intake. Variable geometry is used in the design to accommodate the large variation of engine airflow requirements across the entire flight envelope. The variable geometry solution helps to reduce the loss in total pressure, especially across the supersonic region of the flight envelope. Total pressure loss is undesirable since it reduces the intake efficiency and hence gives rise to an increase in the engine specific fuel consumption. Variable geometry is employed to give maximum economy of operation.

For the two-dimensional intake shape as used in the design of a typical civil supersonic jet, the variable geometry is achieved by using two ramps which can move up and down to vary the cross-sectional shape of the intake when required. Both ramps are mounted at the roof of the intake, with the forward ramp hinged at the leading edge and the rear ramp at the trailing edge. Both ramps are mechanically linked with a torque tube in a manner that makes them move in unison.

Figure 4 & 5 On page 9 clearly illustrates the use of variable geometry.

2.5 Subsonic Diffuser (Duct). After the air decelerates through the inclined shock waves and the final normal shock, a further slow down of the flow is required, to Mach 0.35 - Mach 0.55, which is acceptable to the engine face. This section of the intake is known as the subsonic diffuser or duct. In this part of the intake the cross-sectional area increases, as it here that the duct changes to fit the circular section of the engine.

2.6 Shock Waves. Supersonic flow approaching an intake may be decelerated via a single normal shock, as in a Pitot type intake. This will generate a loss in total pressure, which increases greatly with an increase in Mach Number. See figure 9 on page 11. A large total pressure loss is undesirable, because it reduces the intake efficiency and hence increases the engine specific fuel consumption.

More efficient compression is achieved by allowing the air to pass through a series of inclined shock waves, followed by a normal shock. Following the normal shock the air flow is subsonic. Shock waves are normally stabilized at the leading edges or wedges of the intake.

Clearly the greater number of the inclined shock waves the more efficient the compression process. However, this will result in more complex and a heavier intake. The designer needs to trade off higher compression efficiency with the increase in intake weight.

In case of the Concorde a three-shock system was felt to be satisfactory. See figure 5 on page 9.

2.7 Aircraft Boundary Layers. Boundary layers are very slow moving layers of air immediately adjacent to the surface of the fuselage. They contain relatively low kinetic energy. Boundary layers are undesirable because they reduce the rise in total pressure.

Boundary layers are prevented from entering to the intake by means of bleeds or diverters. The term 'bleed' denotes a separate duct leading the boundary layer away from the intake. The term 'diverter' implies that the intake stands off from a particular surface allowing the boundary layer to escape through an intermediate channel. The bleed or diverter system used to control the aircraft boundary layers is dependent upon the intake location.

In the design of the F-16 (Supersonic Combat Aircraft), the diverter system is used to prevent the fuselage boundary layer from entering to the intake. See figure 2 on page 7.

2.8 Intake Boundary Layers. As the airflow enters the intake, boundary layers forms on the internal surface of the duct. The internal boundary layers interact with the intake shock waves and create further difficulties.

The internal boundary layers are thinned down through the gaps between the compression ramps and through the perforation on the second moveable ramp. The internal boundary layers are expelled through the louvres above the intake.

3.0 Performance of the Concorde intake across the entire flight envelope.

3.1 Behaviour of the intake during Take-off. The intake is designed and sized for the cruise condition. At take-off the engine airflow requirement is much greater. Therefore, the auxiliary doors are fully opened to admit the extra airflow to meet the engine demands. During this flight mode the internal ramps are adjusted to maximise the intake efficiency. See figure 4 on page 9.

3.2 Behaviour of the intake during Supersonic Cruise. This is the design point condition and the aircraft operates with maximum efficiency, and except under emergency condition the aircraft flies at its design Mach Number. During this flight mode the aircraft requires less thrust than at take-off. The auxiliary doors are now fully closed and internal ramps are adjusted to provide a configuration which will optimise pressure recovery. See figure 5 on page 9.

3.3 Behaviour of the intake during Landing. During landing the Concorde intake operates in the subsonic flight mode. The aircraft decelerates to the minimum wing borne speed.

