Hypersonic Concept for Long Range High Speed Vector
(MURALM and SCRAMJET technology)

1st International Symposium on
“Hypersonic Flight: from 100.000 to 400.000 ft”

T. Genito (MBDA), A. Ingenito & F. Gamma (La Sapienza)

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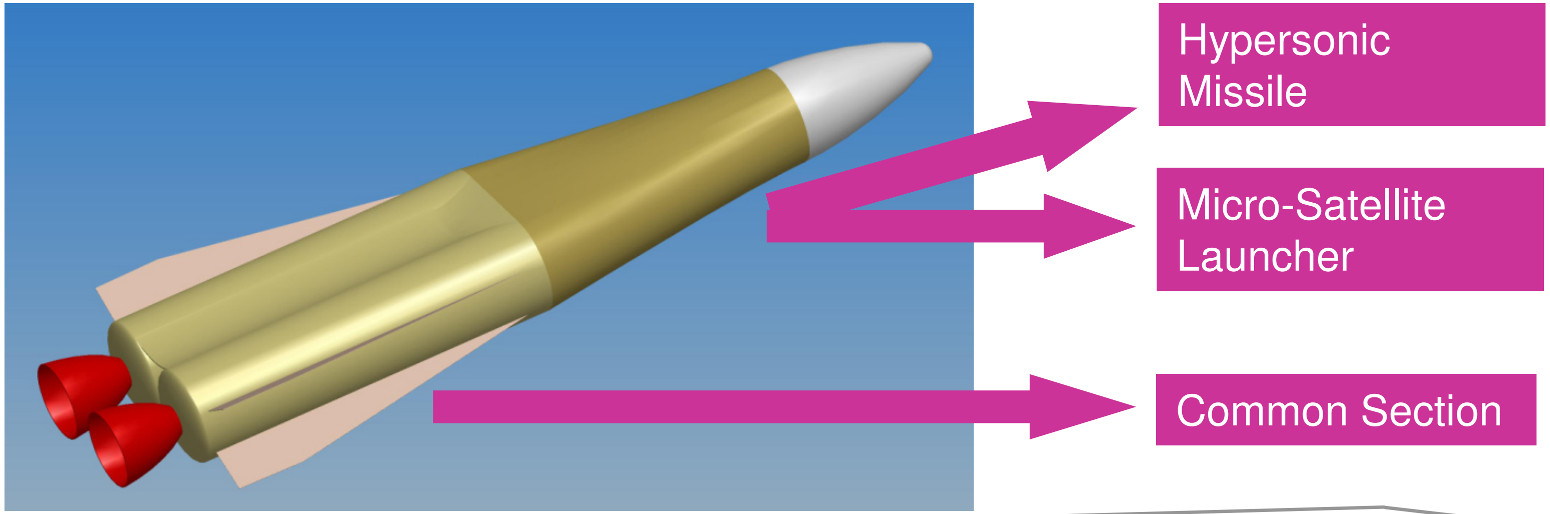
Summary

- MURALM concept
- Architecture and mission profiles
- The Hypersonic Missile configuration could be used as platform for Scramjet Technology Demonstrator
- Assessment of Scramjet technology, studied for MURALM, for Rome-Tokio in 2.5h
  - Preliminary vehicle configuration and feasibility study
  - Overview of Large Eddy Simulation to support the assessment of Scramjet technology

MURALM- Concept

- MBDA defined a Modular and Multi Role Launch Vehicle Concept (MultiRole Air Launch Missile: MURALM)
- The Launcher Vehicle Concept is compatible (Volumes and Weight) with the Tornado Platform
- First Section is a two booster (solid propulsion) first stage common to both configurations
- Second Section is configurable for two role
  - Micro-Satellite Launcher: The second Section Contains the remaining stages for Satellite Orbit Injection
  - Hypersonic Missile: After First Section accelleration to hypersonic range an hypersonic Missile start its cruise using **ScramJet technology**

