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AIR INTAKES FOR A PROBATIVE MISSILE OF ROCKET RAMJET

G. Laruelle

Translation of "Prises d'air pour missile probatoire de statofusée", L'Aeronautique et l'Astronautique, No. 98, 1983, pp. 47-59.

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16. Abstract The methods employed to test air intakes for a supersonic guided ramjet-powered missile being tested by ONERA are described. Both flight tests and wind tunnel tests were performed on instrumented rockets to verify the designs. Consideration as given to the number of intakes, with the goal of delivering the maximum pressure to the engine. The S2, S4, and S5 wind tunnels were operated at Mach nos. 1.5-3 for the tests, which were compartmentalized into fuselage-intake interaction, optimization of the intake shapes, and the intake performance. Tests were performed on the length and form of the ogive, the presence of grooves, the height of traps in the boundary layer, the types and number of intakes and the lengths and forms of diffusers. Attention was also given to the effects of sideslip, flow separation, the forward intake tip, and the intake drag. Finally, the effects of the longitudinal and circumferential positions of the intakes were also examined. Near-optimum performance was realized during Mach 2.2 test flights of the prototype rockets.

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AIR INTAKES FOR A PROBATIVE MISSILE OF ROCKET RAMJET

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Summary /47*

For the studies concerning the rocket ramjet, ONERA has developed, with the support of French Official Services, a probative missile powered by a solid fuel ramjet engine during the cruise flight.

This paper describes the methods and the experiments performed to define and optimize the air-intakes for ensuring the mission of the probative missile.

A special test rig allowing numerous variants has been built at a scale of about 1/3 for some experiments in the S2 supersonic wind tunnel of the Modane Center, in the Mach number range 1.8-3.

The last test has been performed in the S4 hypersonic wind tunnel, equipped for this case with a Mach 2 nozzle, on a real air intake with its duct, in the conditions of a flight at the altitude zero. The scale effect is studied and the results are compared to the ones obtained during the first ballistic flight.

Within the framework of its studies on rocket ramjets, ONERA has worked since 1970 in several directions: new solid fuels, rocket combustion chamber with possibility of integration of the accelerator, external and internal aerodynamics of missiles.

All of these analytical investigations, very encouraging, had to be verified in flight in order to precisely define in particular the

*"Numbers in the margin indicate pagination in the foreign text".

performances of new motors with realistic conditions for a missile.

ONERA was then charged by the French Official Services with devising, constructing, and firing "probative missiles" propelled by rocket ramjets fed with solid fuel. The tactical engine division of AEROSPATIALE and S.N.P.E. have been associated with the office for construction of these missiles.

Two phases were planned:
-The first was accomplished in 1976 by firing two non-guided missiles.
-The second, with guided missiles, has allowed us to verify the maneuverability of the missile and its consequences on the functionning of the motor.

Since 1974, and even more particularly during the accomplishment of this program, significant effort has been devoted to the study of air intakes from the experimental point of view. This work on the various possibilities of integration of air intakes on supersonic missiles continues with the support of the official services and allows ONERA to direct the industries concerned (AEROSPATIALE and MATRA) in the selection of a solution as a function of the mission and constraints retained. Optimization of this solution for the case considered was then made the objective of specific studies in cooperation with industry.

The present article has the goal of describing the methods developed to define the air intakes of this first missile, to explain the selection made, and to present the comparison of the results obtained in wind tunnels with those acquired in flight at the time of ballistic firings.

Notations /48

A_o upstream infinity section of the current tube captured by the air intakes

A_1 frontal section of the air intakes

A_2 section of the air intakes at the end of the sleeve

A_{ref} reference section: mid-ship frame of the missile ($A_{ref}=\pi D^2/4$)

C_x reported drag coefficient at the reference section

D diameter of the missile

h height of the external boundary layer trap

H height of two-dimensional air intakes

L width of two-dimensional air intakes

M_0 Mach number for upstream infinity

p pressure

P_{i0} pressure generated by the upstream infinity

p_{i2} average pressure generated at the end of the diffuser

R radius of fuselage

R_D reported Reynolds number at the fuselage diameter

X.Y.Z coordinates in a trihedron tied to the missile

α incidence

β sideslip

ε flow coefficient

Φ angle of roll

$\eta 02$ efficiency of the air intakes ($\eta 02=p_{i2}/p_{i0}$)

$\bar{\eta} 02$ useable efficiency

Definition of the Probative Model

Mission

Experimentation in flight had two primary goals:
-to verify the total amount of propulsion (thrust-drag)
-to obtain technological data allowing us to validate the technical solutions retained in order to be able to apply them to operational missiles.

In order to attain these two goals, it was indispensable to devise a very realistic missile. Its general architecture has thus been defined by selecting a mission type: Sea-Sea missile flying at Mach 2 in low altitudes, its range should be approximately 100 km with some maneuvers.

Study of the cruising phase being the primary objective of these firings, acceleration has not been optimized; for economic reasons, an existing casing has been used to constitute the accelerator, placed behind the missile.

The first firings were not guided; the missiles have followed a ballistic trajectory, ensuring a significant duration of flight with a lower culmination at 5000 m. Nevertheless, the design of these first missiles was identical to that of future piloted missiles. Thus, the loaded fuel was not yet completely used at the moment of impact in the sea, at the time of ballistic firings.

Architecture of the Missile

Figure 1 presents a diagram of the entire missile. It is constituted of a releasable accelerator and of the missile itself which ensures cruising at a Mach number of approximately 2. This latter has a length of 5.5 m for a bore of 0.40 m. It is equipped with four air intakes followed by fairings to accomodate the guidance actuators between them. This selection of four air intakes, resulting from the method of piloting anticipated, will be precisely defined later.

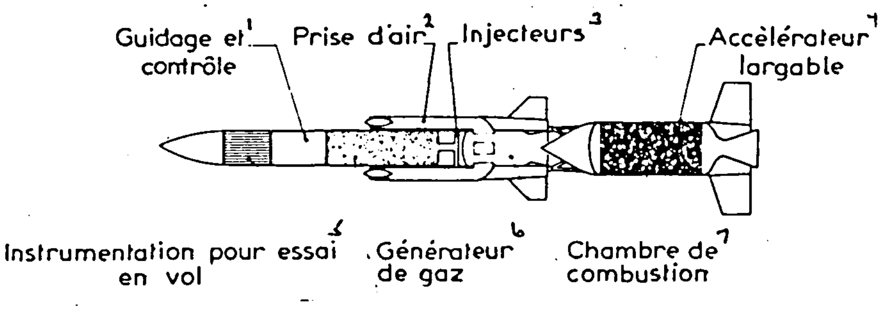

Figure 1. Diagram of the missile.

Key: 1-Guidance and control 2-Air intakes 3-Injectors 4-Releasable accelerator 5-Instrumentation for flight tests 6-Gas generator 7-Combustion chamber.

On the inside of the missile, from the front toward the rear, are located:

-instrumentation for these experimental flights with telemeasurement,
-equipment compartment for piloted flights,
-gas generator,
-rocket ramjet chamber. /49

Figure 2 presents the missile at firing pitch of the Landes test center.

