AIR INTAKES: ROLE, CONSTRAINTS AND DESIGN

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Abstract

The aim of this general paper is to give an overview of the problems that arise in the design of air intakes, giving many current examples from around the world. The role of the air intake is first outlined. Subsonic, supersonic and even hypersonic air intakes, are described before to explain their integration on the vehicle. In the past, the only aspects considered in air intake design were aerodynamic and structural. Nowadays, Radar Cross-Section is often an essential criterion for military applications, so new design approaches and new locations on the vehicle are being introduced. This problem is presented.

The complexity of the internal flow, especially in the throat area where this flow is transonic, with multiple interactions between shock waves and boundary layers in the presence of internal boundary layer bleeds, called for a large number of tests. Some of the set-ups developed for the French ONERA wind tunnels are presented. The author concludes this general overview of air intakes with three remarks concerning the air intake specifications, the captured air flow and the internal design.

Acknowledgments

Air intakes have been one of my themes of work for more than thirty years, and are now essentially a permanent centre of interest. I would like to take the opportunity of this summary to give my hearty thanks to Jacky Leynaert and Pierre Carrière who taught this speciality to me at Sup'Aéro and were then my supervisors when I set out as a young engineer at ONERA's Aerodynamics Department. Without them, the Concorde would not have its air intakes and this paper would never have seen the light of day.

1. Introduction

After many years working on mainly supersonic air intakes, it is important to make an overall review and present a few documents collected over these last thirty years. The reader may acquire some knowledge from this paper, but the author may also get some answers he has been looking for to understand certain choices that are made in designing and positioning air intakes.

2. Role of the air intakes

Any vehicle with air-breathing propulsion needs at least one air intake to feed its engine so it can move. So the role of the air intake is to capture the airflow the propulsion (engines) and conditioning (radiators) systems need.

They must do this in such a way as to yield the best possible propulsive balance, which is expressed in two objectives:

- provide maximum thrust,
- induce minimum drag.

Maximum thrust will be obtained by designing the air intake to transform kinetic energy (*i.e.*, the velocity of the flow as it arrives in front of the air intake) into potential energy (the pressure after the diffuser, at the engine input) with the best possible efficiency. Efficiency is a parameter that is calculated by taking the ratio of the total pressure in front of the engine to that of the upstream flow. This thrust will be maximum if the air intake captures just what the engine needs for each flight configuration and provides the engine input with a flow of good homogeneity (low distortion) to ensure correct engine operation, which is essential for turbojets.

Minimum drag will be obtained with air intakes that are dimensioned to just what the engine needs (critical regime) and whatever the Mach number (Shock-on-lip Mach number). Careful attention is paid to the side walls and cowls in light of the small variations in angle of attack and yaw angle about the flight configurations.

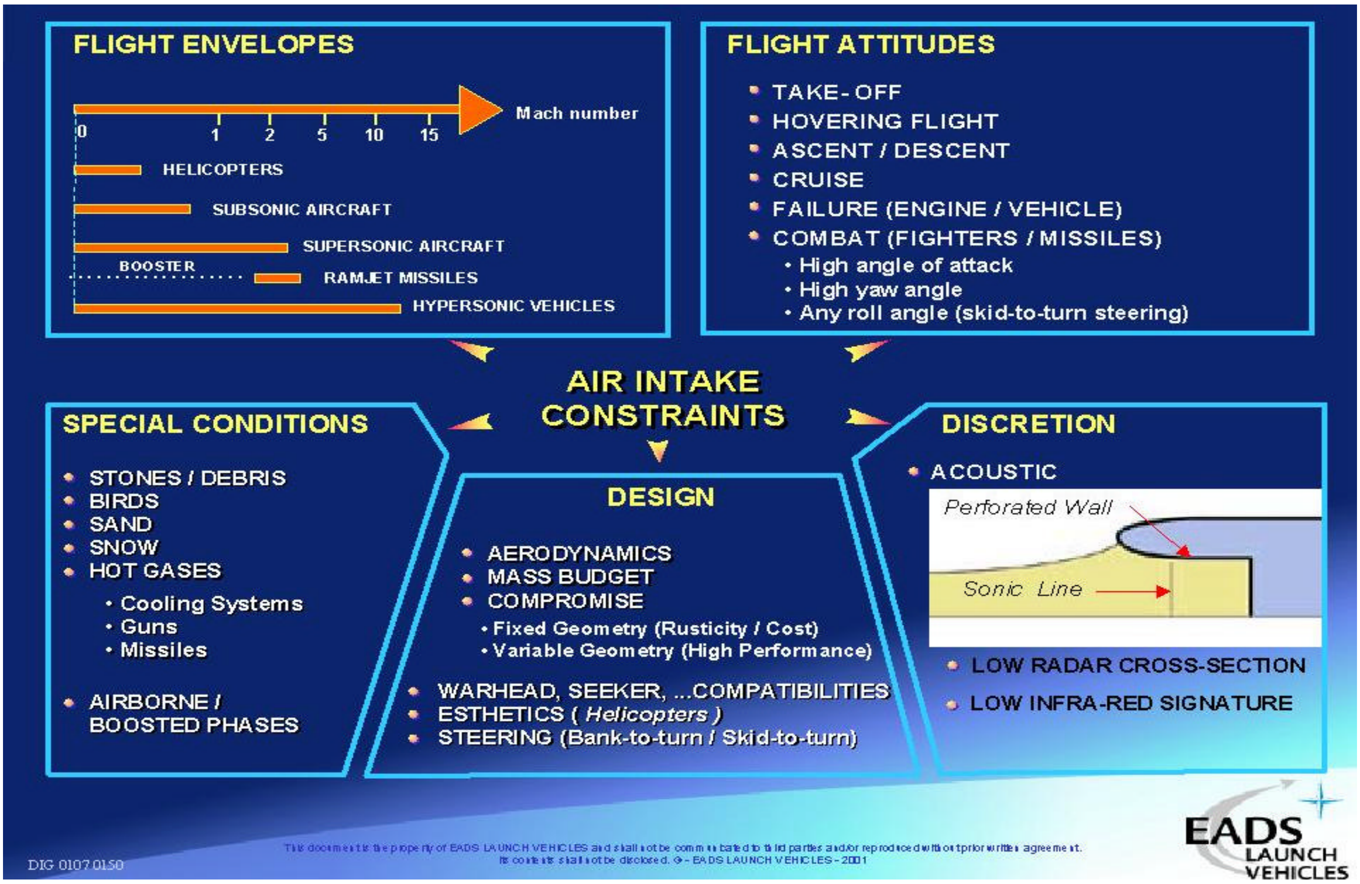
3. Constraints (Figure 1)

3.1 Flight Envelopes

Air intake design depends essentially on the flight envelope of the vehicle considered, and this envelope is very closely tied to the type of vehicle itself.

The first envelope concerns subsonic flight alone; and thus helicopters and subsonic aircraft, the latter of which constitute the vast majority of today's air transport vehicles. Then come supersonic aircraft, which have to cover the sub-, trans-, and supersonic domains. A compromise has to be found depending on how long the aircraft stays in each envelope in practice.

The supersonic transport will call for a high optimisation in supersonic cruise flight, while air combat in high subsonic cannot be ignored for the Mach 1.5 air-fighters. For ramjet-propelled supersonic missiles, these are generally boosted directly to the supersonic envelope by a solid booster phase during which the air intakes are shut, so they will be designed only for supersonic flight. If reusable air-breathing space launchers appear in the coming decades, the air intakes used will have to cover an enormous operating envelope ranging from Mach 0 to 10-12, and will certainly have to supply several different types of engines in succession. A number of projects are on the drawing boards but nothing has been built yet.



FLIGHT ENVELOPES

FLIGHT ATTITUDES

- TAKE-OFF
- HOVERING FLIGHT
- ASCENT / DESCENT
- CRUISE
- FAILURE (ENGINE / VEHICLE)
- COMBAT (FIGHTERS / MISSILES)
  - High angle of attack
  - High yaw angle
  - Any roll angle (skid-to-turn steering)

AIR INTAKE CONSTRAINTS

SPECIAL CONDITIONS

- STONES / DEBRIS
- BIRDS
- SAND
- SNOW
- HOT GASES
  - Cooling Systems
  - Guns
  - Missiles
- AIRBORNE / BOOSTED PHASES

DESIGN

- AERODYNAMICS
- MASS BUDGET
- COMPROMISE
  - Fixed Geometry (Rusticity / Cost)
  - Variable Geometry (High Performance)
- WARHEAD, SEEKER, ...COMPATIBILITIES
- ESTHETICS (*Helicopters*)
- STEERING (Bank-to-turn / Skid-to-turn)

DISCRETION

- ACOUSTIC

- LOW RADAR CROSS-SECTION
- LOW INFRA-RED SIGNATURE

DIG 0107.0150

EADS LAUNCH VEHICLES

FIGURE 1

3.2 Flight Attitudes

Flight attitudes vary widely from one vehicle to another. For all aircraft, the take-off phase with maximum thrust at a standstill has to be considered as well as roll-out on the runway, and without forgetting the possibility of dangerous crosswinds. Usually, ascent and descent are considered, and the cruise configuration is generally the one that is optimised. All the failure configurations having to do with the vehicle itself and its propulsion system must not be forgotten. For helicopters and vertical take-off aircraft, hovering flight has to be considered with possible astern and crosswinds, without forgetting the aerodynamic field induced by the rotor. For air-fighters and missiles, manoeuvrability is crucial in an extensive flight envelope with high angles of attack, yaw angles, and arbitrary roll-angle for skid-to turn steering. And do not forget negative angles of incidence in steep dives.

3.3 Discretion

The most common form of discretion, which especially applies to helicopters and transport aircraft, concerns acoustics. The standing international regulations must be complied with, and these are becoming more and more severe. To do this, we can work on the internal profile of the air intake to create a quasi-sonic flow at the entrance, which will prevent the engine noise from coming out through the air intake. Perforated walls equipped with acoustic materials complement this treatment.

The first generations of air intakes were always designed in accordance with performance objectives, such as thrust, weight, and cost. For a few years now, it is essential that air intakes have a low radar signature for military applications. Actually, if this parameter were not taken into account, the air intake would constitute a very large share of the vehicle's overall signature. This problem will be dealt with more precisely in section 8. For certain military applications, notably for helicopters, a low infrared signature is needed. But this problem generally concerns the nozzle more than it does the air intake.

3.4 Special Conditions

Air intakes are faced with many special conditions in flight. Bird capture will call for structural reinforcements, and the absorption of various debris from the ground can be countered by a pivoting grid (as in the Su 27) to deviate them and then trap them by closing once in flight. Sand and snow can also be trapped by grids or deflectors (Super Puma). Air intake position should be determined in light of the presence of hot air (from helicopter radiator) or combustion gases (aircraft thrust reverses, astern wind in hovering flight, missile plumes and gun gases). If there is gunfire, the possibility of unsteady flows due to the passage of waves induced by exit gases should be checked. For airborne missiles or those boosted by solid boosters, the air intakes are generally completely or partially shut during these phases of flight to avoid instabilities and drag.