The internal ramps are adjusted to maximise the intake flow and the auxiliary doors are fully opened to admit extra flow to meet the engine demands.

It is necessary for the aircraft to approach and land at high angle of attack, for this reason the undercarriage legs are long and its makes the landing manoeuvre more difficult than the conventional aircraft.

At touch down reverse thrust is selected, in order to reduce the forward speed and to stop within the distance available on the runway. Reverse thrust is automatically cancelled when the forward speed is 60 knots. At speeds below 60 knots the reverse thrust may damage the engine and the runway. See figure 4 on page 9.

3.4 Behaviour of the Concorde intake during an emergency engine shut down. If an emergency arises, it is essential to reduce and eventually stop engine rotation. When an engine is shut down, it is necessary to divert the air entering the intake, whilst maintaining the stability of the shock wave systems. The airflow may be diverted to the free stream by opening the auxiliary doors outwards. This is the only method can be used to maintain a stable shock wave pattern at the intake lips. The shock wave pattern must not be destroyed. Maintenance of a stable flow and shock wave system is vital to preserving the stability of flow in an adjacent engine intake. The Concorde is able to fly with two engines, at lower altitudes and with subsonic speed. This allows it to return to the departure point, proceed to the nearest airfield or continue to the destination. The appropriate decision is taken by the pilot based on the fuel reserves, distance travelled and distance to the destination. See figure 6 on page 9.

4.0 Influence of power plant location.

The first supersonic civil jet was to fly the Tupolev Tu-144, which was designed and manufactured in Russia. This aircraft is powered by four engines, all four of which are mounted under the fuselage in a block.

The advantage of this type of configuration is lower drag. Lighter wings and the thrust line along the centre of the aircraft.

The disadvantage is poor accessibility for the purpose of maintenance and servicing of the engines, this is because it is practically impossible to access the middle engines without removing the side engines. As a result the engine maintenance during the service life becomes very expensive.

The most important and major disadvantage is the safety problem. A major incident involving a subsonic aircraft is reported worlds wide. The publicity concerning one involving a supersonic aircraft could possibly result in permanent grounding of the aircraft.

If any engine in an array of four ceased to operate, the stability of the shock wave system on all four intakes would be threatened. This could lead to shut down of all engines.

Probably the best compromise solution is the Concorde layout. The twin engine arrangement makes it possible for the integrity of the intake shock wave system to be maintained during an in-flight engine shut down. This is achieved by the inclusion of the auxiliary doors which are opened in the event of an engine failure.

The Concorde is powered by four engines and had two mounting points, two engines are located at each mounting point, the mounting points are located under each wing. The intakes are fitted with the auxiliary doors, which can be opened outwards to let the flow out, this is in order to maintain a stable flow and the shock wave pattern of the faulty engine intake and to keep the adjacent engine running.

An array of four engines as in Tupolev Tu-144 makes it difficult or even impossible to provide significant area of an auxiliary door.

The layout used in Concorde also allows good accessibility to all engines, thus easing maintenance procedure. The Concorde has been optimised for the transatlantic route, in the event of a single or two engine failures, the aircraft is able to continue its flight with subsonic speed at lower altitudes. Depending upon the point at which the engine failure occurs, the aircraft may return to its departure point, continue to the destination or seek an alternative airfield.

The proposal to design a future supersonic civil aircraft with four separately mounted engines is attractive. However, such a configuration would prove more costly and may lead to a heavier wing. Any future supersonic aircraft would need to be larger to accommodate more passengers and have a significantly longer range.

The figure 7 on page 10 clearly illustrates the different mounting points for all supersonic civil aircraft.

Conclusion.

This paper has discussed some aspect of the aerodynamic design of supersonic intakes for civil aircraft. It is clear that the intake is one of the key components in achieving high overall efficiency. The intake is designed to supply the exact amount of airflow to face of the compressor with desired velocity for a wide range of speeds, altitudes and aircraft thrust requirements. The success or failure of an aircraft can actually depend upon the intake design.

