Towards a renewal of supersonic transport?

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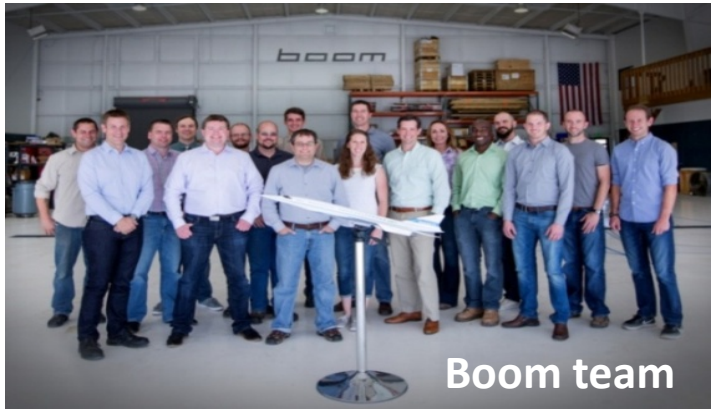
Summary

In the past few years, at least three supersonic aircraft projects have been launched by unknown start-ups to "replace" Concorde. How do they shape up?



Boom team

- Concorde: history et characteristics
- Challenges for a potential successor
- Advanced studies (commercial aircraft): 1975-1990s
- European program High Speed AirCraft: 2004-2009
- New projects: Boom, Aerion, Spike
  - Performance aspect
  - Program aspect
- Conclusion

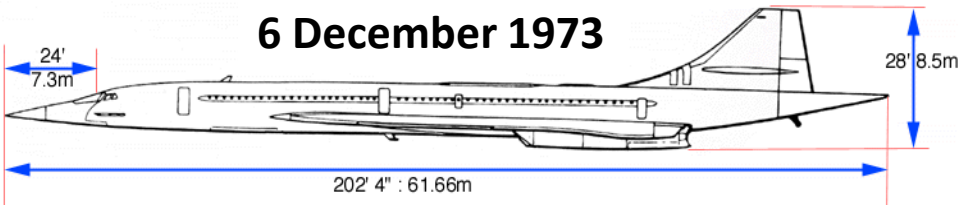
Development program: 1962-1976

- **Programme launched in 1962 and developed by teams that had already designed and flown military and civil aircraft (Trident and Caravelle in France, BAC 111, Vickers VC10 in England):**
  - **used all existing design office and test means built by States (ONERA,…)**
  - **no financial constraints**
  - **mobilized the best European civil aeronautic teams and the most powerful computation means available**
  - **no environmental constraints.**

- **The difficulties encountered to achieve the target (Paris-New-York with 100 passengers) led to major adjustments to definition during the 14 years of development. Take-off thrust was increased by boosting the post combustion in particular.**

2 March 1969

6 December 1973



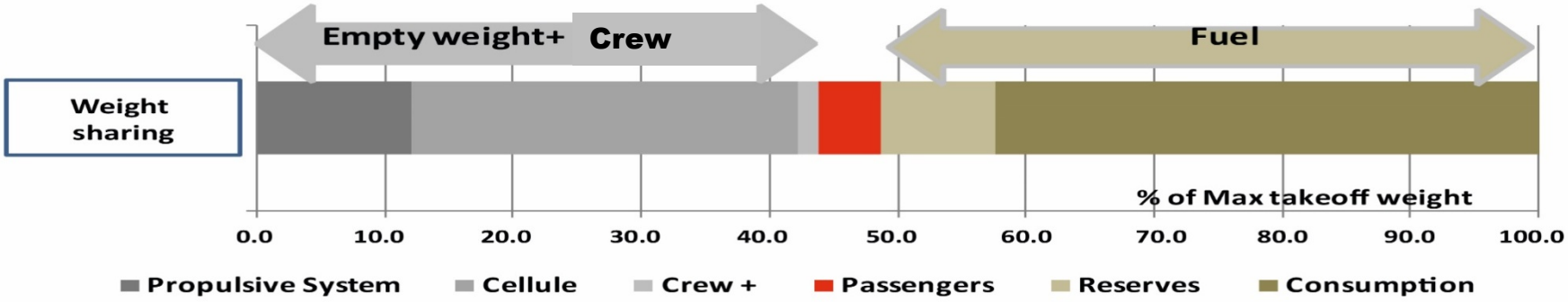
Prototype: 135t, L = 51.8m, W = 23.8m Series: 185.07t, L = 61.66m, W = 25.6m

Concorde

- Only supersonic commercial aircraft.
- Only aircraft able to fly Mach 2 for over 2 hours.
- Only supersonic aircraft able to fly Paris (or London)-New-York, about 6000km, with full payload (100 passengers).

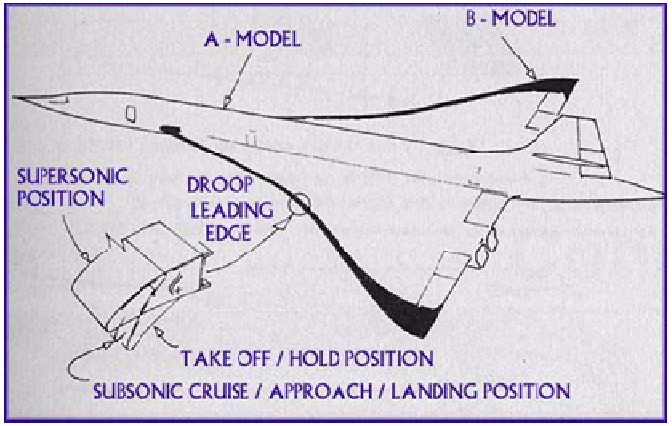
But:

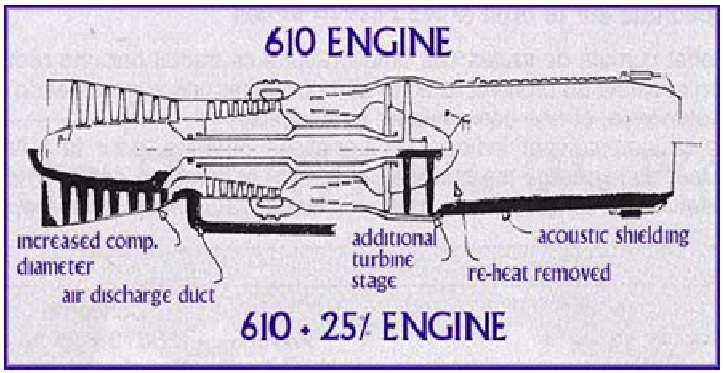
- only 250,000 hours flight hours on 13 aircraft over 27 years
- 800 kg of jet fuel per passenger to achieve New-York
- take-off and landing noise unacceptable today
- unable to fly over populated areas at supersonic speed
- convenient for westward flights, less so for eastward travel
- surface temperature over 100°C (materials but also systems)
- very high operational costs
- for a take-off weight of 185t, to reach NY.



Concorde B

- **In 1976,** Aérospatiale & BAC planned to develop a derivative aircraft: Concorde B, with:
  - **improved aerodynamics:**
    - 12 to 13% take-off lift/drag ratio
    - 7% in cruise
    - but **+1855kg**
  - **derivative engines**
    - 0.25 bypass ratio without post combustion
    - -2.7% cruise SFC
    - -8 to 10 EPNdB for take-off
    - but **+5098kg**
  - **weight reduction** through composite material introduction **(-1088kg).**





- **The resulting aircraft would have seen its range increased by 500NM (900km) with take-off noise reduction and a slight TO weight increase**

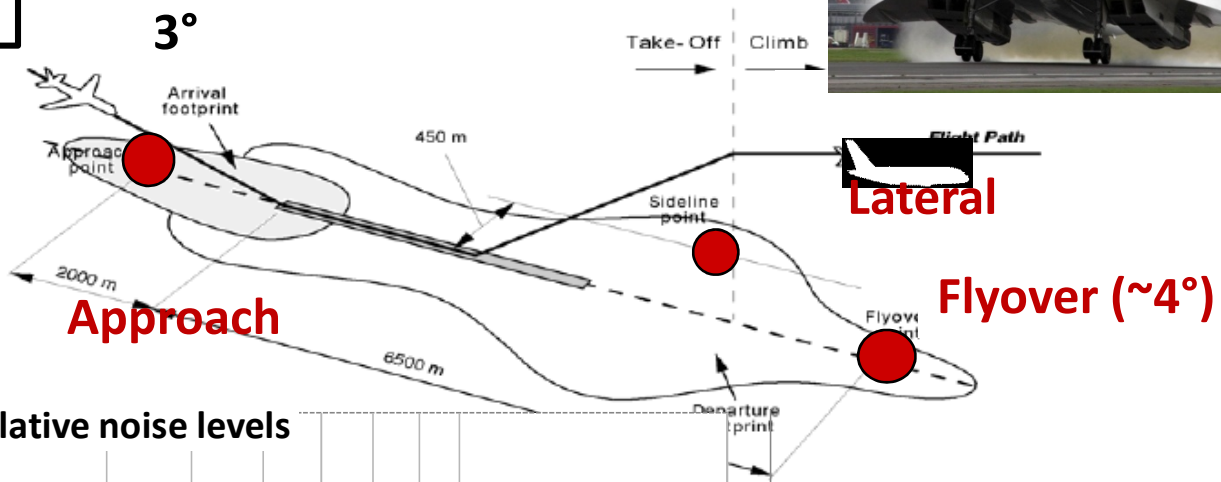
The development would have lasted 5 years.

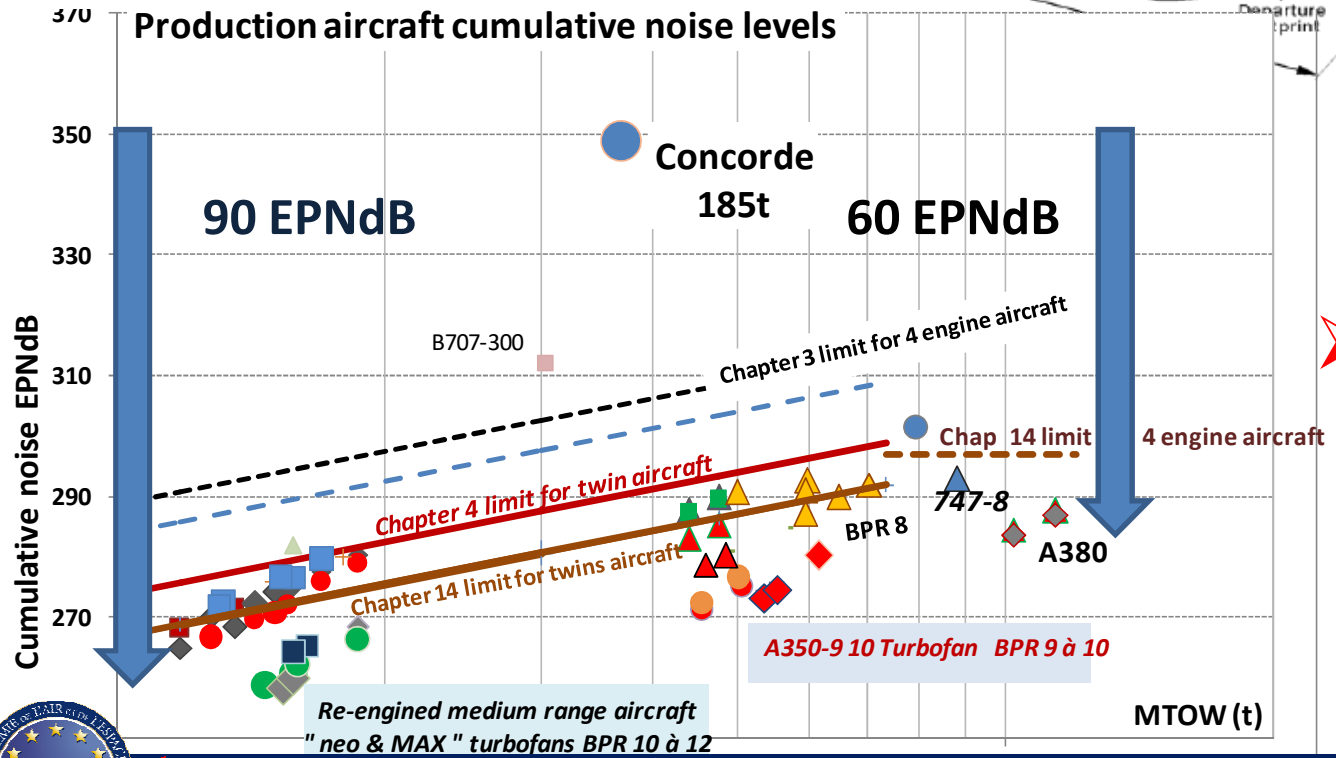
Take-off and landing noise levels unacceptable today