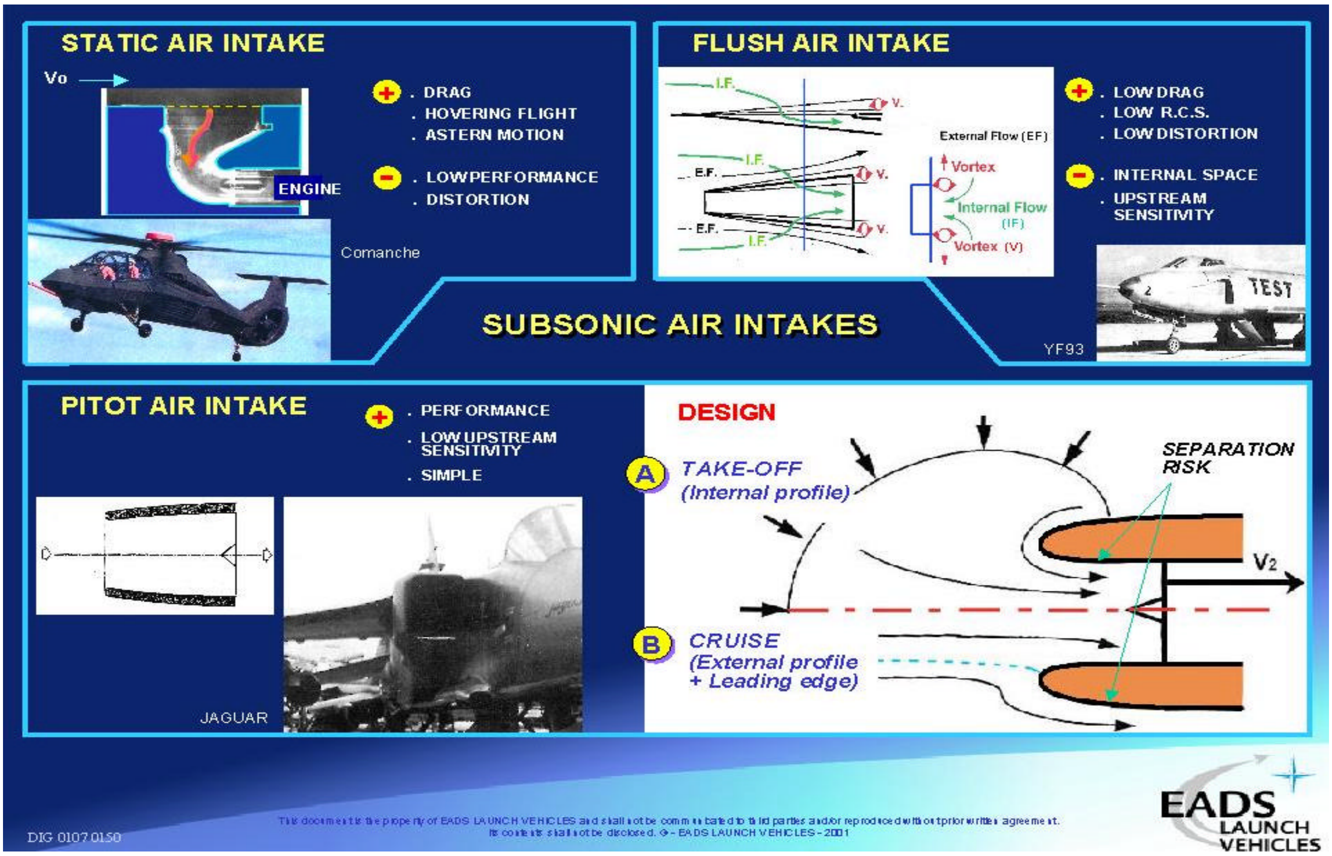


FIGURE 2

3.5 Design

With all of the constraints, which are generally aerodynamic, air intakes can be designed which will of course have to be as light as possible despite the internal loads, which may be steady or unsteady (as in buzz), thermal behaviour for vehicles in high supersonic flight, and treatments (ferrites) for radar discretion. Air intake design and position depend strongly on the vehicle's steering mode (bank-to-turn or skid-to-turn type).

Insofar as possible, the air intake is to be simple and of fixed geometry to ensure rustic operation of the propulsion system and minimum design, manufacturing, and maintenance costs. This is what will lead to highly operational vehicles. Variable geometry will be needed either for high performance or operation over a broad flight envelope. Transitory regimes then need to be analysed and, technologically, sealing will have to be provided.

4. Subsonic Air Intakes

4.1 Concepts (Figure 2)

Subsonic air intakes can be broken down into three broad families, the last of which is the essential one.

Static air intakes suitable for low speeds are just holes in the surface through which the engine draws in its air. These obviously have low drag and are advantageous for hovering flight or flight with an astern wind, but are low-performance and can induce distortion. Helicopters like the Ecureuil and Comanche have air intakes like this.

NACA-type air intakes are also flush with the surface, but with a trapezoidal opening and sharp lateral edges that generate two counter-rotating vortices. This configuration has two purposes:

- first, it deviates the boundary layer, which is the local external flow, to either side of the intake;
- then, by entraining the vortices, it introduces the higher flow into the intake, which has greater energy than the boundary layer.

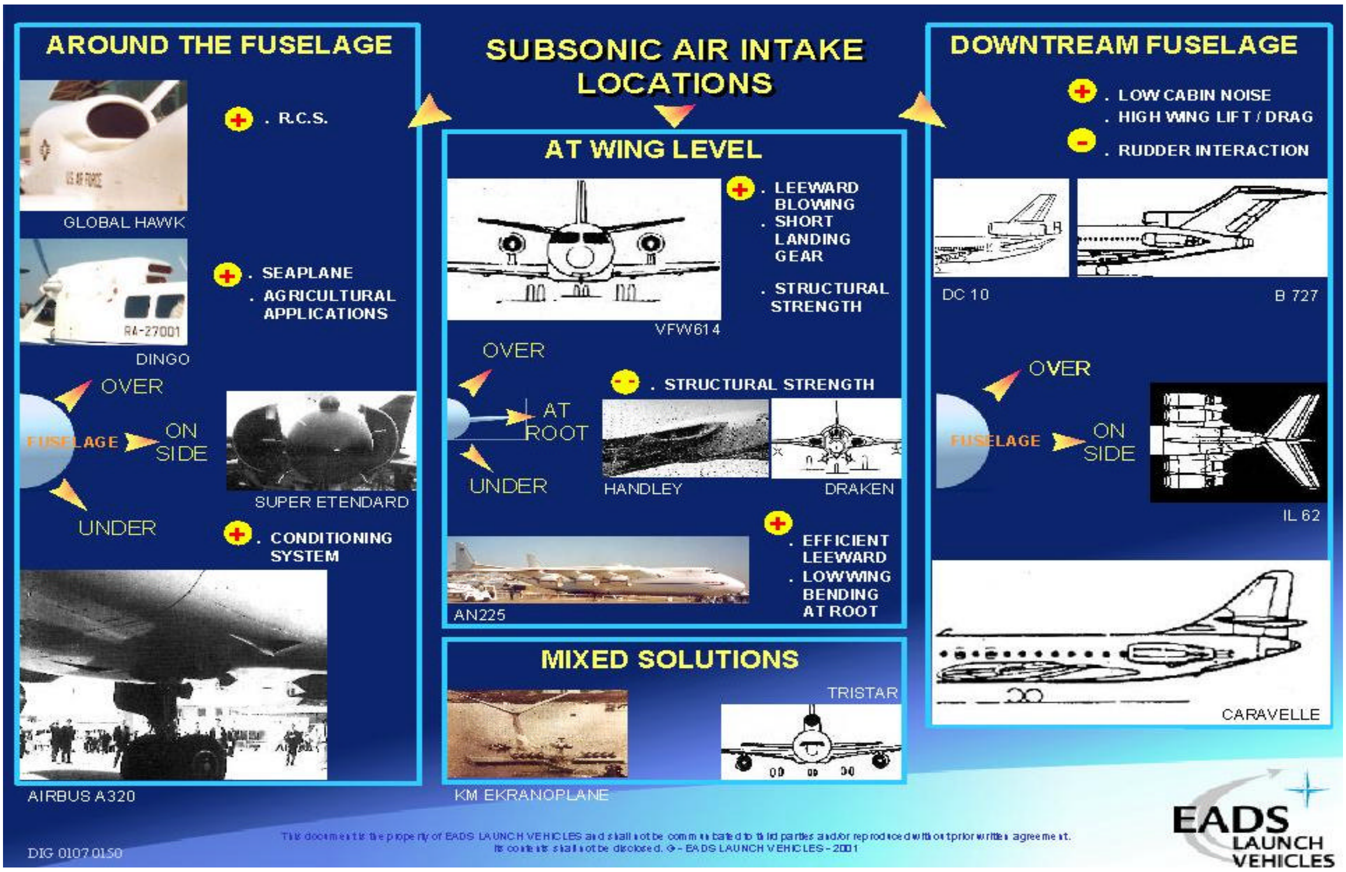
These intakes have very low drag and excellent Radar Cross-Section and, since they are long, they have low distortion. As disadvantages, they take up much more internal space and are extremely sensitive to the vehicle's attitude. They are generally used more for conditioning vehicles (Airbus A320, Fig.3) than for supplying aircraft propulsion systems (XF 93). Their stealth aspects are very important for new projects.

Pilot type air intakes are very simple and more common. The principle is to place a tube in the wind and capture the upstream total pressure These are the best subsonic air intakes, and they are not very sensitive to angle of attack or yaw angle either. They come in widely varied forms, such as the square one for the Anglo-French Jaguar.

4.2 Design (Figure 2)

The aerodynamic profile of these air intakes is defined by iteration optimising the internal profile for no separation may occur during take-off (standstill, roll-out, or crosswind) to provide maximum thrust, and the external profile should not separate either, to minimise the drag in cruise phase.

For flight at high angles of attack, which is to be considered for fighters, special care is needed for the leading edges. Mobile elements are sometimes needed (EuroFighter, figure 9) to open the capture cross-section and achieve a better orientation with respect to the upstream flow.



SUBSONIC AIR INTAKE LOCATIONS

AROUND THE FUSELAGE

+ . R.C.S.

GLOBAL HAWK

+ . SEAPLANE
. AGRICULTURAL APPLICATIONS

DINGO

FUSELAGE: OVER / ON SIDE / UNDER

SUPER ETENDARD

+ . CONDITIONING SYSTEM

AIRBUS A320

AT WING LEVEL

+ . LEEWARD BLOWING SHORT LANDING GEAR
. STRUCTURAL STRENGTH

VFW614

OVER / AT ROOT / UNDER

− . STRUCTURAL STRENGTH

HANDLEY DRAKEN

+ . EFFICIENT LEEWARD
. LOW WING BENDING AT ROOT

AN225

MIXED SOLUTIONS

KM EKRANOPLANE TRISTAR

DOWNTREAM FUSELAGE

+ . LOW CABIN NOISE
. HIGH WING LIFT / DRAG

− . RUDDER INTERACTION

DC 10 B 727

FUSELAGE: OVER / ON SIDE

IL 62

CARAVELLE

DIG 0107 0150

FIGURE 3

4.3 Locations (Figure 3)

Air intakes can be found in many different positions depending on the application.