In the design of supersonic jet the efficiency is very important. The efficiency of the power plant has a direct link with the intake, which is measured in terms of the total pressure recovery. Civil supersonic jets are designed with highest possible total pressure recovery. This is in order to fly across the entire flight envelope with lowest possible specific fuel consumption. This allows the operator to operate the aircraft with maximum economy.

In aviation safety is very important. In the future generation supersonic civil jet the significant safety problem due to the effect engine location can be solved by either producing a bigger aircraft with a large wing span to accommodate all four power plants separately or it may become possible to design an aircraft with just two engines.

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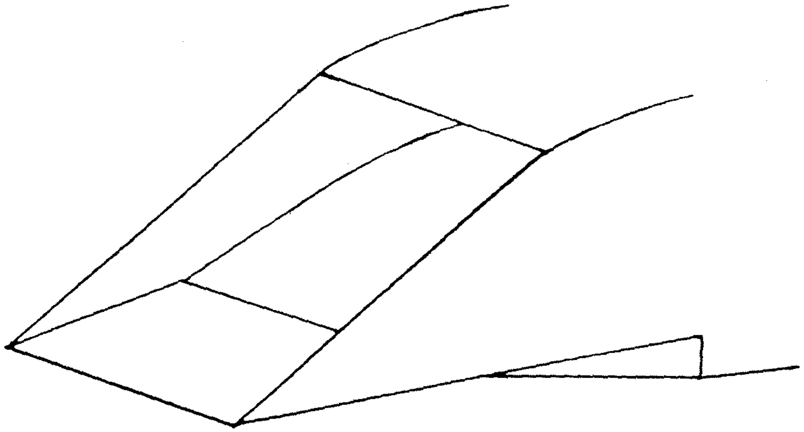


Fig. 1, Two-Dimensional Configuration.

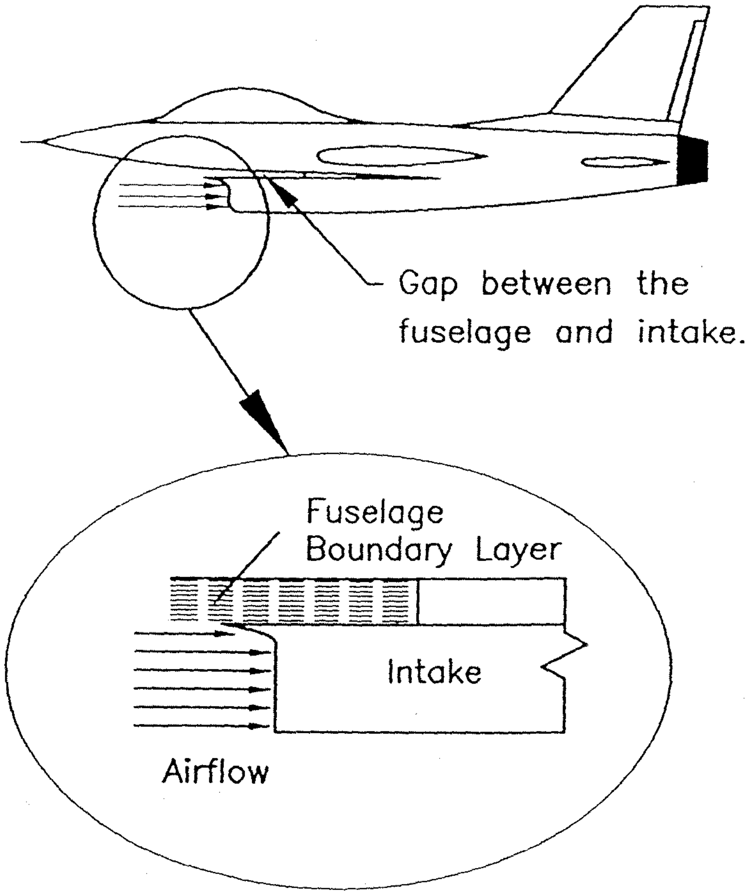


Fig. 2, Control of the F-16 Fuselage Boundary Layer.

