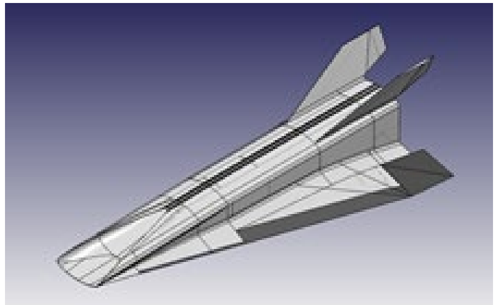
Centro Italiano Ricerche Aerospaziali

Seminari di Cultura Aeronautica sulla Propulsione Supersonica

La propulsione airbreathing per velivoli supersonici ed ipersonici

Marco Marini (CIRA)





Scuola Politecnica e delle Scienze di Base, Università Federico II, Napoli
17 Maggio 2023

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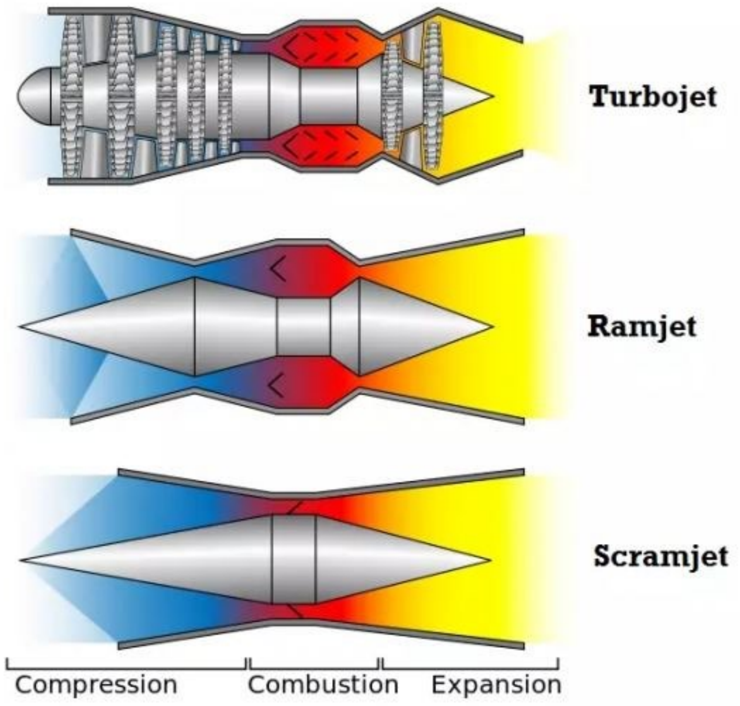

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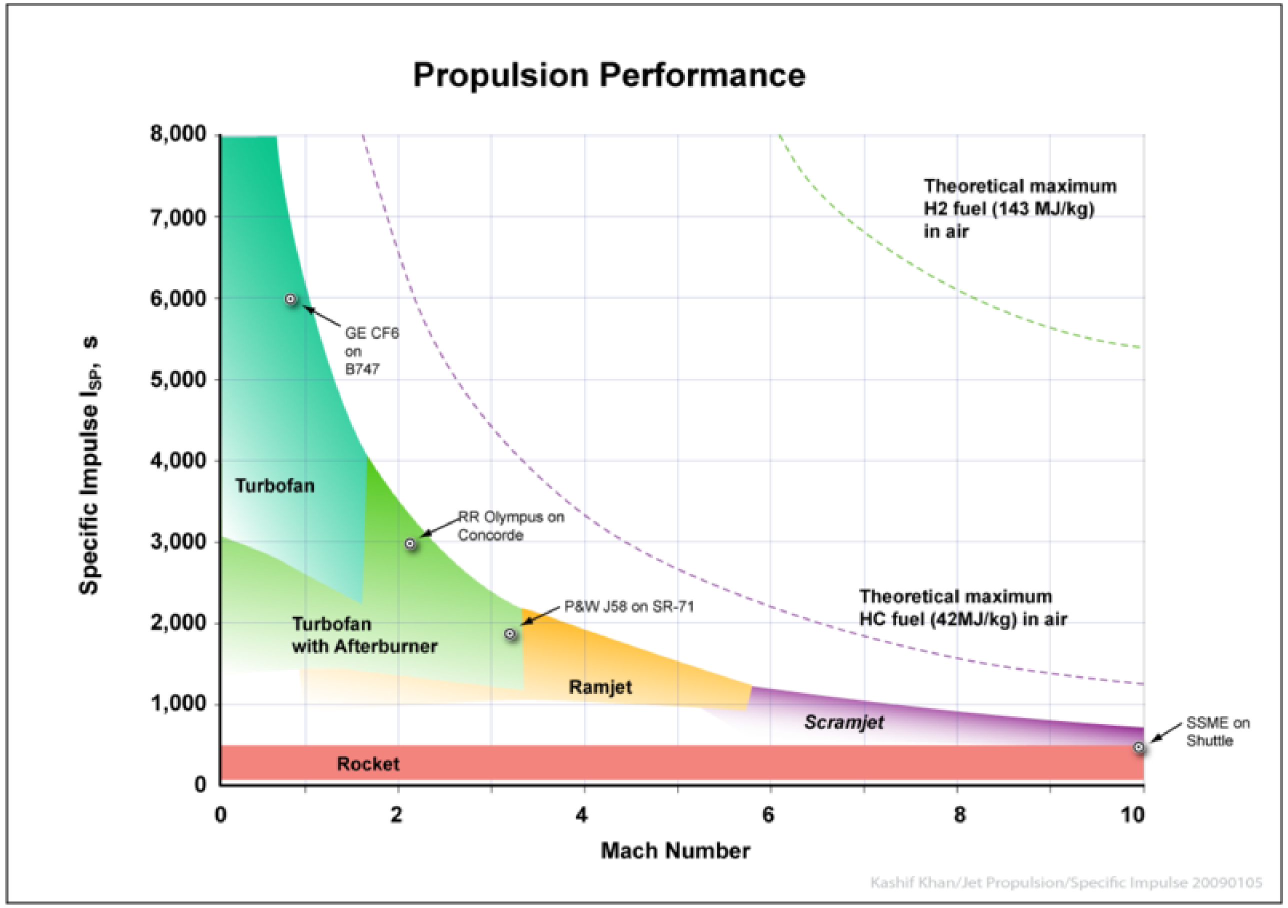
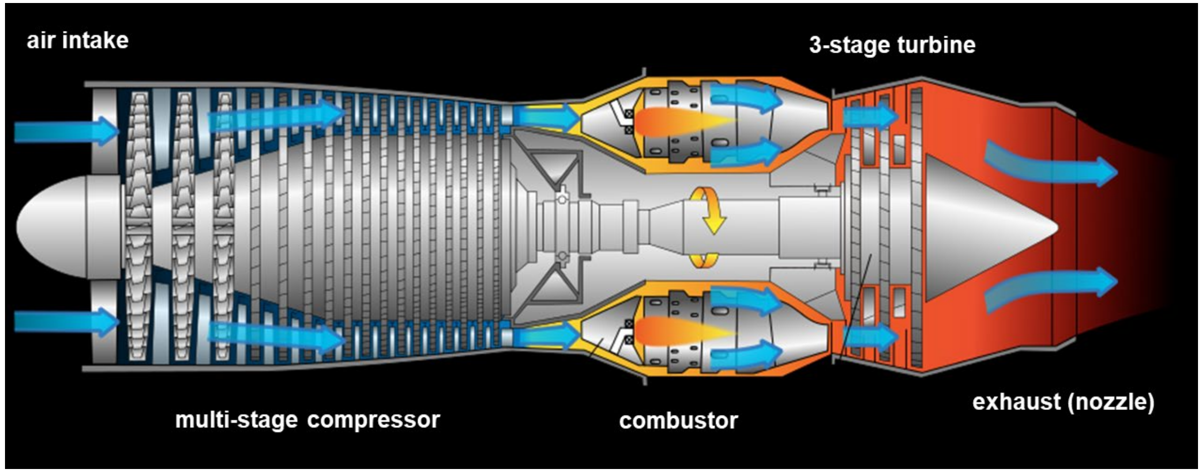
High-Speed Airbreathing Propulsion: Motivation



$$I_s = \frac{F}{g_0 \dot{m}_f}$$ (Specific Impulse)

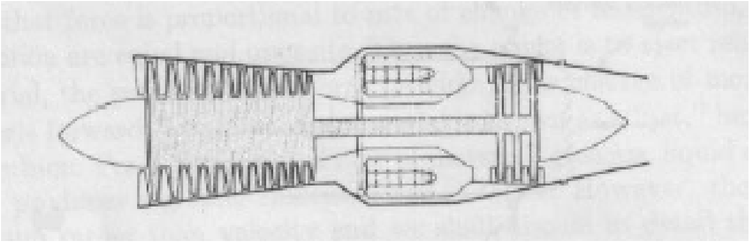
- Mission requirements define the most suitable propulsion system
- Airbreathing engines use atmospheric oxygen for combustion thus allowing for weight and volume reduction and specific impulse increase w.r.t. rockets
- The operative envelope is reduced w.r.t. rockets since the engine functioning strongly depends on Mach number
- For hypersonic flight (Mach>5) the most efficient airbreathing engine is the scramjet

Turbojet Propulsion

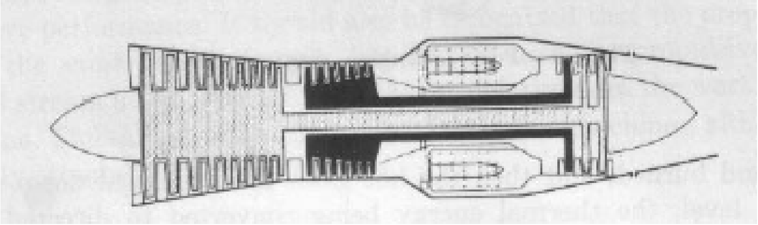


- Compression made by a compressor driven by a turbine, which exploits the energy supplied to the propulsive fluid by combustion
- At turbine exit the gas has a higher pressure than ambient → expansion (acceleration) inside the nozzle and thrust generation
- Thrust produced at V=0

- Most common engine in aviation, both civil and military, due to optimal performance (thrust, SFC, thrust/weight ratio, high efficiency, reduced frontal area, low maintenance)
- Very efficient at high speed → <u>ideal for supersonic aircraft</u>
- The twin-shaft turbojet (high pressure C-T group and low pressure C-T group) has a better response to the power variations produced by varying the fuel flow rate (throttle-ability)



Single-shaft turbojet



Twin-shaft turbojet

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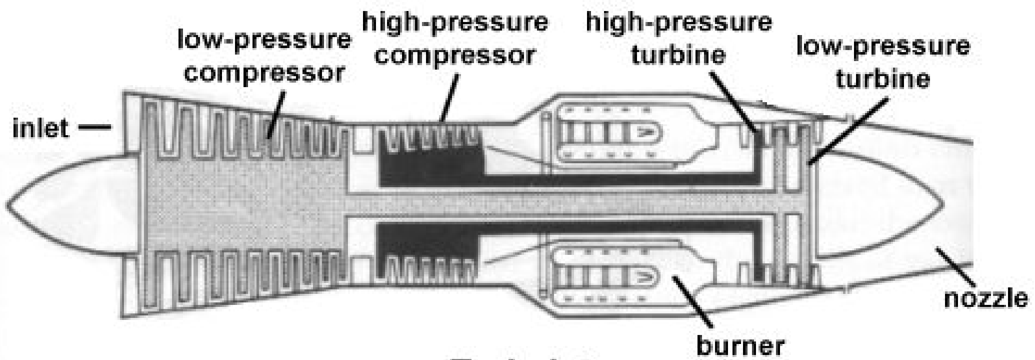
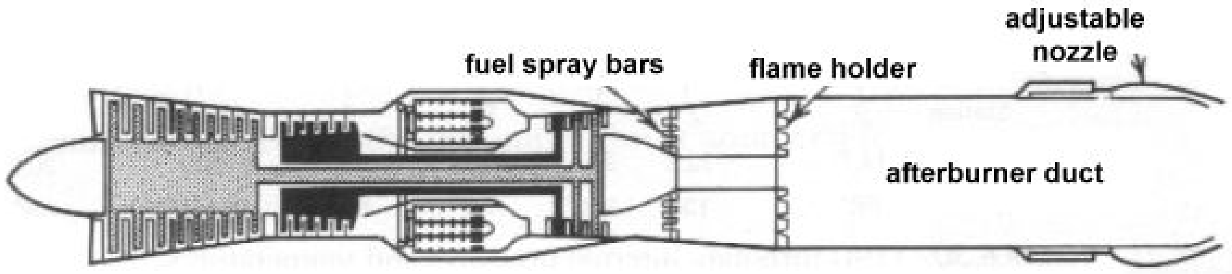
Turbojet with Afterburning Propulsion



Turbojet



Turbojet with Afterburner

Tornado (1979)
2 x 73 kN + A/B

Concorde (1976)
4 x 169 kN + A/B

- To keep turbine blades within allowable temperatures, it is used a «lean» fuel/air mixture
- Afterburning (A/B): second combustion with hot air (in excess) by injecting fuel downstream of the turbine
- Thrust augmentation in critical flight phases for limited time (high SFC)
- Supersonic and military aircrafts