They may be placed directly next to the fuselage, generally on the sides (Super Etendard). The lower side of the wing is obviously a good aerodynamic situation, but raises ground clearance problems. NACA air intakes are very common for conditioning (Airbus A320). The upper side of the wing, though it is not the aerodynamic optimum, is a solution for Radar Cross-Section (Global Hawk), for agricultural applications (Dingo), and for seaplanes.

Aircraft engines are often mounted on the wing. The weight of the engines minimises the aerodynamic bending moment of the wings in flight at the level of their root in the fuselage. There are a few rare examples (VFW 614) with engines placed over the wings to promote blowing of the upper surface and decrease the landing gear height. In configurations like this, the pylon wake and thermal behaviour of the leeward need to be remembered. The commonest solution is to suspend 2/4/6/8 engines under the wings. The Antonov 225 is a good example of such a configuration, and we may note that the B52's eight engines have the particular feature of being grouped in pairs on four pylons. Some older aircraft had air intakes placed at the level of the wing root where drag is low, but this is not an ideal position from the viewpoint of structural, not to mention engine maintenance. In this configuration, one engine (Draken) or two (Handley Victor Page) can be found at each wing root.

Since the Caravelle, designed by Sud Aviation, engines have been mounted on the aft fuselage. This configuration allows better wing aerodynamics and places the engine noise behind the passenger cabin. It has to be checked that the wake from the wing does not interfere with the air intakes placed downstream of it. While the Caravelle had an engine on each side, other aircraft (IL 62) have had two. With the arrival of tri-jet aircraft, a third air intake had to be placed at the foot of the rudder. The engine can be placed directly behind this air intake to reduce the distortions, but this induces a diving moment to the aircraft (DC10). The engine can also be placed at the end of the fuselage (Boeing 727), which calls for a sharp S-shaped diffuser with distortions including the rotation effects of the two counter-rotating vortices induced.

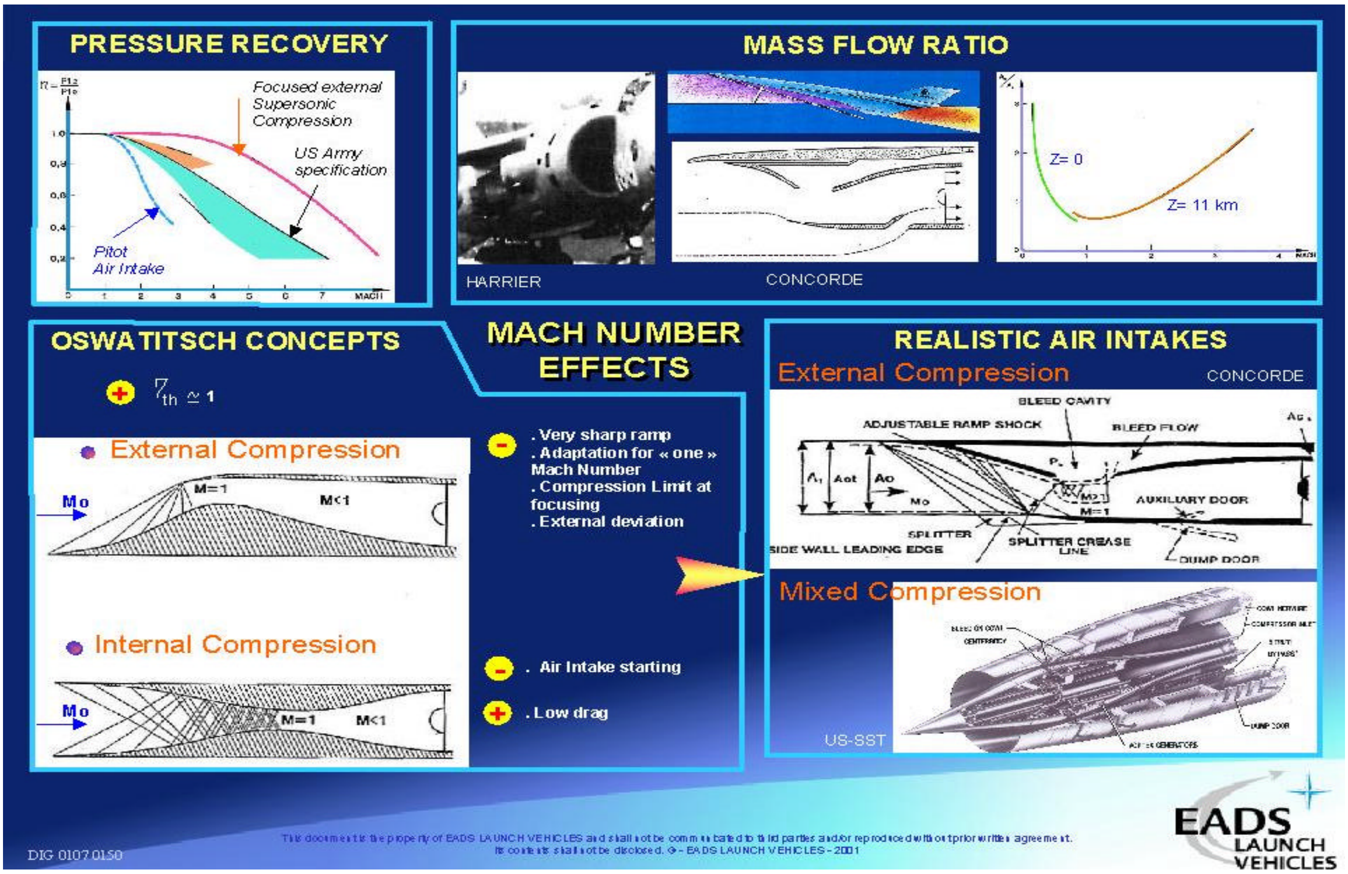
These solutions can of course be combined for multi-engine aircraft. The Tristar, for example, has two air intakes under the wings and the third under the rudder, and note the 10-engine Soviet Ekranoplane (flight with ground effect over the sea), dubbed "KM" for the "Caspian Monster".

5. Mach Number Effects (Figure 4)

5.1 Pressure Recovery and Mass Flow Rate

The passage from subsonic to supersonic domain is characterised by the presence of shock waves inducing compression in the air intake.

The art of designing a supersonic air intake involves prompting this compression with a series of low-intensity (inclined) shocks, which will significantly increase the pressure recovery of the air intake in supersonic flight. The poorest solution is the Pitot type air intake in which the pressure is recovered with a single normal shock.



PRESSURE RECOVERY

MASS FLOW RATIO

OSWATITSCH CONCEPTS

MACH NUMBER EFFECTS

REALISTIC AIR INTAKES

⊕ $\eta_{th} \simeq 1$

● External Compression

⊖ . Very sharp ramp
. Adaptation for « one » Mach Number
. Compression Limit at focusing
. External deviation

● Internal Compression

⊖ . Air Intake starting

⊕ . Low drag

External Compression

Mixed Compression

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FIGURE 4

It should be said, though, that the Pilot intake is an excellent compromise for Mach numbers of less than 1.5 because little pressure recovery is lost up to that point, and the permanent configuration is a simple one.

The mass flow rate an engine needs varies considerably as a function of the Mach number. For aircraft flying between Mach 0.3 and 2, the upstream tube section (A0) is roughly the size of the engine entrance section (A2). For very low speeds though, additional intakes need to be opened to provide the engine with the flow rate it needs. Figure 4 shows intakes like this on the Harrier, which hovers, and the operating scheme of the Concorde's air intake with the opening of an auxiliary trap for flight at low speeds. For high Mach numbers too, the mass flow rate captured has to correspond to several times the engine's entrance section. The windward side of the fuselage is then used as a first compression ramp (Fig. 4 and section 7).

5.2 Oswatitsch Concepts

Oswatitsch proposed two compression concepts for supersonic air intakes, having a theoretical pressure recovery of unity (not counting viscous effects).

The first is based on external supersonic compression with a profile inducing isentropic compression (focusing the waves on the lip of the cowl), with the diffuser providing the subsonic compression. Many design difficulties prevent the construction of such air intakes in practice:

- infinitely thin upstream ramp,
- design for a given Mach number,
- compression limit at the focal point (unstable configuration),
- too much deviation at high Mach.

The second concept concerns internal supersonic compression, with the additional advantage of generating no drag. As before, a crucial problem prevents any practical construction: the air intake cannot self-start.

5.3 Realistic Air Intakes

Again we find two families of air intakes, but with slight variants.

The external compression is performed with low-intensity inclined shocks, limited to about Mach 1.4, so it ends with a normal shock at the level of the cowl. The profile is mobile, to adapt to the Mach number. The Concorde has intakes like this.

Purely internal compression is abandoned in favour of mixed external and then internal compression. As the internal compression is more limited and is for lower Mach numbers (about 2), self-starting is possible. The American SST project had an air intake of this type. We may mention the possibility of translating the central body to adapt the intake to the Mach number.

6. Supersonic Air Intakes

6.1 Practical Configurations (Figure 5)

Pitot air intakes are an excellent compromise if the flight envelope does not go far beyond Mach 1.5. They differ from their subsonic versions by their thinner leading edges, to reduce drag (F16).

Beyond Mach 1.5, external supersonic compression is generally needed. There are essentially two broad families of these supersonic air intakes, for two reasons:

- two-dimensional design (planar or of revolution),
- possibility of variable geometry.

Figure 5 diagrams two such air intakes.