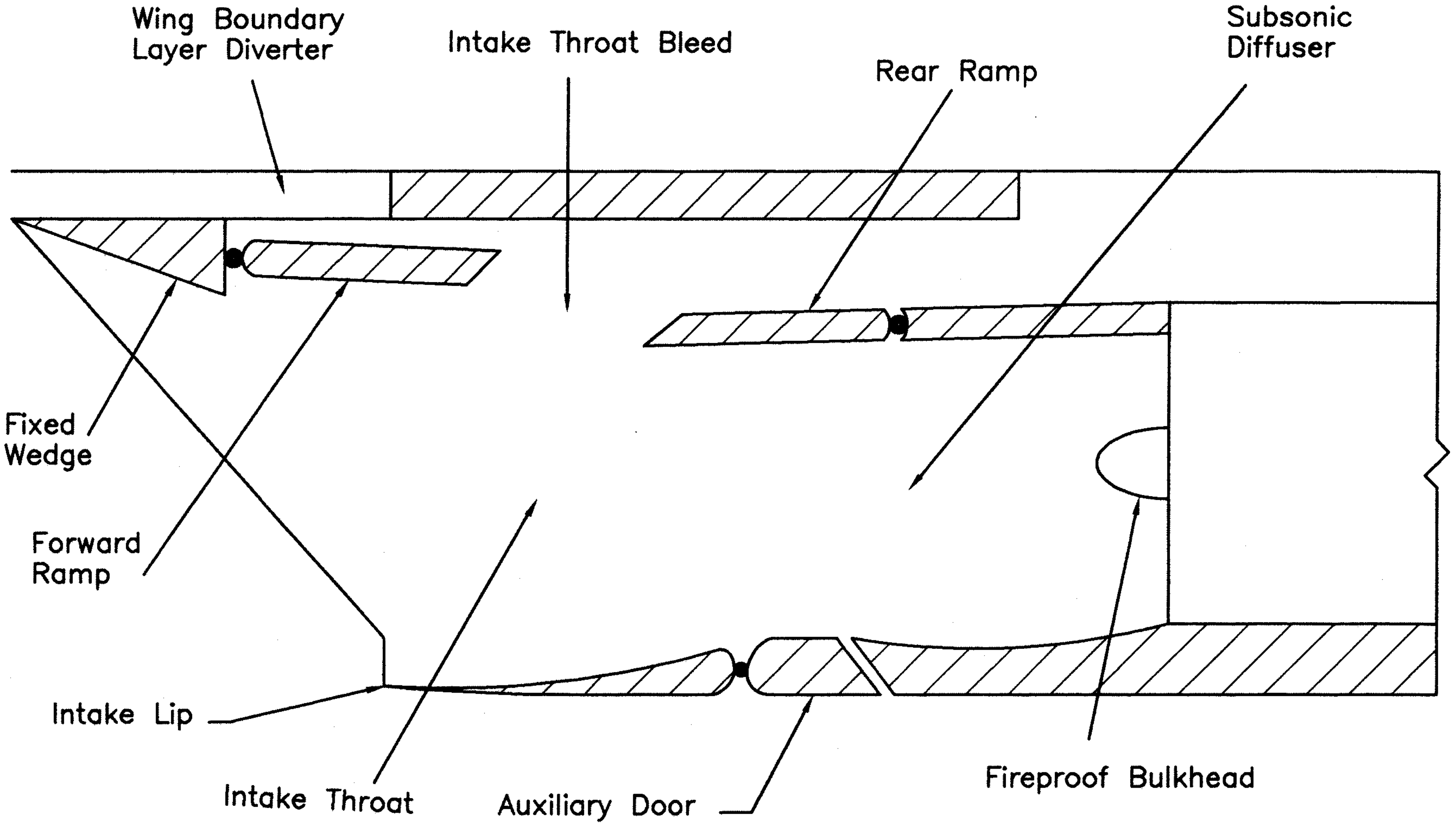


Fig. 3, A Typical Supersonic Intake and its Components Parts.