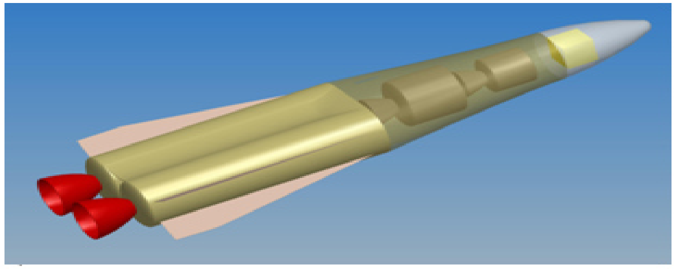


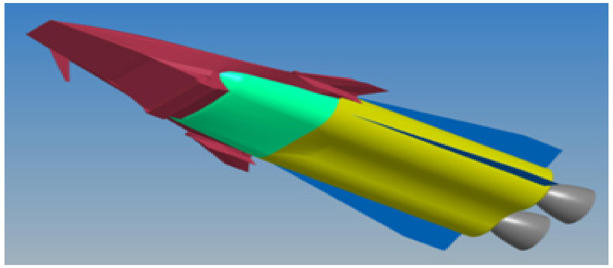
Hypersonic Missile

Micro-Satellite Launcher

Common Section

Architecture and Mission profiles





MURALM
for Microsatellite

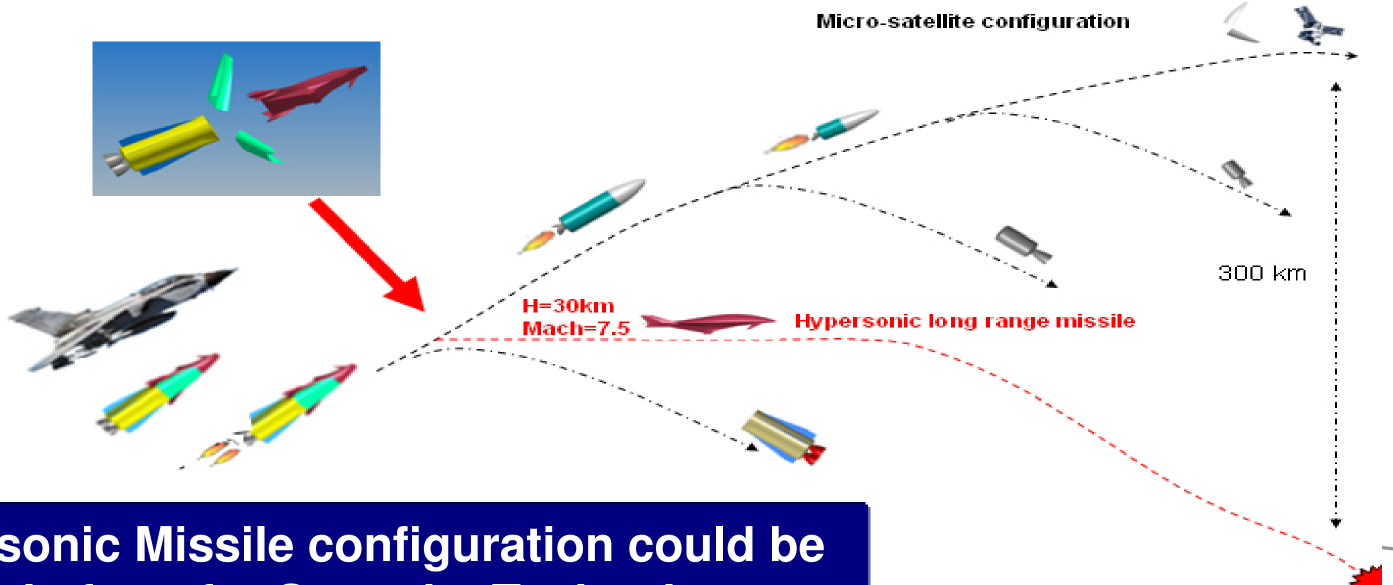
Orbits up to 300km/700km (EQUATORIAL)
Payload up to 60kg/40kg (micro SAT)

Orbits up to 350/700km (POLAR)
Payload up to 20kg/10kg (nano satellite)

MURALM
for Hypersonic Missile

Hypersonic Missile Release Altitude 30 KM

Cruise Velocity: mach 7.5



The Hypersonic Missile configuration could be used as a platform for Scramjet Technology Development, Tests and Demonstrations

SAPIENZA UNIVERSITÀ DI ROMA

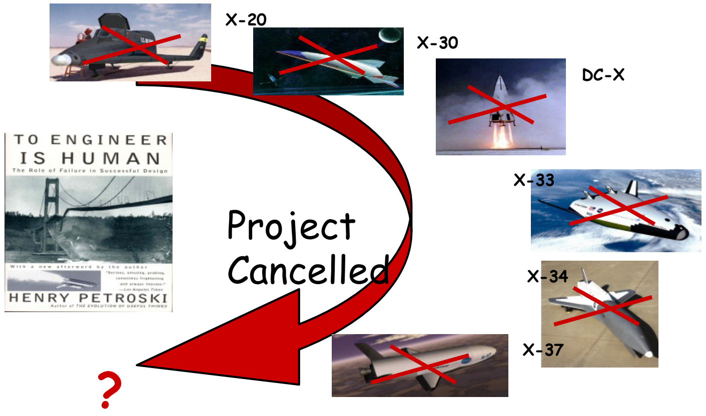
MBDA MISSILE SYSTEMS

Assessment of Scramjet Technology

Preliminary Design of Mach 7 Vehicle: Goal and Criticalities

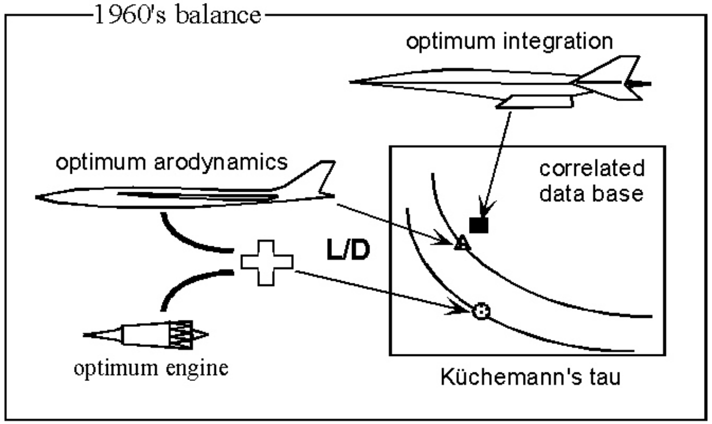
- Preliminary Design of a Successful Mach 7 Vehicle:
  Rome-Tokyo in 2.5 h

- CONFIGURATION/FUEL BEST CHOICE?