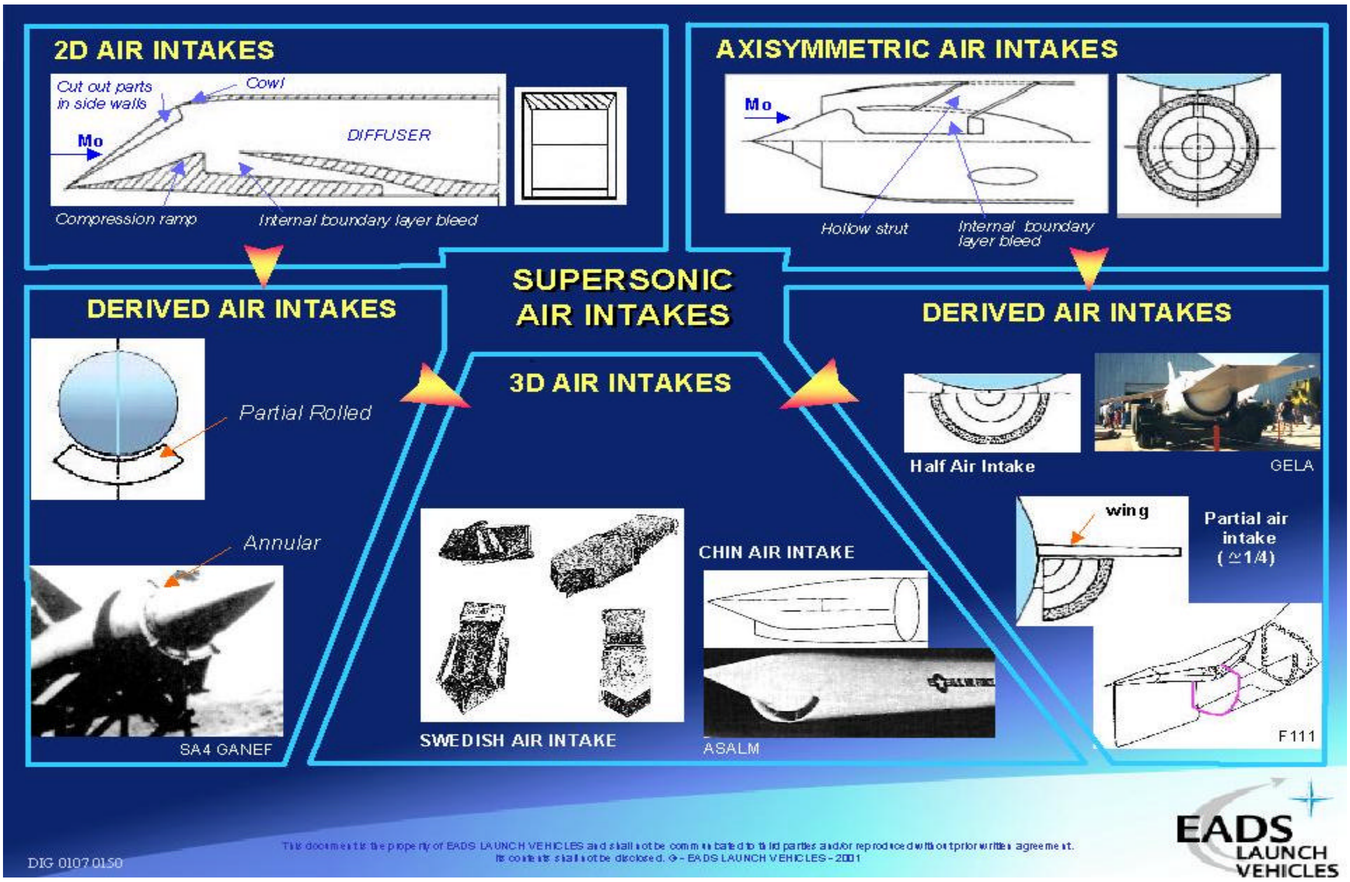


FIGURE 5

Note the presence of the internal boundary layer bleed to attenuate the interaction between the normal shock and the ramp boundary layer.

From the planar 2D concept, we get also intakes that partially or even wholly surround the fuselage. The Russian SA4 Ganef missile followed this principle. The intake has to be very far forward on the fuselage to minimise the capture of the fuselage boundary layer.

From the axisymmetrical concept, we get semi-circular air intakes (Mirage, GELA) or quarter-circle designs (F 111).

Of course, there are also three-dimensional intakes. Two examples can be found in the Swedish works on missiles (with a double intake, theoretically to reduce the missile's attitude sensitivity) and chin air intakes based on the principle of an inclined nose cone to reduce the drag on the leeward side and to induce compression on the windward side where the air intake is.

6.2 Aerodynamic Field (Figure 6)

The fuselage's aerodynamic field knowledge is essential when choosing the location of air intakes. The objective is to place the intakes in overpressure zones (on the windward side of the fuselage or wings) and avoid overspeeds (nose / fuselage connections and sides of the fuselage, for high angles of attack). Low-energy zones are avoided in light of the viscous effects (vortices, boundary layer, and especially the leeward boundary layer because it is thick).

6.3 Locations for Missiles

Missiles generally have one, two, or four air intakes. Where these are positioned depends on the steering mode, which may be of the bank-to-turn or skid-to-turn type.

For skid-to-turn steering, a frontal air intake may be used (Stataltex), or four intakes, making a cruciform missile. These may be semi-circular (RRX5E), circular (probative French ramrocket model), or two-dimensional. In the latter case, two options are possible depending on whether the compression is initiated near the fuselage (ALVRJ) or far from it (French rustic missile). See section 10.3.

For bank-to-turn steering, a plane of symmetry has to be taken into account, which is obtained with configurations of one or two air intakes. With a single intake, it can be under the cone (Matra ASMP project), under the windward surface (American project) or on the leeward surface (TU 141, ALCM). With two air intakes, they are generally two-dimensional and are placed laterally to the fuselage (Aerospatiale ASMP) or, to take advantage of the compression of the fuselage, at an angle of 90° to 120°. Circular air intakes placed under small wings (MRAAM) limit the effects of lateral overspeeds.

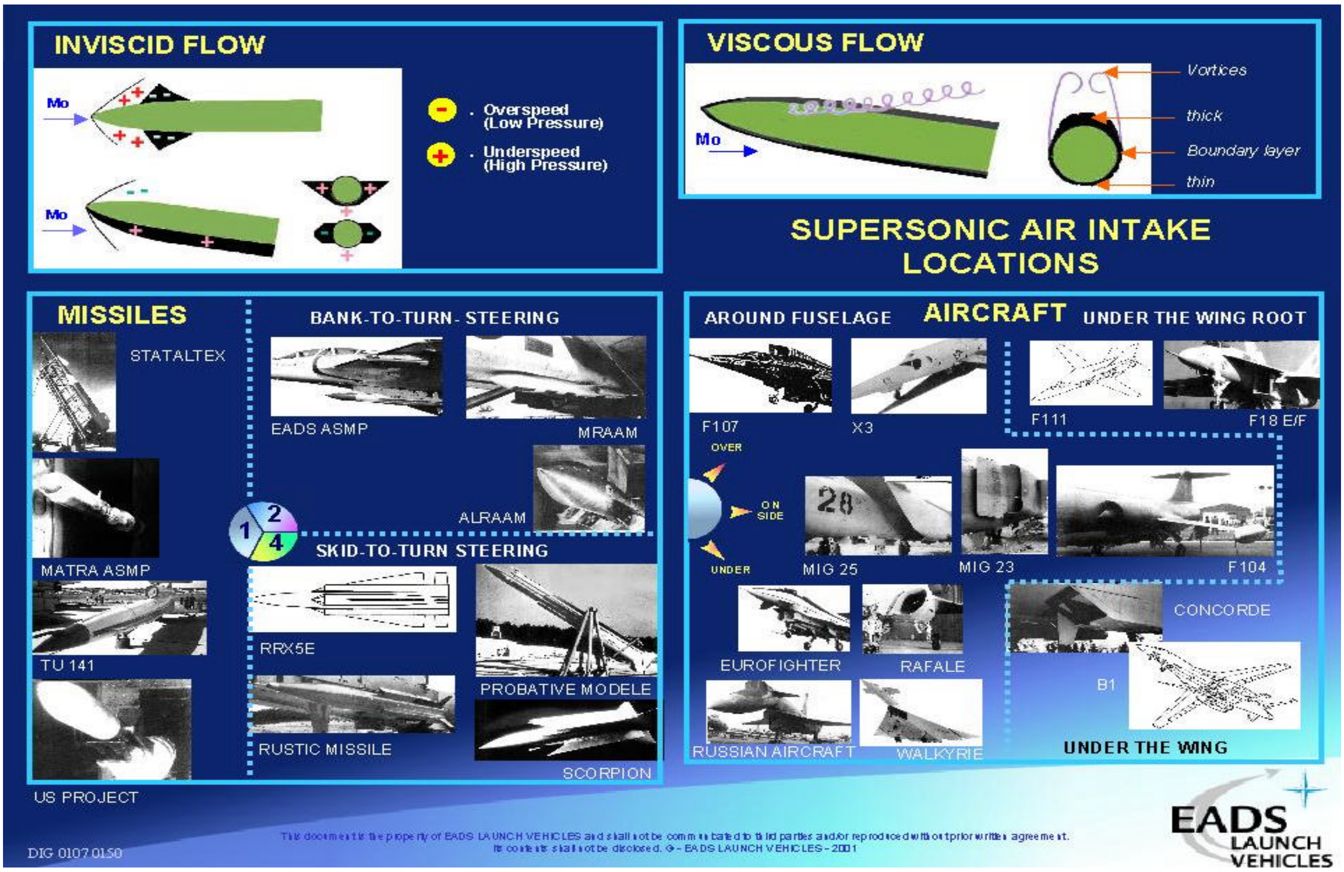


FIGURE 6

6.4 Locations for Aircraft

Let us first consider air intakes that are essentially affected by the aerodynamic field of the fuselage. These are very generally on the sides. They are two-dimensional with a ramp to deviate the flow, either windward (Mig 25) or laterally (Mig 23). This last configuration is very sensitive to high angles of attack because the air intakes are then affected with yaw angle. A classical configuration for minimising drag and aircraft weight is based on two semi-circular intakes (F104, Mirage). In the same way as for missiles, these intakes can be located closer to the windward side (Rafale) but they still have to be separated enough to avoid interactions between them in case of engine failure. Continuing in the same direction, they are placed on the windward surface. Two two-dimensional intakes can be found next to each other (Eurofighter) with each supplying an engine, or a single intake (F16). We might note that the Walkyrie (an American Mach 3 class prototype) has two two-dimensional intakes together, but connected by the compression ramps. There is a Russian plane with exactly the same configuration. Lastly, let us mention the case of intakes on the upper surface with the F107's large air intakes which must not be too strongly affected by the fuselage, and the X3 configuration which was adopted to minimise the transonic drag, and not for purposes of manoeuvrability.

Air intakes can be placed in the corners between the fuselage and the wing roots (F111 with quarte-circles, F18 and EuroFighter are two-dimensional). These configurations generally raise problems of evacuating the fuselage boundary layer, which explains the large splitter plane on the F111 (see Fig. 5 and 10).

The last possibility is an implantation under the wing to get the most out of its compression effect, especially with two-dimensional intakes. For four-engine aircraft, the intakes are placed in pairs, separated by a common side wall (Concorde) or by the compression ramp (B1). This latter configuration has the advantage of isolating the two engines if one of them fails. For the Concorde, this problem is solved by advancing the median side wall to prevent any spillage of flow refused by the failed engine, into the healthy one. Remember that the first prototype of the TU 144 had four engines side by side. This configuration provides little possibility of dealing with a failure of one of the two engines in the middle, and was quickly shelved in favour of a Concorde type configuration.