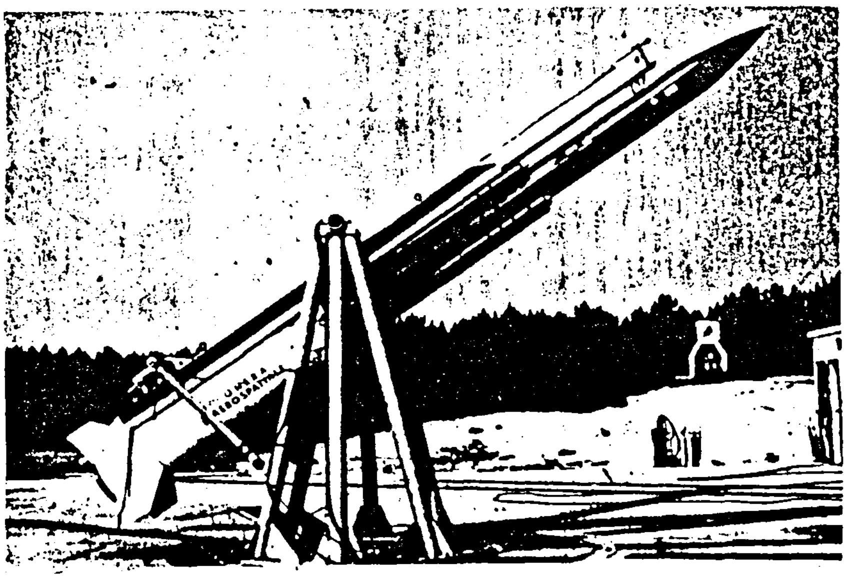

Figure 2. Missile ready for firing at Landes test center.

If we consider the flow around the fuselage, some simple remarks can guide the positioning of the air intakes.

Generally the nose cone cylinder adaptor does not have a continuous curvature and induces a local overspeeding; figure 3 presents the distribution of the Mach numbers at the wall of the probative model for a Mach 2 flight at zero incidence. The role of the air intakes being to decelerate the flow, it is pernicious to place them in a zone of overspeeding, thus toward the end of the nose cone or on the start of the cylindrical body.

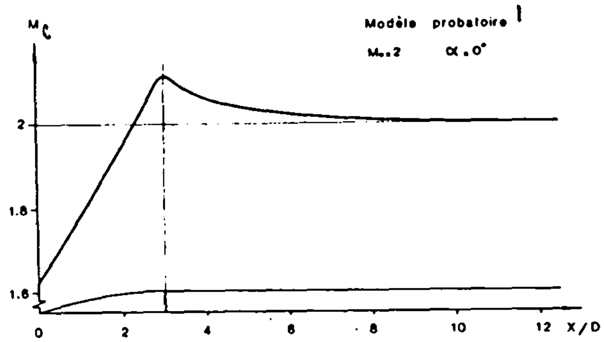

Figure 3. Mach number at the wall.
Key: 1-Probative model.

Flow Around Streamlined Bodies: General Considerations

For a missile of incidence, the theory of slender bodies provides for a local maximum incidence on the generators placed at 90^{o} in relation to those of the lower surface or upper surface, and equal to double the incidence of the body. This signifies that for a missile equipped with lateral air intakes, it would be necessary to design air intakes which, isolated, function in correct fashion at incidences α P. A. clearly greater than the maximum incidence α_m of the missile. Figure 4 demonstrates the decrease of this local incidence α_1 if we extend it onto the fuselage; a ratio $\alpha_{P.A.}/\alpha_m$ of approximately 1.5 is a good average value for the mean flow entering into the air intake.

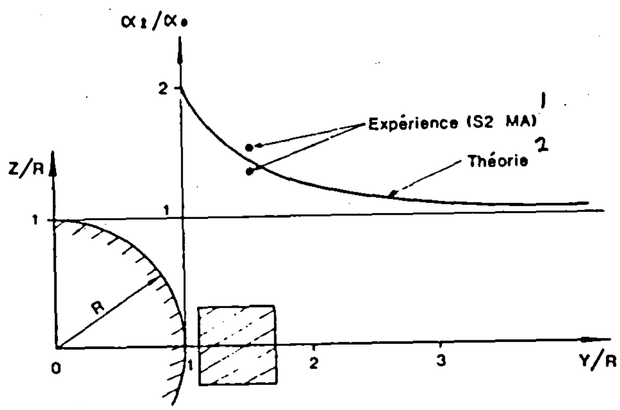

Figure 4. Local incidence
Key: 1-Experimental 2-Theoretical.

In the case of missiles with four entries, for this position in +, the two air intakes will be in side-slipping of high amplitude, which is particularly unfavorable for two-dimensional air intakes; the position in X allows us to attenuate this local side-slipping. /50

The role of the air intakes being able to obtain a recompression as possible, it is necessary to avoid placing them in a zone where the flow is in overspeeding or at low energy.

Such situations clearly present themselves when the incidence of the streamlined body created from vortical structures or when the air intakes are located in a region where the boundary layer is thick. Figure 5 reports that if the air intakes are placed far from the nose cone, they would be affected (according to their position in rolling) by the two vortices created at the upper surface of the body and for more and more moderate incidences when the position of the entries is more remote. Figure 6 presents for two longitudinal positions the thicknesses of the boundary layer of the upper surface measured in the wind tunnel for several incidences. The presence of the vortex at X= 9.9 D is visible from 6°.

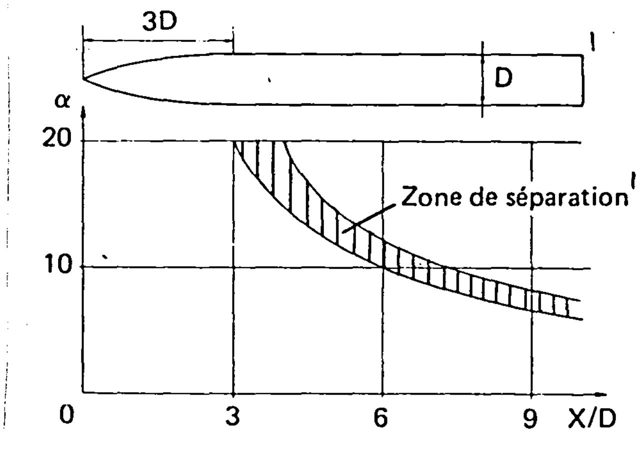

Figure 5. Vortical exhaust.
Key: 1-Zone of separation.

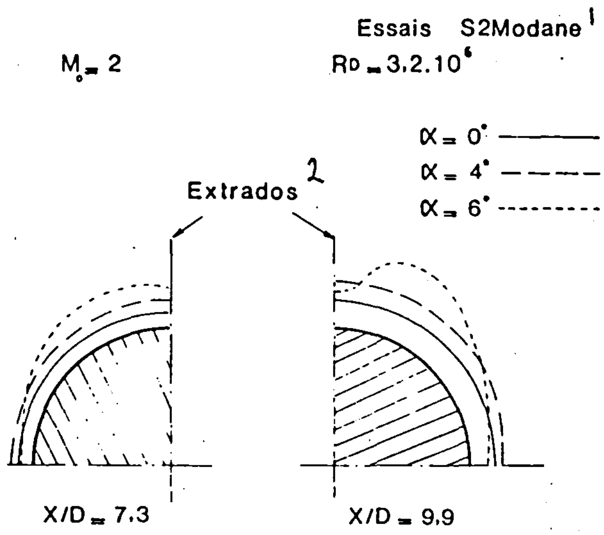

Figure 6. Boundary layers.
Key: 1-Modane S2 tests 2-Upper surface.

Consequently, if the missile must fly at high incidence the very remote positions would be unfavorable for cruciform configurations.