CERTIFIED NOISE

3 control points perceived Noise for standard procedure, MTOW, MLW and adjusted thrust

Cumulative noise: sum of 3 noise levels in EPNdB



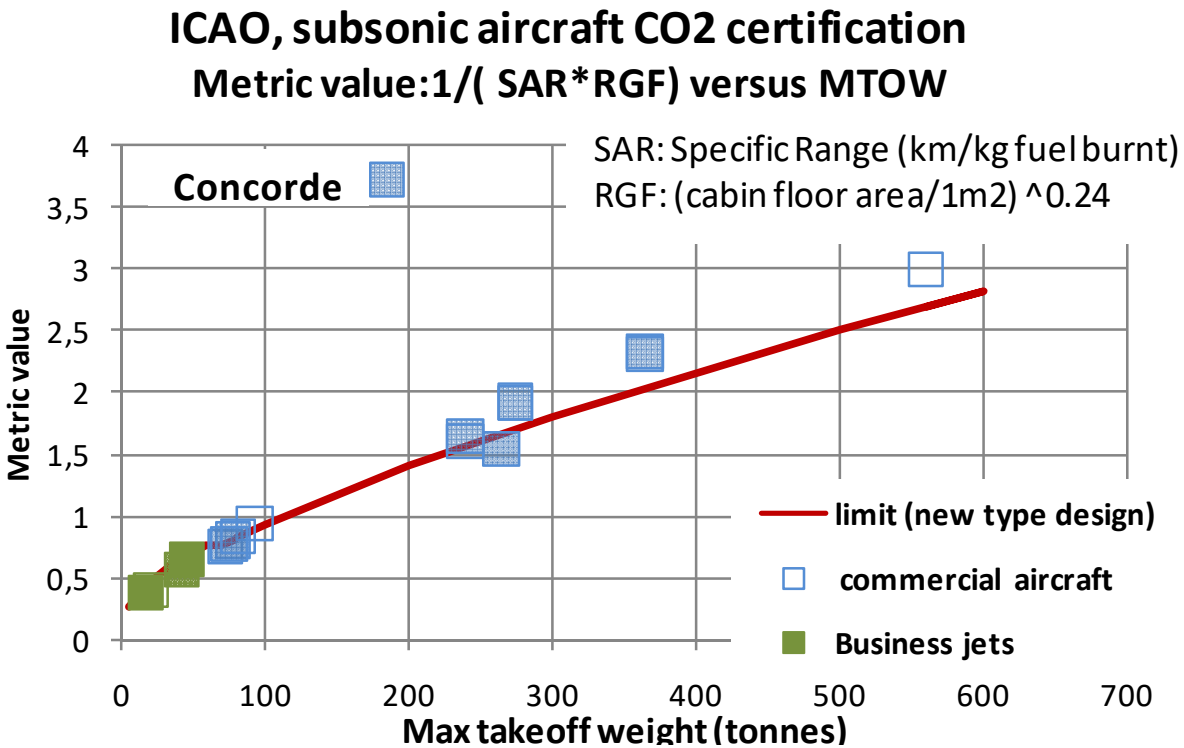


➢ **30 dB/point: acoustic power*1024**

800 kg fuel per passenger to reach New-York

Fuel Consumption: New CO2 standard

Kilometric fuel consumption for roughly the same cabin floor area was 4 times higher than the A320neo, which carries 50% more passengers over the same distance.



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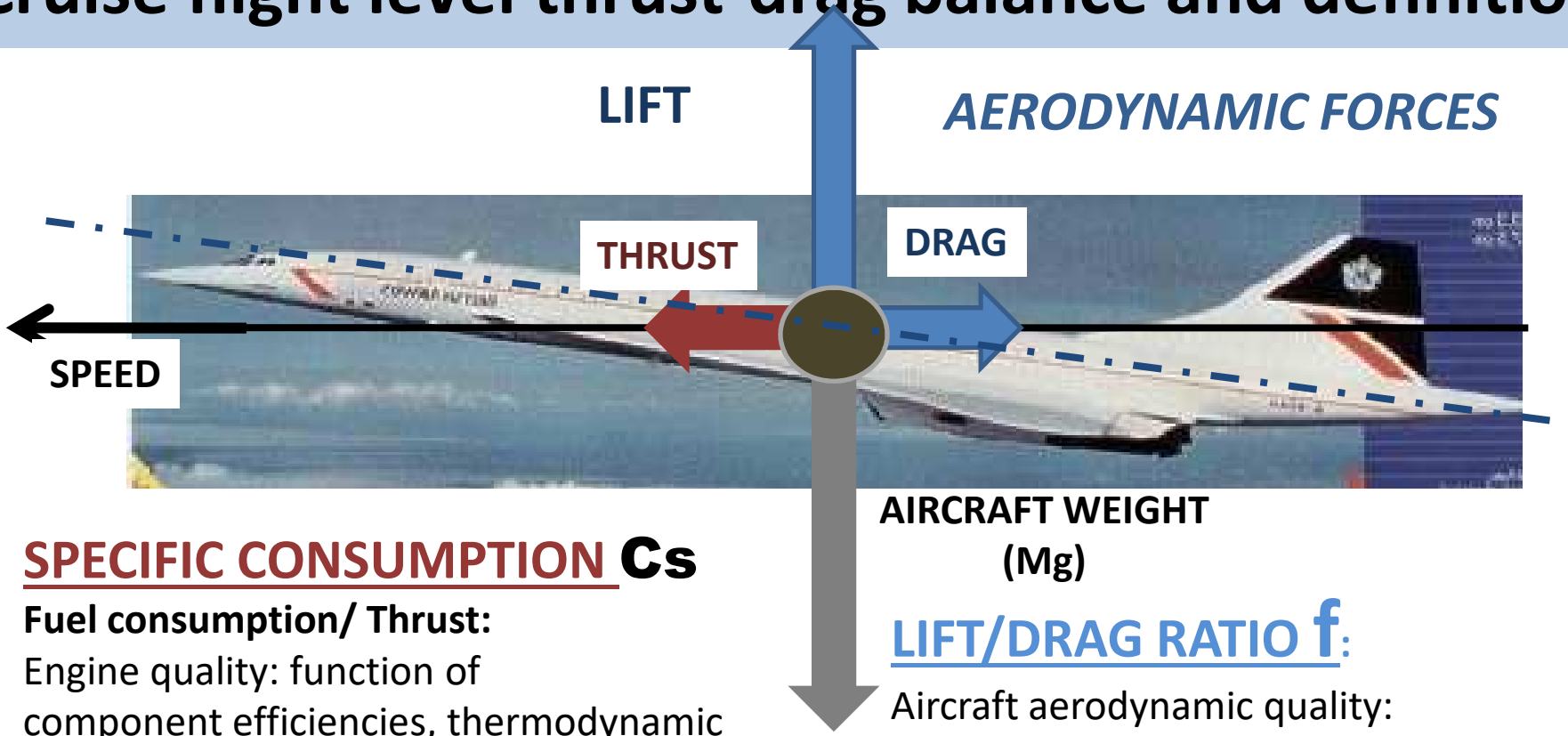
Cruise flight level thrust-drag balance and definitions



SPECIFIC CONSUMPTION Cs

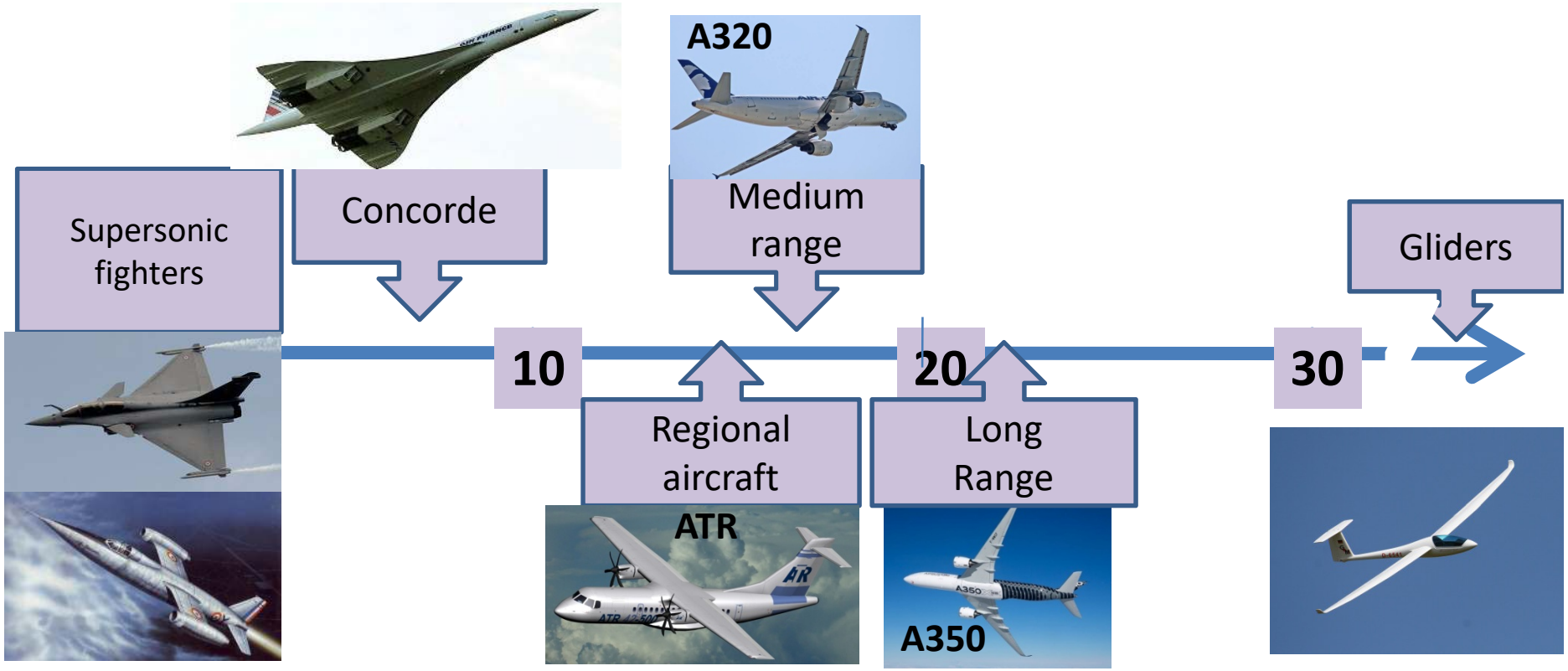
Fuel consumption/ Thrust:
Engine quality: function of component efficiencies, thermodynamic cycle and aircraft speed (kg/daN.h)