7. High Mach Air Intakes (Figure 7)

7.1 Air Intake Concepts

High velocities induce significant heating and thereby very important thermal problems, particularly as concerns the sharp parts needed to minimise drag and the need for mobile elements to adapt the air intake to the flight Mach number. With constraints like this, configurations of revolution have many advantages for the structural aspects. As was seen in section 5, air intakes generally use external or mixed supersonic compression. The low-distortion criterion for turbojets requires the presence of many internal boundary layer bleeds (SR71). With a scramjet, since the engine is supplied with a supersonic

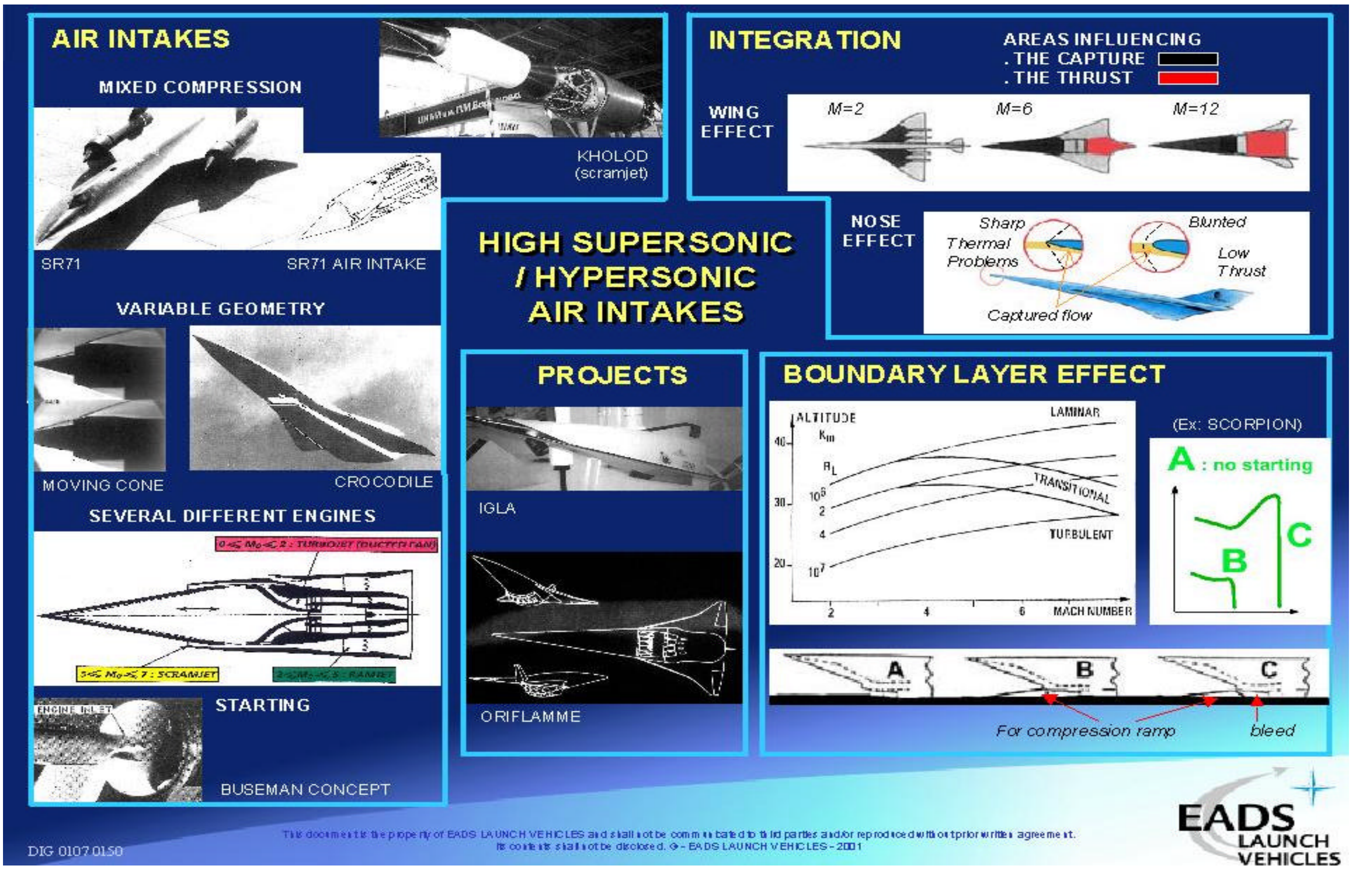


FIGURE 7

stream (Kholod), much less compression is called for as the external compression is then sufficient and the intake pressure recovery is high, whereas the pressure recovery of the supersonic combustion itself is less than that of subsonic. The product of the two pressure recoveries shows the need for beginning with subsonic combustion up to about Mach 6, and going on from there with supersonic combustion.

Mobile geometry is achieved in axisymmetrical configurations by translating the central body, but this provides no way of increasing the capture cross-section with Mach number. Among two-dimensional designs, a "Crocodile" intake has been proposed in which the ramp on the fuselage is fixed while a second ramp opposite it is mobile in rotation. The opening is adjusted as a function of the flight Mach number to increase the capture section and the amount of compression. The main fault with this air intake concerns the handling of shock wave / boundary layer interactions on the side walls, considering the high global compression of the internal type.

This mobile geometry can be used to supply various engines in succession. In-dept analysis of the transitory regimes is indispensable. An example is given in figure 7.

The last problem with these air intakes concerns their self-starting. Large cuts are needed such as is proposed by Buseman. Operational application of intakes like this is yet to be confirmed.

7.2 Integration on the Vehicle

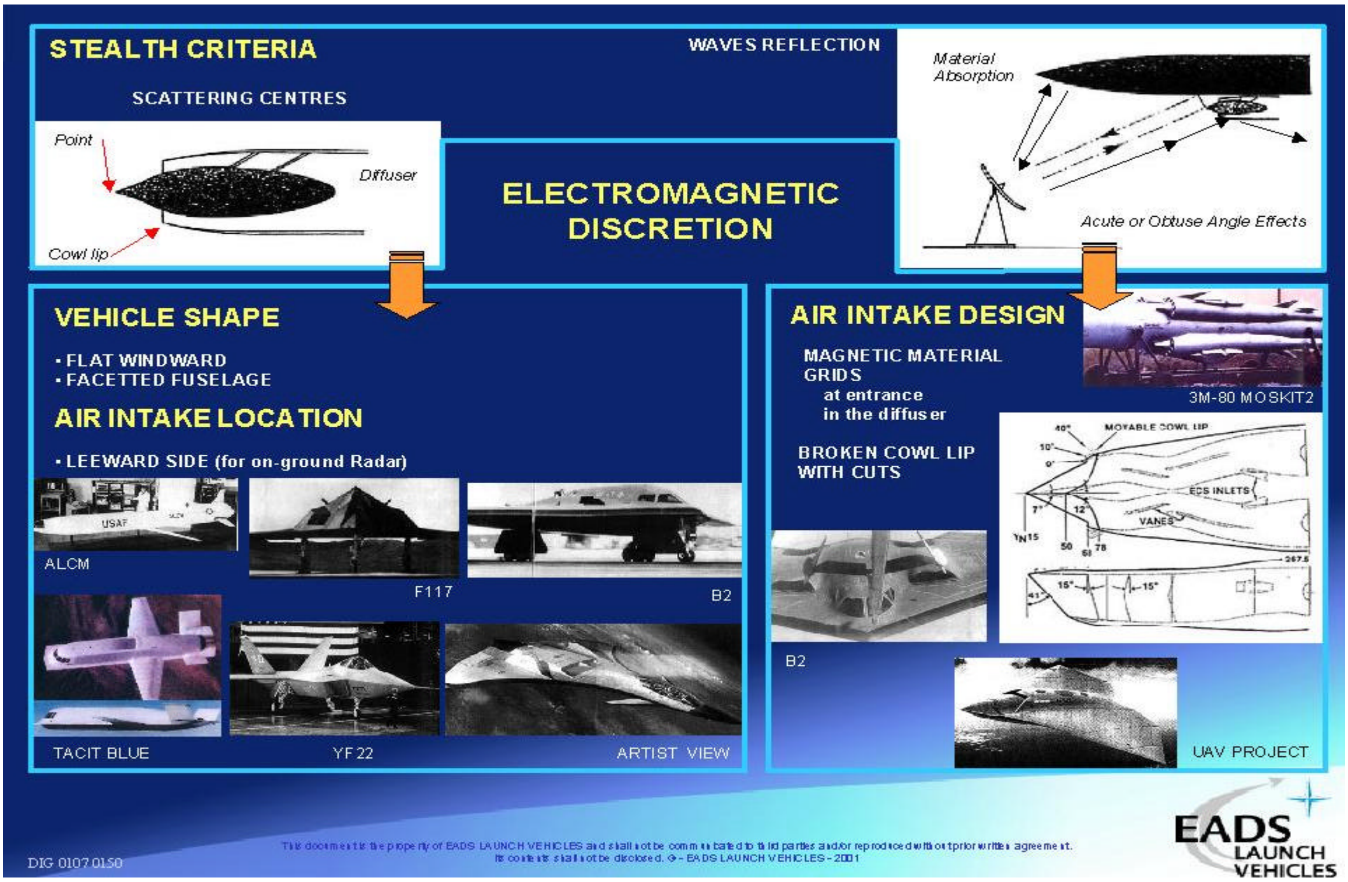
The effect of the fuselage is essential for the integration of high-velocity propulsion systems. Figure 7 shows that this is useful for the air intakes at Mach 2, but it is indispensable for them and the nozzles too, at Mach 12.

A second major parameter is the vehicle's nose radius. This will condition the intensity of the nose shock through which the airflow captured by the intake will pass. Overall pressure recovery will therefore be directly proportional to that of the nose shock. Narrowing the nose, especially in the form of a spatula, is necessary but leads to thermal problems.

We should remember another difficulty for hypersonic missiles which, considering their small size and high flight altitudes, leads to low Reynolds numbers and laminar boundary layers on the fuselage walls. The presence of lateral air intakes such as for the French Scorpion project induces very strong shock / boundary layer interactions. A precompression ramp had to be installed just upstream of each air intake to deviate the fuselage boundary layer and attenuate these interactions (Conf B of Fig 7). This device was operational only when a boundary layer trap was positioned at the end of the ramp to eliminate the effects of the residual interactions (Conf C).

7.3 Projects

Figure 7 gives two examples of hypersonic vehicle projects. The IGLA undertaken by Russia is an in-flight test bench for validating scramjet operation under real conditions. Oriflamme is a French study of a single-stage reusable launch vehicle with air-breathing propulsion. This propulsion mode is relayed by rocket engines beyond about Mach 12.



STEALTH CRITERIA

SCATTERING CENTRES

WAVES REFLECTION

ELECTROMAGNETIC DISCRETION

VEHICLE SHAPE

- FLAT WINDWARD
- FACETTED FUSELAGE

AIR INTAKE LOCATION

- LEEWARD SIDE (for on-ground Radar)

AIR INTAKE DESIGN

MAGNETIC MATERIAL
GRIDS
at entrance
in the diffuser

BROKEN COWL LIP
WITH CUTS

DIG 0107 0150

FIGURE 8

8. Electromagnetic Discretion (Figure 8)

8.1 Physical Principles

Radar transmits electromagnetic waves that electrically charge the illuminated targets. This has two effects for air intakes:

- waves entering the air intake cavity, after multipath reflections inside, will be re-transmitted out through the entrance plane in many directions;
- electrical charges travelling through the skin of the structures will concentrate on the leading edge (point effect) and transmit from there.

When the air intake is integrated in the fuselage, this will lead to many additional multipath reflections with normal or acute angles that cause waves to be returned to the radar (monostatic case) and thus a major signature. The ideal would be to have only flat surfaces and obtuse angles, to prevent returning the waves. On the whole, the air intake constitutes a very large share of the vehicle's total electromagnetic signature.

8.2 Air Intake Design

One way of reducing air intake Radar Cross-Section is to cover the walls with materials that absorb the waves, thereby avoiding reflections. This means using significant thicknesses of ferrite, notably, which are particularly harmful for the weight budget.

Another approach is to work on the air intake shape. We can begin by adjusting the entrance cross-section or gridding it. The wavelengths of the re-transmitted waves will then decrease with the narrowness of the openings (Moskit 3M80 missile). A comparable effect can be achieved by placing a series of blades in the diffuser and/or curving the diffuser duct (B1), which prevents the radar from identifying the turbojet installed in the aircraft.