Test Methods

Three wind tunnels of the Office have been used to qualify the air intakes of missiles in the Mach realm of 1.5-3:
-Wind tunnel S2 of the Modane Avrieux center where a complete installation has been created at significant scale to study the influence of the fuselage;
-Wind tunnel S5 installed in the Paris region at Chalais-Meudon where little tests on isolated air intakes are carried out;
-Hypersonic wind tunnel S4 of Modane modified with a Mach 2 nozzle of large enough dimensions allowing us to test an actual air intake with exact conditions generated from a Mach 2 flight at zero altitude.

Wind Tunnel S2 of Modane-Avrieux

This wind tunnel has continuous functionning. It is pressurized

(P_i=1.64 at Mach 2) and possesses two interchangeable streams: transonic and supersonic. This latter has a height of 1.83 m for 1.75 m width.

Deformation of the walls at the level of the collar allows us to obtain continuous development of the Mach number between 1.5 and 3.1.

For the studies of air intakes, we use a model of 150 mm diameter, and whose diagram is presented in figure 7 and a view in the stream on the following figure (8).

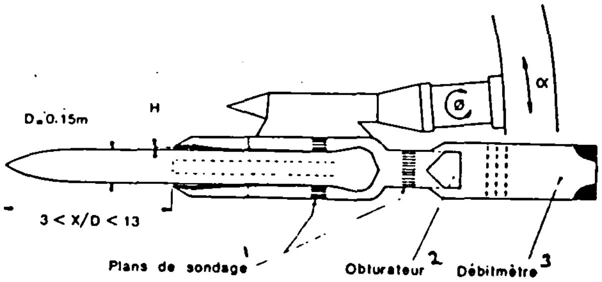

Figure 7. Diagram of the installation with fuselage.

Key: 1-Probe surfaces 2-Obturator 3-Flowmeter.

This model is constituted of a set hung under the tip of the wind tunnel which allows us to vary the incidence and the roll. Different parameters can also be studied: /51

-length of the nose cone;

-shape of the nose cone;

-height of the boundary layer trap;

-presence of grooves;

-types and number of air intakes (1, 2, 3, or 4);

-length and shape of diffusers.

Static pressure and arresting intakes placed at the end of the sleeve and in the rocket ramjet chamber allow calculation of the effi-

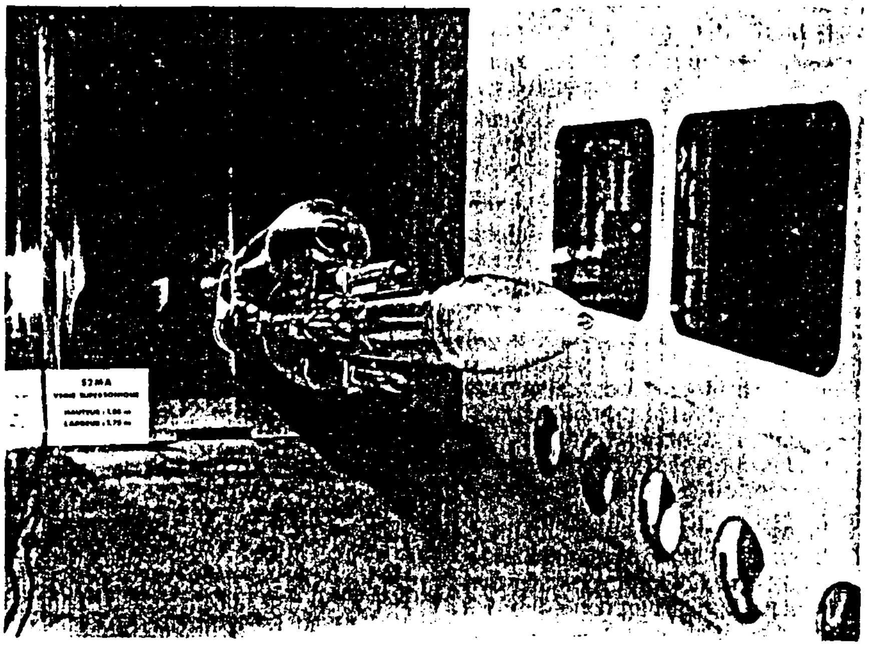

Figure 8. Model at Modane S2.

ciency. The flow is measured thanks to a sonic collar flowmeter placed downstream of an adjustable obturator which allows us to simulate the various functionning regimes of the air intakes.

The Reynolds number obtained is approximately 1/6 that of a low altitude Mach 2 flight.

Wind Tunnel S5 of Chalais-Meudon

This is also a continuous supersonic wind tunnel, with return, whose stream has 30 cm on one side. The conditions generated are approximately ambient atmospheric conditions. Thanks to an assortment of 6 pivoting nozzles, all the Mach numbers included between 1.5 and 3.2 can be accomplished.

The size of this wind tunnel allows us to focus the air intakes constructed for the model devised for S2 MA. Various tests are possible, for example:
-influence of cutting up of the sides of the two-dimensional air in-

takes placed in side-slipping;
-tests of abrupt disengagement;
-study of the stems forming the external boundary layer trap;
-measurement of the drag of air intakes on wall balance (figure 9).

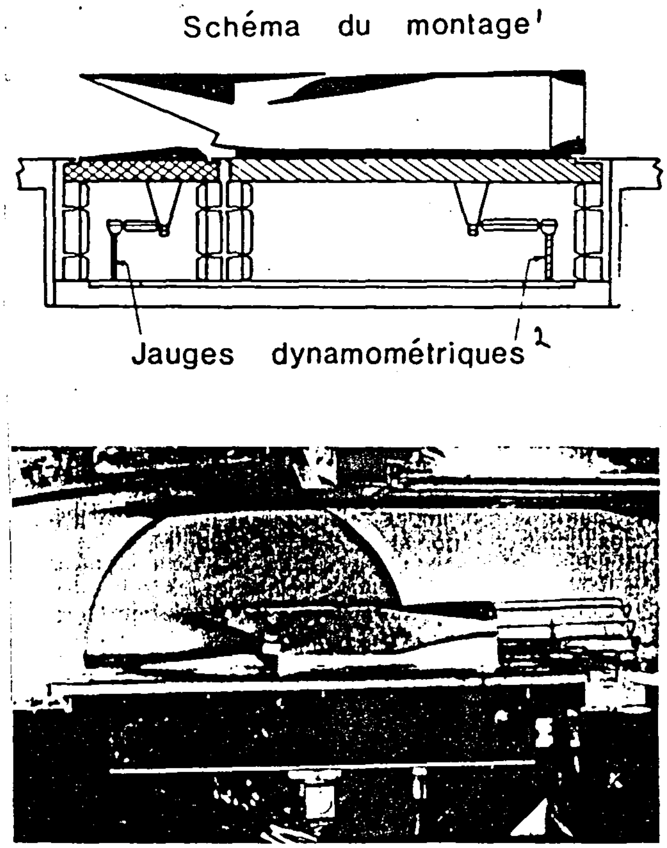

Figure 9. Measurement of drag at Chalais S5.
Key: 1-Diagram of the installation 2-Dynamometric gauges.

Wind Tunnel S4 of Modane-Avrieux /52

The hypersonic wind tunnel S4 of Modane-Avrieux is gusty. It presently possesses a single Mach 6 nozzle of 68.5 cm diameter. With the possible conditions generated P_i=25 b and T_i=1600°K (1800°K max), it is possible to simulate an actual flight at Mach 6 and 30 km altitude.