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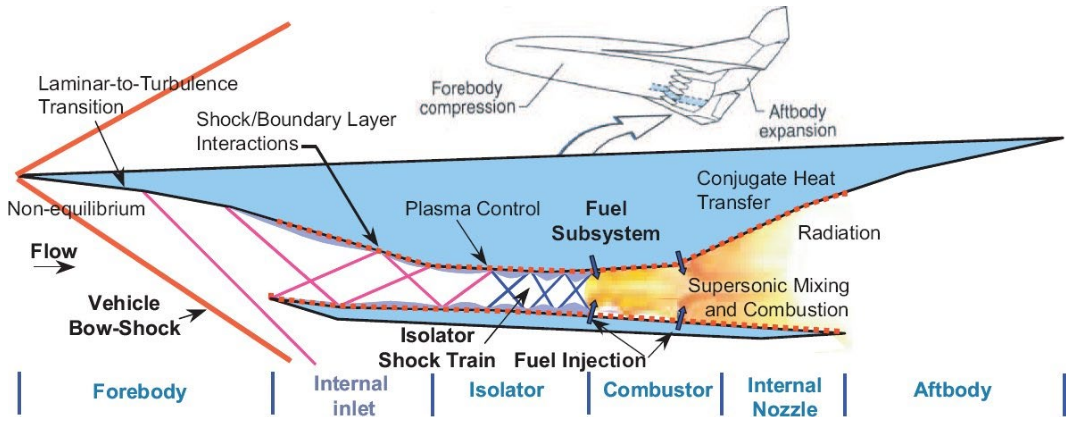
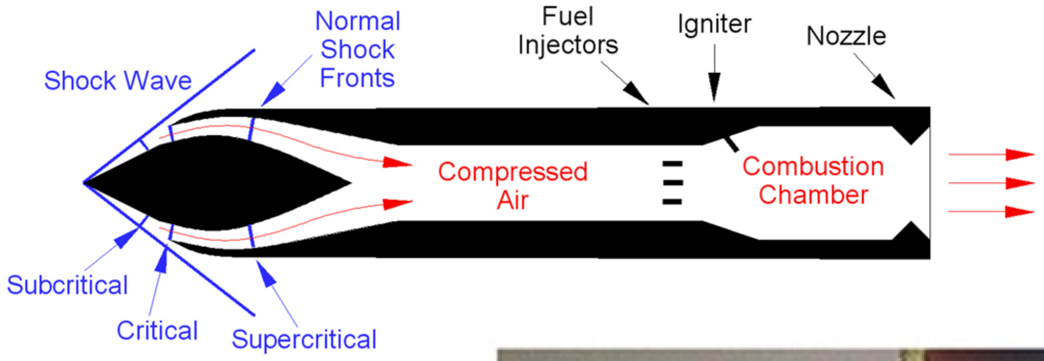
Ram/Scramjet Propulsion: Advantages and Drawbacks

- Compression and expansions without turbomachinery
- Air slowed down and compressed inside the intake
- No thrust produced at V=0
- Aircraft engines: it reduces the time for long flights
- Weapon systems: it increases the range and reduces time-to-target
- Launchers: it reduces the fraction of the weight of the propulsion system
- Supersonic/hypersonic UAV: Rescue System, . . .





Advantages

- Mechanical simplicity associated to high propulsive efficiency
- Wide Mach number range: 2 < Mach < 6÷8

Drawbacks

- High thermal loads for the nozzle and the combustor
- Mechanical actuators to adjust (intake and/or nozzle) to different flight conditions

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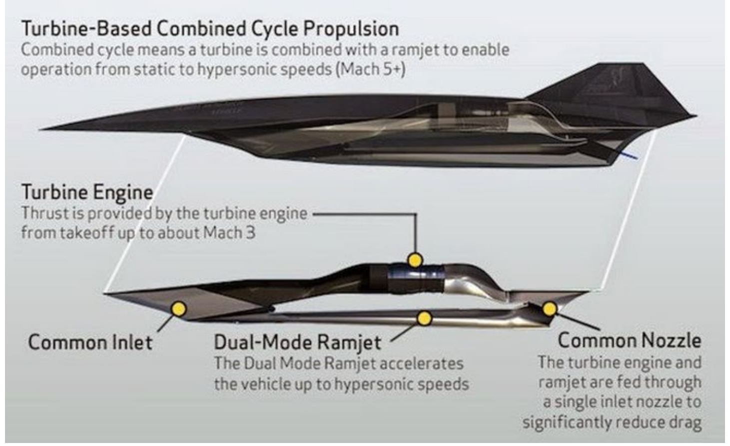
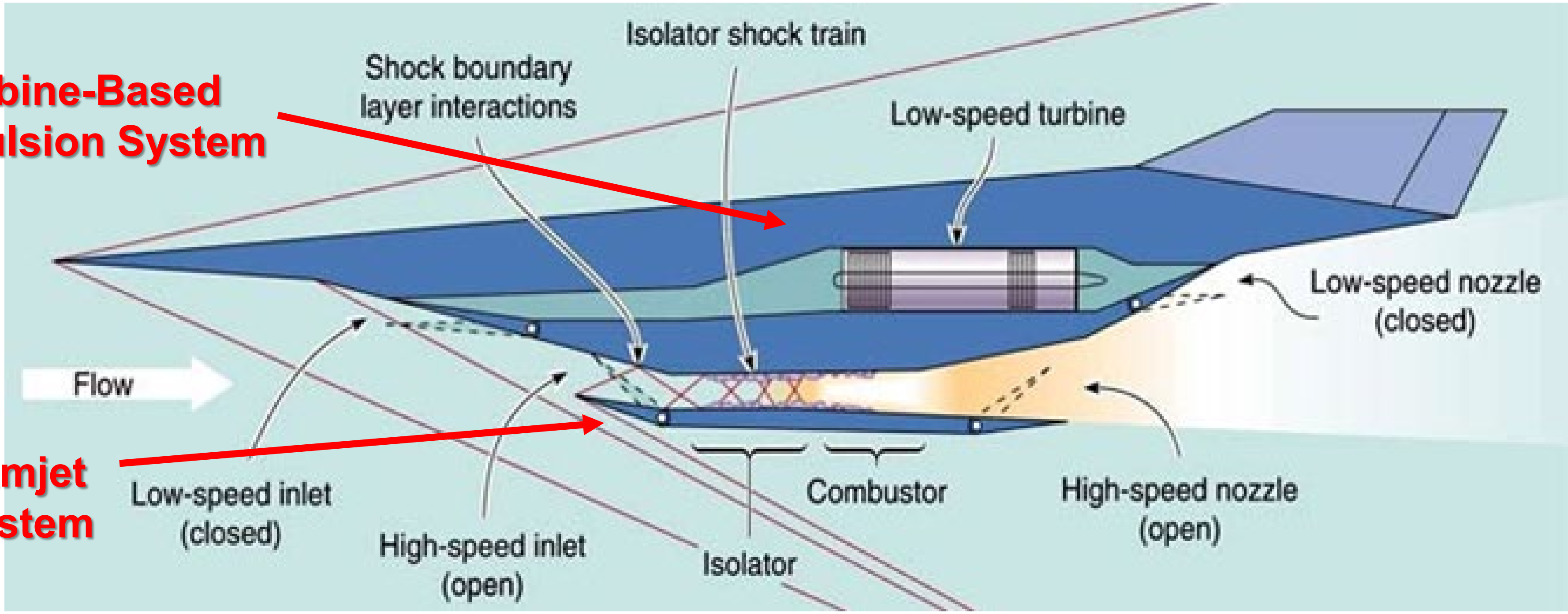
Combined Propulsion System

- Combined cycle for propulsive system: merging of turbojet and ramjet engines
- Operation from take-off to hypersonic cruise and finally to landing
- Variable geometry for common inlet and propulsive nozzle



Turbine-Based Propulsion System

Dual Mode Ramjet Propulsion System



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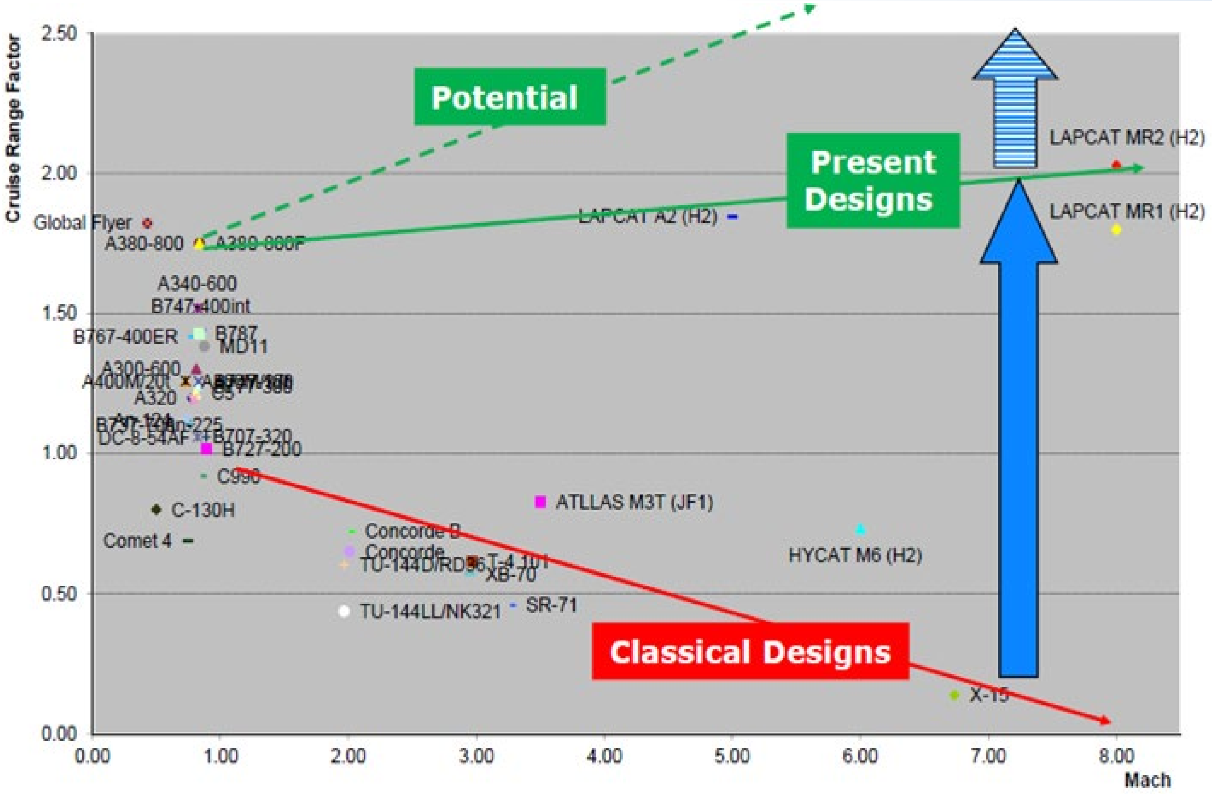
Hypersonic Airbreathing-Propelled Vehicles



- Hypersonic transport historical weakness: small cruise range due to high fuel consumption
- Classical designs: performance decays linearly with Mach number (i.e. Concorde, TU-144, SR-71, X-15)
- Trend reversal with modern highly integrated design approach (high-lift configuration coupled to efficient propulsion systems)
- Such integrated approach potentially may produce a hypersonic airbreathing-propelled vehicle with
  - Flight times of intercontinental antipodal routes (p.e. Bruxelles-Sydney) of 2÷4 hours
  - Passenger safety level similar (or higher) of current aircraft
  - Propulsion system with reduced emissions w.r.t. current aeronautical engines (hydrogen w.r.t. hydrocarbons)
  - Ticket price not so larger w.r.t. that of intercontinental flights (3 times the one of current business-class)
- Use of hydrogen has drawbacks
  - Production and storage of LH_2 (impact on infrastructures and flight ticket)
  - NOx and H_2O emissions (impact on environment, global warming)

Panavia Tornado MRCA

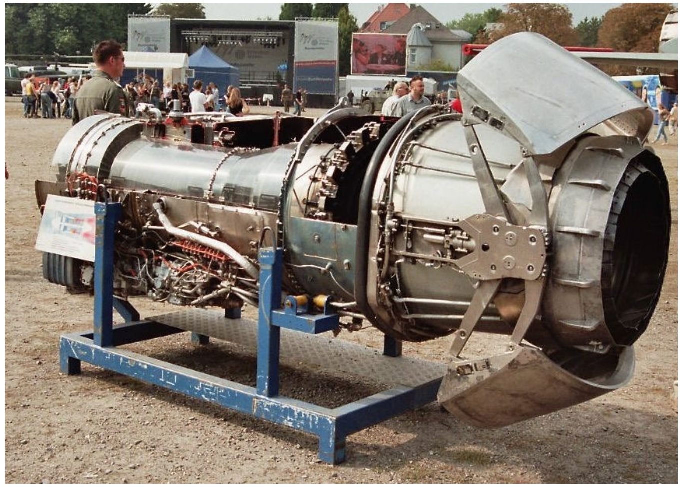
Fighter-Bomber and Interceptor

Multi-Role Combat Aircraft with variable sweep wings

Max speed	Mach 2,2 a 9000 m
Length	16,70 m
Wingspan	8,60÷13,91 m
Height	5,95 m
Wing Surface	26,60 m^2
Empty Weight	13600 kg
MTOW	28000 kg
Max. range	3800 km
Max. altitude	15240 m

Engines: 2 x Rolls-Royce/Turbo Union RB-199-34R

Thrust = 73 kN for each engine with A/B
Low bypass ratio (1.1:1)
Variable intake ramps
Annular combustion chamber
Variable geometry nozzle
Thrust reversers



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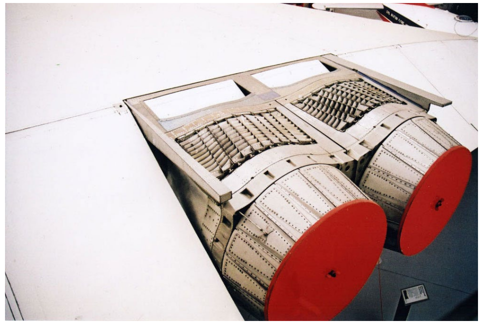
Aérospatiale-BAC Concorde