TAKE ADVANTAGE FROM LESSON LEARNED

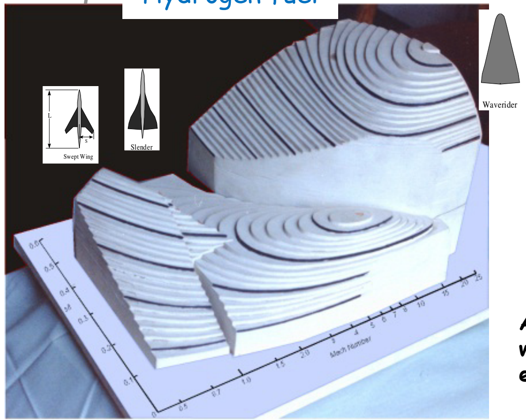
$$\text{"OPTIMUM SYSTEM"} \neq \sum_{i}^{j} \text{"OPTIMUM COMPONENTS"}$$



Preliminary Design of a Mach 7 Vehicle: Approach and Methodology

- Key Factor: **Kuchemann’s tau 3-D Solution Space**

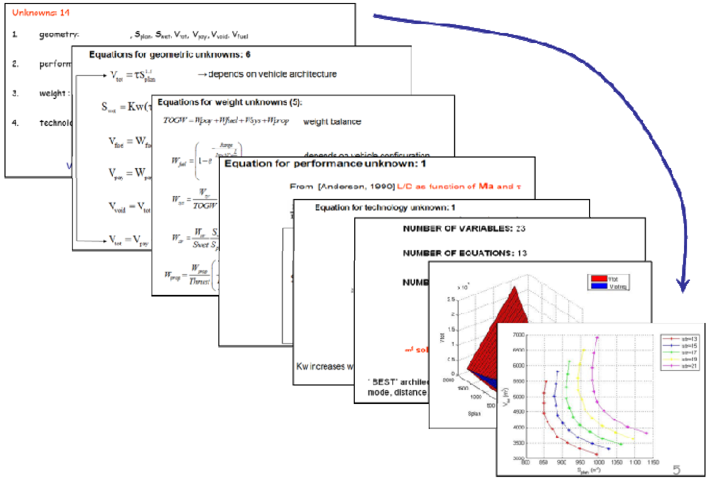
Hydrogen fuel



	Minimum Wing- Body	Minimum Blended Body	Slender	Nominal	Stout
tau	0.032	0.032	0.063	0.104	0.229
K_w	2.698	2.447	2.50	2.65	3.39
K_V	0.383	0.340	0.394	0.400	0.399
$S_{wet}/V_{tot}^{(2/3)}$	26.8	24.2	15.8	12.0	9.06
$\beta \cdot C_{D0}$	0.0615	0.0613	0.0674	0.0809	0.0986
L/D	4.82	4.81	4.71	4.57	4.13

Figure 73. Blended-Body Characteristics

A hydrogen fueled aircraft with range equaling the earth's circumference



Unknowns: 14

1. geometry: , S_{plan}, S_{wet}, V_{tot}, V_{pay}, V_{void}, V_{fuel}

2. perform

3. weight :

4. technolo

Equations for geometric unknowns: 6

$V_{tot} = \tau S_{plan}^{1.5}$ → depends on vehicle architecture

Equations for weight unknowns (5):

$TOGW = W_{pay} + W_{fuel} + W_{sys} + W_{prop}$ weight balance

depends on vehicle configuration

Equation for performance unknown: 1

From [Anderson, 1990] L/D as function of Ma and τ

Equation for technology unknown: 1

Kw increases w

NUMBER OF VARIABLES: 23

NUMBER OF EQUATIONS: 13

' BEST' archite
mode, distance

- *SUCCESSFULL APPROACH?*
- Based on subsonic aircraft methodology (Loftin, 1980) and hypersonic approach by Vandenkerckhove (VDK) and Czysz (1992)
- BEGIN SIZING from MISSION REQUIREMENTS (mission distance, payload , Ma∞): components NOT independently sized, designed and assembled

Preliminary Design of a Mach 7 Vehicle: Mission Requirements

- Tokyo Rome in ~ 2.5 h :
  - Range ~ 10000 km
  - Cruise; Mach 7
  - Payload: 1000 kg
  - fuel: HYDROGEN/KEROSENE
  - H=30000m

1. FIX a range of tau and Splan:

tau=0.01-0.2

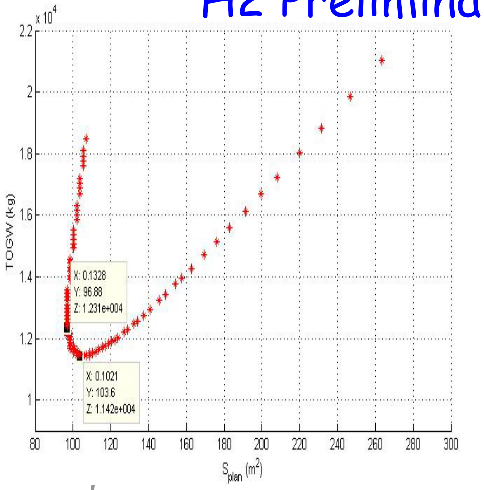
Splan=1000-20000ft^2

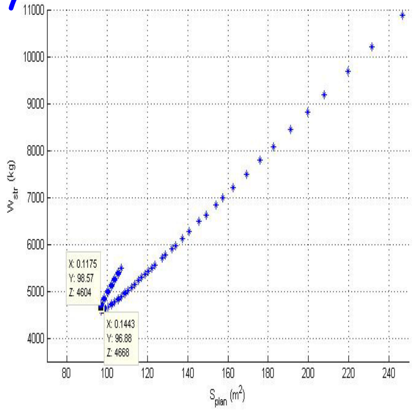
2. From equations **CALCULATE** all variables: Swet, Vtot, Vpay, Vvoid, Vfuel, L/D, TOGW, Wsys, Wprop, Wfuel, Wstr, Kw(t)

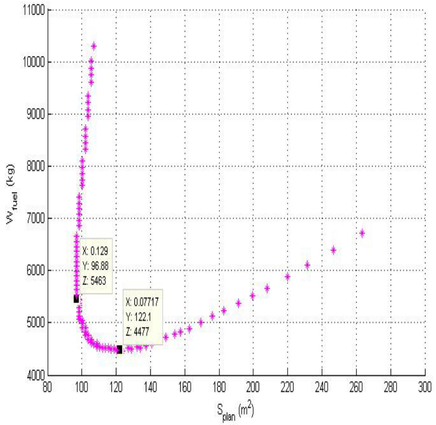
3. ITERATE until **HYPERSONIC CONVERGENCE**