For tests concerning present rocket ramjets (Mach 2-3), we only use its possibilities of storage and significant flow of compressed and warm air and special nozzles are created as a function of the missiles to be tested. For tests at Mach 2, it is possible to restore flight conditions at approximately 1 km altitude (altitude of the Modane test center). For a Mach number of approximately 3, the agreement with hollow spheres placed downstream of the wind tunnel allows us to simulate altitudes greater than 20 km.

Figure 10 demonstrates a view of the wind tunnel with the Mach 2 nozzle of 24.3 cm diameter placed in front of an actual air intake of the probative missile. Such tests allow aerodynamic studies, but also technological studies of air intakes; the "Experimental study" paragraph precisely defines this installation.

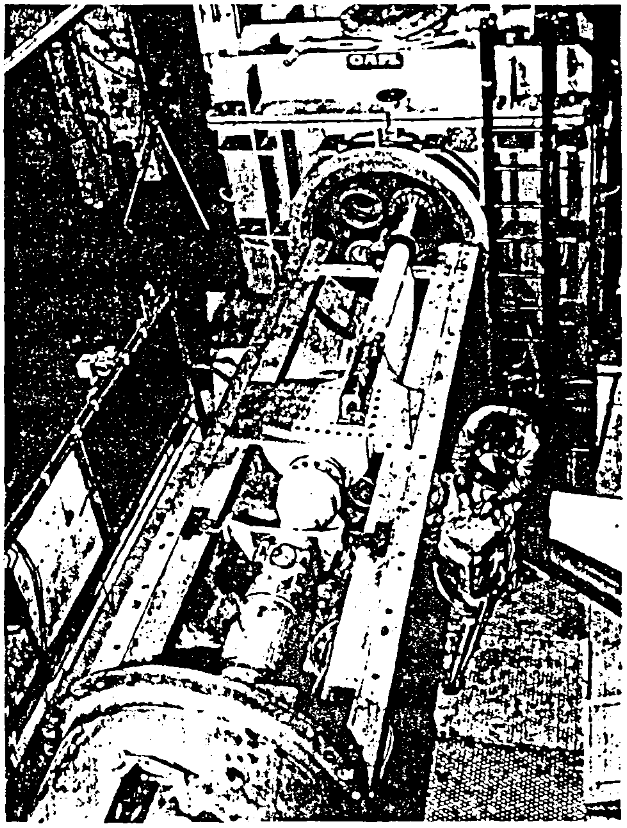

Figure 10. Test of an air intake at Modane S4.
Possible side-slipping.

For the probative model, a second installation with 4 rotating nozzles feeding the four air intakes has also been constructed. It has allowed us to ensure good functionning of the rocket ramjet (preserving thermal protections) during tests of long duration.

Selection of Air Intakes

Number of Air Intakes

With the mission of the probative model, maneuvers in all directions have been retained, which has led to investigation of the most axisymmetric configuration possible:
-A single air intake placed in front has not been retained in order to have a realistic missile whose propulsion portion is uncoupled to the maximum from the operation portion (load-compartment).
-Two air intakes only favor a plane of symmetry, which imposes a piloting type plane with response times too long for such a missile.
-All the configurations with at least three air intakes are possible. The number 4 is justified by the custom of missile makers of putting four fins to uncouple the classes by yawing and pitching; a missile with three intakes and three fins downstream would have also responded to the problem.

Increasing the number of air intakes beyond 4 has no interest.

Types of Air Intakes

Shapes Studied

For cruciform missiles, four types of air intakes have been studied in wind tunnels in the presence of the fuselage (figure 11):
-semi-circular with a conical point;
-circular with a conical point (same definition as semi-circular), but biconical;
-two-dimensional called "standard" with the compression slope placed on

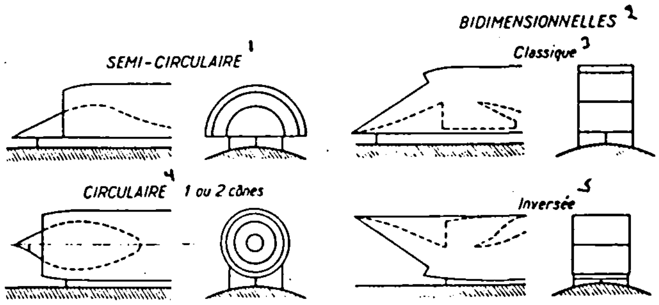

Figure 11. Air intakes studied.
Key: 1-Semi-circular 2-Two-dimensional
3-Standard 4-Circular 5-Inverted.

the fuselage side;
-two-dimensional called "inverted" with the compression slope becoming the flow toward the fuselage. /53

Semi-circular and circular intakes were not equipped with internal boundary layer traps, contrarily to the two-dimensional intakes.

Theoretical Considerations

On figure 12, the four families of air intakes have been designed from the face. They present two common characteristics:
-the entry section characterized by the rates of motorization (A_1/A_{ref}= 0.4 for the four entries);
-the height of the external boundary layer trap, that is to say the distance between the fuselage and the closest rim (h/D=0.063).

The shaded portions represent the keels or the thickness of the sides, and these hatches, the skin of the rocket ramjet chamber at the level where the four sleeves open.

From detailed study of the principal parameters of functionning (geometric and aerodynamic), it has been possible to define a certain number of considerations of general significance summarized below.

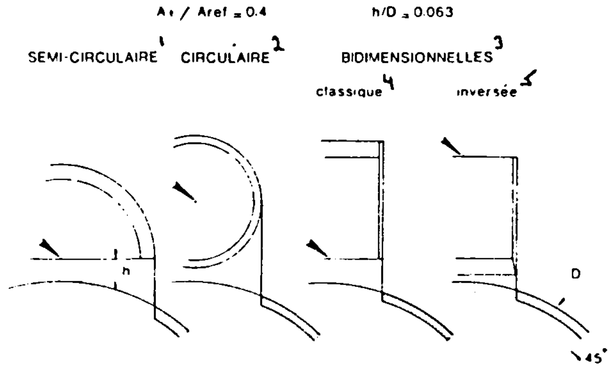

Figure 12. Shapes of air intakes.
Key: 1-Semi-circular 2-Circular 3-Two-dimensional 3-Standard 4-Inverted.

They should allow us to direct the selections and justify the compromises with which the architecture of a missile is confronted.

<u>Position of the Start of Compression</u>

This position is identified in figure 12 by an arrow: for semi-circular and standard two-dimensional intakes, compression is initiated in the vicinity of the fuselage, thus more or less in the boundary layer according to the incidence of the missile. Thus standard two-dimensional air intakes will be veritable "scoops" at the boundary layer, which is unfavorable for yield and produces a higher sensitivity to the incidence.

For circular intakes and "a fortiori" for inverted two-dimensional intakes, the flow is captured in a zone less affected by viscous effects, whose yield will be better.

If the start of compression is carried out in the vicinity of the fuselage, the keel will be from the opposite side, thus in the clear flow and the resultant drag will be increased (1/2 circular and standard two-dimensional intakes). For circular intakes, the keel will be partially within clear flow and within the boundary layer, but for inverted two-dimensional intakes, if the height of the trap is low, the keel will primarily be placed within the viscous layer, thus the drag will be lower and, besides, the stem separating the intake of the fuselage will be lower.