LIFT/DRAG RATIO f:

Aircraft aerodynamic quality: Function of the geometry and aircraft speed.

$$\textit{Aircraft range} = \frac{\text{Aircraft speed}}{g} \times \frac{\text{Lift / drag ratio}}{\text{Specific consumption}} \times \ln \frac{\textit{Landing weight + fuel burn}}{\text{Landing weight}}$$

Some orders of magnitude: Lift over drag ratio

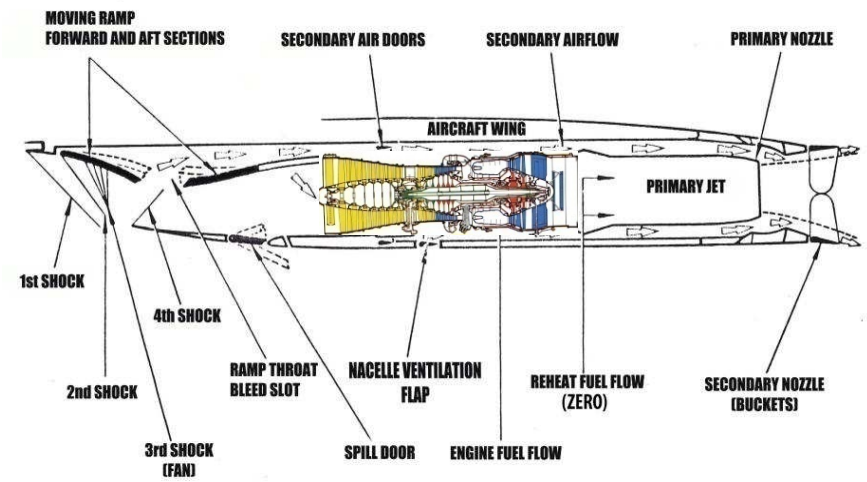


The geometric characteristics of aircraft are the result of optimisations taking into account speed, wing weight, fuel capacity and targeted range.

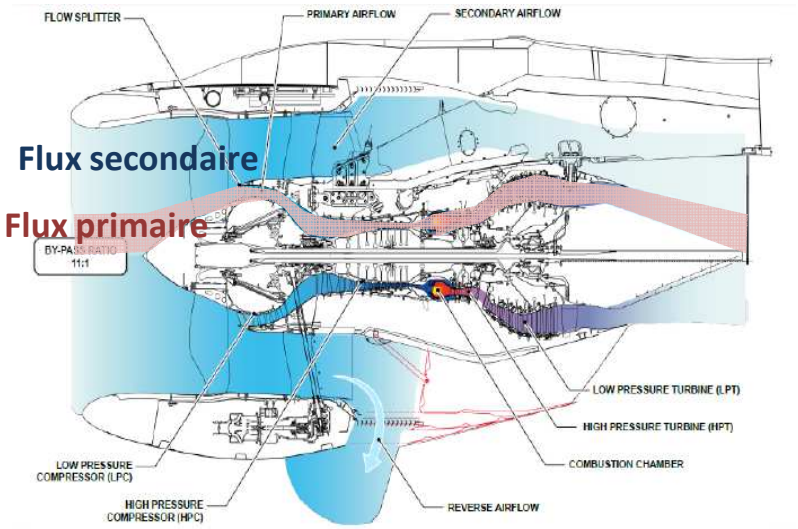
Current CFD computations will enable improved optimisation of aerodynamic shape without dramatic changes to lift/drag levels.

Some orders of magnitude: specific fuel consumption

Turbojet engine Olympus L/D ~ 10



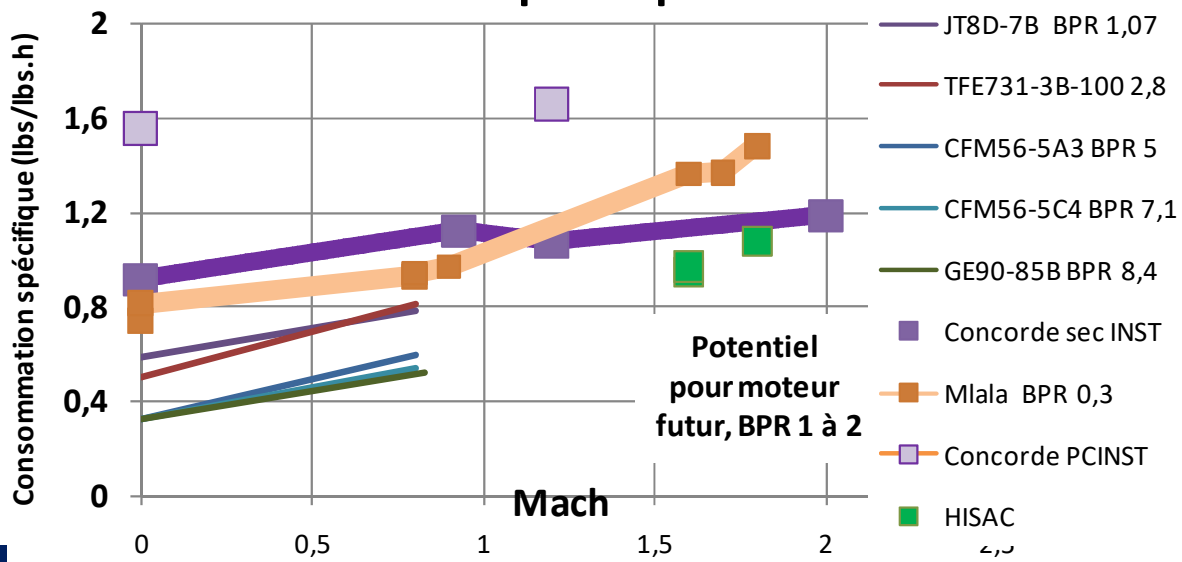
Moteur Leap 1A: BPR=11 L/Φfan= 2.4



Specific fuel consumption varies with:

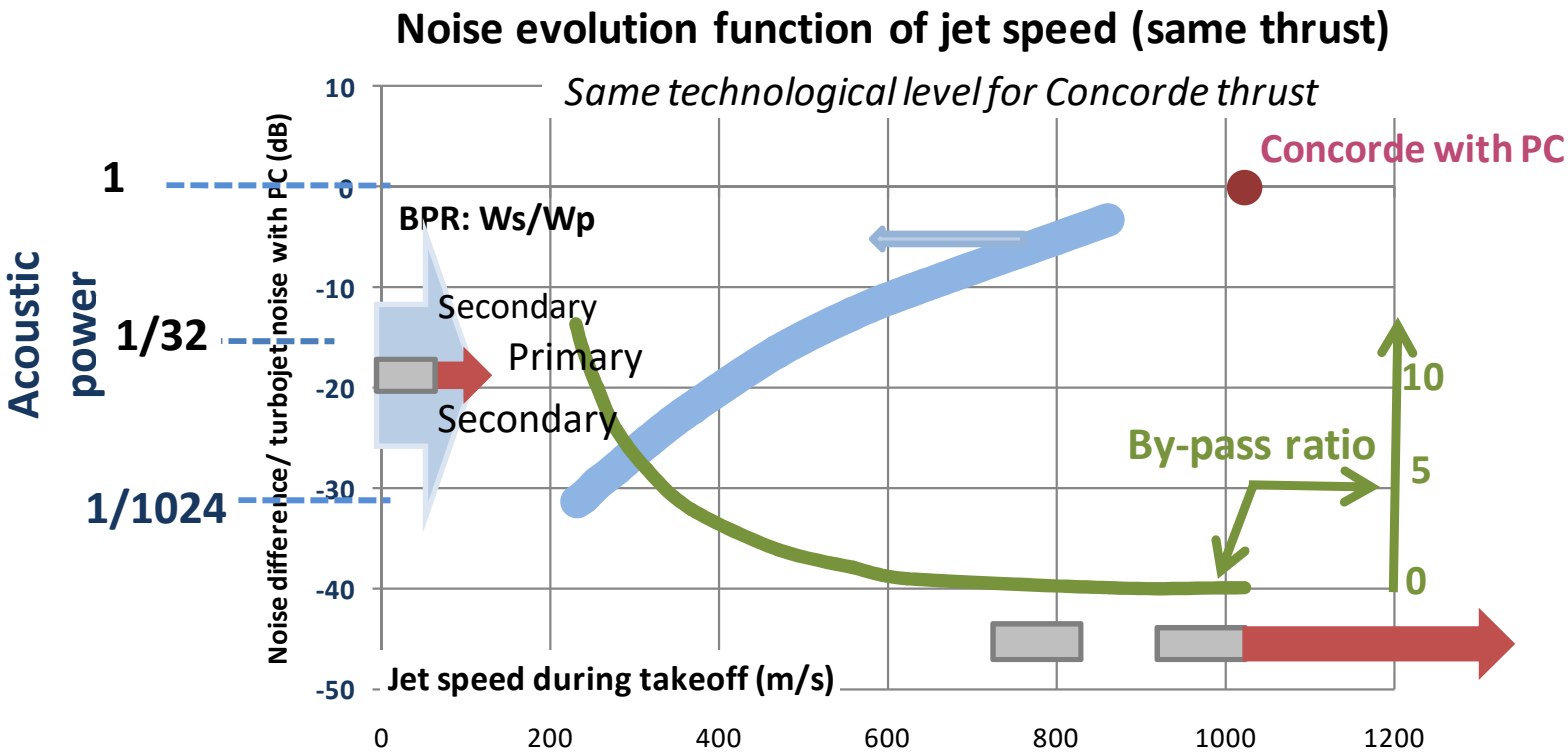
- **engine thermal efficiency (overall pressure ratio, components and internal temperature)**
- **propulsive efficiency (BPR and aircraft Mach number)**

Consommations spécifiques de moteurs



Some orders of magnitude: Take-off noise

Sound power increases mainly with jet speed: (d^2*V^8) or thrust * V^6 (Vx2: Noise x 64)