Supersonic Airliner (144 passengers)

Max speed	Mach 2,04
Cruise speed	2179 km/h (Mach 1,8) at 15630 m
Length	62,10 m
Wingspan	25,50 m
Height	11,30 m
Wing surface	385,20 m²
Empty weight	78700 kg
MTOW	185066 kg
Max. range	6230 km
Cruise altitude	17000 m
Max. altitude	18300 m



Engines	**4 turbojets Rolls-Royce/Snecma Olympus 593**
Thrust	139 kN for each engine
	169 kN for each engine with A/B
Fuel	Jet A1
Compressor	Axial, 7-stage LP and 7-stages HP
Turbine	1-stage HP, 1-stage LP

Intake and nozzle with variable geometry

A/B only used at TO and in transonic regime from Mach=0.9 to Mach=1.7 (high fuel consumption)

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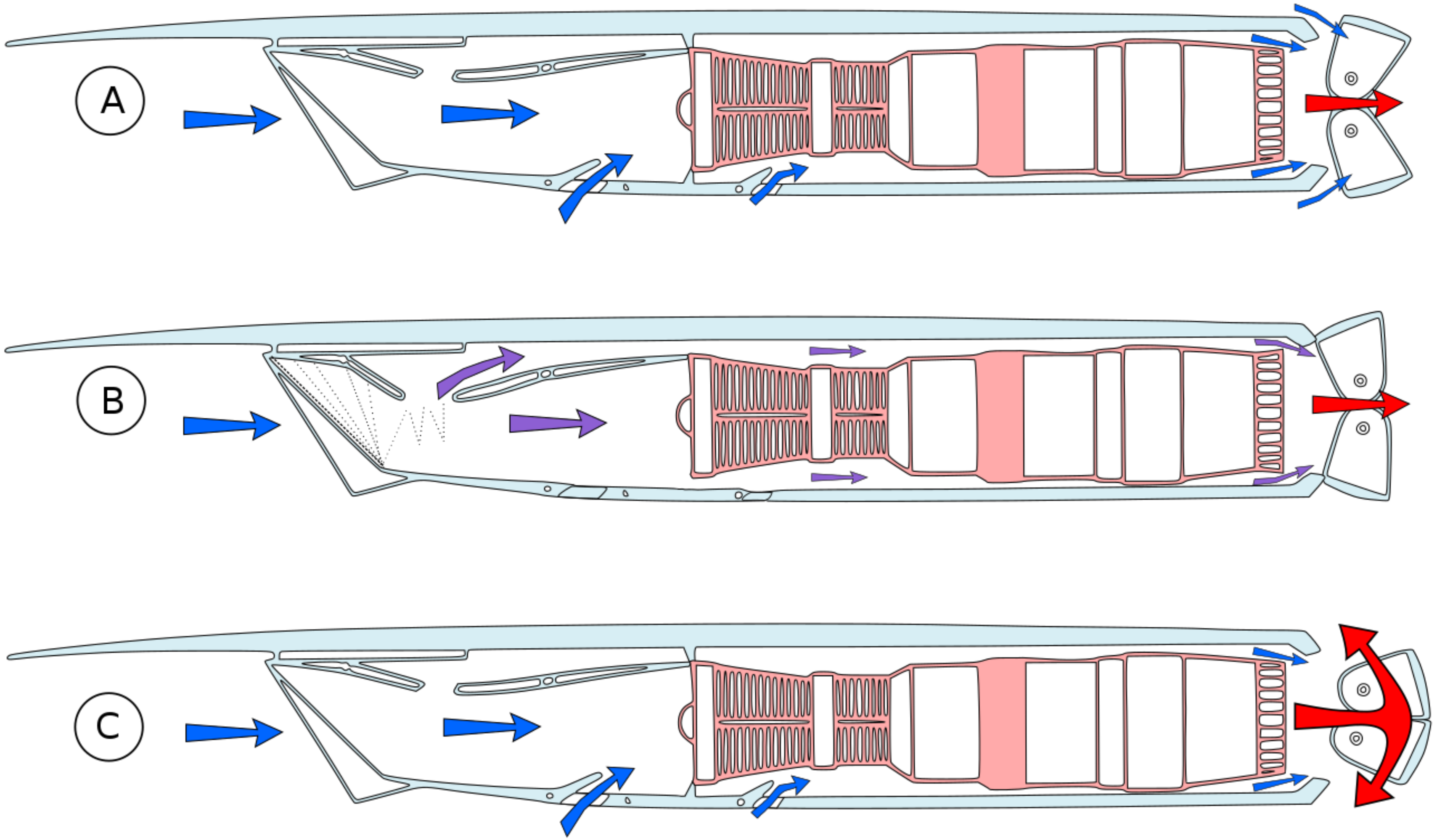
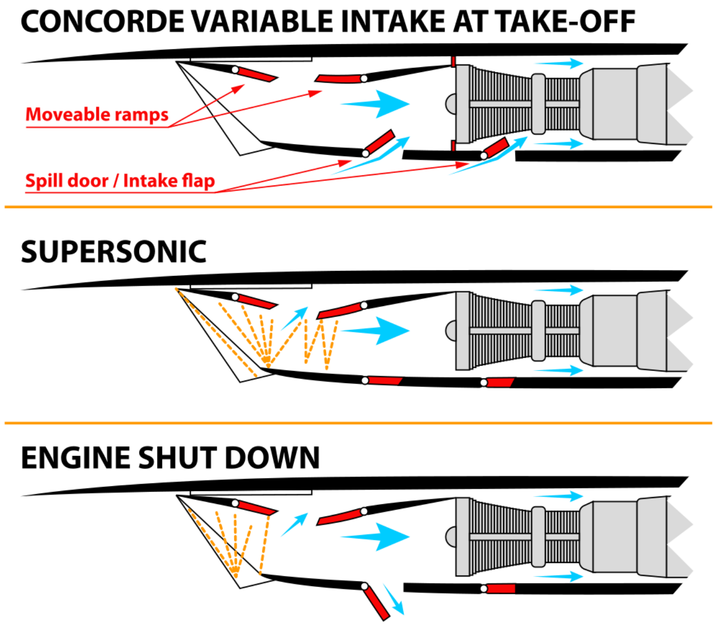
Aérospatiale-BAC Concorde





Need for mechanical actuators and control systems for intake movable ramps and/or deflectors and nozzle petals

Variable geometry intake and nozzle for takeoff (A), supersonic cruise (B) and with thrust reversers (C)

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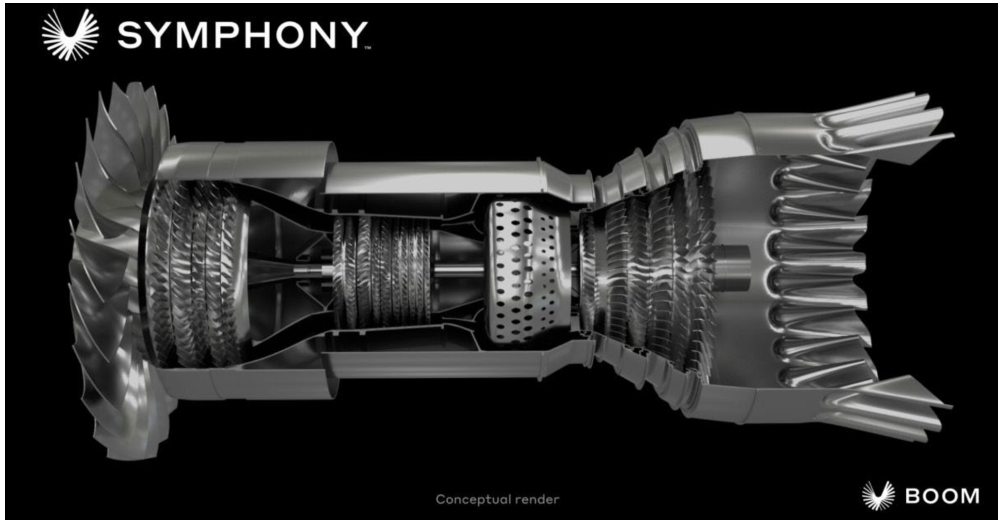
Boom Overture

- Supersonic airliner for Mach 1.7 cruise, 65÷88 passengers, 7870 km of range
- Boom Technology plans to introduce it in 2029 (for certification) predicting a market for 1000 aircraft with business class fares (76 commitments by Dec. 2017)
- First flight test in 2027
- The aircraft has a delta wing configuration and it will be built with composite materials
- Regulations for takeoff noise or overland boom can be met or changed



- Overture is intended to be powered by 4 medium-bypass classic architecture twin-spool turbofans (67÷89 kN thrust, no afterburning), i.e. SYMPHONY
- 160 kN of thrust at takeoff and burning 100% sustainable aviation fuel
- Boom-designed axisymmetric supersonic intake, matched with a variable-geometry low-noise exhaust nozzle and a passively cooled high-pressure turbine
- Its single-stage fan highlights whisper-quiet operation and will be fully compliant with all FAA and EASA Part 33 requirements

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Lockheed SR-71

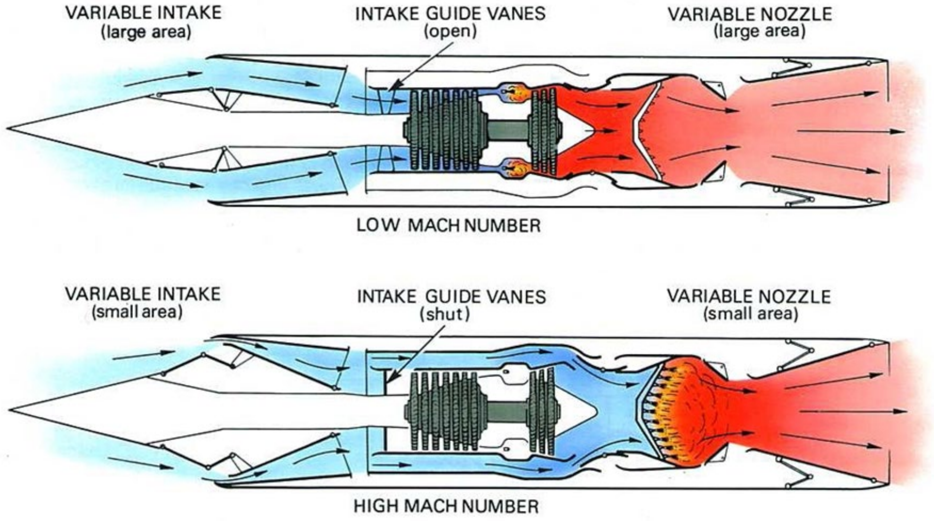
SR-71

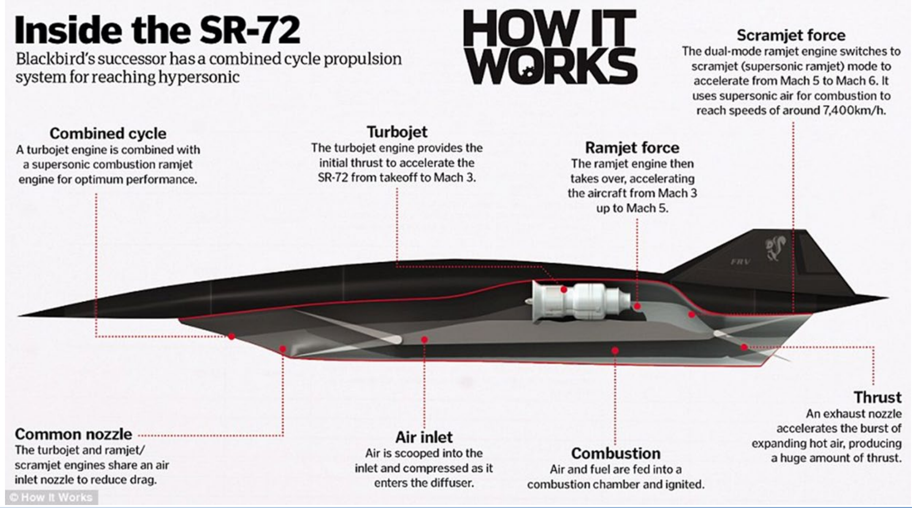
SR-72 vs. SR-71

	Lockheed SR-71 Blackbird	*Lockheed Martin SR-72*
Role	**Strategic reconnaissance**	**Strike and reconnaissance**
Crew	**Two** (pilot and systems operator)	**Optionally manned**
Propulsion	**Turbojet** (x2)	**Combined cycle** (x2)
Maximum speed	**Mach 3.3** (4,075km/h)	**Mach 6** (7,400km/h)
History	First flight **1964** Retired **1999**	Test flight **2023** Operational **2030** (projected)