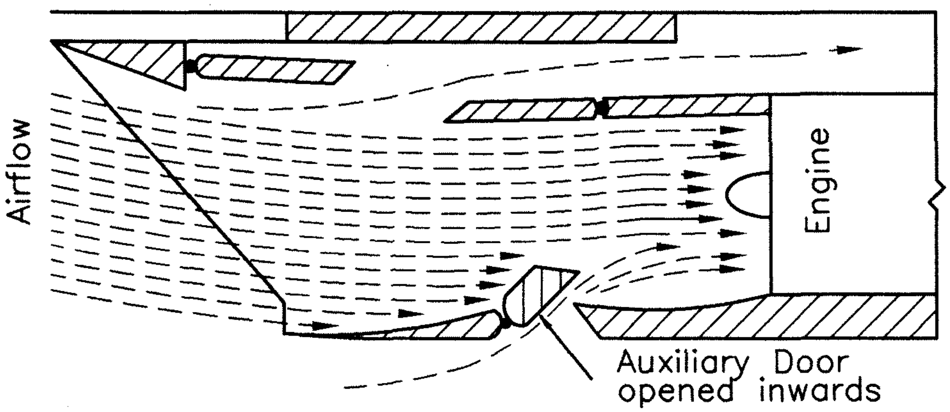


Fig. 4, Behaviour of Concorde Intakes During Take-off and Landing.

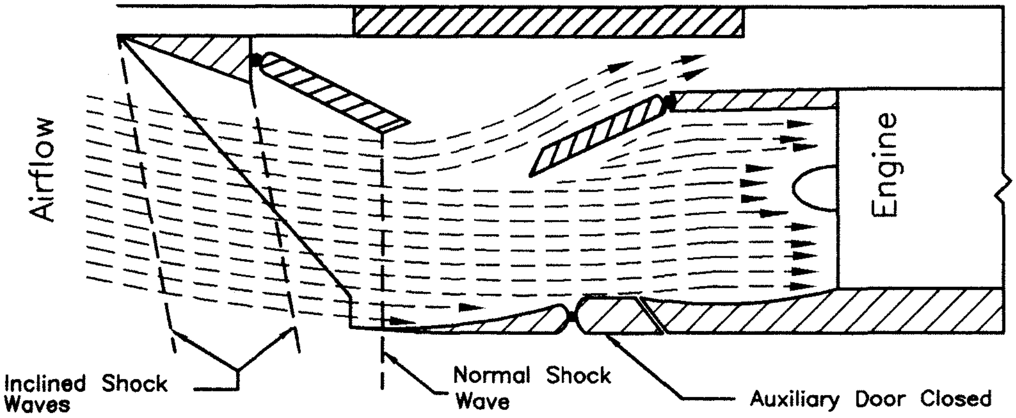


Fig. 5, Behaviour of Concorde Intakes during Supersonic Cruise.