To reduce the point effect of the cowl, they are designed with broken lines and each element is electrically insulated. The frequencies transmitted diminish with the length of the segmentation (B2, UAV Project).

8.3 Vehicle Design

Before dealing with the air intake, it is important to have a discreet airframe. Two approaches are possible:

- have as flat as possible a windward surface, which leads to the flying wing concept (B2);
- have multiples facets to avoid a continuous signal, which is a target lock-on criterion for the radar. This leads to the F117 concept with its nonlinear flight polars that are very harmful for flight qualities and pilot comfort.

Using a fuselage like this and placing the air intakes on the leeward surface, we can get a vehicle that is discreet for on-ground radar (ALCM, F117, B2). Of course, this location contradicts the aerodynamic constraints. It can always be said that, if the vehicle is very discreet, it will not be detected and therefore will not have to manoeuvre. Aerospatiale's ASLP concept is based on this principle with an leeward surface air intake combined with a radar detector. If acquisition is made anyway, the missile no longer has to be discreet but its performance must be increased. It turns over and the air intake is then on the windward surface where it can be efficient.

Electronics is also doing marvels by distorting the re-transmitted waves, but this is very far from the subject of air intake aerodynamics.

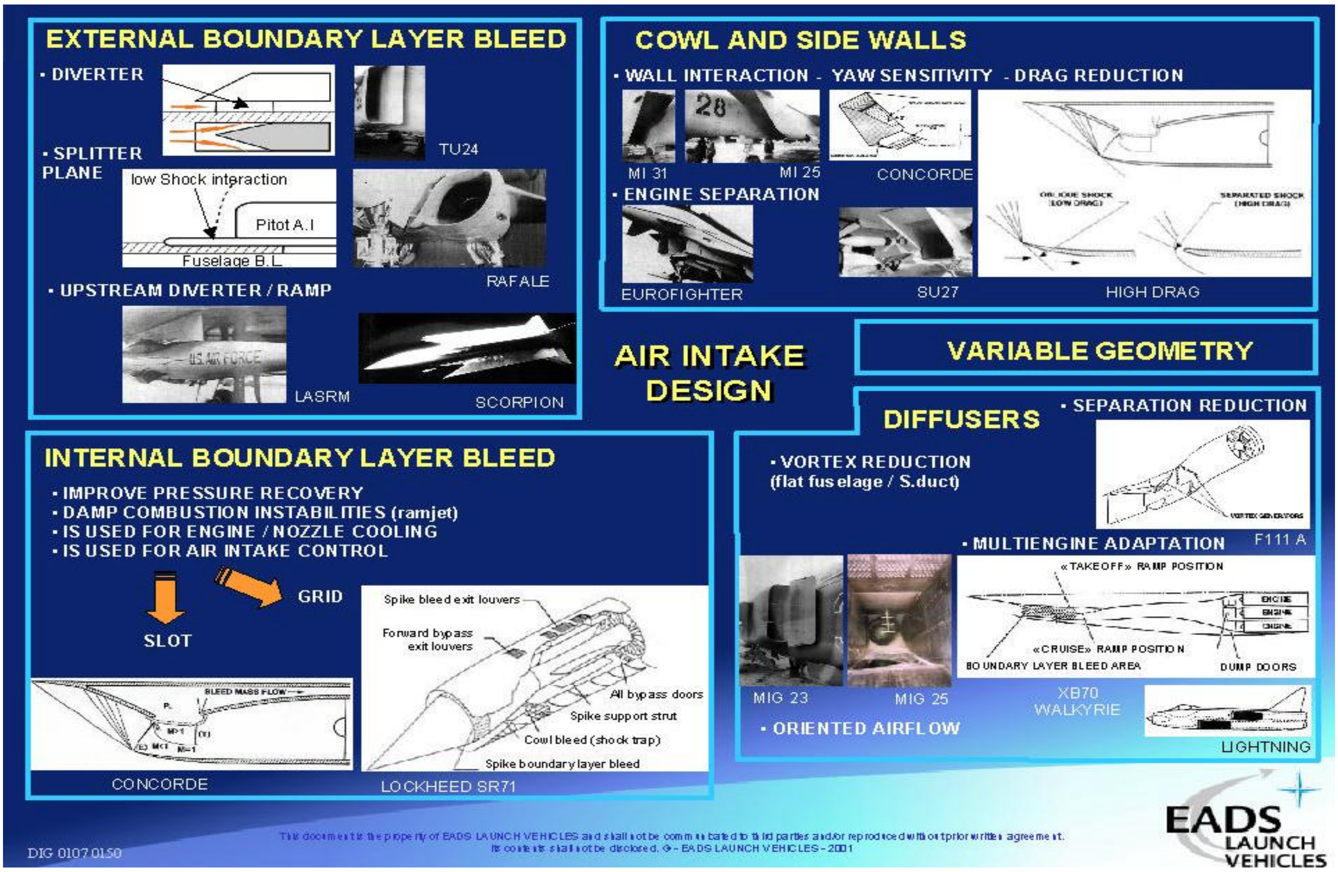


FIGURE 9

9. General Air Intake Design (Figure 9)

9.1 External Boundary Layer Bleeds

In many configurations, the air intake is close to the fuselage wall. It is essential to separate the intake from this wall in order to avoid capturing the boundary layer that develops there. The resulting space between the intake and the fuselage is called the external boundary layer bleed. It generally consists of a sort of diverter that deviates the boundary layer to either side of the intake. The flow is sometimes totally or partially captured for the conditioning system. The initial angle and position of the diverter optimised to prevent the interaction with the boundary layer from entering the intake. The broader the air intake, or if there are several of them side by side, the more critical the problem of evacuating this flow will be. The trap height is an optimum between the propulsive performance of the nacelle and its drag.

With air intakes on the fuselage, notably the Pitot type, the normal shock positioned at the entrance interacts with the fuselage boundary layer.

This is generally very much attenuated by the presence of a splitter plane just upstream (Rafale). It should be noted that this interaction, while limited, may induce a slight compression by oblique shock, which is more favourable than the nominal normal shock. This interaction favours the starting of air intakes with mixed compression.

As was already pointed out for the hypersonic air intakes of the Scorpion (section 7.2), a precompression ramp or upstream diverter (LASRM) can also be used for air intakes with ramp to deviate the flow toward the fuselage.

9.2 Cowls and Side Walls

To avoid these interactions with the fuselage boundary layer, deep cuts can be made in the side walls (Mig M31, Mig 25).

The purpose of the side walls on two-dimensional air intakes is to ensure:

- a two-dimensional internal flow,
- the structural strength of the air intake.

However, these generate at least two problems:

- interactions between their internal boundary layers and the shocks from the ramps (critical for the Crocodile air intakes)
- high sensitivity to yaw angle, which can be attenuated by appropriate cuts, but which produces mass flow rate losses at zero yaw angle (Concorde, SU 27).

While the cowl lip is thick in subsonic flight, to create a suction effect that will minimise drag, it is essential in transonic and supersonic flight to have sharp lips to create oblique shocks rather than strong shocks that influence the air intake's propulsive performance, in addition to the drag (Concorde diagram).

The side walls are also expected to keep the engines from interfering with each other if one of them fails. To do this with two-dimensional air intakes separated by a side wall, this common one must be extend farther forward (Eurofighter).

Of course, this will not improve the sensitivity to yaw angle, which requires side wall cut as discussed before.

9.3 Internal Boundary Layer Bleeds

These bleeds are generally indispensable in supersonic air intakes (except for the Pitot type) to prevent internal interactions from propagating their effects to the engine. These traps:

- improve air intake pressure recovery,
- serve to damp instabilities from the engine (notably for ramjet combustion instabilities),
- are used to capture the flow needed to cool the engine and/or the nozzle (Concorde), serve as air intake operating regime reference (cavity pressure) in the servo loop for moving components.

There are two broad families of internal boundary layer bleeds:

- wide open cavities (Concorde),
- perforated surfaces (Lockheed SR 71).

These bleeds are very delicate to perfect, and this can only be done by experimental means today. Air intake performance depends very strongly on the success of these bleeds. This also demonstrates the need for large-scale models and for large and/or pressurised wind tunnels to achieve Reynolds numbers as close as possible to those of flight. Otherwise the shock inclinations will not be right and the shock will impact the walls at the wrong points. This is even catastrophic for intakes with several internal shock reflections: the errors are amplified.

9.4 Diffusers

The diffuser is a duct linking the air intake to the engine entrance plane, so the non-alignment of the intake and entrance plan has to be considered along with their different sectional areas and shapes. The diffuser is used to convert the flow to the desired speed for the engine, and with minimum distortion (which is not critical for ramjets as long as the distortions are known).

Certain configurations induce vortex flows:

- upstream of the air intakes for flat fuselages with sharp corners,
- in S-shaped intakes.

To break up these vortices, plates are placed longitudinally in the diffuser (Mig 23). Other devices can be installed in the same way to re-orient the internal flow, such as by fixing the plate on some moving element like the ramp (Mig 25).

For large variations of form or cross-section, internal separations can be avoided by equipping the diffuser with vortex generators (F111A). The electromagnetic discretion of these diffusers is discussed in section 8.2.

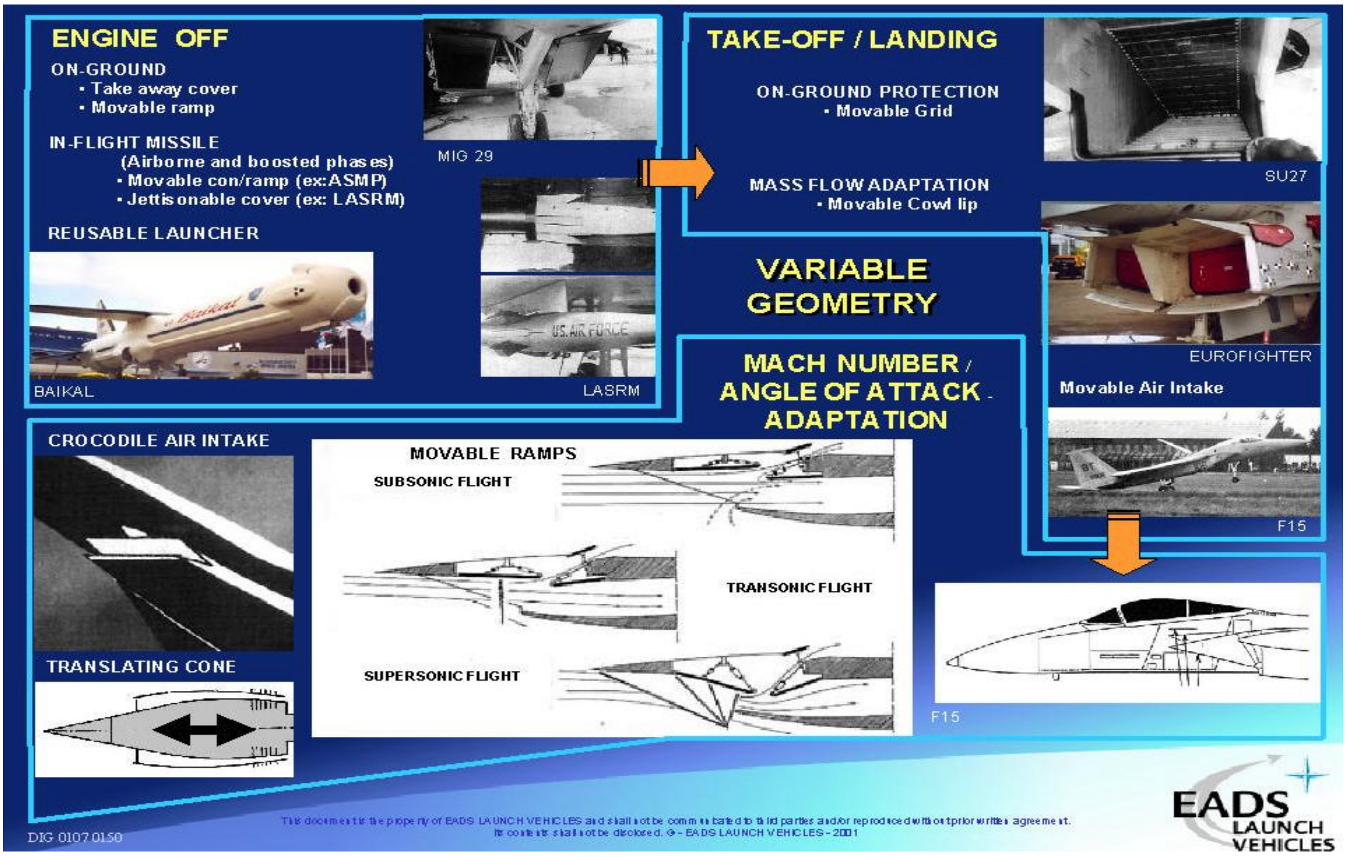
Exceptionally, a single air intake may supply several engines. This is a risk that is rarely taken because of the delicate problems it induces if ever an engine fails. We may mention two examples, though: the Lightning and the XB70 Walkyrie. In the latter, each intake in fact feeds three engines, but a discharge trap is provided just upstream of each engine to be opened quickly in case of failure, to evacuate the excess flow.