Sources: Aviation Week, Lockheed Martin

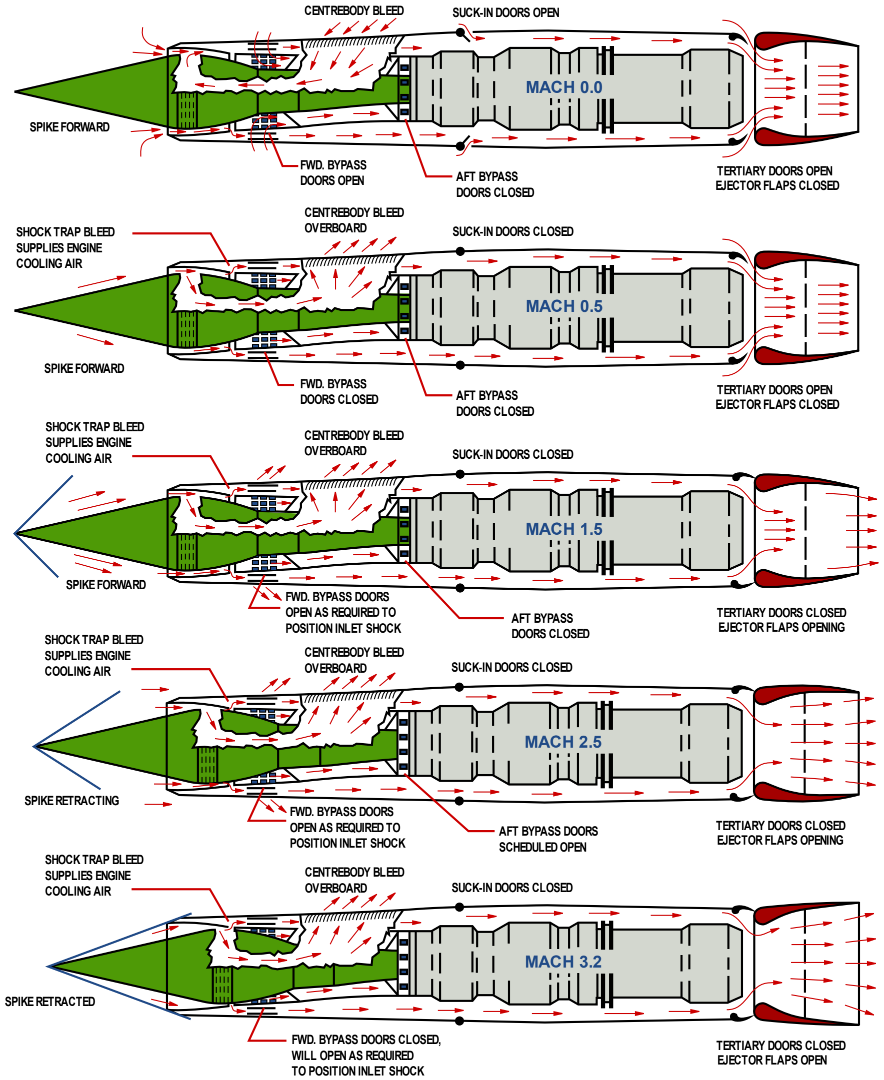
High-altitude, strategic reconnaissance aircraft equipped with J58 Turbo-Ramjet engines



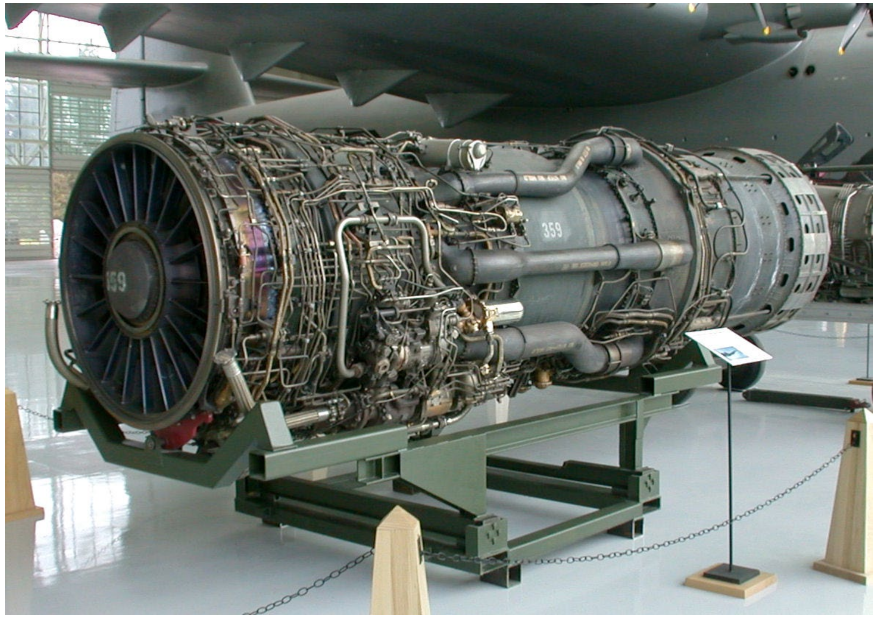


- ❑ Turbine-based combined propulsion cycle to accelerate the vehicle from standing to hypersonic speeds
- ❑ Turbine engine and DMR fed through a common inlet thus significantly reducing drag
- ❑ Variable inlet and nozzle ramps open and close to match propulsion cycle requirements

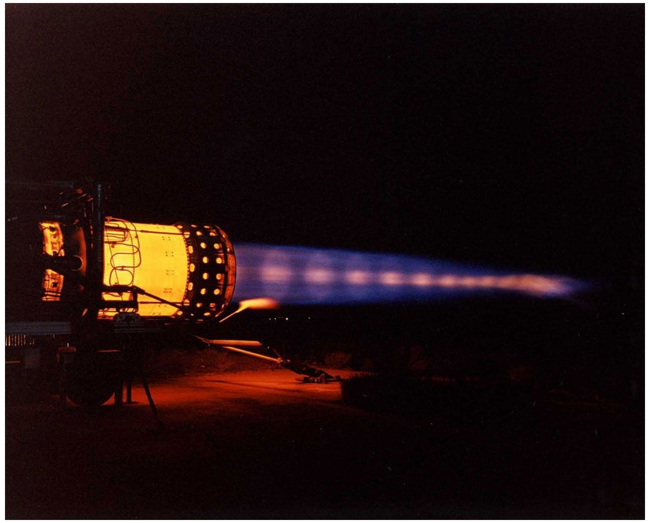
Lockheed SR-71



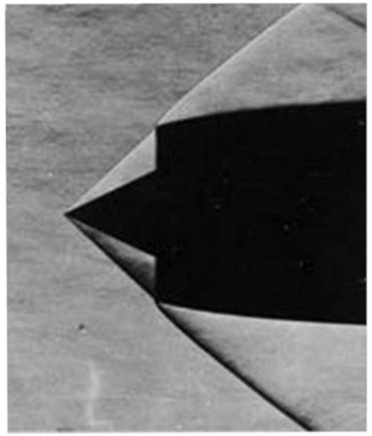
Operation of the air inlet and nozzle showing air flow through the nacelle



J58 turbo-ramjet on full afterburning showing shock diamonds



Unstarted inlet



Started Inlet

Schlieren technique flow visualization at unstart of axisymmetric inlet at Mach 2

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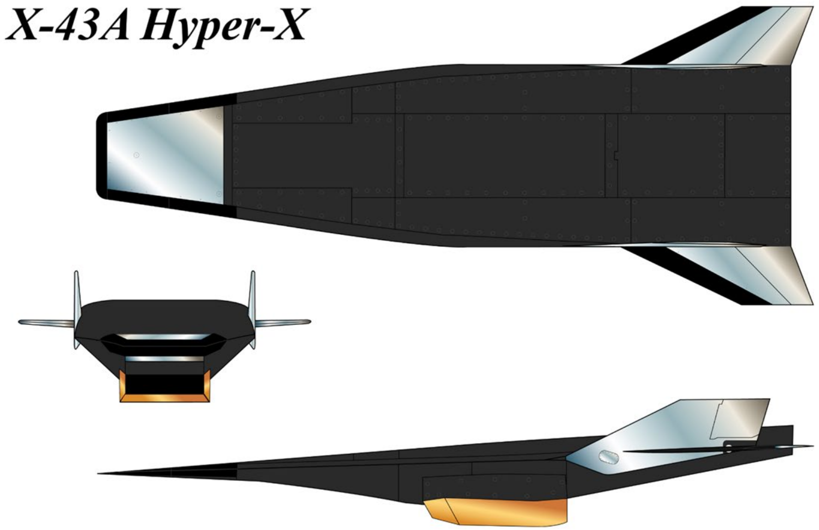
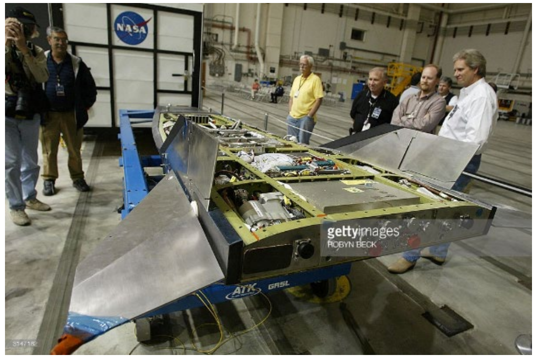
X-43A





- NASA Program Hyper-X
- Expendable unmanned vehicle
- Length 3.65m, weight 1300kg
- Carrier Boeing B-52
- 1st stage (rocket) to target velocity and altitude
- March 2004: 29km altitude, Mach=6.83, 11s of scramjet operation
- November 2004: 34km altitude, Mach=9.68, 10s of scramjet operation

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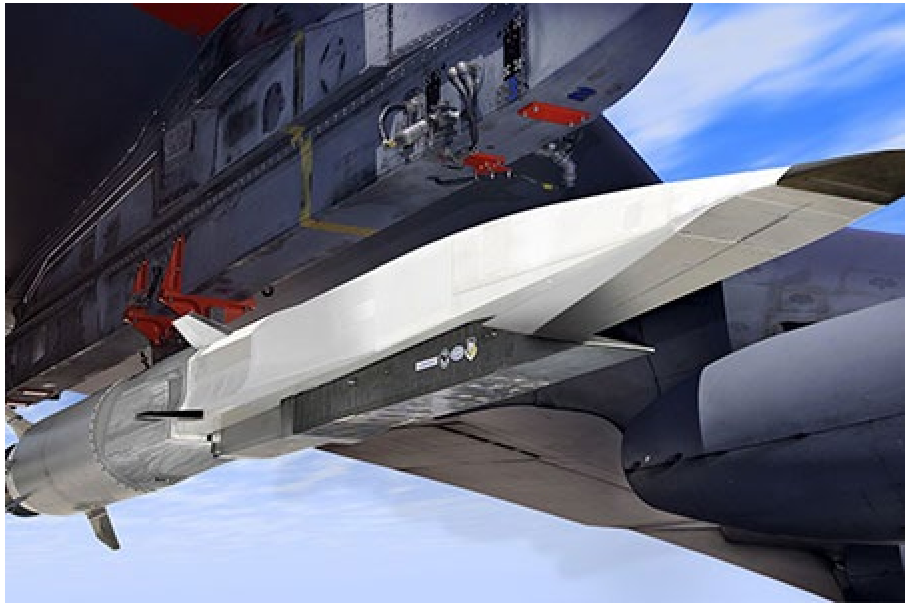
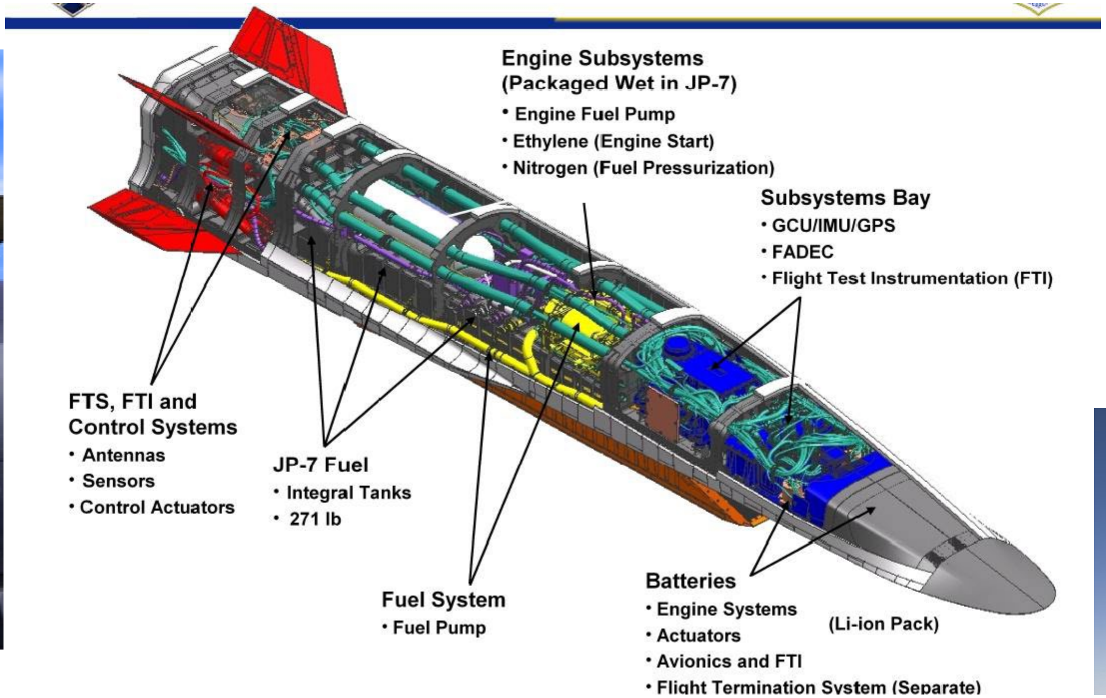
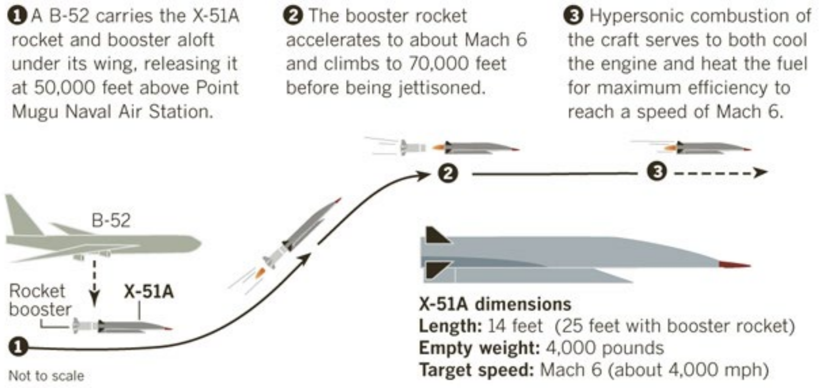
X-51A