A second interesting point to note is the intersection of the shocks issuing from the air intakes with the boundary layer of the fuselage at the time of cases of flight at Mach numbers lower than that of the adaptation: the shocks issuing from the compression slopes then pass upstream of the keel. For "Mach 2-Mach 3" missiles flying at moderate altitude, the boundary layer of the fuselage is turbulent and the shocks indicated above induce slight loosenings which are going to require as small precompression slopes as can be favorable for the yield.

Width of Air Intakes

The larger the air intake, the larger the stem below it will be; this leads to more significant drag. From this point of view, two-dimensional and circular intakes are equivalent, only semi-circular intakes are penalized.

In the same fashion, the larger the entry, the greater the possibility of capturing the flow of the boundary layer. This is also true for collecting of the vortices issuing from the nose cone. When the incidence of the missile increases, vortices diverge from the fuselage; thus, with semi-circular intakes, the probability of capturing vortices as a function of the position in roll, and at the time of low incidences, is maximum.

The last point of this analysis is technological: if the entries are large, the inlets required at the level of the chamber are more significant, which reduces the width of the skin transmitting longitudinal strains; this would lead to a chamber bottom which is thicker, and thus heavier, and consequently, to a setback of the center of gravity.

Height of Air Intakes

Two antagonistic effects were observed: reduction of the height of the air intakes is favorable to the compactness of the missile, but leads to a reduction of no~mal stresses, which can impose the need for the presence of wings to allow significant maneuvers at altitude.

Useable Efficiency

Figure 13 presents a diagram precisely defining the definition of the efficiency called "useable" at $\alpha = 0^{o}$, taking into account a possible maneuver at a maximum incidence $\alpha = \alpha_o$, whatever the position in roll. The most critical incidence α_{CRIT} is generally the maximum incidence α_o. Indeed, the engines are generally designed with a fixed geometry for the air intakes and the rocket ramjet collar. If the flow of the fuel is prescribed, of a low modulation (case of solid fuels), it is necessary to size the collar of the motor in a fashion to avoid at any time an occurrence of evacuation of the air intakes.

Thus, we call $\bar{\eta}_{02}$ the "useable efficiency" for a flight in which the incidence attains the value α_o, the efficiency obtained at zero incidence with optimum adjustment of the collar allowing, at Mach number M_o considered, maneuvers going up to incidence α_o, for positions of /54
roll, without encountering evacuation.

It is necessary to note that the incidence α used presently is the angle formed by the direction of the wind and the engine axis. Then the position of the missile around its axis is identified by the angle of roll $\varnothing$, which is zero when one of the air intakes is placed on the upper surface.

Test Results

Figure 14 allows us to compare the development of useable efficiency at zero incidence as a function of the maximum incidence considered, for the various air intakes studied. The entries are placed

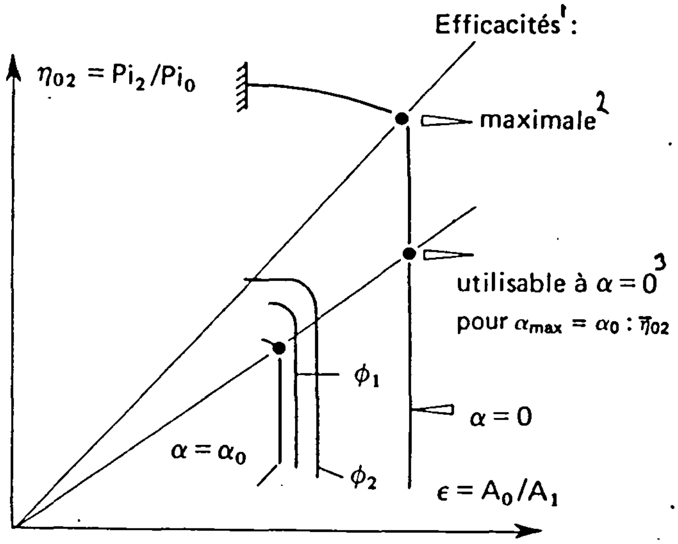

Figure 13. Definition of useable efficiency.
Key: 1-Efficiencies 2-Maximum 3-Useable at $\alpha=0$ for $\alpha_{max}=\alpha_0$: $\bar{\eta}_{02}$.

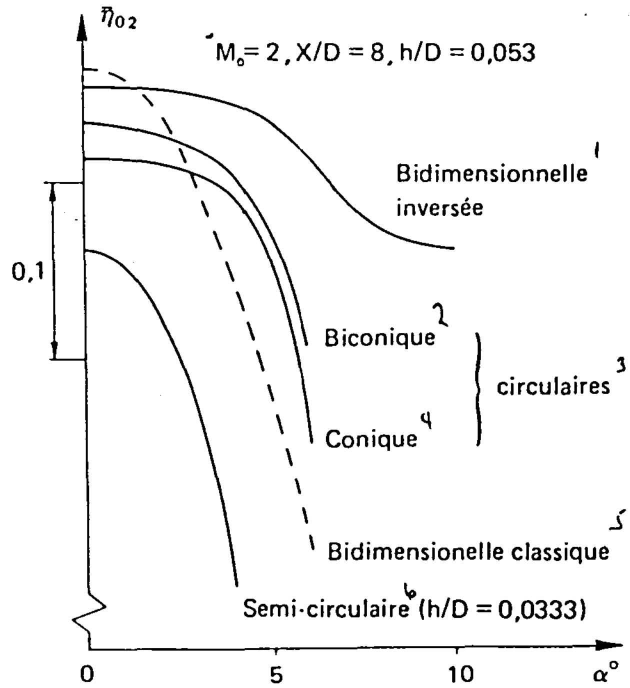

Figure 14. Comparison of the various air intakes studied.
Key: 1-Inverted two-dimensional 2-Biconical 3-Circular 4-Conical 5-Standard two-dimensional 6-Semi-circular.

on the body at approximately 8 diameters of the nose of the nose cone with a boundary layer trap of 0.053 D height (except for semi-circular intakes where the only test has been carried out at h/D=0.033).

At zero incidence, semi-circular intakes led to a much lower efficiency than circular intakes with conical points, while having the same compression and the same law of internal section, for the following reasons:
-the presence of a supplementary wall in the semi-circular intakes and the angles thus formed led to additional losses by friction;
-the external trap of the semi-circular intake is lower in height, the air intake captures a more significant portion of the boundary layer of the fuselage.

The trap being small, we observe a very great sensitivity of semi-circular air intakes to incidence. Even so, increase of the height of the trap is possible and the sensitivity will be reduced, but drag is going to rapidly increase.

Circular air intakes (conical or bi-conical) led to developments of equivalent useable efficiency, the difference is explained by modification of the outline of the central body (isentropic compression provided even greater efficiency).

Two-dimensional air intakes have even greater efficiency at zero incidence: this is easily explained by taking into account the definition of the compression slope (3 dihedrons) and the presence of an internal boundary layer trap.

Concerning the development of efficiency with incidence, the two two-dimensional intakes considered, standard and inverted, are very different. Standard two-dimensional intakes have performances which fall rapidly with incidence; they are comparable to semi-circular intakes as these have been planned and indicated in the paragraph entitled "Theoretical considerations".

On the other hand, inverted two-dimensional intakes have a clearly reduced sensitivity to incidence in relation to the other air intakes studied.

Drag of Air Intakes

/55

For each flying engine, attainment of good performances results from a satisfactory compromise between drag and thrust, this latter term being directly a function of the effectiveness of the air intakes.