10. Variable Geometry (Figure 10)

10.1 Engine Off

The air intakes are plugged in parking mode, to prevent the entry of any foreign matter:

- generally with a removable rigid or flexible cover, sometimes by turning the ramp (Mig 29).



ENGINE OFF

ON-GROUND
- Take away cover
- Movable ramp

IN-FLIGHT MISSILE
(Airborne and boosted phases)
- Movable con/ramp (ex:ASMP)
- Jettisonable cover (ex: LASRM)

REUSABLE LAUNCHER

MIG 29

BAIKAL

LASRM

TAKE-OFF / LANDING

ON-GROUND PROTECTION
- Movable Grid

MASS FLOW ADAPTATION
- Movable Cowl lip

SU27

EUROFIGHTER

Movable Air Intake

F15

VARIABLE GEOMETRY

MACH NUMBER / ANGLE OF ATTACK ADAPTATION

CROCODILE AIR INTAKE

TRANSLATING CONE

MOVABLE RAMPS

SUBSONIC FLIGHT

TRANSONIC FLIGHT

SUPERSONIC FLIGHT

F15

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FIGURE 10

For air-breathing missiles, there are two flight configurations to be considered with the engine off:

- when the missile is being carried by the aircraft,
- during boosted phase by solid booster.

For this:

- a mobile element (ramp or central body) can be used to block the intake totally or mostly, during these flight phases, and then be set to its nominal operating position by a pyrotechnic device at the time of ramjet ignition (ASMP).
- or an ejectable block can be placed in front of each air intake (LASRM), but this alternative is generally refused for reasons of safety for the carrier aircraft pilot.

An entirely new possibility is coming to light for reusable space launchers. The first stage becomes reusable with the deployment of a wing and auxiliary propulsion such as a turbojet.

The Baikal project proposes a Pitot air intake on the nose of the first stage, with a pivoting cover to shut the intake in the ascent phase.

10.2 Take-off and Landing

The protective grid for roll-out has already been mentioned in section 3.4 (SU 27).

The large need for air at low velocity may call for a mobile cowl to increase the capture cross-section, with a profile designed to avoid separation (EuroFighter). The American F15 goes beyond this: the entire forward part of the air intake pivots, thereby simultaneously modifying the captured air flow and serving as aerodynamic flight control surfaces.

10.3 Shock-on-lip Mach Number and Angle of Attack

For two-dimensional air intakes, the mobile elements described above are used directly for flight at high angles of attack. If the Mach range is large, they are combined with internal variable geometry. One of the diagrams in figure 10 also shows mobile ramps to either side of the internal trap for the F15, and the regulation controls for the trapped flow. This configuration allows a large cross-section of passage at the throat in transonic flight, and good compression in supersonic flight. The other means presented in this figure have already been commented (section 4.2).

11. Particular Integrations (Figure 11)

11.1 General

Figure 11 summarises the variation in fuselage-mounted air intake pressure recovery at Mach 2 as a function of the angle of attack. Here, the excellent behaviour of intakes on the windward surface of the fuselage or wing is confirmed, in contrast to those on the leeward surface. This is confirmation of what was said in section 6.2 where the explanations are given. Despite this, special configurations exist aside from those stemming from electromagnetic discretion. A few of these are mentioned here.

The associated diagram is a quantitative example of the various fuselage effects: overspeed, local deviation, and Mach gradient, which in this ordinary case account for 5 % of losses and confirm the importance of the air intake location and orientation.

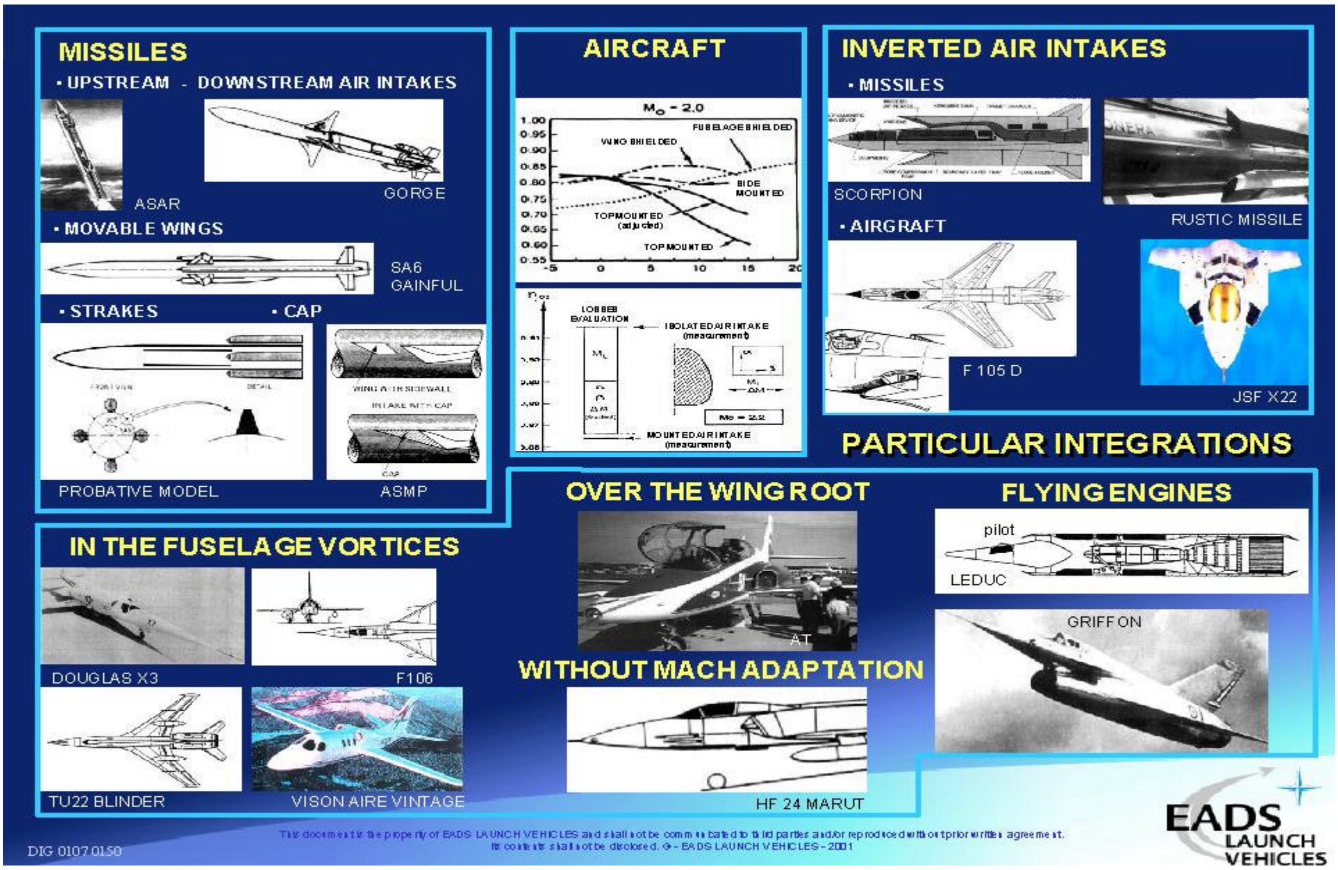

FIGURE 11

11.2 Missiles

While lateral intakes for missiles are generally positioned at about the middle of the fuselage, certain extreme cases can be found, at least at the level of projects:

- air intakes on the nose cone (ASAR), which are advantageous for the local overpressure but which must be catastrophic for the mass budget and aerodynamic pressure centre;
- downstream air intakes (GORGE), which are certainly ideal for the weight balance but are aerodynamically poor for two reasons:
  - the diffusers are very short and hardly efficient,
  - the boundary layer is captured, with vortices when placed at incidence, and wing wakes.

Another way of countering the effects of angle of attack on the air intakes is to limit this incidence as much as possible by providing missile lift with mobile wings. This technique has been applied to old Soviet missiles (SA6 Gainful). For missiles equipped with air intakes globally running along the aft half, the intakes themselves are lifting surfaces for the missile.

French and English work on cruciform missiles have shown the advantages of strakes along the fuselage upstream of the intakes. For angles of attack less than about ten degrees, these serve to disorganise the two fuselage vortices which are very harmful for the two leeward surface air intakes, and replace them with four smaller vortices that initiate much farther downstream, beyond the air intakes. ONERA's probative model was designed this way.

In the same way, for lateral two-dimensional air intakes (ASMP), flight at high Mach number at incidence was initially dealt with by placing a small wing just upstream of each intake.

Then the wing and air intake were merged, which meant adding an additional ramp to the initial air intake to replace the wing effect. This concept allows a much lighter global structure.

11.3 Inverted Air Intakes

For cruciform missiles with high manoeuvrability, the intakes can be placed as scoops to capture essentially the healthy flow far from the fuselage, thereby deviating the boundary layers and vortices to either side of the air intakes. This principle has been flight-validated for Mach 2 (rustic missile) and wind tunnel-validated from Mach 3 to 6 with the Scorpion project. This kind of configuration can be found on old aircraft (F105 D) and new (JSF X22).

11.4 Special Configurations

Certain experimental vehicles can be viewed as flying engines, with a fuselage mounted on the engine rather than the reverse (Griffon). The fuselage can even be the nacelle and the pilot has to cram himself into the nose ahead of the air intake (Leduc).