- AFRL Program WaveRider
- Expendable unmanned vehicle
- Length 7.9m, weight 1814kg
- Carrier Boeing B-52
- 1st stage (rocket) to target velocity and altitude
- May 2010: M=4.8 after booster ignition, 21km altitude, Mach=5
- May 2013: 18km altitude, Mach=5.1, 240s of scramjet operation



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LAPCAT-II A2 and MR2.4

Long-term Advanced Propulsion Concepts And Technologies II (LAPCAT-II)

- LAPCAT-II project had the objective to reduce the duration of antipodal flights (flights between two diametrically opposite points on the globe) to less than two to four hours
- Two novel concepts – for Mach five and Mach eight cruise flight – were studied deeply in LAPCAT-II
- Major focus was on the assessment of aerodynamic configurations, propulsion systems and mission target achievements, by using both numerical methods (low/high fidelity, with the necessary modelling developments) and experimental testing
- The project, co-funded by the European Commission, lasted 62 months and involved 16 EU partners


Courtesy by REL

LAPCAT-II A2

Courtesy by ESA/ESTEC

LAPCAT-II MR2.4

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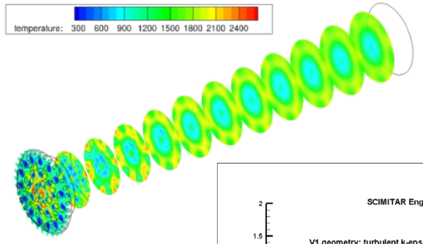
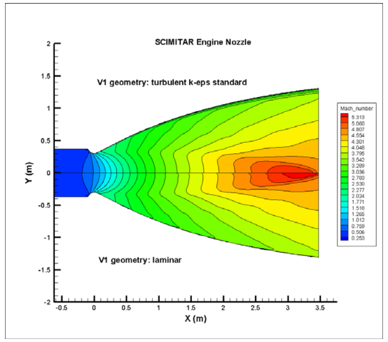
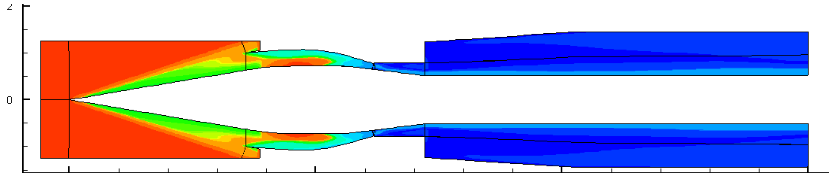
LAPCAT-II A2

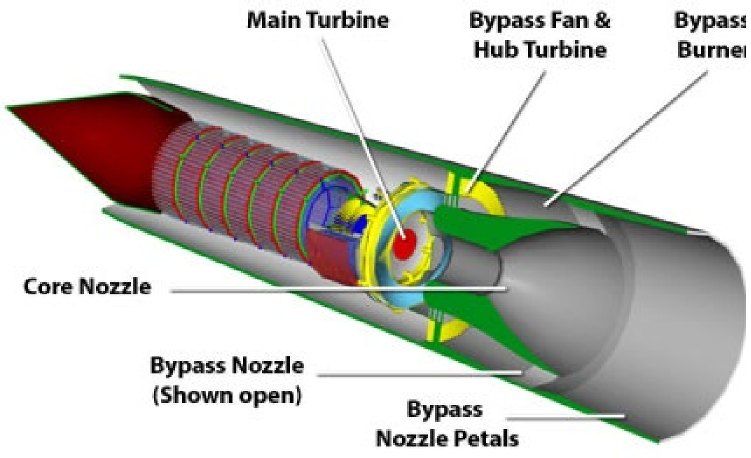
SCIMITAR engine for A2 Mach 5 cruiser

- Pre-cooled turbofan/ramjet engine (technology similar to SABRE but designed for much longer lifetime) with high bypass for great efficiency; LH_2 as fuel; use of lightweight heat exchangers in the cycle
- CFD support to the detailed design of main components (intake, combustor, nozzle)
- Numerical and experimental assessment of performance of intake, combustor and nozzle
- Combustion efficiency and emissions
- CFD support to wind tunnel test campaigns









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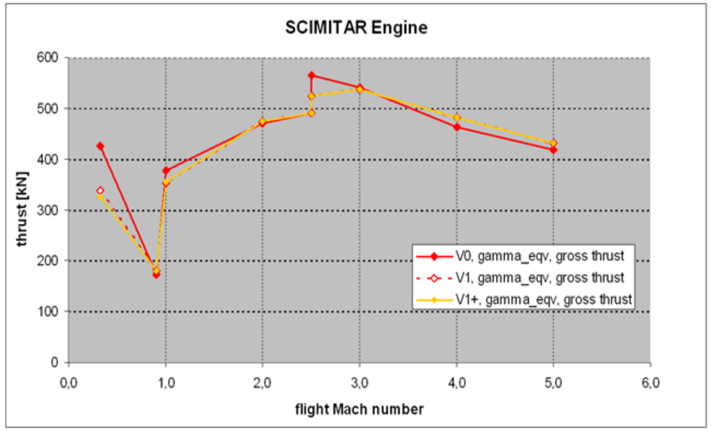
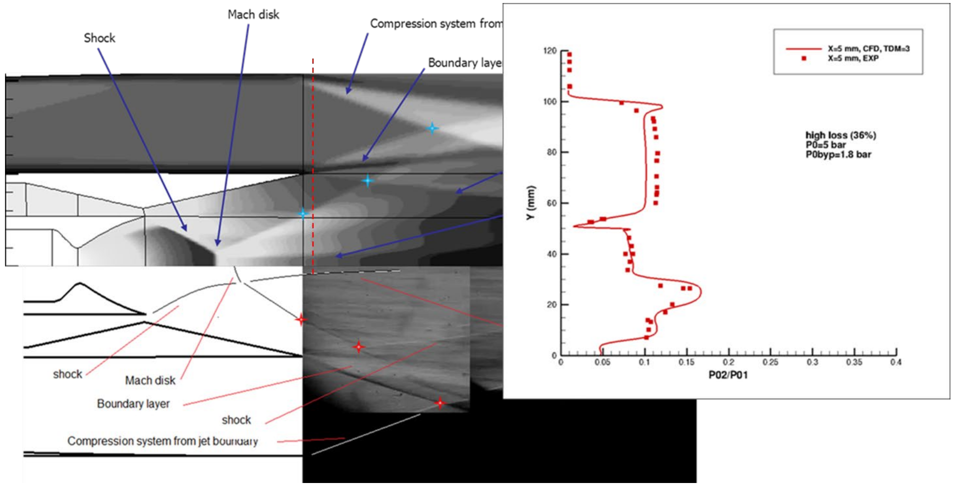


- Cruise condition: Mach Number 5 at an altitude of 25.4 km



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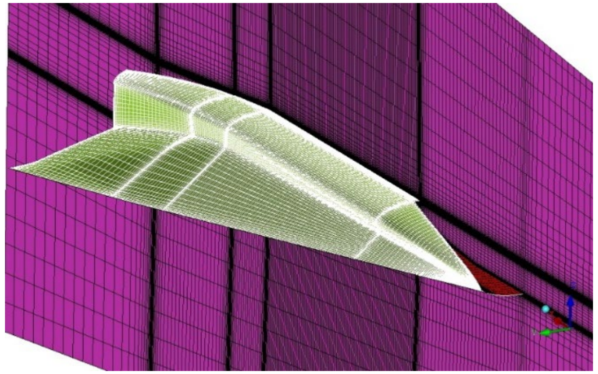
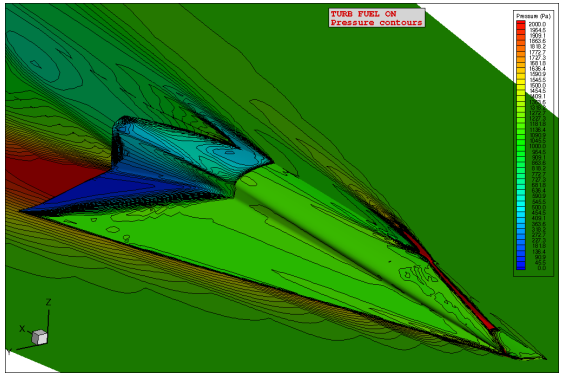
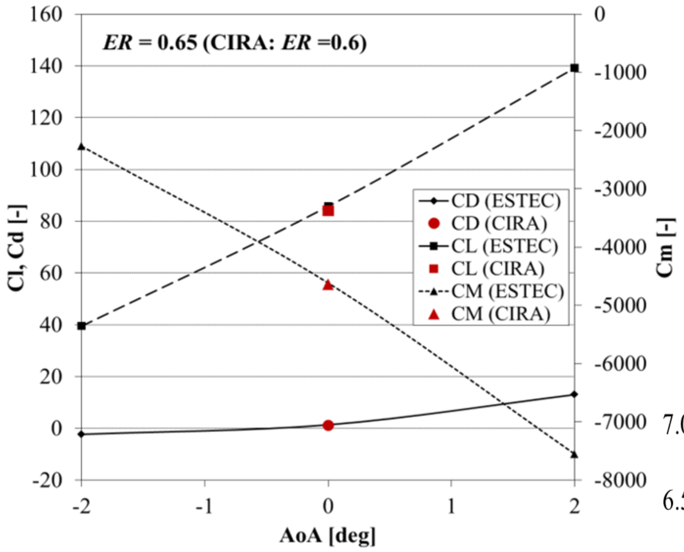
LAPCAT-II MR2.4

Analysis of a Mach 8 concept vehicle propelled by a scramjet engine

- Nose-to-Tail simulation of a full-scale vehicle by using a CFD 3D code for both internal (scramjet operating mode) and external flow

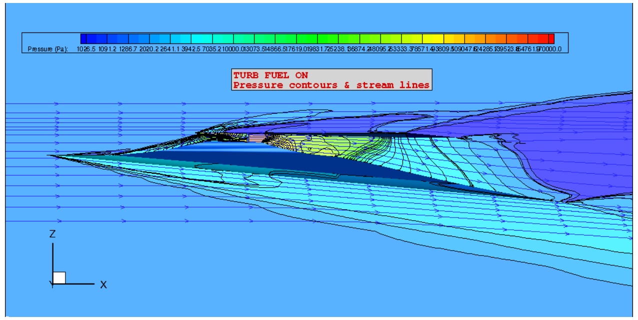


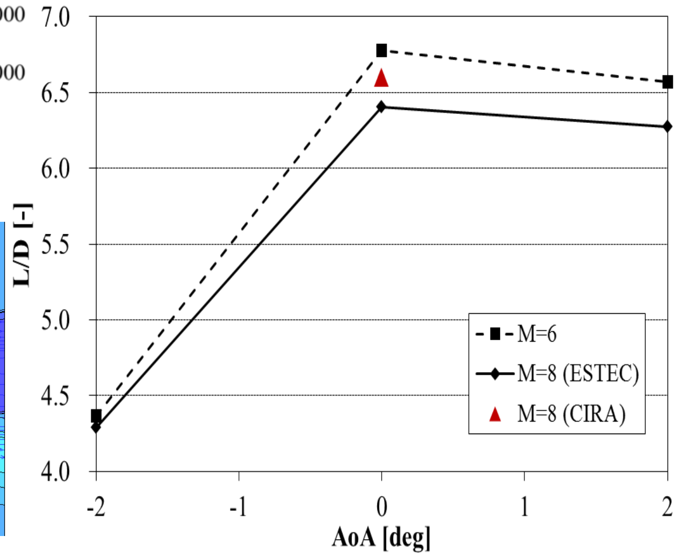




M = 8, (H=32-33 km)
p = 896.09 Pa
T = 228.46 K
Rho = 0.01367 kg/m^3
u = 2423.82 m/s
$m_{dot\ air}$ = 1238.38 kg/s

- Cruise condition: Mach Number 8 at 32÷33 km
- Analysis of the aero-propulsive balance of the scramjet vehicle in fuel-off and fuel-on conditions
- Laminar and turbulent flow hypotheses
- Contribution to aero-propulsive database of the vehicle
- Assessment of aero-propulsive balance (L≥W, T≥D)