Figure 15 presents a theoretical comparison of three large families of air intakes, from the point of view of drag. The air intakes are broken down into elements (keel, sides, ...) on which the drag wave is obtained by integration of the local pressure calculated by an expansion shock method from the uniform flow at the downstream infinity; we neglect the presence of the fuselage. Frictions are estimated by assimilating the various surfaces of the flat plates.

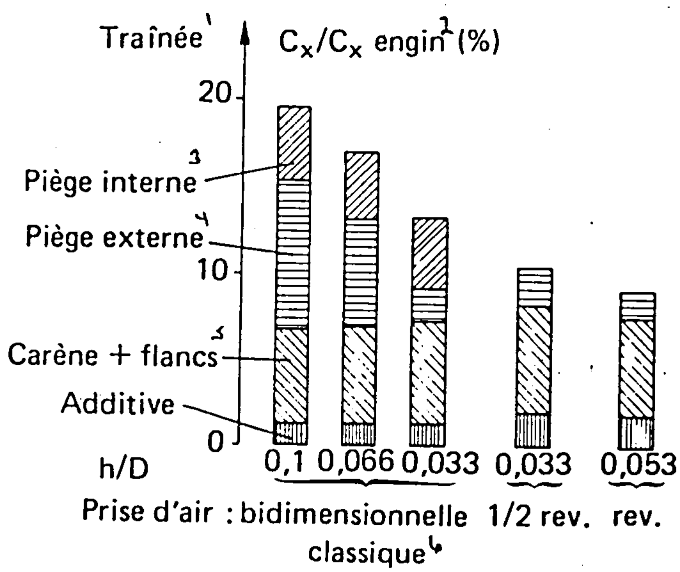

Figure 15. Schedule of drag.

Key: 1-Drag 2-Engine 3-Internal trap 4-External trap 5-Keel and sides 6-Air intakes: two-dimensional standard.

Standard two-dimensional air intakes have a better efficiency, but at the price of additional drag due to the internal boundary layer trap. At the same height of the trap, the air intake in rotation leads to minimal drag.

An experiment accomplished at the S5 Ch wind tunnel has allowed us to precisely define these theoretical results for the air intake in rotation and the inverted two-dimensional air intake which has very good performances. Figure 9 presents a view of the model in stream with the diagram of the force installation. With the inverted two-dimensional air intake, the keel is thus placed close to thefuselage, at the level of the boundary layer, which reduces drag. These tests have demonstrated that both air intakes were almost equivalent from the point of view of drag.

Influence of Height of Boundary Layer Trap

This influence is presented for standard two-dimensional intakes placed 8 diameters from the point of the nose cone at Mach 2.

On figure 16, the useable efficiencies at $\alpha=0$ for different maximum incidences are presented as a function of the height of the trap.

At zero incidence, the traps remain greater than the height of the boundary layer, the efficiency is almost constant.

If the incidence increases, the boundary layer of the upper surface becomes thicker, which produces an increase of the flow of air at low energy which passes into the air intake and the efficiency falls. This is even more accentuated when the trap is smaller. A certain saturation is nevertheless noted for traps of low height h, combined with high incidences: the efficiencies are poor and it thus varies little with incidence.

In comparison with these efficiencies, figure 16 presents the drag reported of four air intakes to that of the engine and demonstrates the

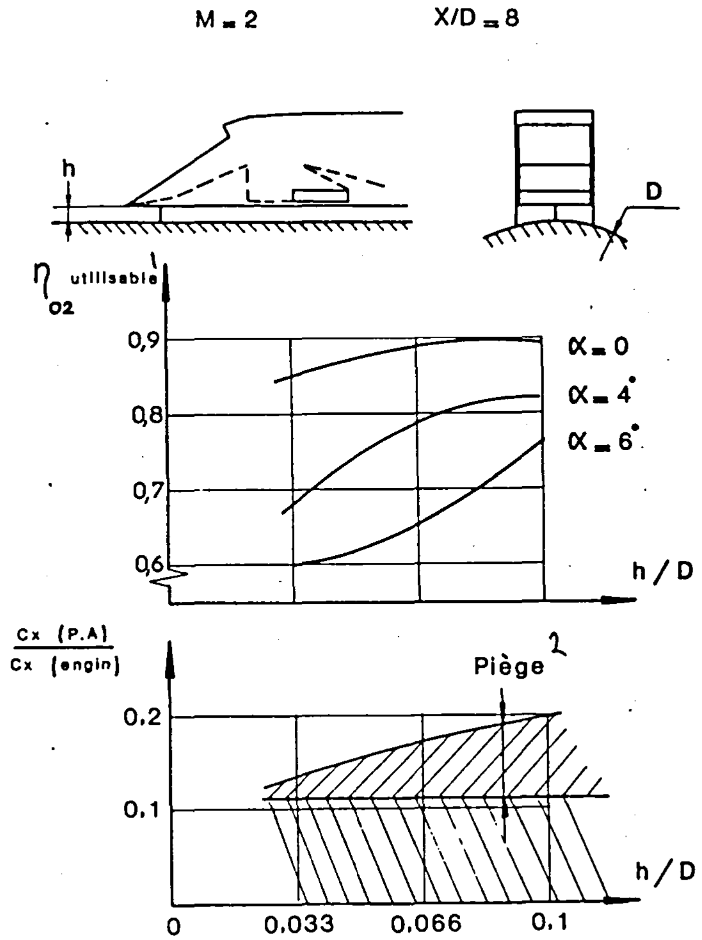

Figure 16. Influences of the height of the trap.
Key: 1-Useable 2-Trap.

part taken by the external trap.

These two diagrams demonstrate well that for maximum incidence given to the missile, it is necessary to establish a compromise between efficiency and drag to define the height of the boundary layer trap: calculation of the sensitivity of the parameters is necessary.

A good compromise is obtained with a trap height of approximately the height of the boundary layer at zero incidence for taking into account placements at incidences on the order of 5 to 6.

Influence of Longitudinal Position

Figure 17 demonstrates some results obtained at Mach 2. If the air intakes are placed at the end of the nose cone, the boundary layer is not thick, but there is locally an overspeeding which makes the efficiency fall. On the contrary, if the intakes are located more downstream on the body, the overspeeding diminishes and the yield increases. But in moving back the air intakes, the local boundary limit layers become thicker (in particular with incidence) and above all the zones affected by the vortices grow larger, which induces a decrease of yield.

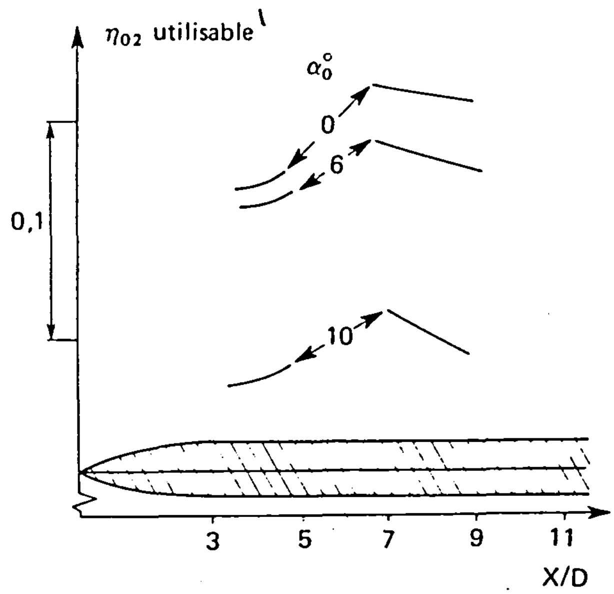

Figure 17. Influence of the distance of the air intakes from the nose of the engine.
Key: 1-Useable.