The case of the Douglas X3 with its air intakes on the upper surface and slightly separated has already been presented and explained in section 6.4. The "Vison Aire’Ventage" business jet may enter this same category in a first approximation, but it is much more difficult to explain the choice of this configuration for fighters (TU 22 Blinder and F106 Delta Dart).

An equivalent configuration is found with the "AT" trainer, for which the air intakes are placed at the wing root, but above and slightly downstream of the leading edge in an overspeed zone. This recent choice of configuration deserves a few explanations.

The last configuration to be presented is nothing special in terms of the air intake location, but by the orientation of the intake section, which is not perpendicular to the compression cone. This orientation could be explained by the probable direction of the local flow, but leads to a configuration in which the shock-on-lip Mach number is not definable.

12. Wind Tunnel Tests (Figure 12)

Wind tunnel tests are essential for designing air intakes and require many set-ups to cover all requirements. The means developed in France for ONERA wind tunnels are presented here.

12.1 Visualisations and Measurements

The schlieren is the basic flow visualisation in supersonics. It is crucial for piloting such tests (visualisation in the first Concorde interaction model). To analyse internal flows, especially for high angles of attack, smoke visualisations are conducted with illumination by laser planes and analysed by a minuscule camera on the end of an optical fibre.

Air intake characteristics are based essentially on three parameters:

- pressure recovery, which is generally obtained by integrating the Pitot pressures measured with a rake,
- distortion, which is determined from these same measurements,
- mass flow rate, which is generally deduced from the measurements made by a sonic throat flow-meter (in supersonics) or a Venturi (in subsonics).

These three parameters are acquired throughout the air intake's operating domain, which is simulated by continuously reducing a sonic throat downstream. This geometric blockage is equivalent to increasing the engine's operating fuel to air ratio, a thermal blockage. A very important point in the measurement is knowing the exact operating limit in subcritical regime, which corresponds to a passage through buzz regime, which is very dangerous considering the intensity of these oscillations. For modern fighters, the first two parameters also have to be acquired in non-steady flow, notably for the configuration at high angles of attack. A rake with many non-steady sensors is used for this (48-sensor rake).

However, drag measurements are needed, notably to optimise certain components like the precompression ramp on the Scorpion missile (set-up at S5 Chalais).

12.2 External Field

The aerodynamic field around the fuselage is now generally known, thanks to computer simulations. For a cylindrical fuselage common to various missiles, it is also possible to obtain this field by moving a rake through the flow carrying multi-hole probes and reading the local pressure and direction of flow.

12.3 Internal Performance of Isolated Air Intakes

The first step in developing an intake is to qualify it alone, without counting in the effects of the fuselage. Figure 12

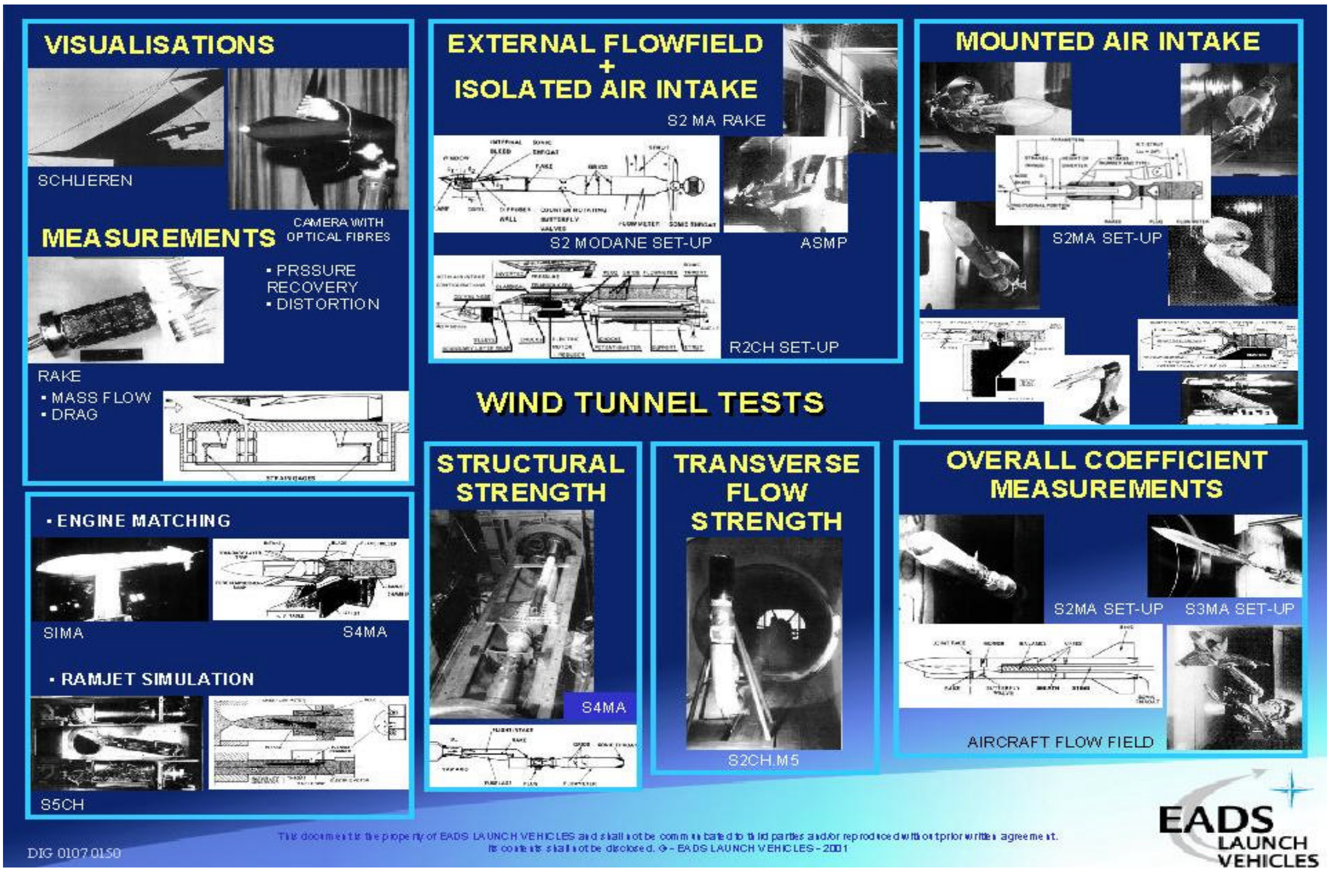

FIGURE 12

shows the full-scale set-up used for the ASMP intake at the S2 wind tunnel in Modane. There are a number of drives for moving the ramps in order to perform the maximum number of measurements during the test, which can be as long as desired in this continuous wind tunnel.

The side walls are equipped with glass windows to visualise by schlieren the internal flow at the level of the throat where the internal boundary layer bleed is located. The pressure recovery is measured with a rectangular rake. The obstruction is varied by two counter-rotating flaps, which have two advantages:

- moderate control torques,
- the flow is not deviated, so its homogeneity is of better quality at the level of the flow-meter.

Another set-up with the same functions is presented for the development of the Scorpion air intake. It is smaller, in order to be compatible with the R2 Chalais wind tunnel. The motorised systems for varying the geometry are replaced by interchangeable parts, considering the brief duration (< 30 s) of the tests in this blowdown wind tunnel.

12.4 Internal Performance of Integrated Air Intakes

While the above step is needed for choosing the type of air intake and its main geometric characteristics, it is entirely insufficient for qualification purposes, for which the aerodynamic field of the fuselage is very generally indispensable. In supersonics, just the part of the fuselage upstream of the air intake entrance plane needs to be represented.

One set-up for the S2 wind tunnel at Modane has been diagrammed. This has been used on many occasions for missile development in the wind tunnel's Mach 1.6-3.2 envelope, a few examples of which are presented. Two other set-ups developed for blowdown hypersonic wind tunnels in the framework of the Scorpion work are also presented in figure 12.

12.5 Overall External Coefficients

The external aerodynamics can be qualified experimentally only if the stream tubes passing through the air intakes are simulated correctly. The model tested at S3 Modane is mounted on a six-component dynamometric balance. The effect of the internal flow is corrected by measuring the captured mass flow rate with a sonic throat placed in the plane of the base. The air intake regime is in this case rarely modified in the course of testing, and is then supercritical. The regime is varied in the second set-up presented here because, for nose air intakes, this parameter significantly affects the overall external coefficients.

The S2 wind tunnel at Modane is also equipped with a "six-degree-of-freedom" device to simulate a gradually varying missile trajectory in the aerodynamic field of the carrier aircraft during firing phase.

12.6 Cross-flows

Crosswinds, and high angles of attack in general, lead to internal separations that must be qualified, notably with non-steady measurement means. This set-up designed for S2 Chalais is based on a suction device associated with a rake positioned in the compressor entrance plane.

12.7 Structural Strength

The test presented was necessary for validating the structural strength of an air intake in wound composite materials.

Three points were verified during the test:
- intake performance at full scale with flight components,
- the strength of the composite with the internal flow representative of real flight conditions,
- the buckling strength, as buckling conditions may occur at times when the air intake is operating in very supercritical regime, when the booster has been jettisoned but the ramjet is not yet ignited.

12.8 Air Intake / Engine Matching

The first test presented, which was conducted at S1 Modane, was to test the intake in the presence of the turbojet in sub- and transonic flight. The electromagnetic and infrared discretion were measured at the same time.

The second concerns a ramjet test at Mach 6 in the S4 Modane wind tunnel with the missile at incidence and in its poorest roll position as concerns air intake operation. The engine is installed in place of the flow-meter used in the first air intake qualification tests.

The third test presented was conducted at S5 Chalais to determine the effects of low-frequency combustion instabilities (ramjet) on air intake operation. The instabilities were simulated by a sinusoidal oscillator (a voice pipe as used in the navy to talk between ships). This is a delicate point because it has stopped ramjet missile projects in the past.

13. Conclusions

Air intakes are necessary for all vehicles propelled by air-breathing means, whether they be aircraft, missiles, helicopters or, in the future, reusable space launchers. They will directly condition the propulsive performance (thrust, drag, weight, thermal properties, lift) of the vehicles in which they are mounted. They are subject to a multitude of constraints (Mach number, angle of attack and yaw angle, possible injections, discretion, engine failure, among others).

The first step in air intake design is thus to **"clearly identify all of the air intake's specifications"**.

After a short phase in which the air intake is defined alone comes the phase in which the external aerodynamic field is effectively considered with its over- and under-speeds, vortices, boundary layers, transverse gradients, nose and other effects.

The second step is thus to "**find the best location for the air intake(s) and, if possible, modify the upstream part of the fuselage to improve the captured air flow**".

Air intakes have very complex internal flows, including sub-, trans-, and supersonic zones simultaneously. There are many interactions (shock/shock, shock/boundary layer, vortex/wall, corner effect) and they are generally combined. Many non-steady aspects are to be considered, and notably the buzz which is critical for structural dimensioning and operating limits. The air intake's matching with the engine that it supplies must always be ensured.

The third step is then to "**carry out some calculations, but use essentially previous experience (bibliography, personal knowledge) and wind tunnel tests at high Reynolds numbers**".

Air intakes must be designed by a "System" approach. Optimising them is a long and difficult process.

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