Preliminary Design of a Mach 7 Vehicle: Solution Space

H2 Preliminary Results







Q t range from 0.08 to 0.2 but best choices from 0.1 to 0.13

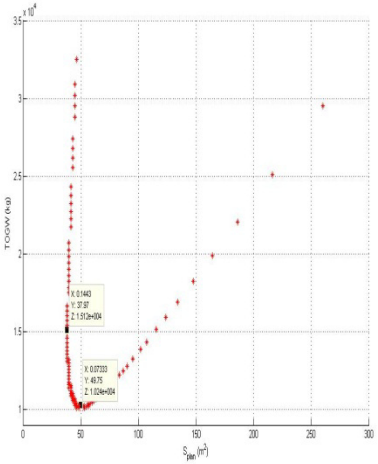
Q TOGW range from 11.42 to 12.31 tn

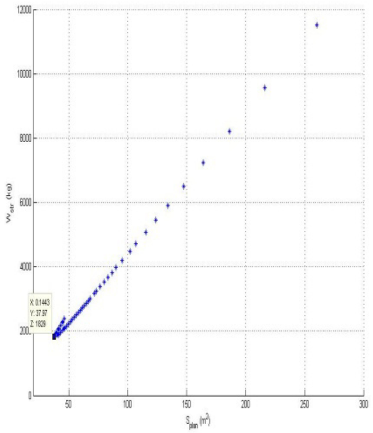
Q H2 range from 5.463 to 4.477 tn, i.e. 44% of weight