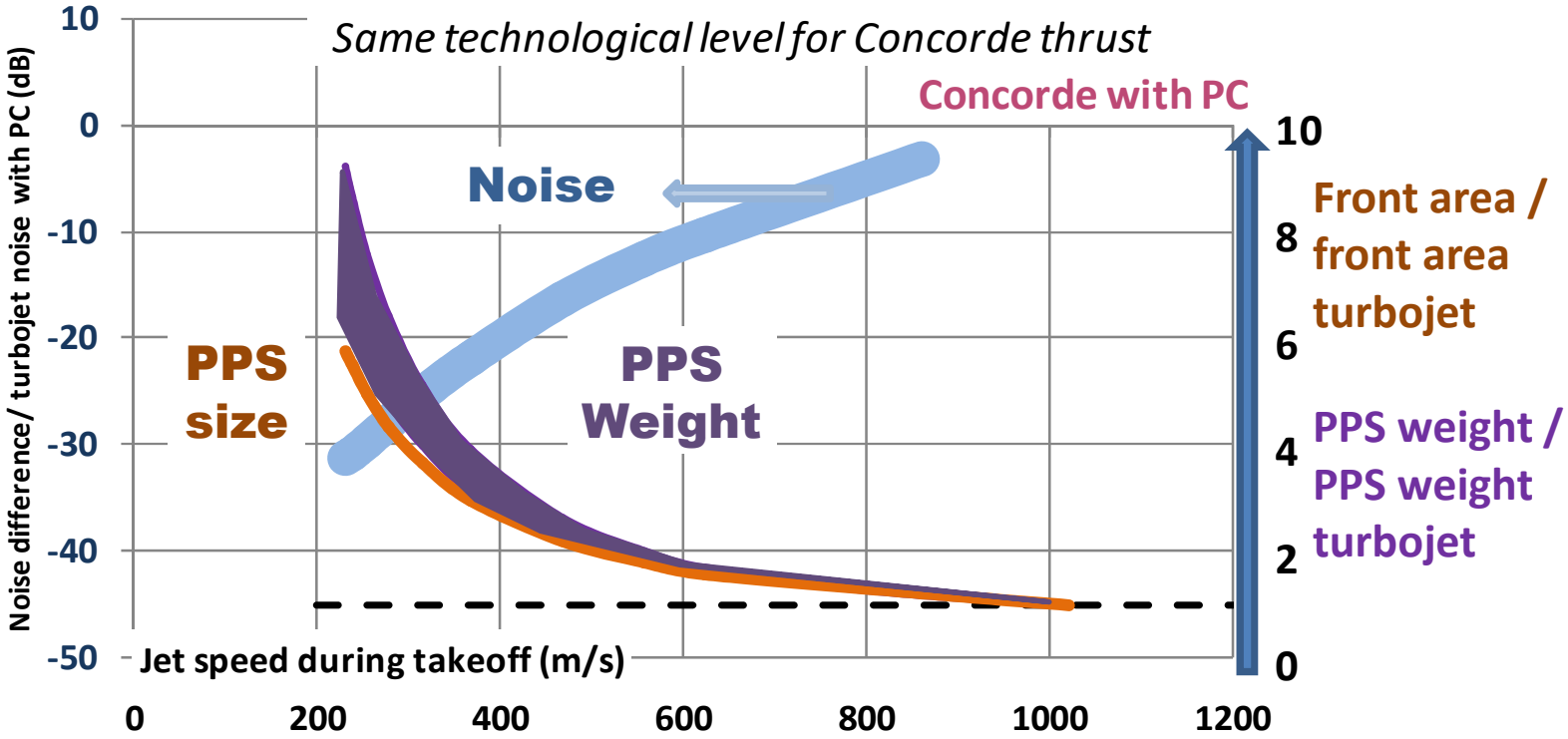


<u>BPR ratio</u>: **secondary** airflow going through the fan over the **primary** airflow going through the compressor, heated in the combustion chamber and ejected through the nozzle after providing the necessary energy thanks to the turbines

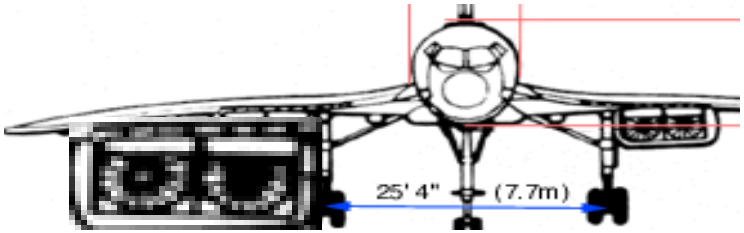
Some orders of magnitude: Take-off noise

Noise increases mainly with jet speed: ($d^2 * V^8$) or thrust * V^6

Size & weight function of jet speed (same thrust)



To achieve a noise level close to the latest subsonic aircraft with the same take-off thrust, the PPS would need an air inlet 5 to 6 times larger and would be 6 to 9 times heavier than for a turbojet.



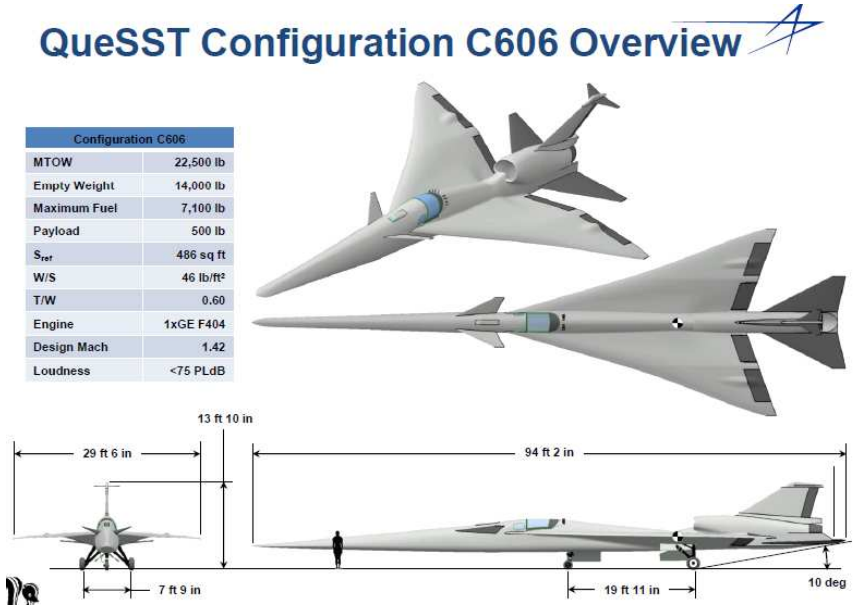
To reduce overland sonic boom

During cruise, supersonic aircraft produce a “sonic boom” (noise and overpressure) perceived on the ground, which led to a ban on flight over populated areas.

Numerous studies are currently underway, essentially in the US, to reduce this effect, with two possible approaches:

- the use of atmospheric characteristics – pressure and temperature gradients – to absorb the boom, up to **Mach 1.1 to 1.2** (e.g. the Aerion project)
- the use of specific aerodynamic shapes to limit the boom to an acceptable level, up to **Mach 1.4 – 1.5** (e.g. NASA L.M. QueSST prototype).

According to a NASA paper of May 2012, this would lead to prohibitive fuselage length – 244 m for a 30-80 passenger aircraft – and a small aspect ratio.



Configuration C606	
MTOW	22,500 lb
Empty Weight	14,000 lb
Maximum Fuel	7,100 lb
Payload	500 lb
S_{ref}	486 sq ft
W/S	46 lb/ft²
T/W	0.60
Engine	1xGE F404
Design Mach	1.42
Loudness	<75 PLdB

The possible speed above populated areas, according to the literature, would clearly be lower than Mach 2.

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Challenges for a successor

- **To comply with the certification requirements in force at aircraft launch date:**
  - **design**
  - **environmental (?):**
    - ✓ to reduce airport and cruise (bang) noises and allow flight over populated areas at supersonic speeds
    - ✓ to significantly reduce greenhouse emissions.
- **To reduce operational costs:**
  - fuel burn
  - acquisition costs, in particular development costs
  - and above all maintenance costs for commercial operations.
- **To improve services:**
  - to significantly increase range
  - to enable significant flight time savings.

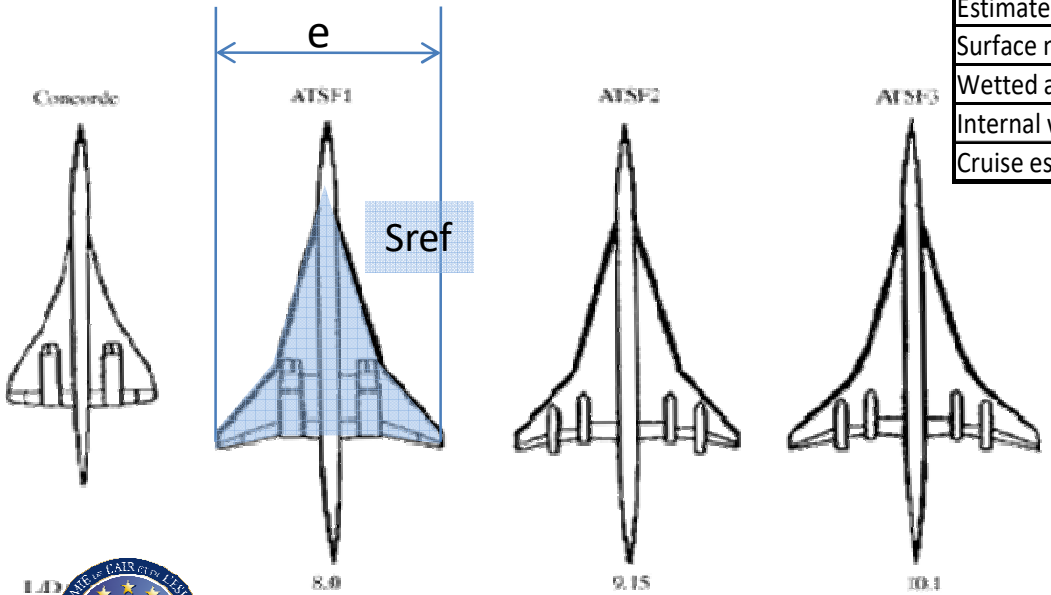
Supersonic pre-projects (1975-1990s)

- **From 1975 to the 1990s,** Aérospatiale maintained a small team of engineers to capitalise on expertise cumulated over the space of 20 years in all aircraft definition disciplines (79,000 hours of wind tunnel and computing resources – important for aerodynamics in particular – tests in the different laboratories and ultimately more than 5,000 hours of flight tests).
- The goal was to define the characteristics of a new supersonic aircraft taking advantage of:
  - the latest progress in aerodynamics and propulsion
  - improvements enabled by technological developments (systems and composite materials,…)
  - and changes to certification requirements.

Aircraft studied from 1975-1990s (Aerodynamics)

- The aircraft studied were larger than Concorde: 250 passengers for ATSF.
- The lift-to-drag ratio improvement was achieved thanks to:
  - a significant span increase (aspect ratio, induced drag)
  - a relative reduction in fuselage front area as compared to wing (form and friction drags)
  - for the last project, the lift-over-drag ratio improvement on Concorde was put at about 40%.