Influence of the Roll Position

The interest in a cruciform missile is to be maneuverable in all directions, thus without control of roll. Thus, the air intakes will be at one time or another in unfavorable positions, that is to say in the axis of the vortices emitted by the nose cone.

Figure 18 presents developments of the flow coefficients captured by the inverted two-dimensional air intake, for two Mach numbers and at various incidences, as a function of the roll position (ϕ=0 corresponds to the upper surface). Developments of the maximum efficiencies are comparable.

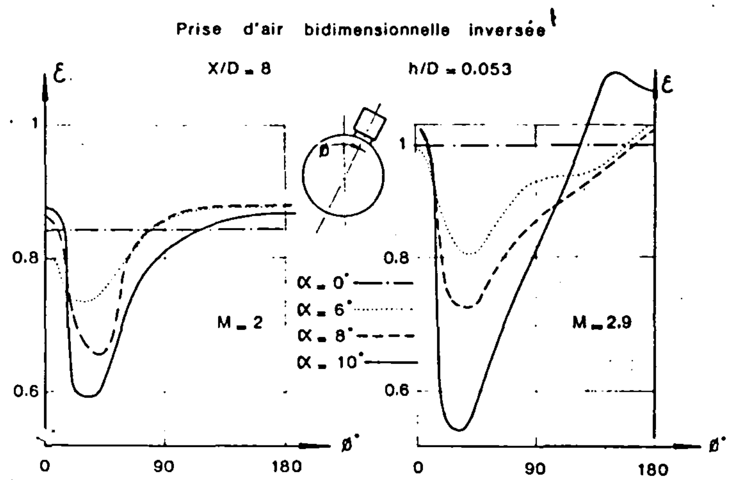

Figure 18. Influence of the roll position.
Key: 1-Inverted two-dimensional air intake.

This plate demonstrates the pernicious effect of these vortices on the air intakes. Works relative to disorganization of the vortices issuing from streamlined incidence bodies, or as well from their capture by longitudinal grooves placed between the air intakes, demonstrates that significant gains can be acquired for flights at average incidences (5-6^{O}). At low incidence, the drag of these grooves is not compensated by the increase of efficiency of the air intakes. /56

Mach Number Adjustment

This Mach number adjustment must be slightly greater than the nominal Mach number of the flight in order to take into account small variations of local incidence which induce the penetration of the shocks formed on the slope of the air intake, under the keel, and thus a loss of efficiency. The slight difference between the Mach numbers of the flight and of adjustment ($\Delta M \sim 0.1$) induces a very low additive drag.

Air Intakes of the Probative Model

Definition of the Air Intake

Comparative study of the various solutions of air intakes for cruciform missiles demonstrates that inverted two-dimensional air-intakes constitute a very good solution, as well as rotating air intakes which give very close results.

The developments with incidence provided by the probative model being limited, rotating air intakes have been retained, for reasons of technological simplicity.

They are constituted of a biconical central point of 20-28^o from the half-angle of the tip; the central body is maintained at the keel by three internal outlined struts (figure 19).

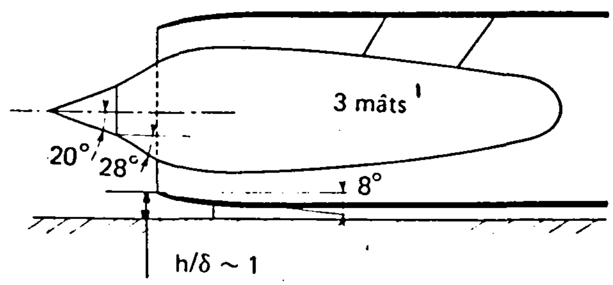

Figure 19. Definition of the air intake of the probative module. Key: 1-3 struts.

The air intake is separated from the fuselage by a stem of 12.5^o from the half-angle of the tip which constitutes the external boundary layer trap.

The exact longitudinal position retained results from that of a strap of a gas generator used to ensure a point of coupling.

For this configuration, preliminary tests of an actual sleeve have been carried out with the goal of verifying its performances, with the conditions generated in flight, as well as its mechanical content, in particular before ignition of the rocket ramjet or even in case of evacuation.

Experimental Study

S4 Installation at Modane (Figure 20-10)

As has been indicated in the paragraph on the "S4 Wind Tunnel", this is thus used in generating hot gases. It provides approximately 40 kg/s of air at 540°K for two minutes. /57

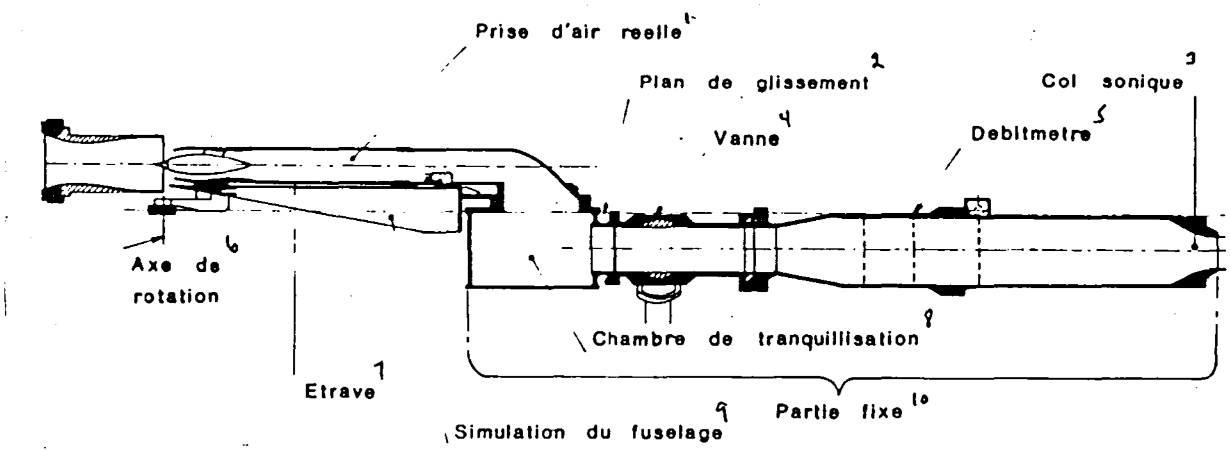

Figure 20. Diagram of the S4 installation at Modane.

Key: 1-Actual air intake 2-Side-slipping plane 3-Sonic collar 4-Valve 5-Flowmeter 6-Axis of rotation 7-Stem 8-Plenum chamber 9-Simulation of fuselage 10-Fixed portion

For this test, all the flow passes into a Mach 2 nozzle of 242 mm diameter in the exit plane, situated downstream of the usual caisson of the wind tunnel. The model set-up is then placed into a chamber constituting the diffuser of the wind tunnel in hypersonic versions.

The "air intake + sleeve" set-up is mounted on a rolled sheet of 400 mm diameter simulating the body of the engine. The fasteners in front and behind this set-up conform to those of the engine.

The rocket ramjet chamber is replaced by a drum having the form of a 1/2 cylinder, the upper portion being flat.