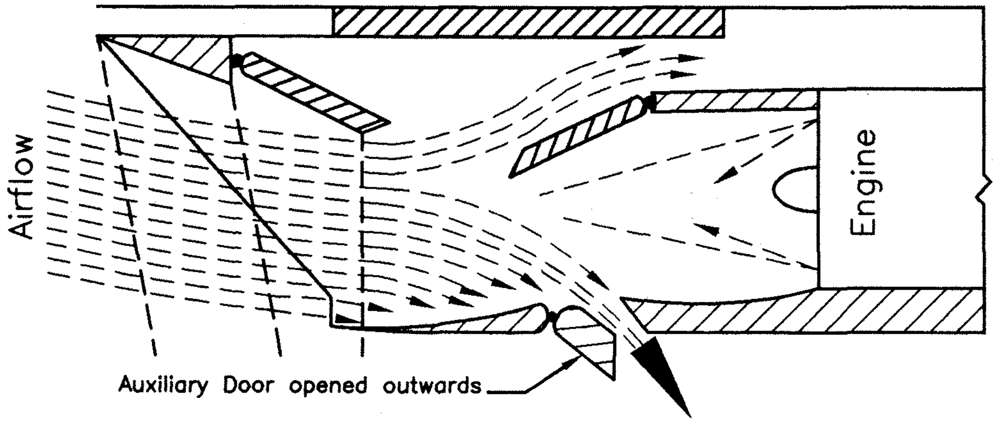
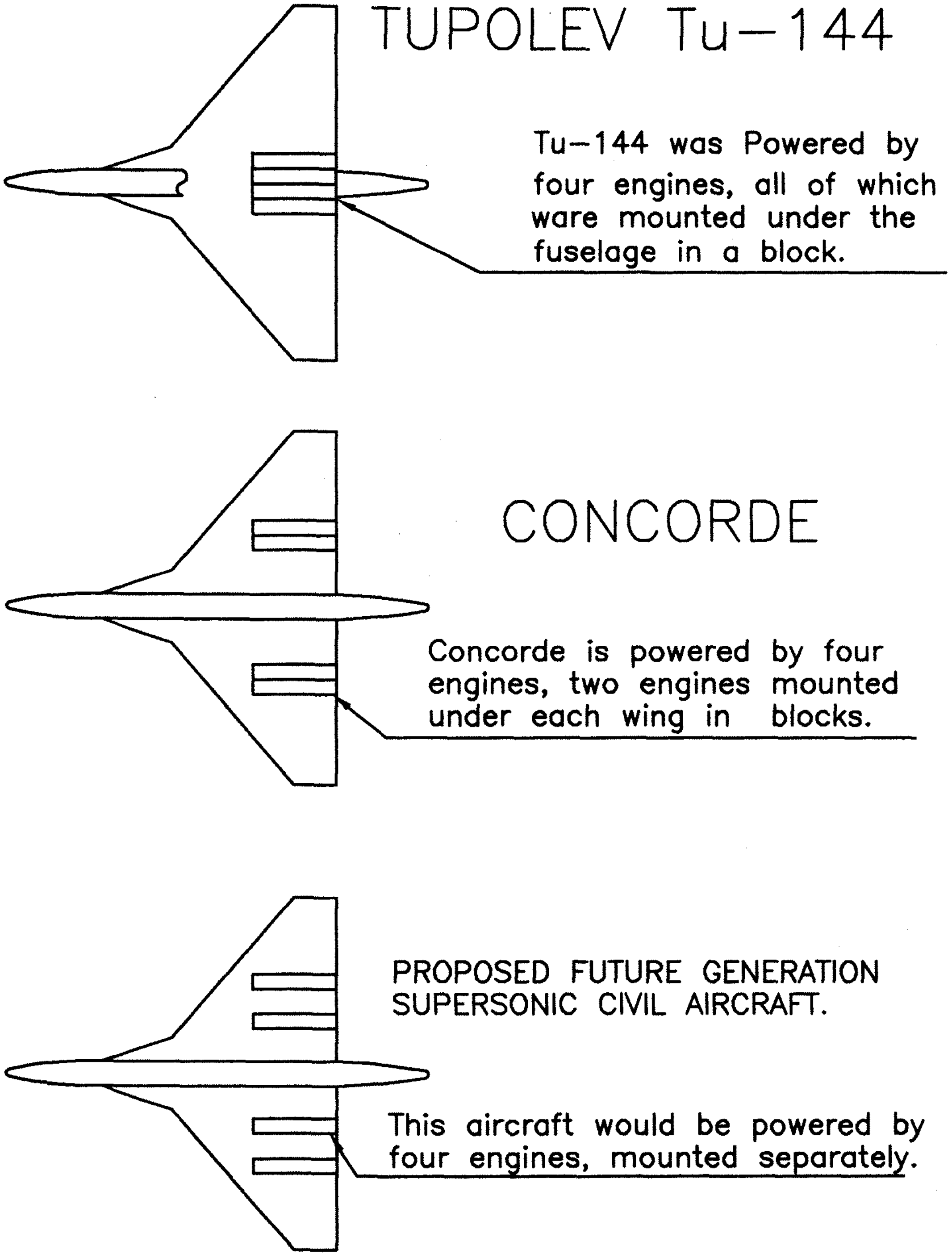


Fig. 6, Behaviour of Concorde Intakes During Emergency Engine Shut Down.