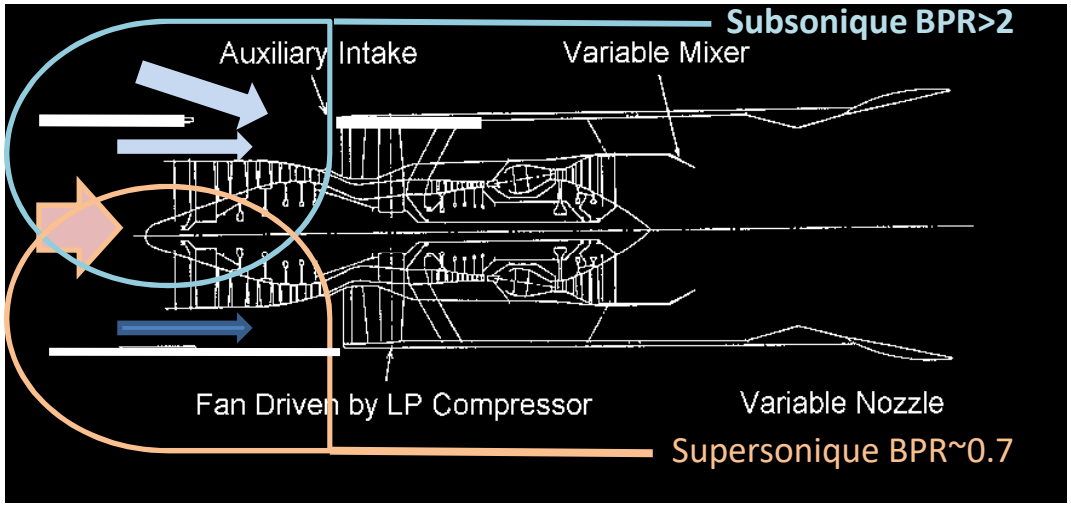
	Concorde	ATSF
Cruise Mach Number	2	2
Reference aera Sref (m2)	358	755
Wing span:e (m)	25,6	41-42
Estimated aspect ratio (e2/Sref)	1,83	2,34
Surface maître couple fuselage/surface de référence	0,0204	0,0127
Wetted aera / reference aera	2,977	2,690
Internal wingsweep (°)	17	19
Cruise estimated lift/drag ratio	7,3	~10



Aircraft studied from 1975-1990s (Propulsion systems)

- These projects came up against the challenges of defining a Propulsion System with both reduced noise and improved performance (specific fuel consumption, weight and drag).
- The aircraft optimum performance was achieved with a low bypass ratio Propulsion System (high jet speed)
  - with a specific fuel consumption close to the Olympus
  - not enabling a significant reduction of airport noise.

  This led to the idea of a variable cycle engine: Bypass ratio "large enough during takeoff" and initial climb and "~ turbojet" in cruise.
- In Europe, Rolls-Royce, SNECMA and others studied designs (1993): Rolls-Royce (Tandem Fan System) and SNECMA (Mid fan system, project MCV 99).



Aircraft studied from 1975-1990s (Propulsion systems 2)

- Noise reductions were not enough to meet regulations in force (1993, stage 3), and the resulting noise level would have been far above the current chapter 14.
- The PPS were a lot more complex, heavier and with higher SFC in cruise.
- On top of that "development of such an engine, with the targeted characteristics and the reliability needed for a commercial market ,…, would require 15 years and huge investment". *SNECMA, Essor des marchés civils (1986-1996).*

These engine manufacturers stopped feasibility studies some time ago

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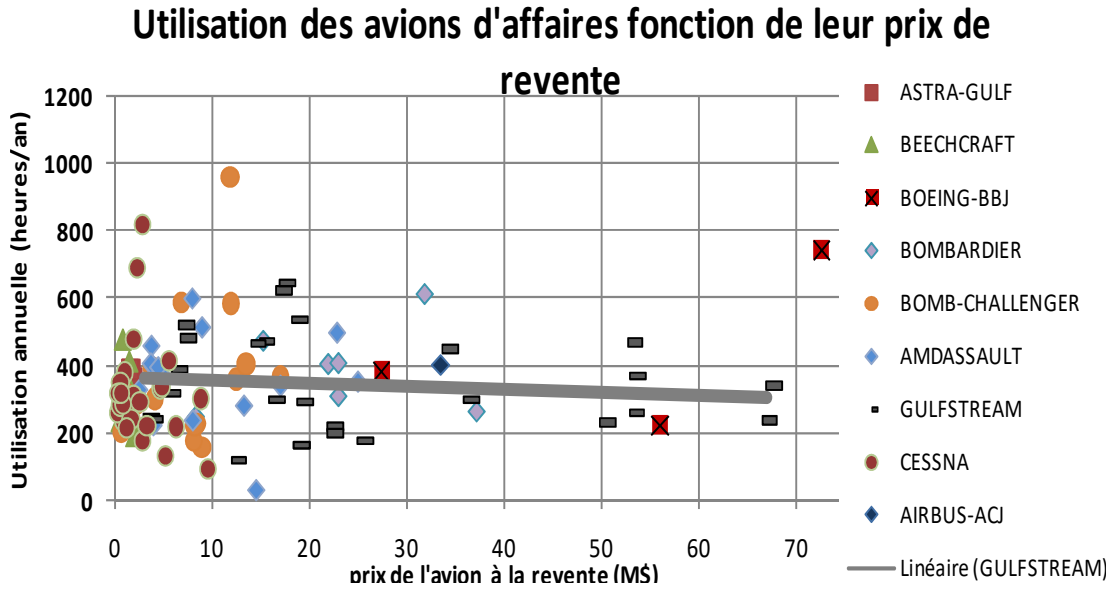
Business jet market

Given the technical and economic obstacles, supersonic aircraft designers sought to build smaller business jets both to alleviate environmental constraints and to achieve an acceptable return for such a market.



Whatever their price, business jets clock up a limited number of flight hours per year, close to 1h a day.

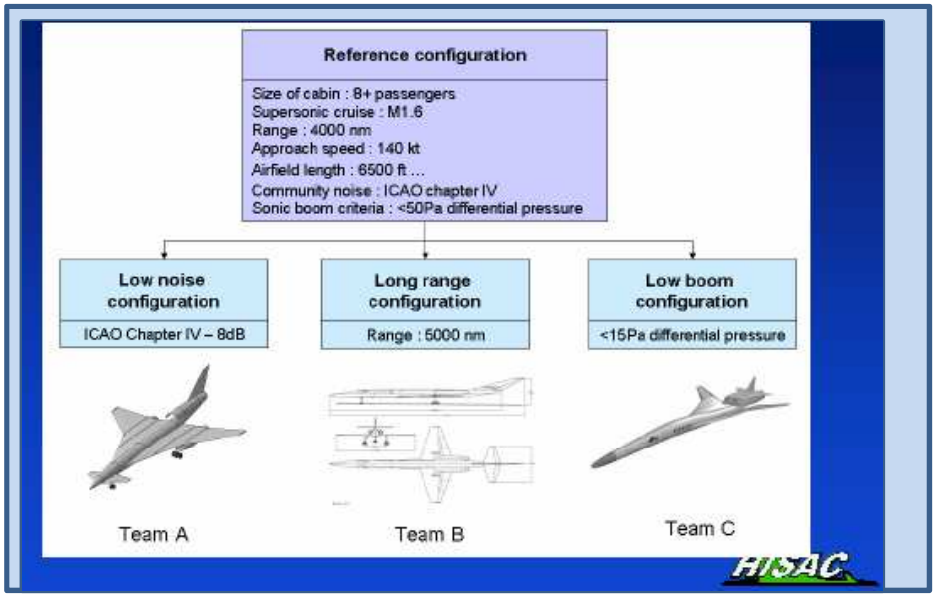
The most recent subsonic aircraft meet "chapter 14" rules for environmental CO2 and noise.

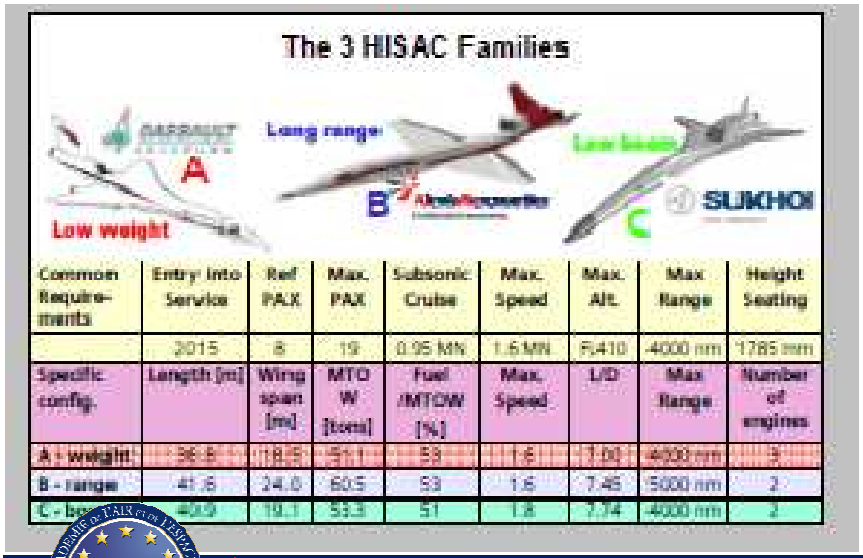
Supersonic business jets would be aimed at wealthy clients.

Is it possible to find manufacturers to invest in this "niche" market, estimated by its promotors at 500-700 aircraft?

European research program HIghSpeedAirCraft (2004-2008)

This European research program, with 37 partners, was supposed to define an economically viable, hi-tech, environmentally friendly product.





Common Requirements	Entry into Service	Ref PAX	Max. PAX	Subsonic Cruise	Max. Speed	Max. Alt.	Max Range	Height Seating
	2015	8	19	0.95 MN	1.6 MN	FL410	4000 nm	1785 mm
Specific config.	Length [m]	Wing span [m]	MTOW [tons]	Fuel /MTOW [%]	Max. Speed	L/D	Max Range	Number of engines
A - weight	36.8	18.5	51.1	53	1.6	7.00	4000 nm	3
B - range	41.6	24.0	60.5	53	1.6	7.45	5000 nm	2
C - boom	40.9	19.1	53.3	51	1.8	7.74	4000 nm	2

The engine specific fuel consumption was estimated at **0.97 and 1.0 kg/daN.h (M=1.6, for the A and B projects) and 1.09 kg/daN.h (M=1.8, C projects).**

The lift-over-weight ratio varying from 7 to 7.74.

The program was halted.