Downstream of this drum are arranged a valve allowing us to vary the regime of the air intake and a subsonic collar flowmeter equipped with gratings ensuring homogenization of the flow.

The drum-valve and flowmeter set-up is attached, and placed along the axis of the wind tunnel. In order to simulate side-slipping, the air sleeve with simulation of the fuselage turns around a vertical axis situated in the exit plane of the nozzle; the downstream end of the sleeve shifts on the flat portion of the drum. Various series of drillings allow us to obtain discrete side-slipping positions, with an upper limit of 12°.

At the end of the sleeve, a toothed plate equipped with 19 arresting pressure intakes associated with 4 static intakes allows us to locally designate the flow and calculate the efficiency.

A Schlieric bank was associated with the installation.

Results

Figure 21 presents the characteristics obtained at S4 MA for side-slippings $\beta=0$, 4, and 8°. It is necessary to note that taking into account the aerodynamic field of the fuselage with incidence, these side-slippings only partially simulate the flow in front of the lateral air intakes ($\phi=90^{\circ}$) placed on an engine at 0, 2.5, and 5° incidence. For $\beta=0$, the simulation is correct.

The results are compared on the same figure with those obtained at the time of tests carried out at S2 MA; differences are observed.

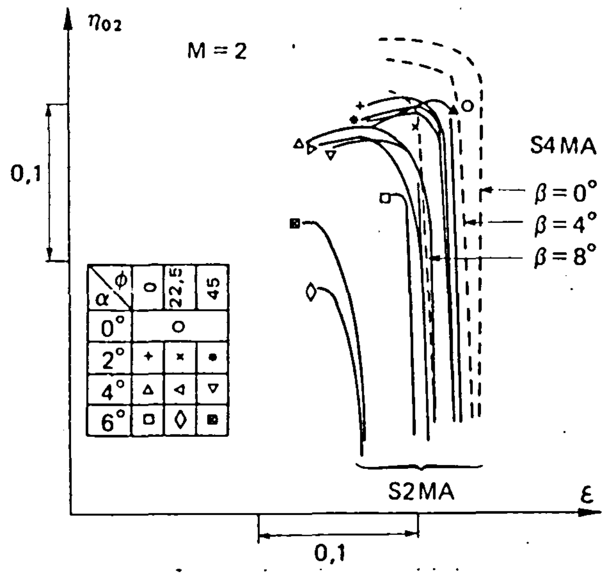

Figure 21. Comparison of the characteristics of air intakes.

The flow coefficient obtained at Modane S4 is approximately 1.5% greater than that of tests of S2, in particular for ϕ=0, which can be explained by several reasons:

-the Reynolds number is multiplied by 6 at S4;

-the leading edges of the air intake are very thin at scale 1;

-the air intake at S4, not able to absorb the boundary layer, takes into account its position within the nozzle;

-the generating temperature being 540°, the entry section expands approximately 0.5%, thus it is not taken into account in the reference section which is assumed to be constant and calculated at ambient temperature.

As for the flow, the efficiency is greater at the time of tests of Modane S4; several facts can explain it:

-the Reynods number is higher at S4;

-at Modane S2, the captured flow has traversed the shock of the nose cone (η~0.995 at the nose); /58

-at S2, to attach the shocks to the base of the second cone of the air intakes, artificial transistion is ensured thanks to silicon carbide;

-the fundamental difference must result from the shape of the diffuser, which is simple at scale 1 and very complex at small scale since the model, which is adaptable for all sorts of air intakes has rotating diffusers just downstream of the entries, which then changes to have a rectangular section in front of the turn into the ramjet chamber.

On the other hand, we can note on this plate that the evacuation limits obtained with the two wind tunnels are very close and that stable subcritical regimes are very limited.

Tests in Flight

The last figure (22) presents the developments as a function of time of the efficiency of the air intakes at the time of the first two ballistic flights of the probative model; they are presented by comparing the instantaneous Mach number to the maximum efficiency deduced from tests at Modane S4. We can state that as a function of the selection of the collar section of the two rocket ramjets, the supercritical guards had to be 15 and 5% in the Mach 2-Mach 2.2 realm for flights V1 and V2, respectively, conditions very close to the optimum.

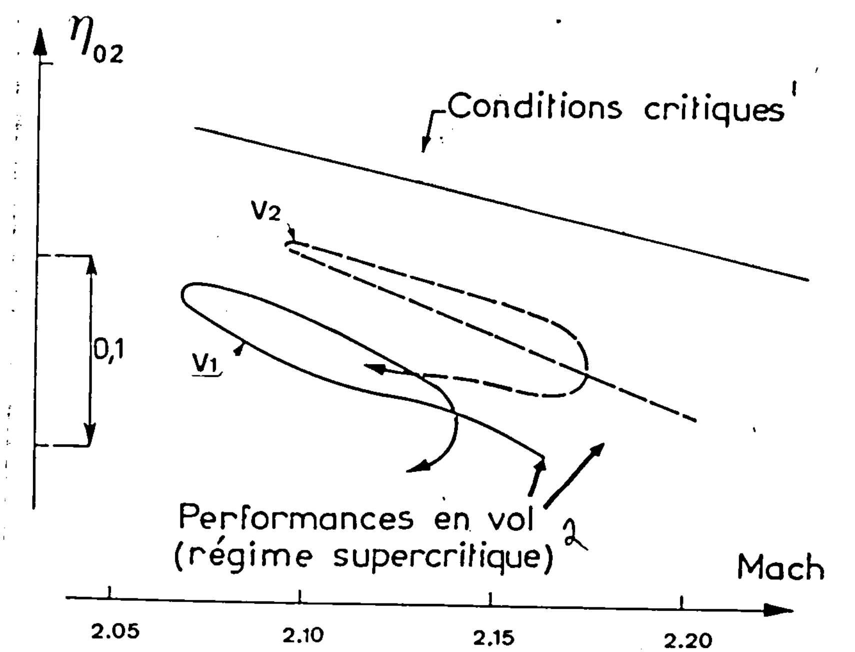

Figure 22. Efficiency in flight.

Key: 1-Critical conditions 2-Performances in flight (supercritical regime).

Conclusion

At the time of the definition of a new missile, the architect henceforth possesses a certain number of general rules to guide him, taking into account the mission retained and existing constraints.

The number of air intakes generally results from the mission and consequently from the type of piloting adopted. Positioning of the air intakes is a function of the maximum incidences anticipated. High incidences lead to advancing the air intakes without always placing them in the vicinity of the nose cone-cylinder juncture whre overspeeding appeared. The type of air intake also depends on the maximum incidences anticipated, but above all on the performances demanded. Nevertheless, a compromise is necessary between very good performances (inverted two-dimensional air intakes with internal traps) and a lower cost associated with much simpler and lighter construction (circular air intakes).

The rough estimate being established, actual performances of air intakes can only be known from tests in wind tunnels for which there exists at ONERA a set of complementary methods. Chalais S5 allows us to precisely define the definition of isolated air intakes. Modane S2 with the existing installation provides internal characteristics of the air intakes in the presence of the fuselage and Modane S4 ensures synthesis tests for aerodynamics, propulsion, and technology of the rocket ramjet-air intake set-up.

For the development of the solid fuel rocket ramjet probative model, first missile of the new generation, ONERA has followed various stages precisely defined above to result in tests in flight which have confirmed the validity of the performances measured in wind tunnels and allows the launching of rocket ramjet tactical missiles by France.

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