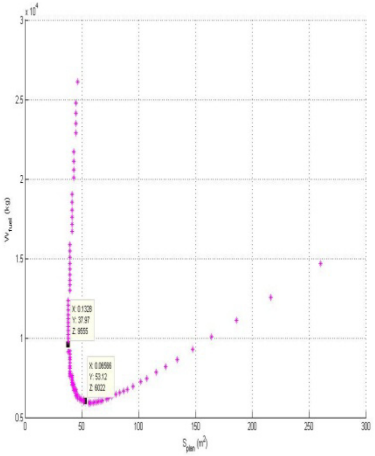
Q Wstr minimum=4.6 tn

Q Splan range from 100 to 96 m2

Kerosene Preliminary Results







Q t range from 0.08 to 0.2 but best choices from 0.07 to 0.14

Q TOGW range from 10 to 15 tn

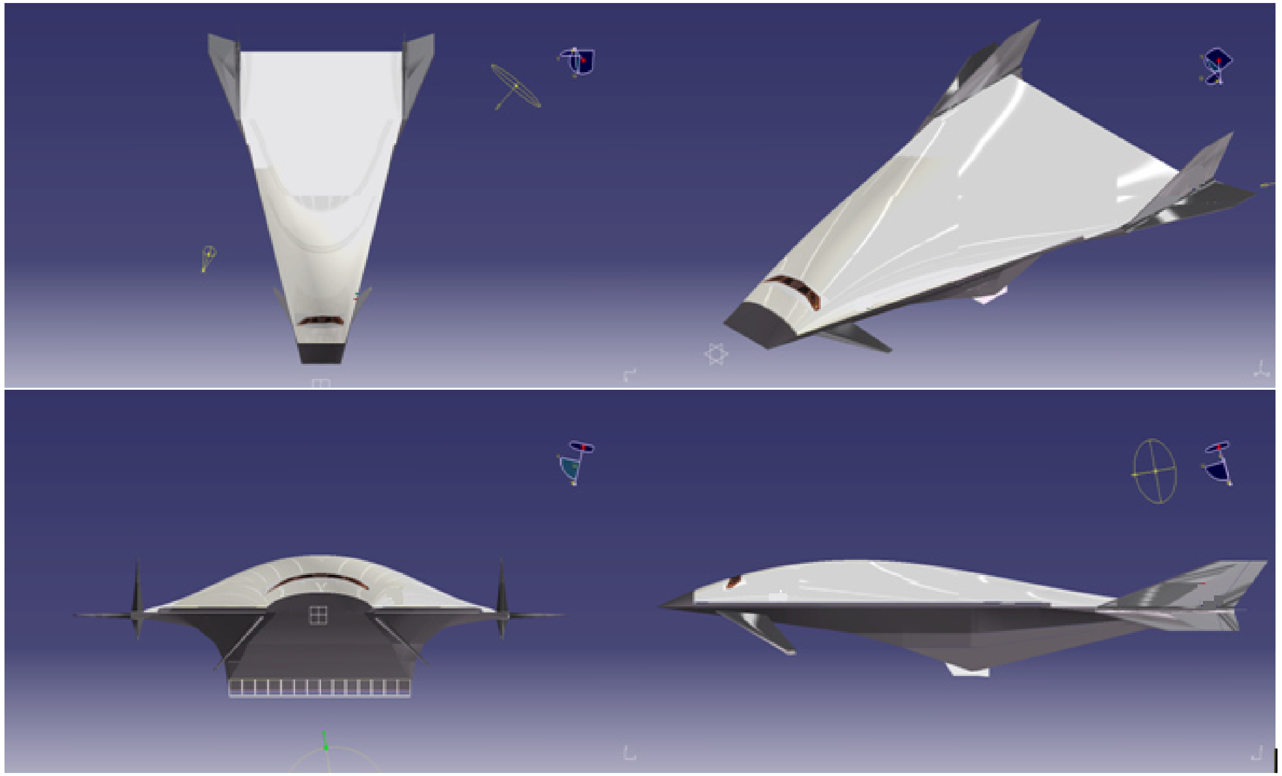
Q kerosene range from 6 to 9 tn

Q Wstr minimum=1.8 tn

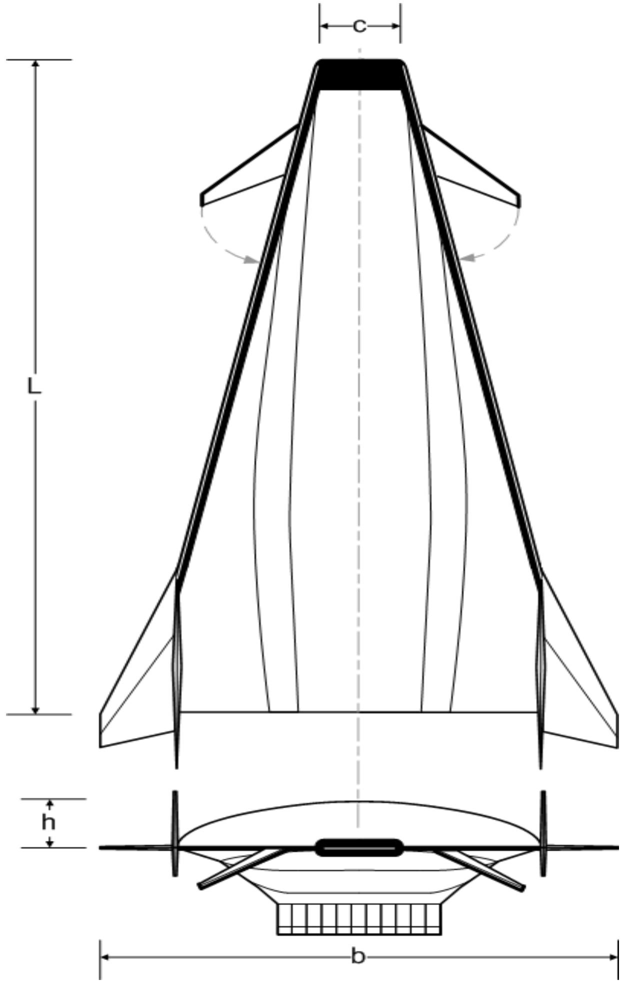
Q Splan range from 37 to 50 m2

Preliminary Design of a Mach 7 Vehicle: Configuration Choice

Successful Configuration found
t=0.08-0.1 (blended configuration)



Preliminary Design of a Mach 7 Vehicle: H2/kerosene comparison



	H2	Kerosene
ETW	13	13
Geometry		
t	0.1	0.07
Spln (m^2)	100.3	49.75
b (m)	9.4	7.10
c (m)	1	0.7
L (m)	21.35	15.30
h (m)	2.3	1.58
Weight		
TOGW (kg)	11420	10000
Wfuel (kg)	4477	6000
Wpay (kg)	1000	1000
Wstr (kg)	4600	1800
ff	0.44	0.6

Conclusions

- **MultiRole Air Launch Missile (MURALM) concept could be used as demonstrator of SCRAMJET technology.**

- **A preliminary assessment to realize a vehicle with SCRAMJET propulsion has been done:**

  Preliminary Sizing Results show that:

  a hypersonic configuration for Rome to Tokyo requirements is feasible under theoretical point of view:

  - kerosene better than hydrogen: (more compact)
  - Wstr much lower for kerosene (1800 kg instead of 4600 kg)
  - TOGW of order of 10-11 tn for H2 or kerosene

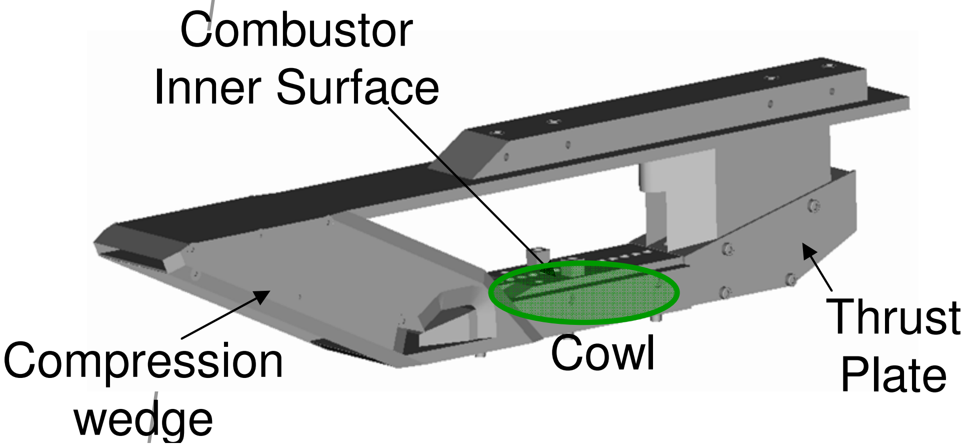
  <u>BUT:</u>

  - Calculations have been done for cruise, <u>none analysis for climb and descent</u> phase has been done (impact on Inlet)
  - <u>Demanding thermal conditions</u> have to be assessed and core technology has to be studied for thermal protection system and hot structures
  - Scramjet technology to be assessed with demonstrator

- **SCRAMJET KEY ISSUES: MIXING and ANCHORING in supersonic flows**
  - **First step of mitigation to assess in detail mixing and anchoring is based on Large Eddy Simulation (LES):**
    - numerical scheme to properly simulate shock waves and the turbulent structures away from discontinuities
    - a proper modeling of the small subgrid scales for supersonic combustion
    - a highly detailed kinetic scheme accounting for the radicals formation and recombination to properly predict the flame anchoring

BACKUP
(LES results)