Aerion: Cruise Mach 1.4 (8 to 12 passengers)

Price: 80 M$, Development: 2 to 3 Mds $
Op. speed **M 1.6, Max range 4200NM @ M 1.4**
MTOW: 40.8t, 2 engines JT8D- 219
L: 41.3mm; W: 19.6m; Cabin width: 1.9m

2007 Certification: TBD; EIS: 2017-2018
2014 Certification :2021; EIS: 2022 (TBC)

Price: 100 then 120 M$, Devel: 4 Mds $
Op. speed **M 1.5, Max range 4750NM @ M1.4**
MTOW: 52.1 then 54.9 t, 3 engines (type ?)
L: 49 then 51.8m; W:21 then 18.6m Cabin: 2.2m

First flight 2018-2019; EIS: 2023

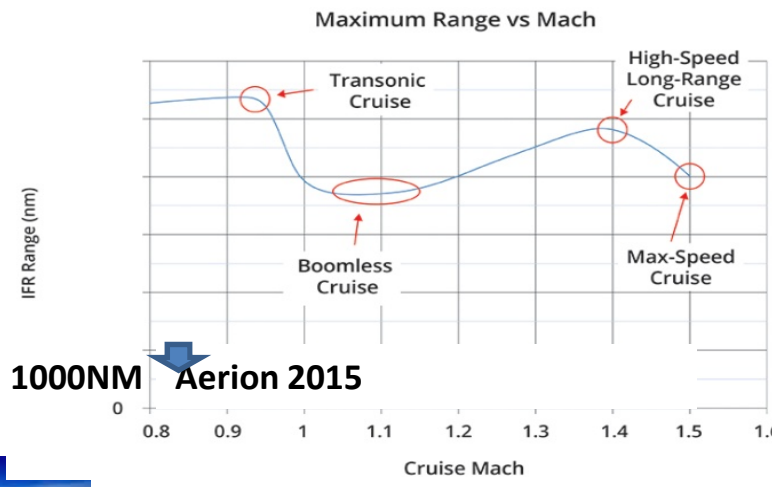
Price :120 M$, Devel: 4 Mds $
Max range 4200NM @ M 1.4
MTOW: 60.3 t, 3 engines type? GE?
L: 51.8m ; W: 23.5m Cabin: 2.2m

«laminar wing: *net friction drag reduction is up to 20 percent"*

First flight 2023; EIS: 2025

Aerion AS2: Cruise Mach 1.4 (8 to 12 passengers)

- Flight over populated areas will be performed at Mach < 1.2 if atmospheric conditions are adequate & temperatures and winds favourable.
- In this case, the time saving would not be more than 12 à 25% as compared to subsonic aircraft.



From 2007 to 2017

- According to Aerion, in order to carry 8 passengers over 4200NM without wind
  - The Entry into service date has been put back 8 years
  - 3 engines, 2 under wing + 1 central instead of 2
  - Same length and span as Concorde prototype
  - The MTOW has been increased from 40.8t to 60.3t (135t for the Concorde prototype)
  - No information about empty weight
  - Mission fuel consumption greater than 3 tonnes per passenger

Propulsion:
Aerion: GE Affinity engine Feb-Oct. 2018: 18000 lbs (8000 daN)

22 February 2018: Flight Global:

- The proposed engine will keep the CFM56-7B/5B HP module (HP comp+ c.c. + HP turbine) with an adapted BP module: 1.33m fan diameter (BPR~3) and LP turbine.
- Doubts about achieving chapter 14 noise level. A lower TOW cited in the news-paper (54.4t: but - 1200NM versus 60.3t) : 2 versions?

18 October 2018: GE Affinity Présentation

Two stages large cord titanium " blisked"fa

Fixed inlet guide vanes with movable flaps

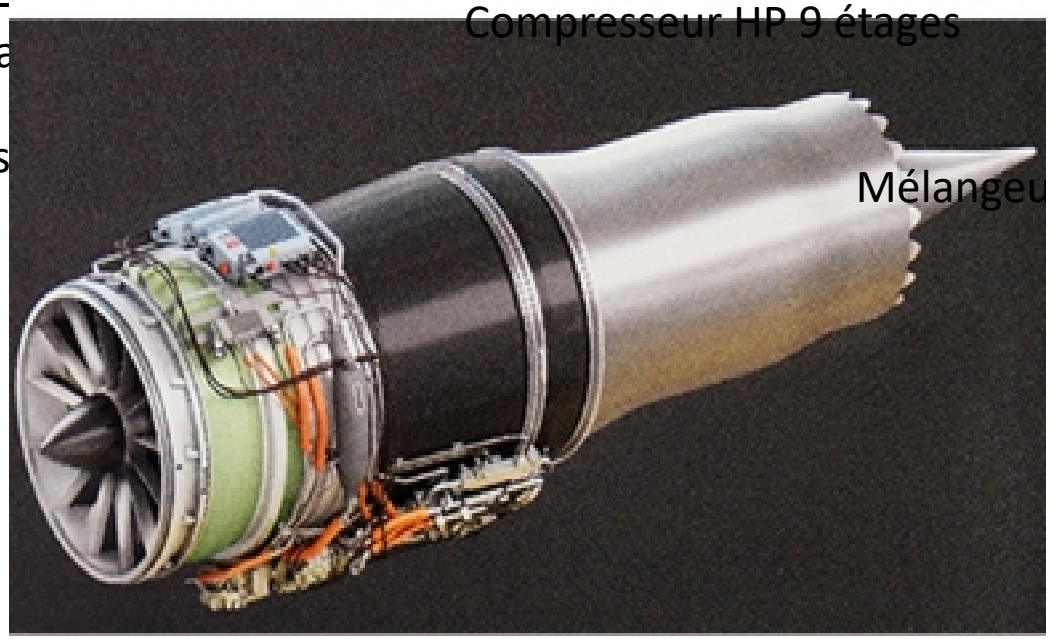
Variable aera nozzle

ByPass Ratio ~3.1

3,500 lbf (16 kN) at Mach 1.4 and FL500

SFC Mach 1.4: >0.94 (installed?)
No weight provided

Estimated PPS weight larger than 3000Kg



Updates of the December 2017 aircraft performance has not been published

Spike S-512 Mach 1.6 cruise (12 to 18 passengers)

Price: 60 to 80 M$, ***Development: ?***
Max speed **M1.8,** Max range **4000NM @ M 1.6**
MTOW*: 38.2t*, OEW: 17.2t **2 JT8D- 219**
L: 40 m; W: 19.6 m; **Cabin width: 2 m**

2014 - launch: 2018; EIS: ?

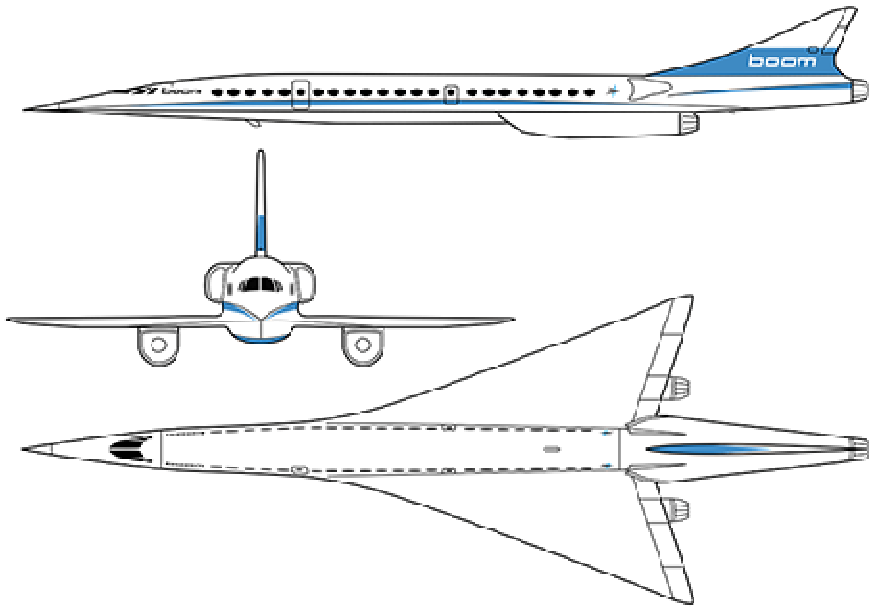
Price: 100 M$, **Development: ?**
Max. speed **M1.8,** Max range **6200 NM @ M1.6**
MTOW: 52.2t, OEW: 21.4t **2 engines ?**
L: 37- 40.8m; W: 17.7 m **Cabin: 2.7m**

2017: Certification 2023; EIS: ?

Compared to Aerion:
passengers x 1.5, range x 1.5, max speed x 1.25
but MTOW / 1.16 !!!!

Boom

First flight 2020, (now 2023) and EIS 2023 (now 2025)



"Tri engines, delta wing, 45 to 50 pax, 18m span, 51 m length, price would be 200 M$ 2016 without options for cabin."

Long-Range Cruise, Supersonic	Mach 2.2 (1,451mph, 2,335km/h)
Long-Range Cruise, Subsonic	Mach 0.95
Maximum Route*	9,000nmi (17,668km)
Balanced Field Length	8,500ft (2,590m)
Community Noise	Better than Stage IV

***Routes over 4,500nmi include a brief tech stop, included in listed flight times. Passengers do not need to deplane or exit their seats.**

- **No information about the characteristic weights of the aircraft on the official site**
- MTOW varying from 77,100 kg (Flight global) to 120,000 kg (military-factory, 5/2017).
- ***3 moderate bypass ratio turbofans with variable design air inlet and nozzle, 15 to 20,000 lbs of thrust (****Blake Scholl, CEO of Boom)*

Boom: Mach 2.2: its demonstrator Baby Boom XB1

Boom planned "*to fly in 2017, a scale 1/3 demonstrator with 2 crew members,* *powered by **3 GE** J85-21s of 1560 daN (but only 2 air inlets), Wingspan 5.2 m, length 20.8 m and TOW of 6.12 t, Mach 2.2 with a range of about 1000 NM. »*

Spring 2017:

- a third air inlet introduced
- **first flight postponed to end 2018!**

July 2018:

- Engine change: GE J85-15
- **first flight postponed to end 2019**

June 2019: first flight early 2020

What can be demonstrated with the Baby Boom?

- This aircraft is overpowered for take-off and cruise (x 2+).
- Could take off with reduced thrust (noise) and could fly supersonic even with poor lift/drag ratio, providing its flying qualities and the air inlet characteristics are OK.
- The engines, different to the Boom ones, will not allow for design of the variable air inlet and nozzle controls (10 years development to design adequate control for Concorde)

Aerodynamic synthesis: Lift / drag ratio

	Concorde	ATSF	Boom	Aerion Dec 2017	Spike 2
Passenger number	100	250	45-55	. 8 - 12 .	. 12 - 18 ,
Cruise mach number	2	2	2 -2,2	1,4	1,6
Length (m)	61,66	92	51	51,8	37
Wing Span (m)	25,6	41-42	18	23,5	17,7
reference aera Sref (m2)	358,25	754,76	217,63	160,00	163,59
estimated aspect ratio (e2/Sref)	1,83	2,34	1,49	3,45	1,92
Fuselage front aera/ reference aera	0,020	0,013	0,032	0,030	0,038
Wetted aera/ reference aera (exclusing PPS)	2,98	2,69	3,33	4,04	4,00
Flèche aile interne (°)	17	19	20	71	24

The geometrical characteristics do not include any specific sonic bang requirements and will not be able to achieve a lift over drag ratio comparable to Concorde, at the best 7 to 8.

Propulsion: Thrust and SFC

Aerion: Mach 1.4: GE Affinity engine

- Estimated specific consumption 0.95 kg/dan.h.
- Jet speed would just enable the aircraft to meet chapter 15 noise limit.
- Transonic and cruise thrusts will be too low, in particular the announced aircraft ceiling with the estimated aerodynamic characteristics. Can it be increased?