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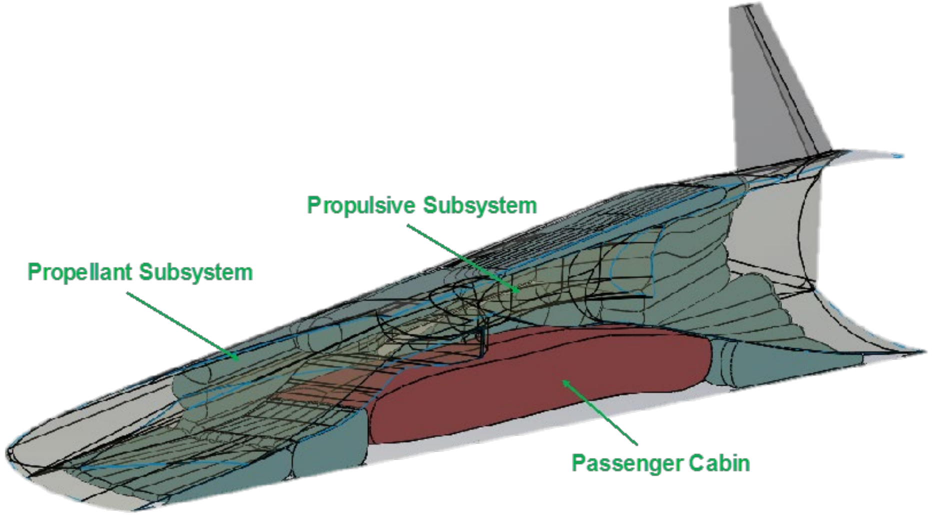
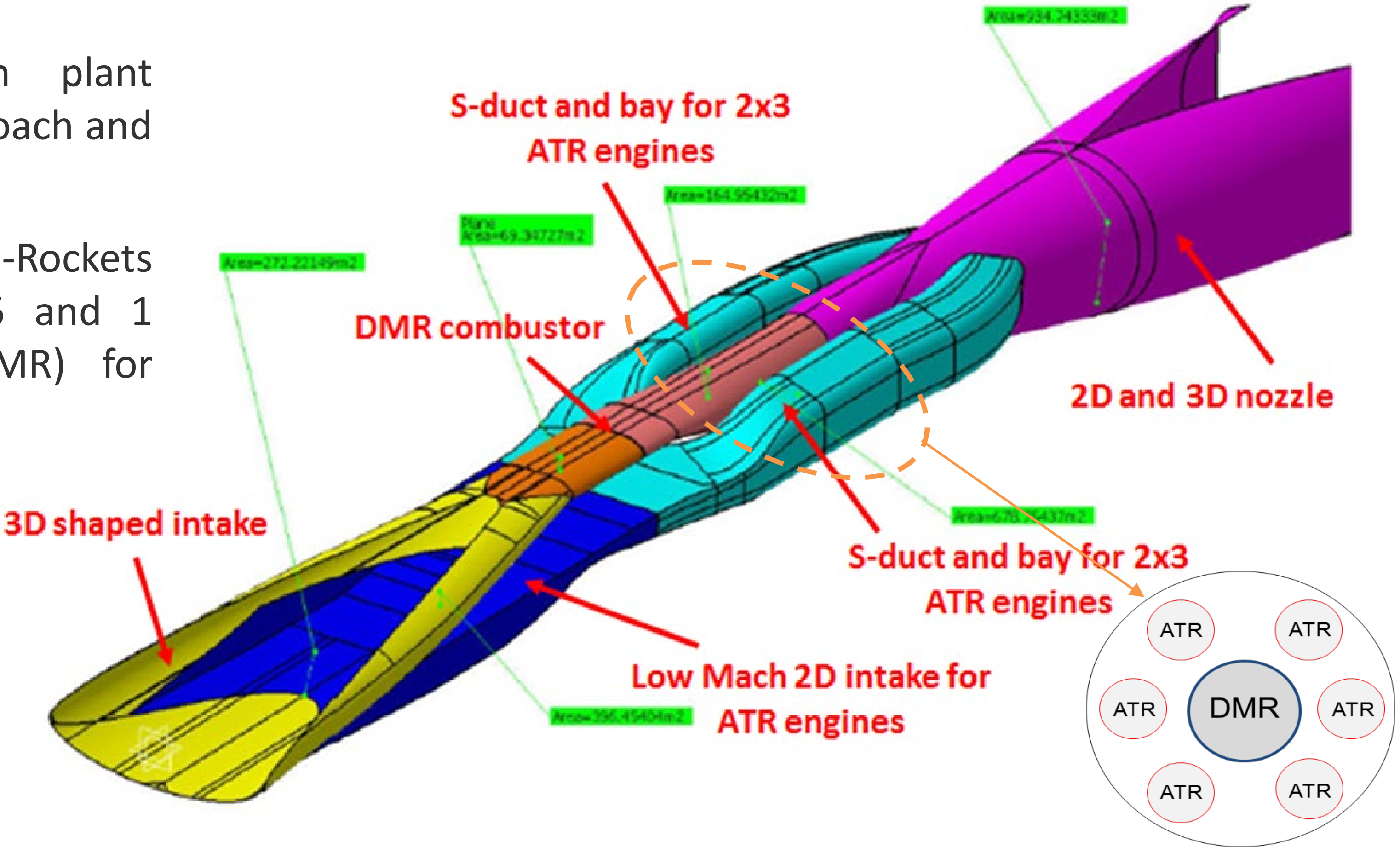
LAPCAT-II MR2.4

Mach 8 Vehicle's Propulsive System

- Dorsal mounted combined propulsion plant enabling take-off, acceleration, cruise, approach and landing solely with airbreathing engines
- Propulsive system merging 2x3 Air-Turbo-Rockets (ATR) mounted laterally for Mach=0÷4.5 and 1 central mounted Dual-Mode-Ramjet (DMR) for Mach=4.5÷8





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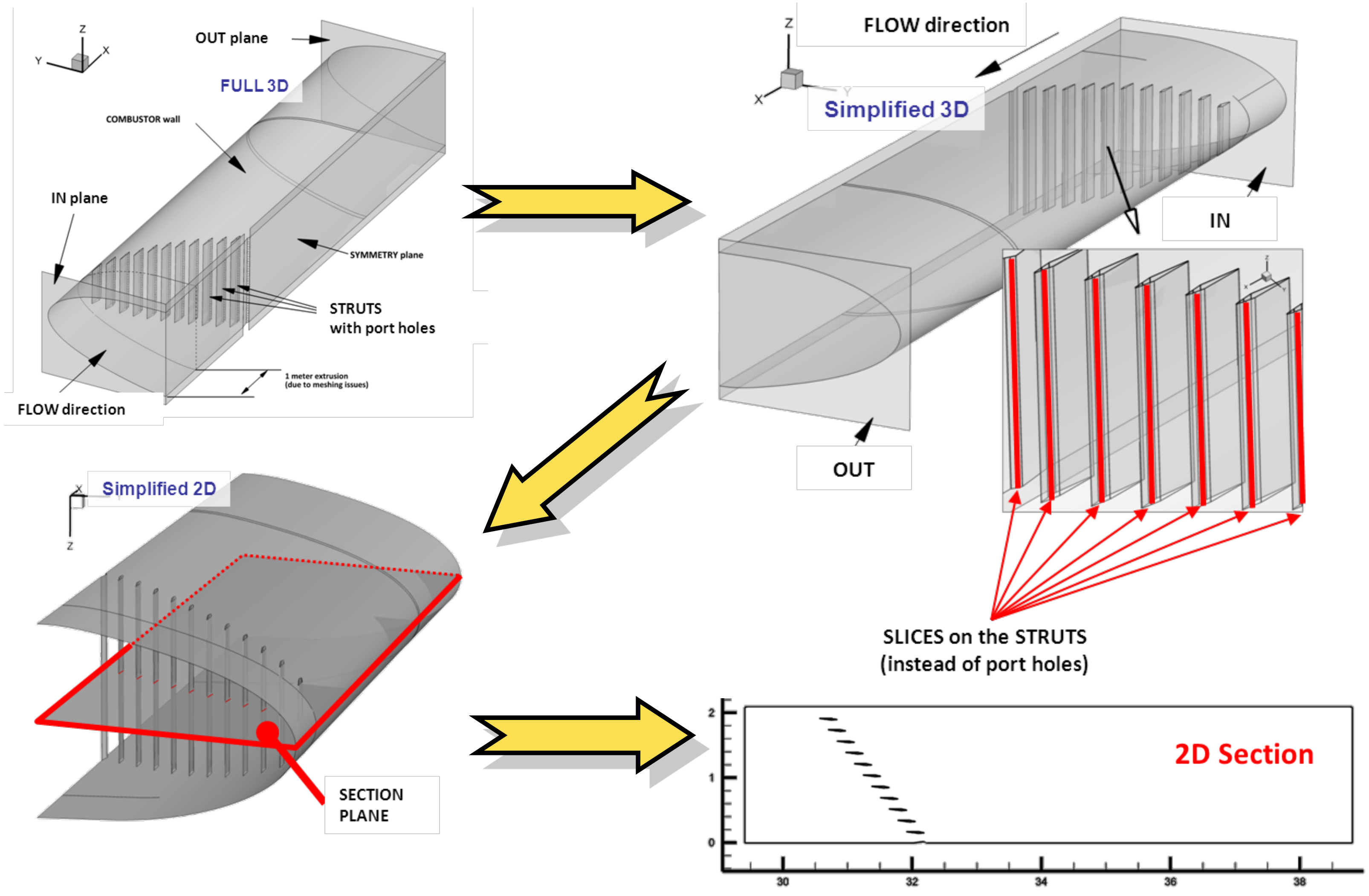
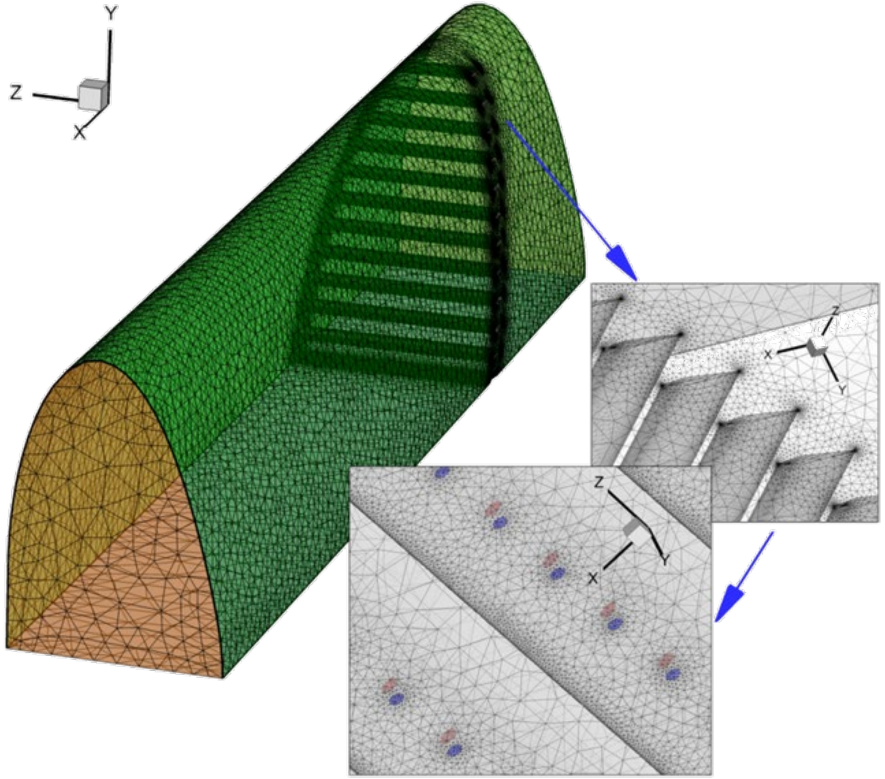
LAPCAT-II MR2.4

Mach 8 Scramjet combustor detailed analysis





- 8m long DMR combustor (with elliptic section) with a counter-V struts array
- 2D and simplified 3D geometry: structured mesh
- 3D detailed geometry: unstructured mesh (11M cells) and use of ANSYS-FLUENT v13

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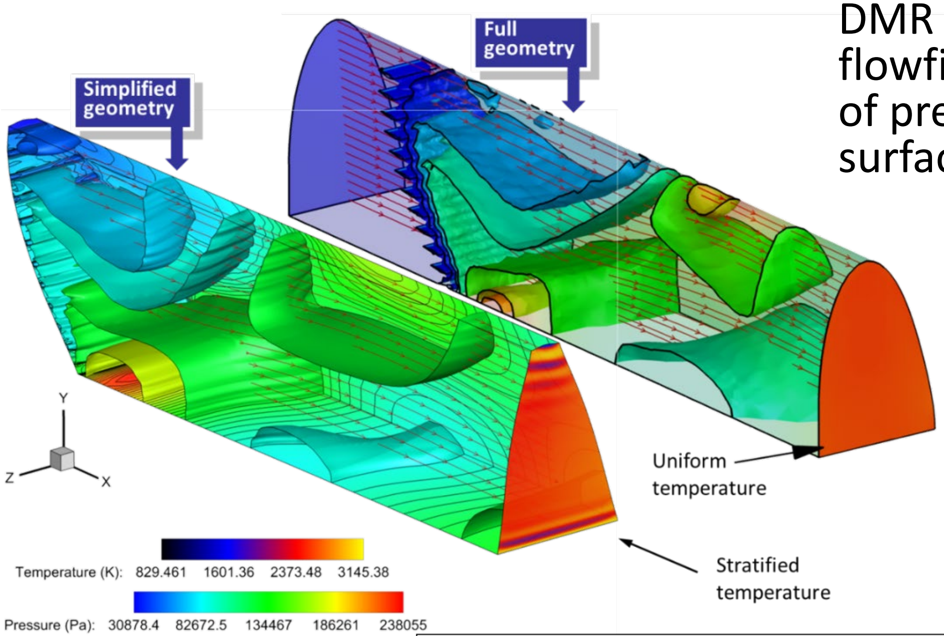
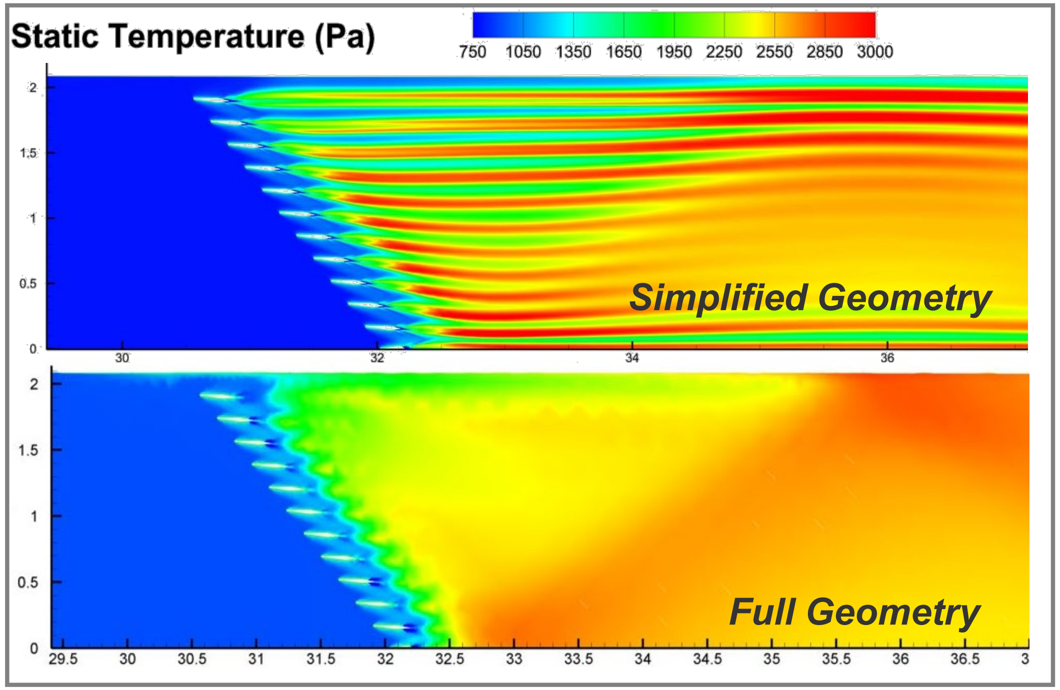
LAPCAT-II MR2.4