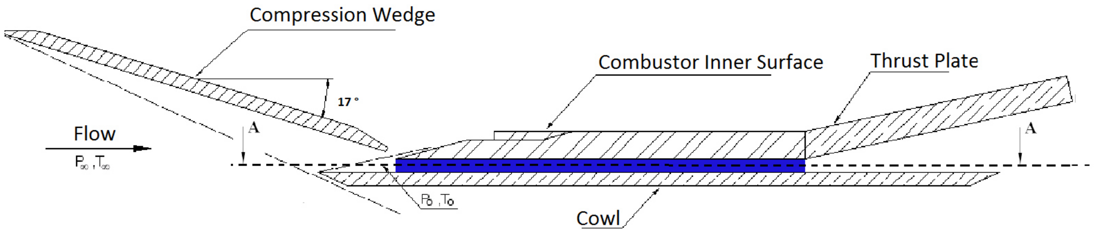
HyShot II Geometry and BC



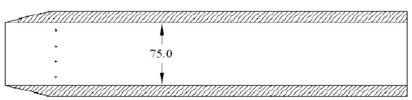
Flight Conditions (35 - 23km)

	Flight	Ground
M_∞	7.6	6.5
p_∞ [kPa]	0.6 - 4.0	0.9 - 5.8
T_∞ [K]	218 - 223	285 - 291

Scramjet Schematic



cut A-A



Hydrogen transversally injected by four 2-mm diameter injectors

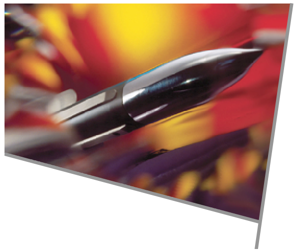
300 mm x 75 mm x 9.8 mm

Computational domain:
in blue

GRID: 880x130x450
(51,480,000) cells

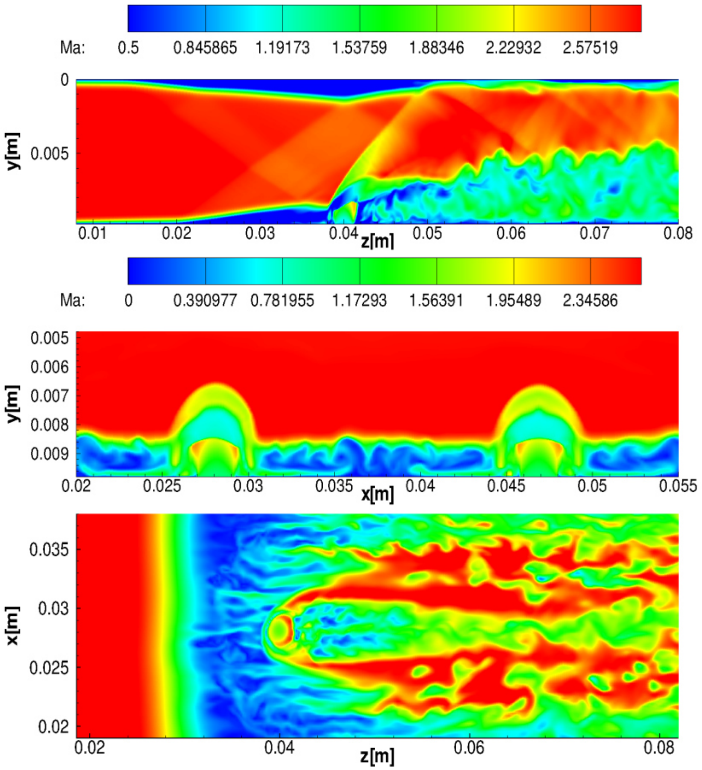
INLET CONDITIONS:

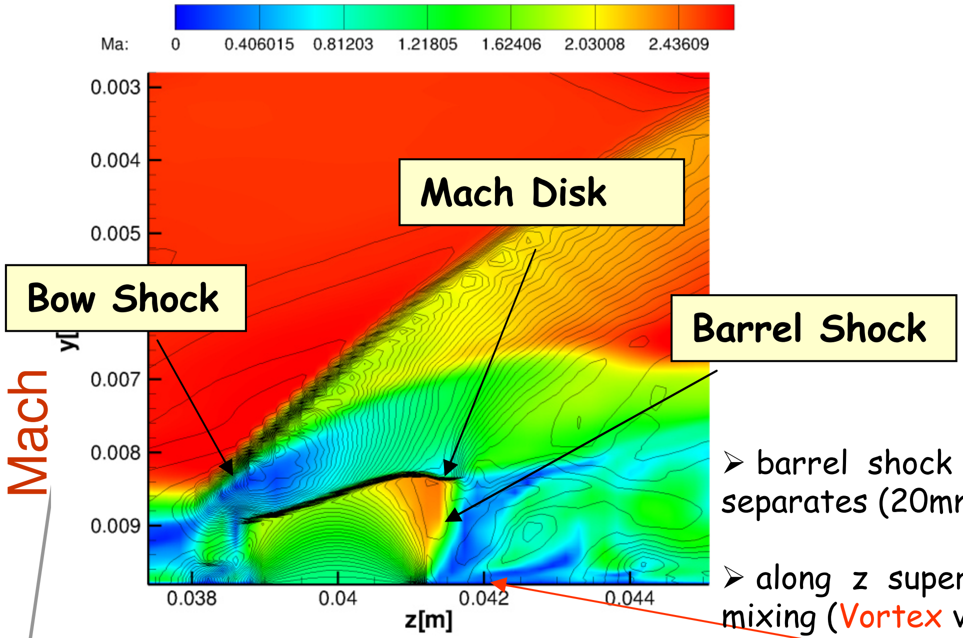
	H2 Injection	Flow at Air Intake
Pressure [Pa]	307340	82110
Mach No.	1	2.79
Density kg/m3	0.3020	0.2358
Temperature [K]	250	1229
Sound speed	1204.4 m/s	682.9 m/s
Flow velocity	1204.4 m/s	1905.291 m/s
E.R.	0.426	