TUPOLEV Tu-144

Tu-144 was Powered by four engines, all of which ware mounted under the fuselage in a block.

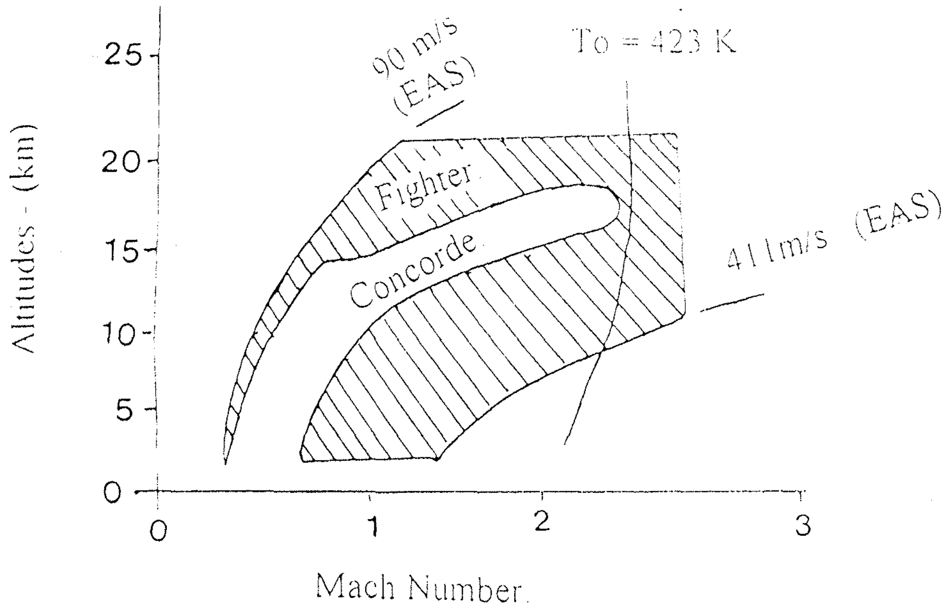
CONCORDE

Concorde is powered by four engines, two engines mounted under each wing in blocks.

PROPOSED FUTURE GENERATION SUPERSONIC CIVIL AIRCRAFT.

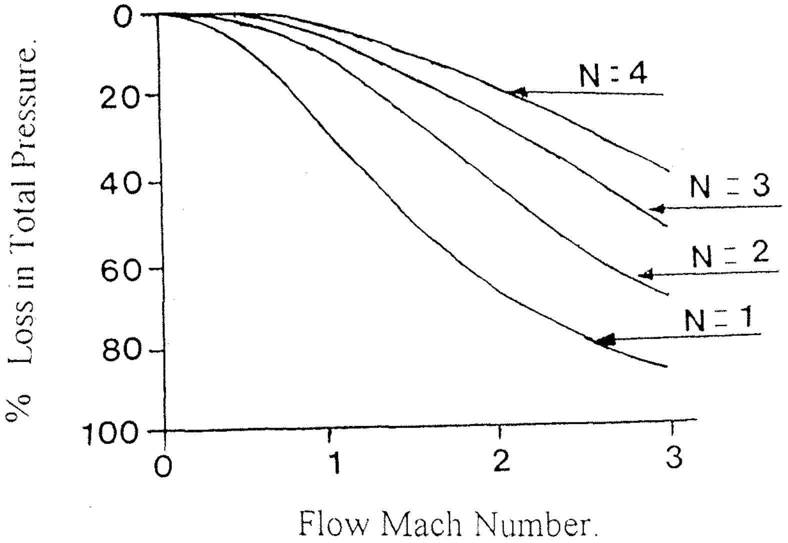
This aircraft would be powered by four engines, mounted separately.

Fig. 7, Engine Location of all Supersonic Civil Jet.



To: = Inlet Total Temperature.
EAS: = Equivalent Air Speed

Fig. 8, Flight Envelope.



N:= Total Number of shock Waves.

Fig. 9, Total Pressure Loss Curve.