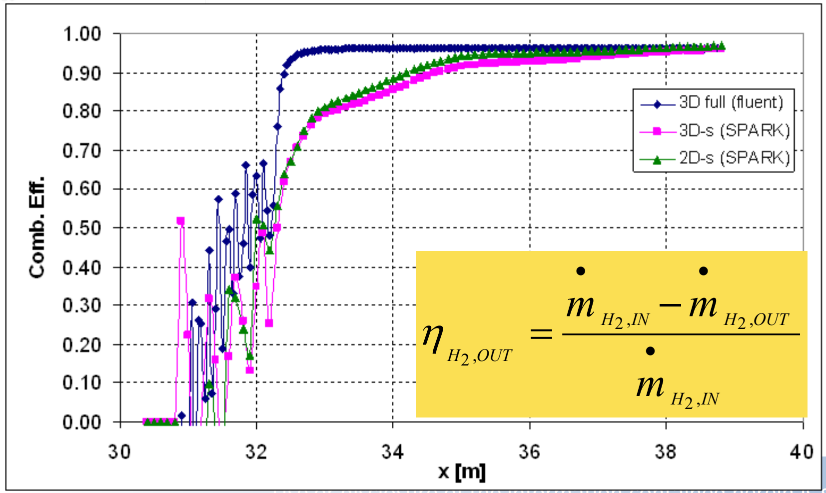
Mach 8 Scramjet combustor detailed analysis



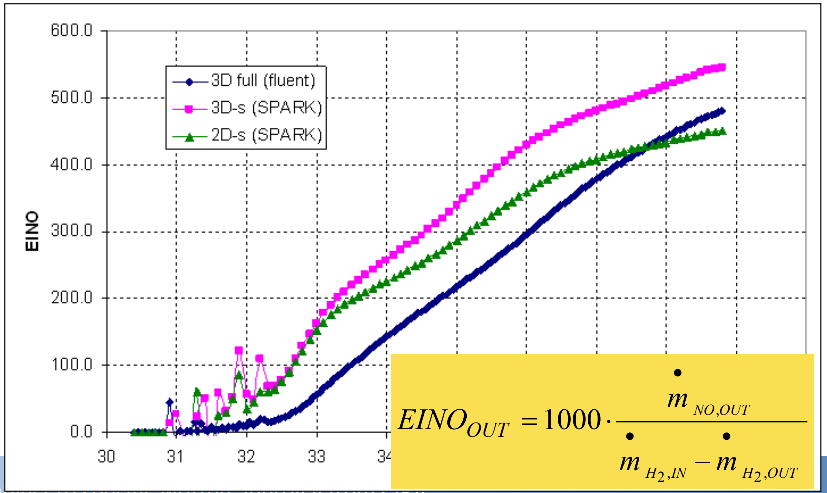
DMR combustor flowfield in terms of pressure iso-surfaces



DMR combustor X-distribution of combustion efficiency and NOx emission index



$$\eta_{H_2,OUT} = \frac{\dot{m}_{H_2,IN} - \dot{m}_{H_2,OUT}}{\dot{m}_{H_2,IN}}$$



$$EINO_{OUT} = 1000 \cdot \frac{\dot{m}_{NO,OUT}}{\dot{m}_{H_2,IN} - \dot{m}_{H_2,OUT}}$$

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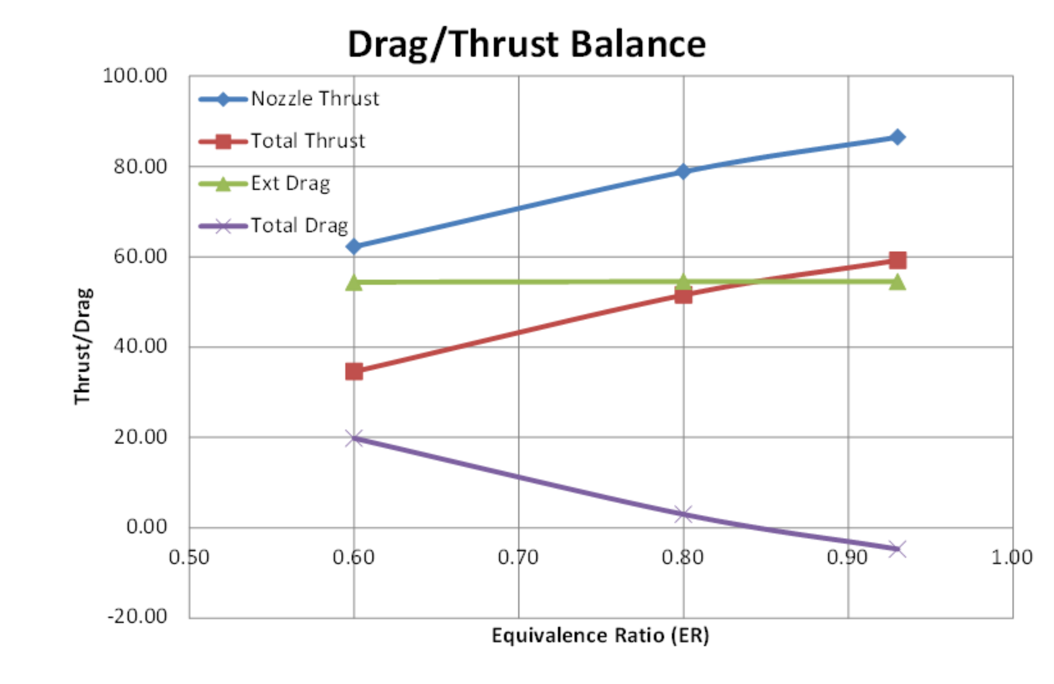
Analysis of a Mach 8 concept vehicle propelled by a scramjet engine

- Analysis of the aero-propulsive balance of the scramjet vehicle in fuel-off and fuel-on conditions
- The aero-propulsive balance is satisfied (D_{tot}<0) for both laminar and turbulent simulation (k-e) in fuel-on conditions
- Lift-to-drag ratio (external) around 6 for more reliable CFD simulations
- Sensitivity of aero-propulsive balance to equivalence ratio (ER)



Grid level	Engine state	Flow regime	L	D_{tot} (ext + int)	D_{body} (ext)	D_{prop} (int)	D_{intake}	D_{cc}	D_{nozzle}	Eff Aer
[-]	[-]	[-]	[tons]	[tons]	[tons]	[tons]	[tons]	[tons]	[tons]	[-]
L_3	ON	LAM	347.81	-26.88	34.08	-60.95	18.01	1.44	-80.41	10.21
L_3	ON	TURB k-e	341.69	-17.25	37.23	-54.49	20.62	3.41	-78.51	9.18
L_3	ON	TURB-SA	347.12	11.82	58.78	-46.96	23.79	4.47	-75.21	5.91
L_3	ON	TURB-SA0	343.76	4.48	52.11	-47.63	22.87	4.32	-74.81	6.60

M = 8, (H=32-33 km)
p = 896.09 Pa
T = 228.46 K
Rho = 0.01367 kg/m^3
u = 2423.82 m/s
$m_{dot\ air}$ = 1238.38 kg/s

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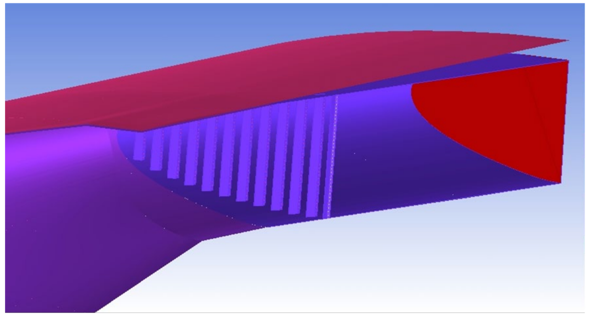
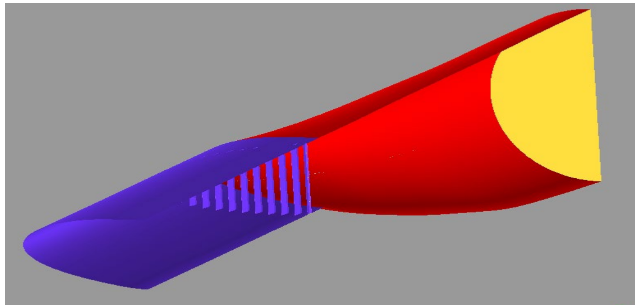
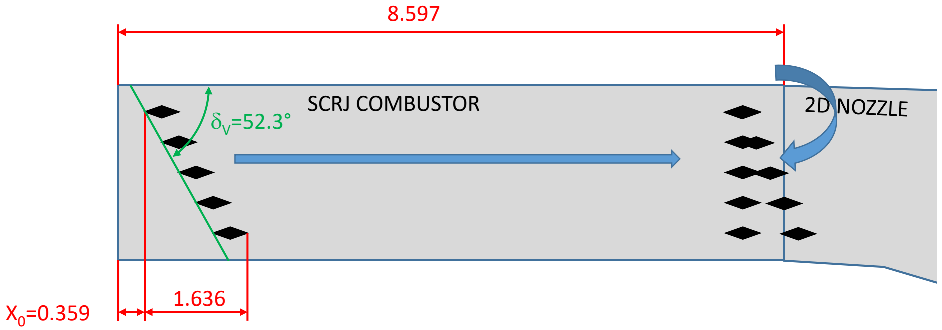
STRATOFLY MR3

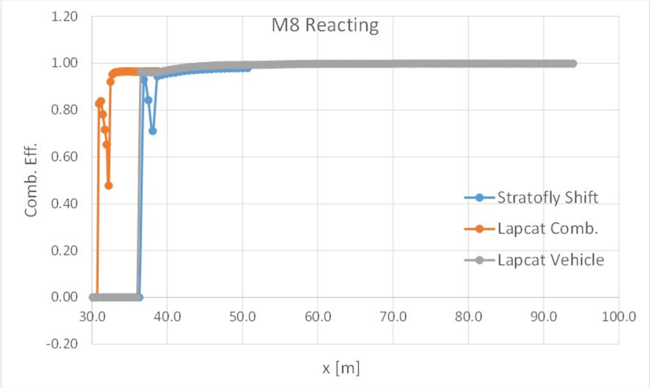
Mach 8 Scramjet combustor detailed analysis and optimization

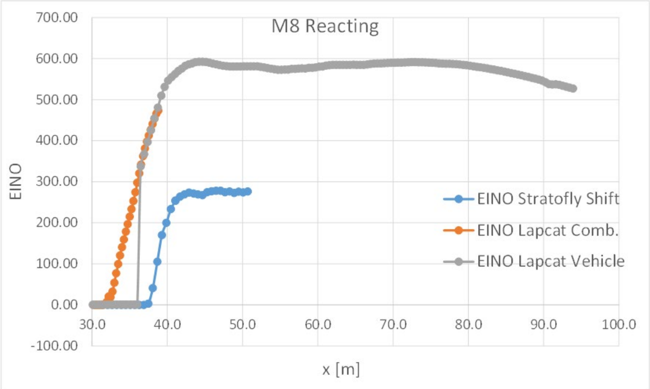


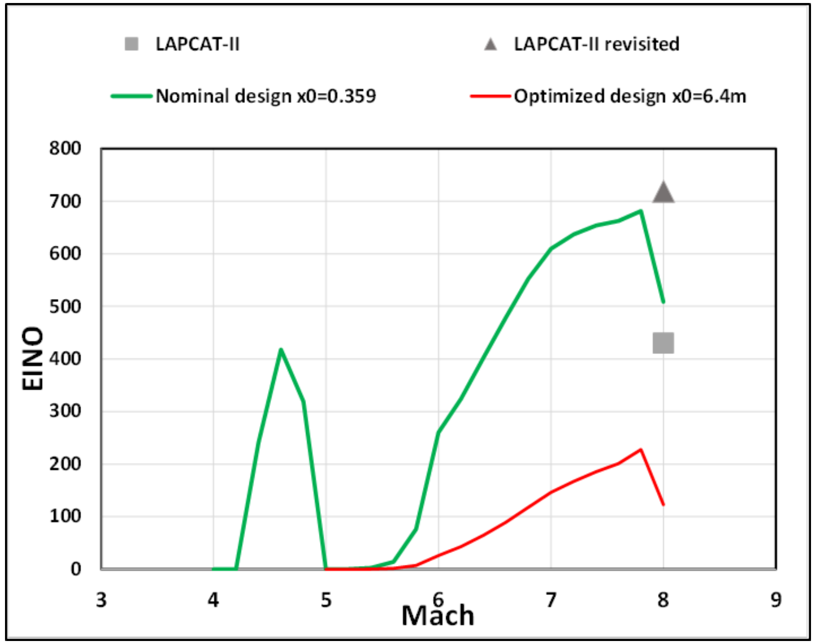




- Optimization of DMR combustor to reduce NOx emission without affecting combustion efficiency and thrust produced
- Tradeoff study on the effect of strut array position and displacement angle → same V-shape strut array of original combustor and 6m shift of it to complete combustion inside combustor
- Reduction of about 80% in EINO preserving propulsive performance