LES RESULTS: Pressure and Mach fields

- COMPLEX FLOWFIELD:
  - SW train reflects from the bottom wall and impinges the flame front
  - 3D bow shock forms due to the H_2 crossflow injection within the airstream, the barrel shock and Mach disk

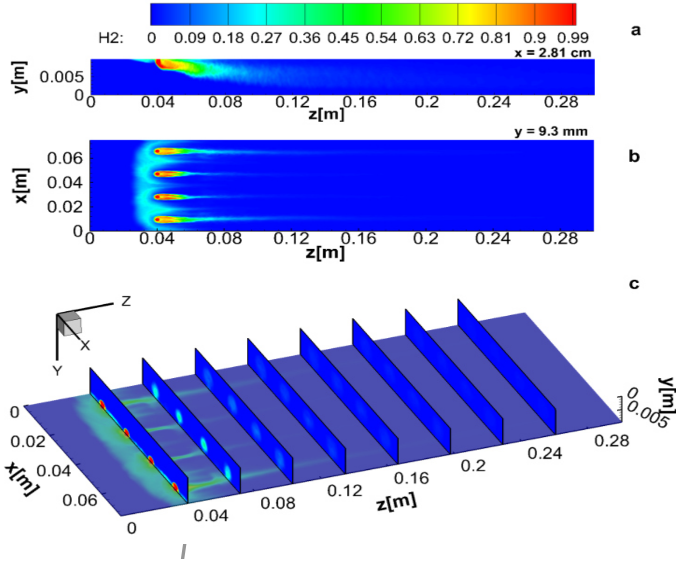


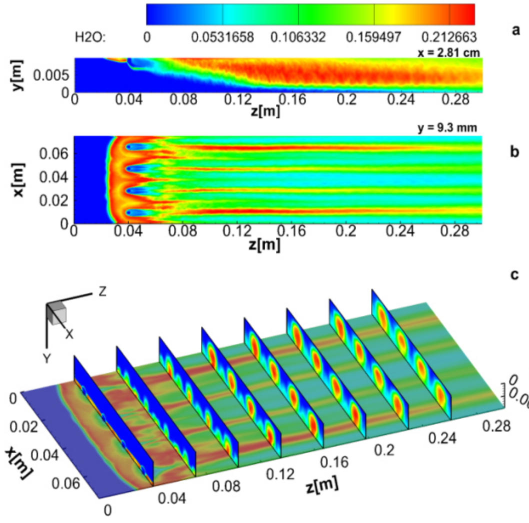


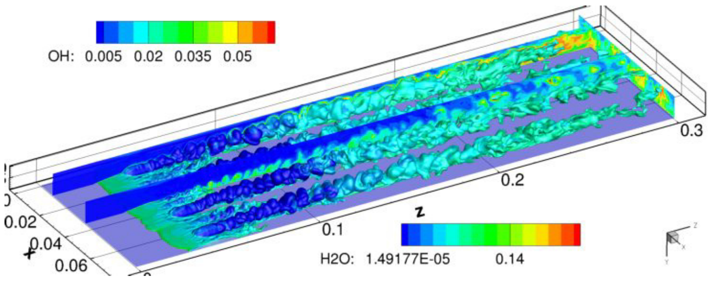
Average pressure and Zoom of the injection region

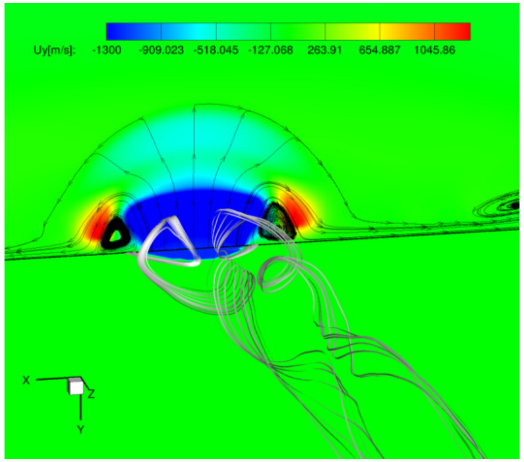
- barrel shock recompression → P ↑ → boundary layer thickens and separates (20mm upstream the injectors) → hairpin shocks form
- along z supersonic and subsonic vortex speeds alternate enhancing mixing (Vortex velocities ~ 900 m/s)