Spike: Mach 1.6 – 1.8

- The first engine, JT8D-2019 (1970 engine derivative), was too heavy, too noisy, with an inadequate thermodynamic cycle for supersonic speed.
- The proposed thrust: "2 engines, with 20 000 lbf (89 kN) thrust each" is clearly too low: one extra engine would be needed for take-off…
- No information about the second-generation aircraft, its air inlet and nozzle that must have variable geometry to operate at Mach 1.8.

Boom: Mach: 2.2

Powerplant: 3X non-afterburning medium bypass turbofan; proprietary variable geometry intake and exhaust: **Indicated thrust far too low. Weight, consumption?**

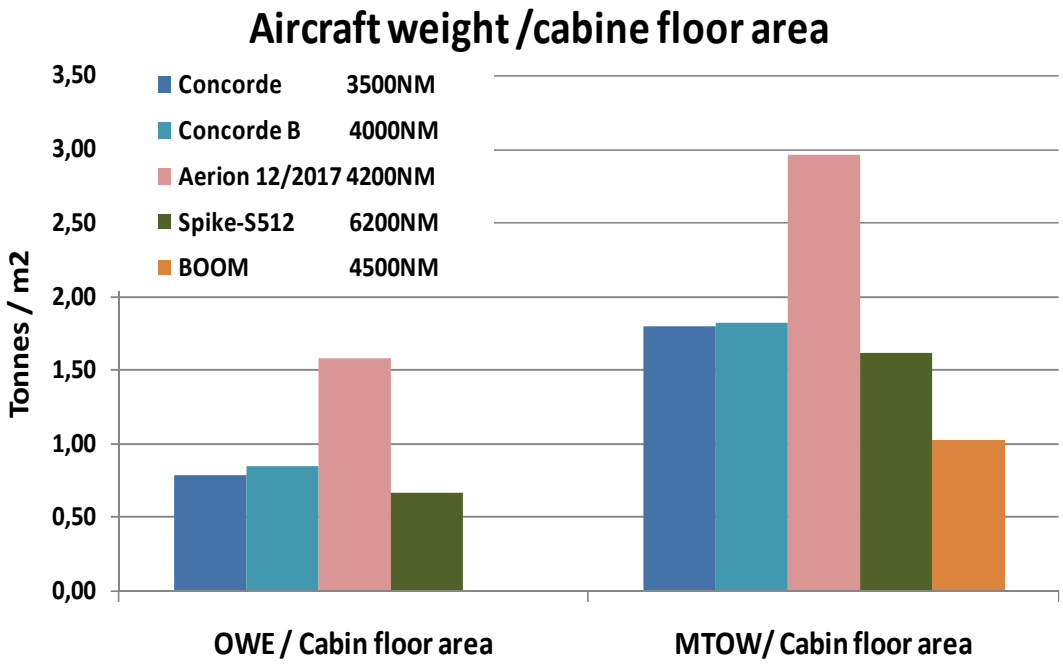
The GE Affinity does not meet the performance level required by Aerion and cannot be used for the other aircraft (temperatures, pressure ratios and thrusts).

Regardless of take-off noise, the specific fuel consumption of such engines could vary at best from 0.9 at Mach 1.4 to 1.1 kg/daN.h at Mach 2.

Summary: weights

Aircraft weights / cabin floor area

- Aircraft weight over cabin floor area ratio:
  - increases when aircraft size decreases: e.g. FALCON (20m2) ratio 50% higher than A320 (100m2)
  - increases with range.

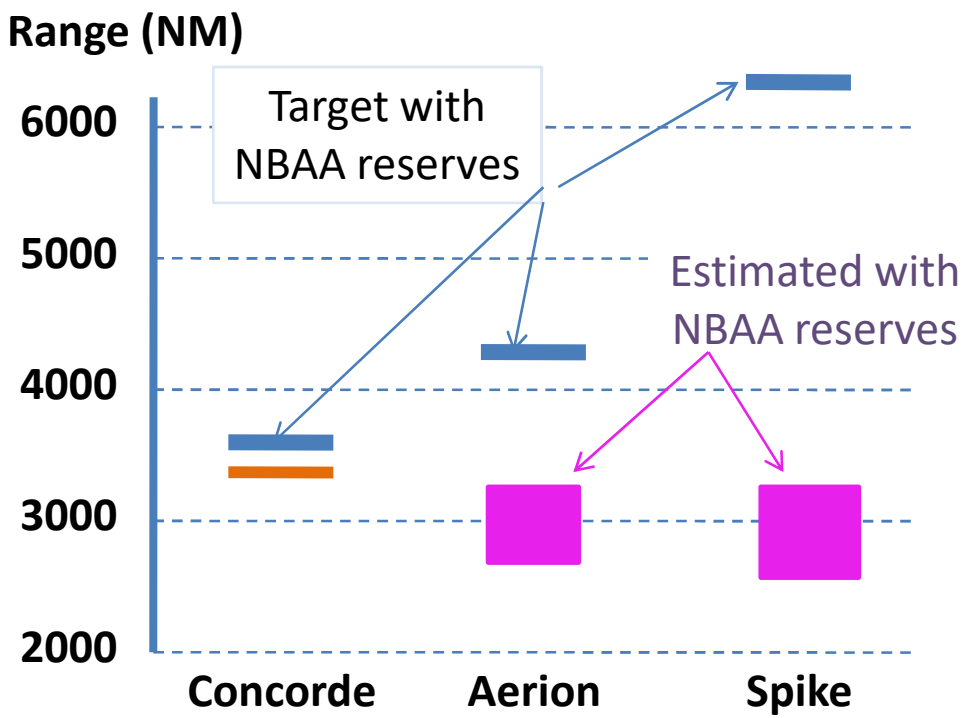


- Compared to Concorde, business jets will be penalized
  - by their size
  - by new certification requirements which will not be compensated by the use of composite materials, since these are not very efficient for small aircraft.

- **The Spike S 512 weights are largely underestimated.**

- **What to think about the Boom that would have a MTOW/cabin floor area close to 1 if a MTOW of 77.1t is used?**

Proposed & Estimated ranges



Range was estimated using:

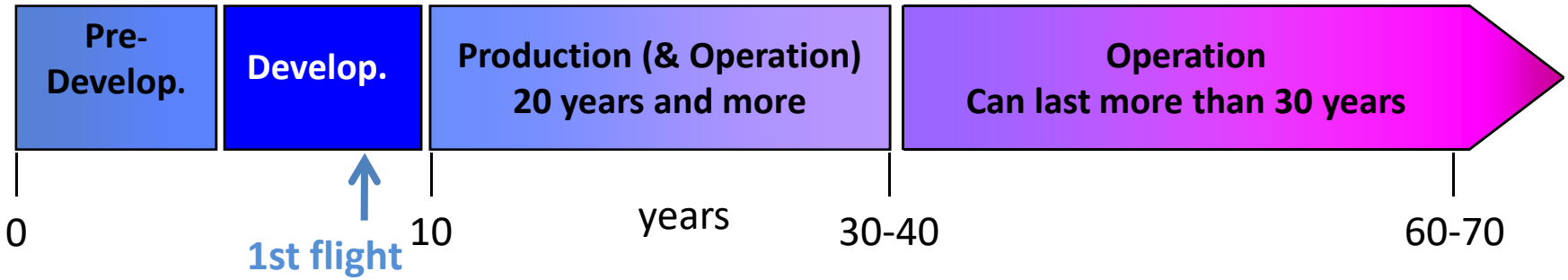
- ❖ estimated lift / drag ratio
- ❖ "best probable" SFC
- ❖ weights provided by developers, even if they are underestimated.

No estimation was made for Boom as no "official" information is available.

- ➢ Due to the fact that engine thrusts and weights are considerably underestimated, estimated ranges are for below announced ones.
- ➢ Crossing the Atlantic is not achievable.
- ➢ On top of that, margins for error would need to be left to allow for "development" issues.

Programme considerations

Typical subsonic aircraft development



- At the end of the pre-development phase:
  - the aircraft and propulsion system definitions must be frozen and the knowledge of their characteristics (performance and overall design) accurate enough to guarantee performance, noise, delivery dates… to potentials customers. With penalties if these guarantees are not met
  - knowledge of the equipment and interfaces within the aircraft must include cost, weight and performance specifications, in order to launch calls for tender.
- **The propulsion system, a major component, must be well known at the beginning of the pre-development phase.**

The proposed programs are far from having achieved the necessary maturity to consider Entry into Service dates

Conclusions (1)

- An analysis of Concorde reveals the reasons for the failure of supersonic commercial aircraft:
  - airport and supersonic cruise noise levels not compatible with public demands
  - fuel consumption per seat and operational costs too high

  It also indicates the improvements that would have to be made to allow for the design and operation of potentials successors.

- Projects initiated by major airframers from 1975 to the 1990s identified areas of improvement but also their limits:
  - aircraft size in particular has to be increased to allow a relative reduction of the fuselage impact and aerodynamic improvement
  - the impossibility for the Propulsion Systems to solve the noise-performance dilemma.

Conclusion, new projects

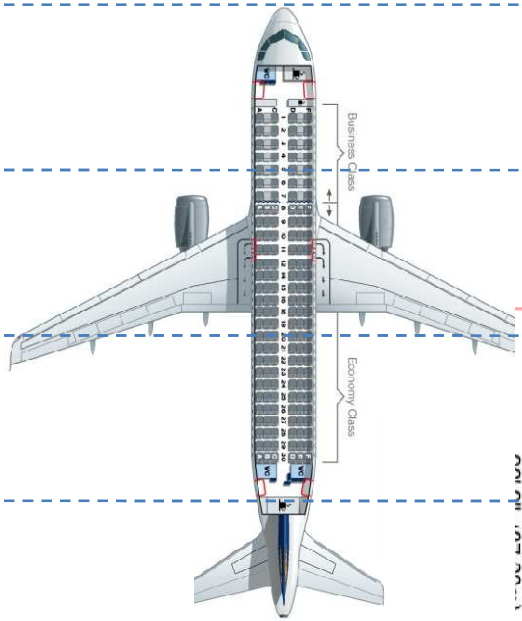
- Proposed aircraft goals are very different, varying from 8 to 55 passengers and from Mach 1.4 to Mach 2.2.
- The size of the business jets under study does not permit**:**
  - the necessary aerodynamic improvements
  - the required propulsion system, in terms of noise and specific consumption.
- The proposed empty weights are at best very ambitious and often totally under estimated.