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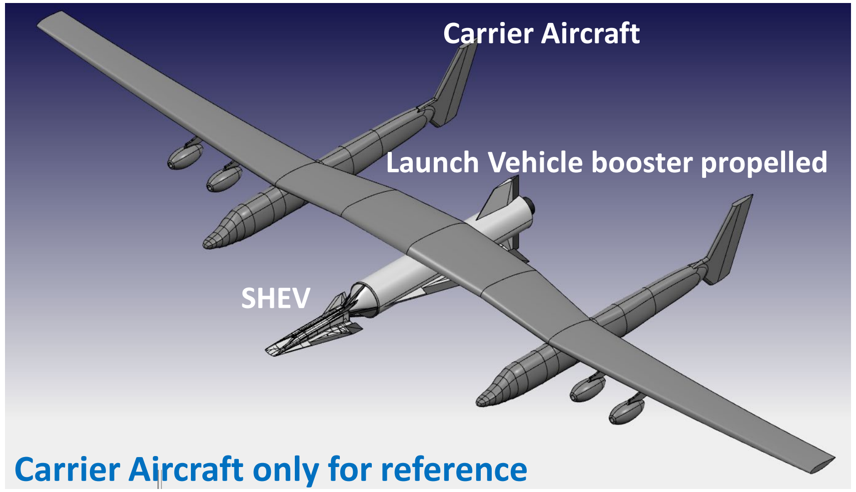
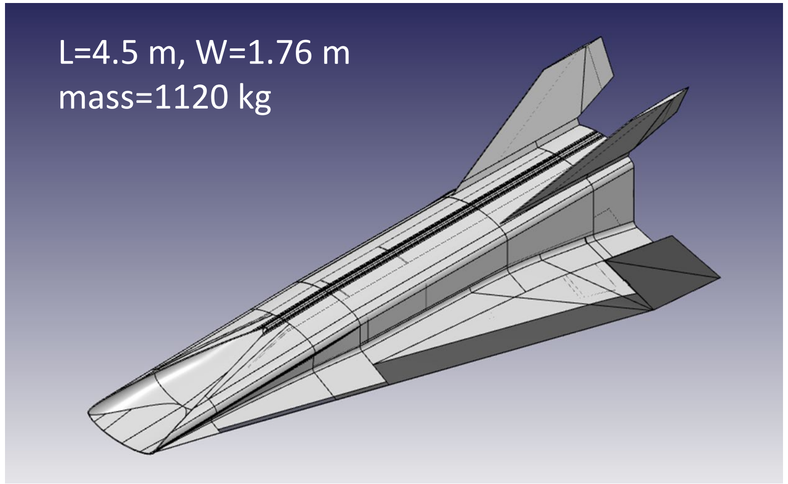
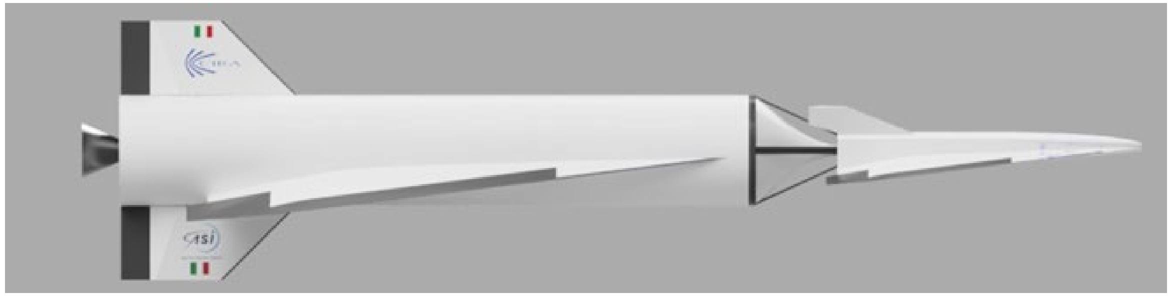
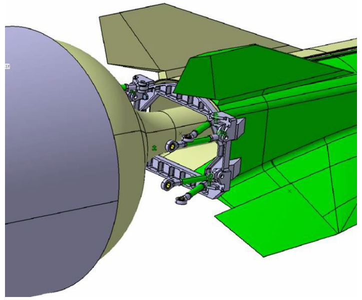
Scramjet Hypersonic Experimental Vehicle

- Detailed design of a Scramjet Hypersonic Experimental Vehicle (SHEV) able to perform a propelled levelled flight at 27÷32 km and Mach 7÷8, with the aim at designing and testing relevant technologies for future hypersonic transports
- The hypersonic demonstrator is released at the target altitude by a launch system composed by a carrier aircraft and a launch vehicle









Key Technologies

- Design and manufacturing of the combustion chamber
- Design and manufacturing of CMC parts for high temperature components (intake, wing and fin leading edges, elevons, etc.)
- GNC system
- On-board systems and in-flight experiments

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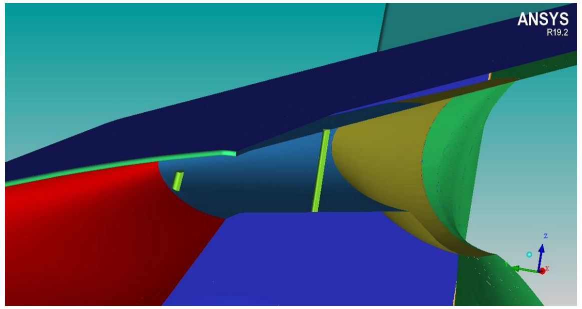
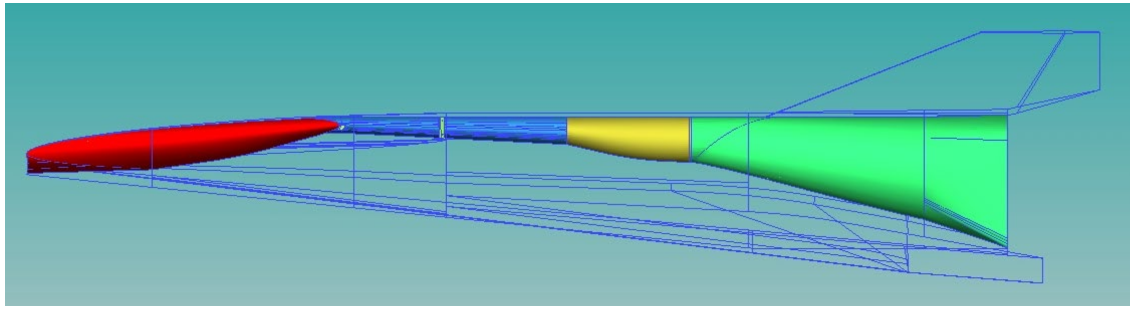
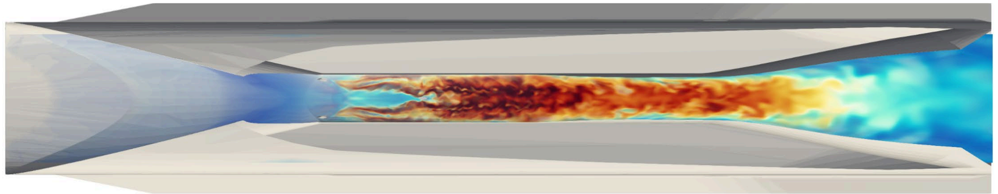
Scramjet Hypersonic Experimental Vehicle

- ➢ Simplified scramjet combustor with two semi-struts just after the entrance of combustor and a full-strut at mid length

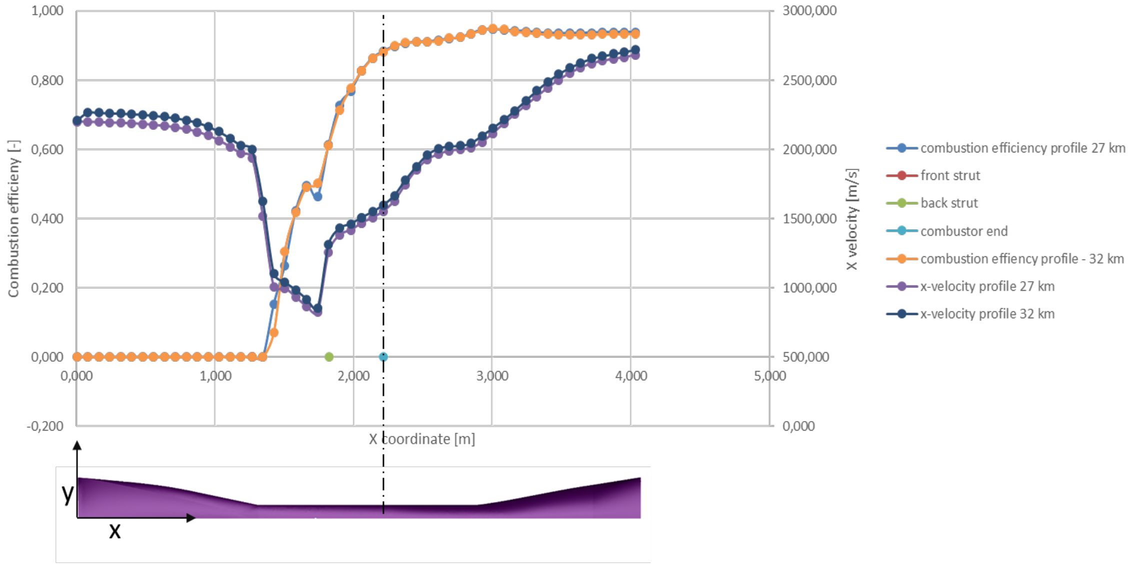


- ➢ Thrust production and aero-propulsive balance (T≥D) verified
- ➢ High combustion efficiency

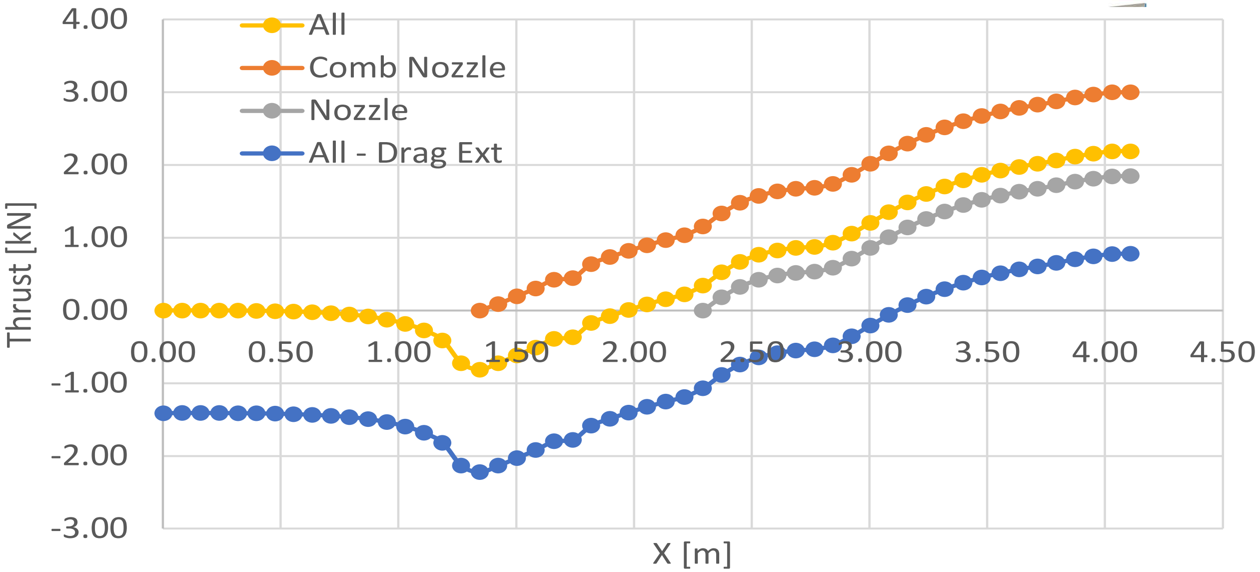




LES simulations courtesy by Lund University



Combustor efficiency at combustor end	0.882
Combustor efficiency at scramjet end	0.933



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Conclusions

- A number of propulsion systems for supersonic and hypersonic aircraft have been reviewed (turbojet, turbojet+afterburning, turbo-ramjet, dual-mode-ramjet, scramjet)
- Flight requirements define the most suitable propulsion system
- Main design issues related to propulsion systems:
  - High thermal loads for turbine blades (TJ+AB) and combustor and nozzle (ramjet/scramjet)
  - Mechanical actuators and control systems for intake and nozzle geometry (to be adapted to flight condition), and thrust reversers
  - Reduction of NOx (and H_2O) emissions for air-hydrogen combustion used for hypersonic aircraft
  - Need for a combined propulsion system coupling turbojet and DMR for complete flight mission of hypersonic aircraft (no thrust for DMR at V=0)
- Improve the integration of propulsion systems in the airframe to enhance global aircraft efficiency (reduction of fuel consumption)
- Reduction of combustion and jet-noise emissions of propulsion systems for minimizing aircraft environmental impact and being compliant with FAA and EASA rules