LES: H2, OH, H2O mass fraction



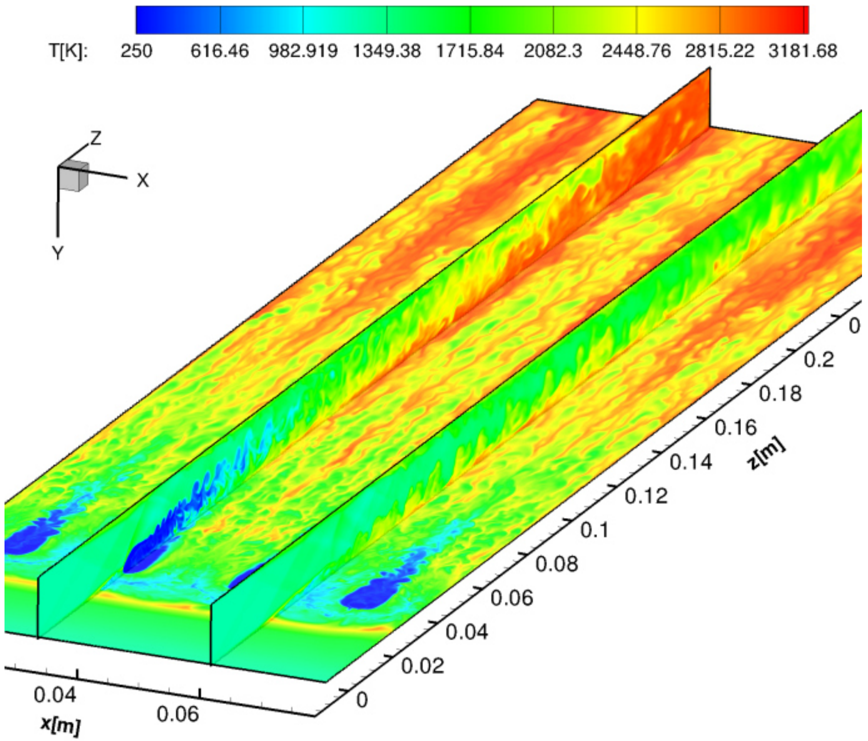




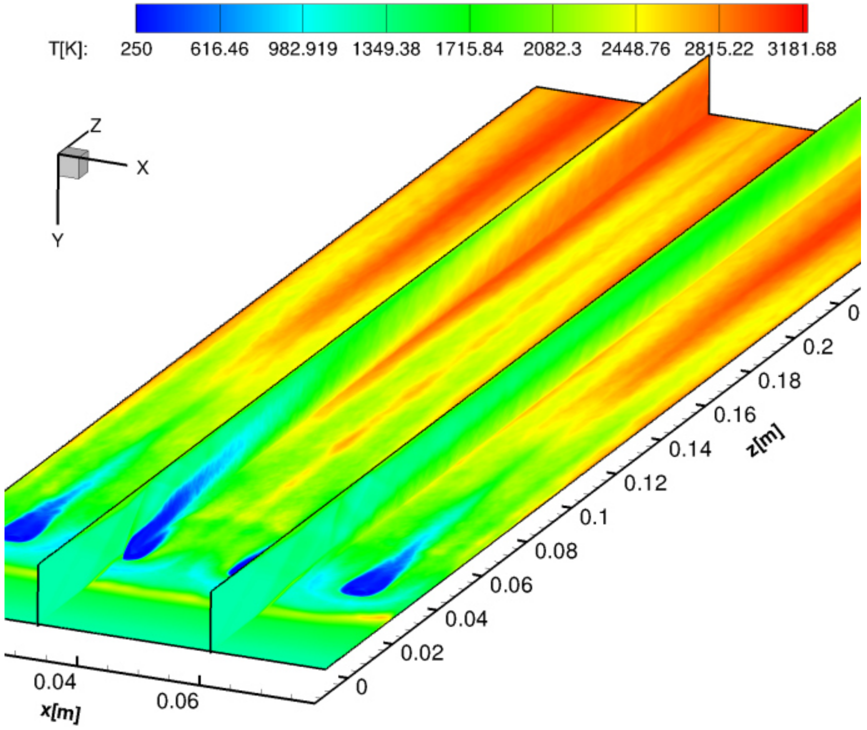


- ➢ FAST MIXING
- ➢ H2 and H2O predicted in-between hydrogen streams
- ➢ Contra-rotating vortices convect hydrogen outwards, toward the two eddies in-between adjacent H2 streams
- ➢ FAST ANCHORING
- ➢ fuel fraction reduced by 50 % in about 15 orifice diameters (3 cm downstream of the injectors)
- ➢ YH2 ≈ 0.2 % at the combustor exit
- ➢ 13% water already produced at Z=0.06 m

LES: Temperature



Instantaneous



Averaged

- high temperature (peak~ 2800 K) indicates high combustion intensity-->what about NOx?
- comparison between instantaneous and averaged mass fraction field highlights the existence of turbulent structures promoting air/fuel mixing → see flame structure

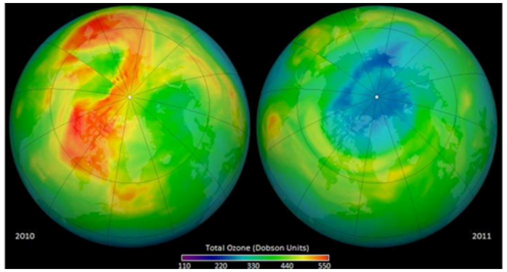
LES Conclusions

- **LES results of the HyShot II simulation show mixing is very efficient:** the BAROCLINIC TERM is the main vorticity source. That explains old and recent experimental observations of short flames
- Accordingly, predicted combustion efficiency, calculated by the unburned H2 mass fraction (only 0.2% at the combustor exit) is ~ 99.8%
- Thus vorticity sources enlarge scales in the compressible regime → truncated turbulence in supersonic flows? in SC smaller eddies may become larger than flame thickness → the smallest vortices can only wrinkle the flame without entering it → any CFD approach must account for what found above when building a SGS model
- High temperature (peak~ 2800 K) indicates high combustion intensity-->what about NOx?

	INLET: t=0s	OUTLET: t=10 ms
Mass fraction H_2	0.017176	3.37E-04
Mass fraction O_2	0.229008	8.85E-02
Mass fraction OH	0	8.93E-03
Mass fraction H_2O_2	0	2.39E-07
Mass fraction H_2O	0	1.46E-01
Mass fraction N_2	0.753817	7.54E-01
Mass fraction NO	0	1.25E-05
Mass fraction NO_2	0	4.76E-09
Ppm di NO_x	0	13.7

Atmospherical chemistryCRITICAL TASK :
O3 depletion vs H2 fuel consumption and NOx EI

1 FLIGHT:
Rome- Tokyo
H2 consumed: 11.42 tn → 3.36 kg of ozone destroyed
O3 in atmosphere: 3,3E+09 tn
Total % of O3 destroyed: 0,0000000001 %



A FLEET of 200 aircraft, 360 flights a year:
0.00000733%

→ negligible impact (much less than 1 ‰)

HOWEVER, although the immediate impact of a fleet of 200 aircraft could be considered “negligible”, the life time of NOx is of years→ a negligible percentage of NOx starts the ozone depletion reactions!