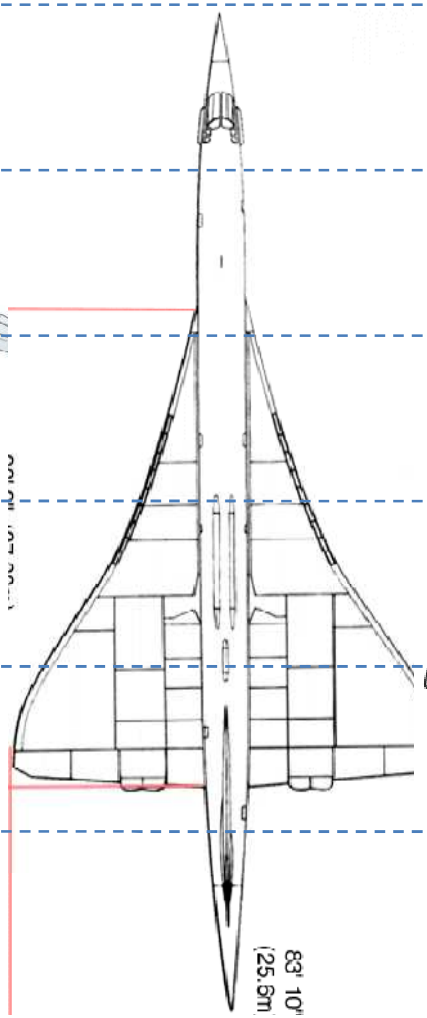
These specifications are incompatible with proposed ranges (guaranteed with wind…)

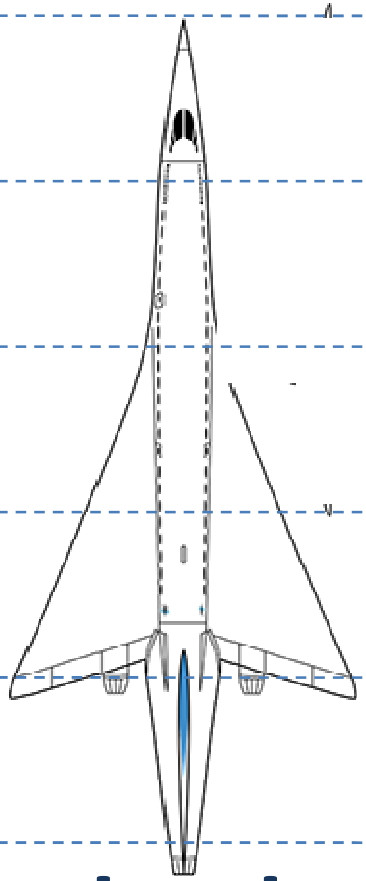
- These aircraft would be very far from meeting environmental (noise and CO2) limits governing current subsonic aircraft. Are derogations possible? Acceptable?
- The proposed Entry into Service calendars are not compatible with aircraft and propulsion system developments that require breakthrough technologies.
- Will the promised performances (range and time savings) of the most credible project meet potential customers' expectations?
- Indicated development costs are considerably under-estimated for constructors since they would have to be amortized without spare parts sales. (More than 10 to 12Mds $ for a replacement of A320).

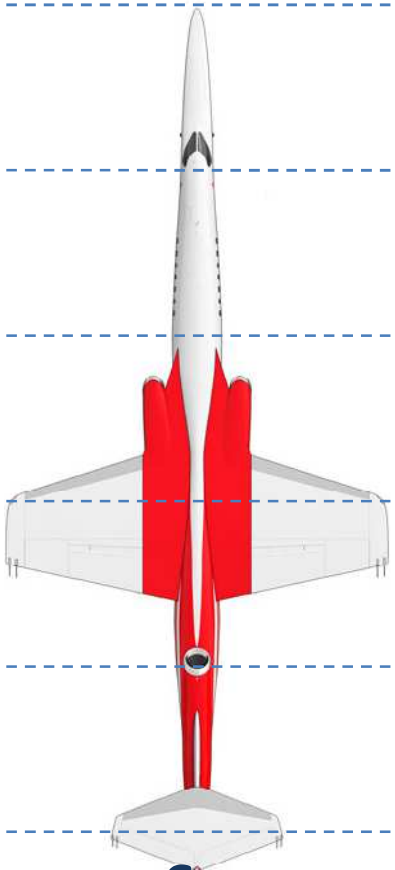
***Both "studies"* and "buzz" will last a long time**

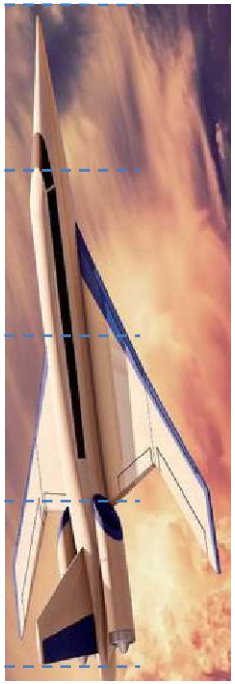
A320	Concorde	Boom	Aérion	Spike
160p	100p	40-45p	8-12p	12-18p





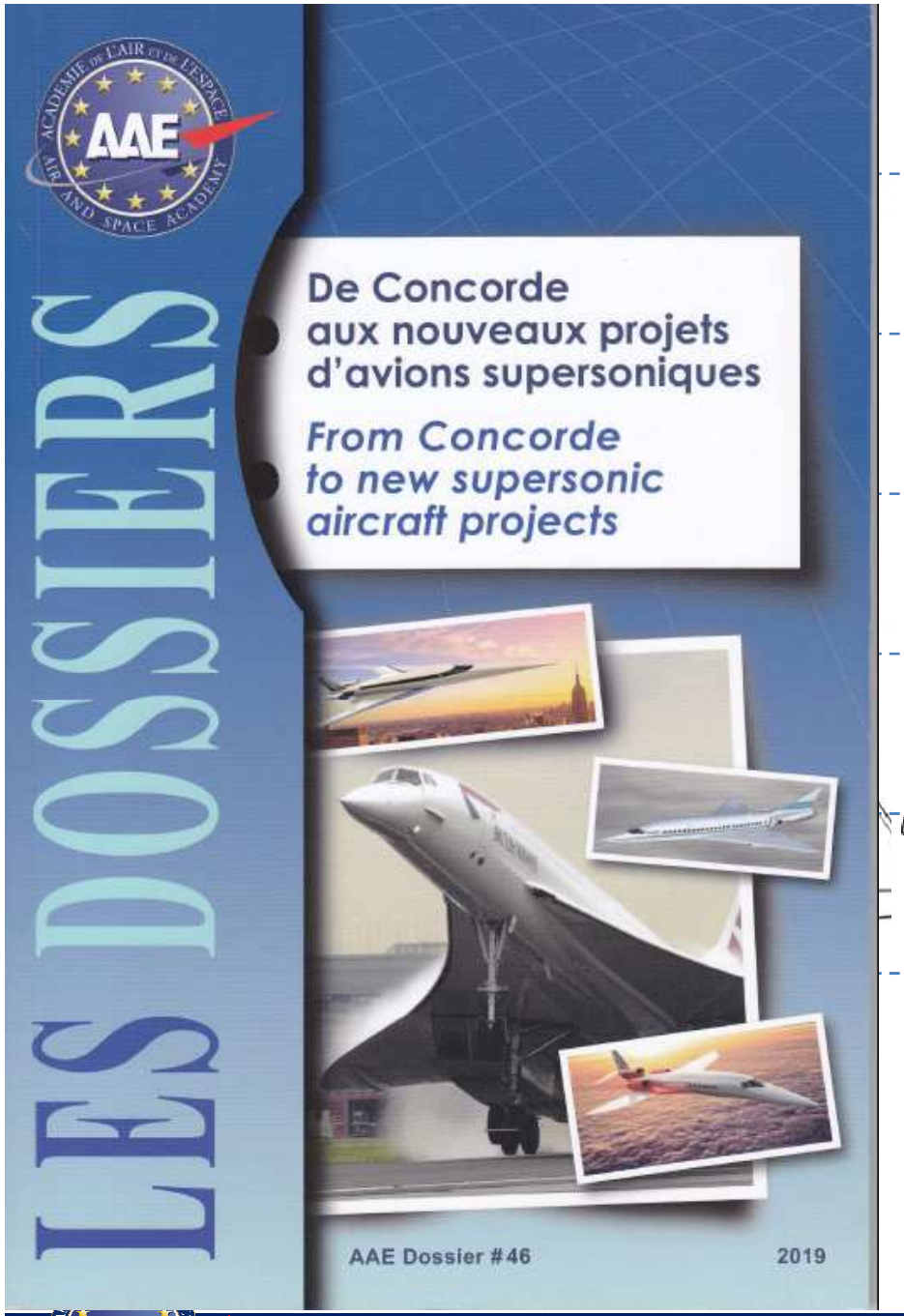






Thank you for your attention

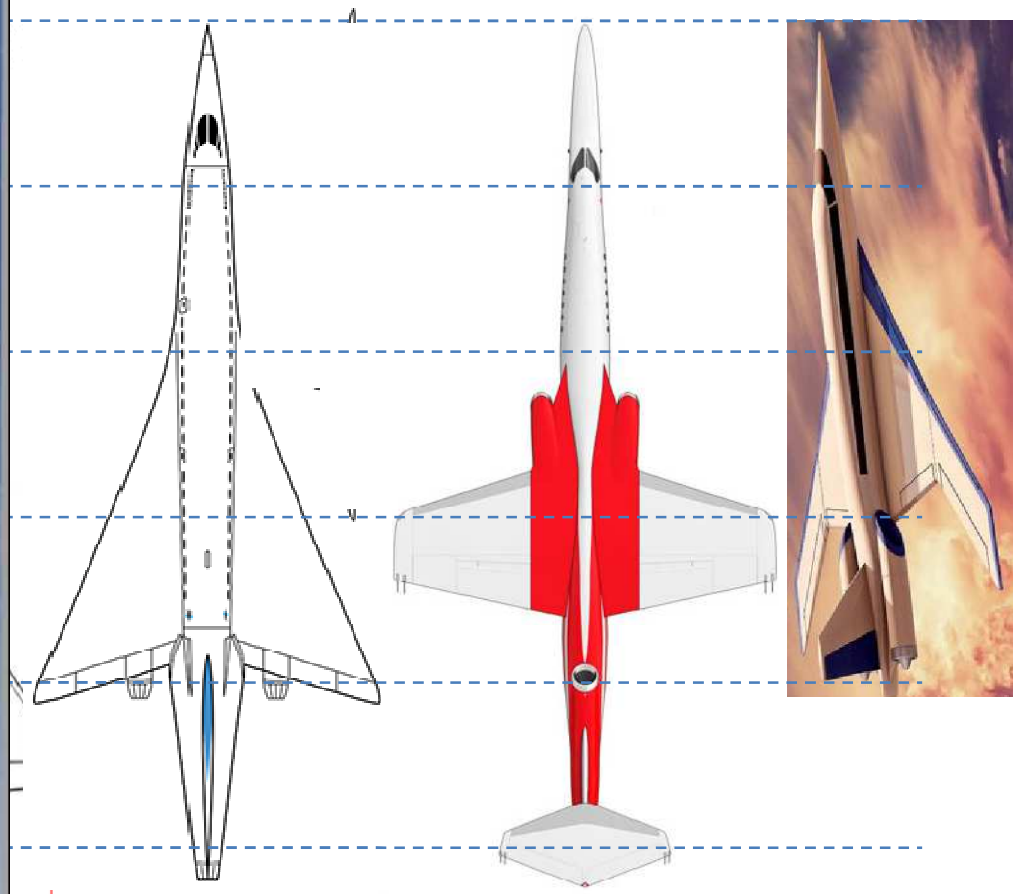
Any questions?



Boom
40-45p

Aérion
8-12p

Spike
12-18p



Dossier available.
AAE