Subsonic to Supersonic combustion

……from the more known to the less known

- Premixed or diffusion – differences, Jet diffusion flames – diffusion and premixed
- Gas turbine main combustion chamber, Afterburners of gas turbines, ramjets transition to supersonic ram jets (Scramjets)
- Scramjets - Geometry, Aerodynamics, Flight boundary
- Fuels, Injection system, Ignition, Mixing, Combustion performance

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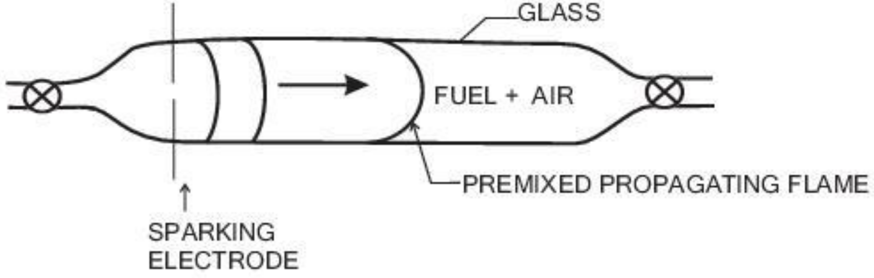
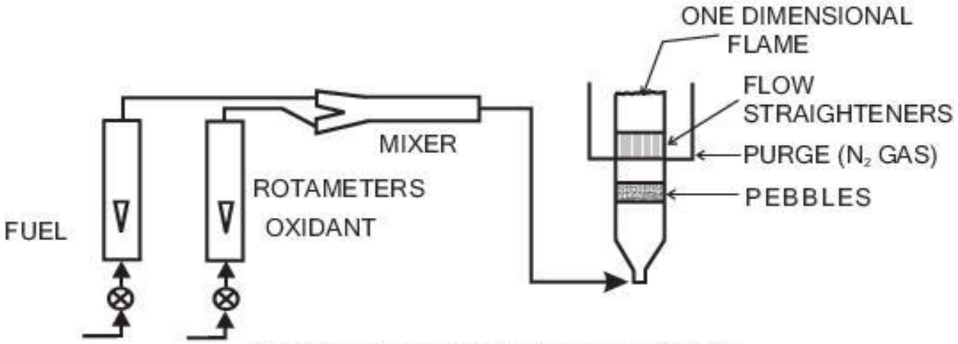
Premixed combustion of domestic stove
Fuel = LPG, p = 1 atm, T_0~ 300 K
M_0 ~ 0.40/344 = 0.0012

Premixed combustion of wick based kerosene stove, p = 1 atm, T_0 = 300 K
M_0 ~ 0.0012



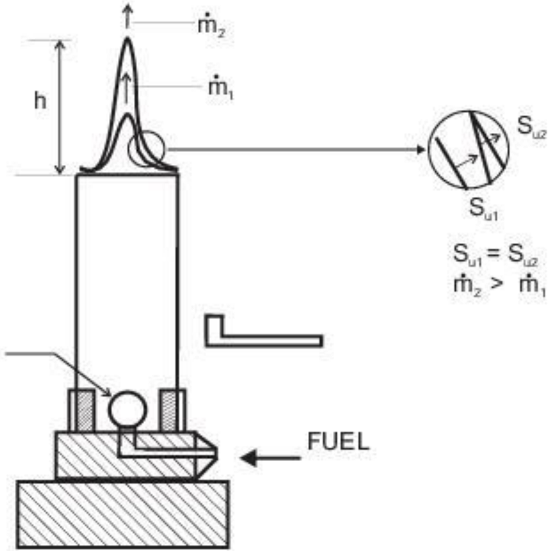
(a) Propagating Flame Apparatus



(b) One dimensional Flame Apparatus

Premixed
Flame speed
~ 0.4 m/s
(Hydrocabon –air)

~ 2.5 m/s for
Hydrogen - air



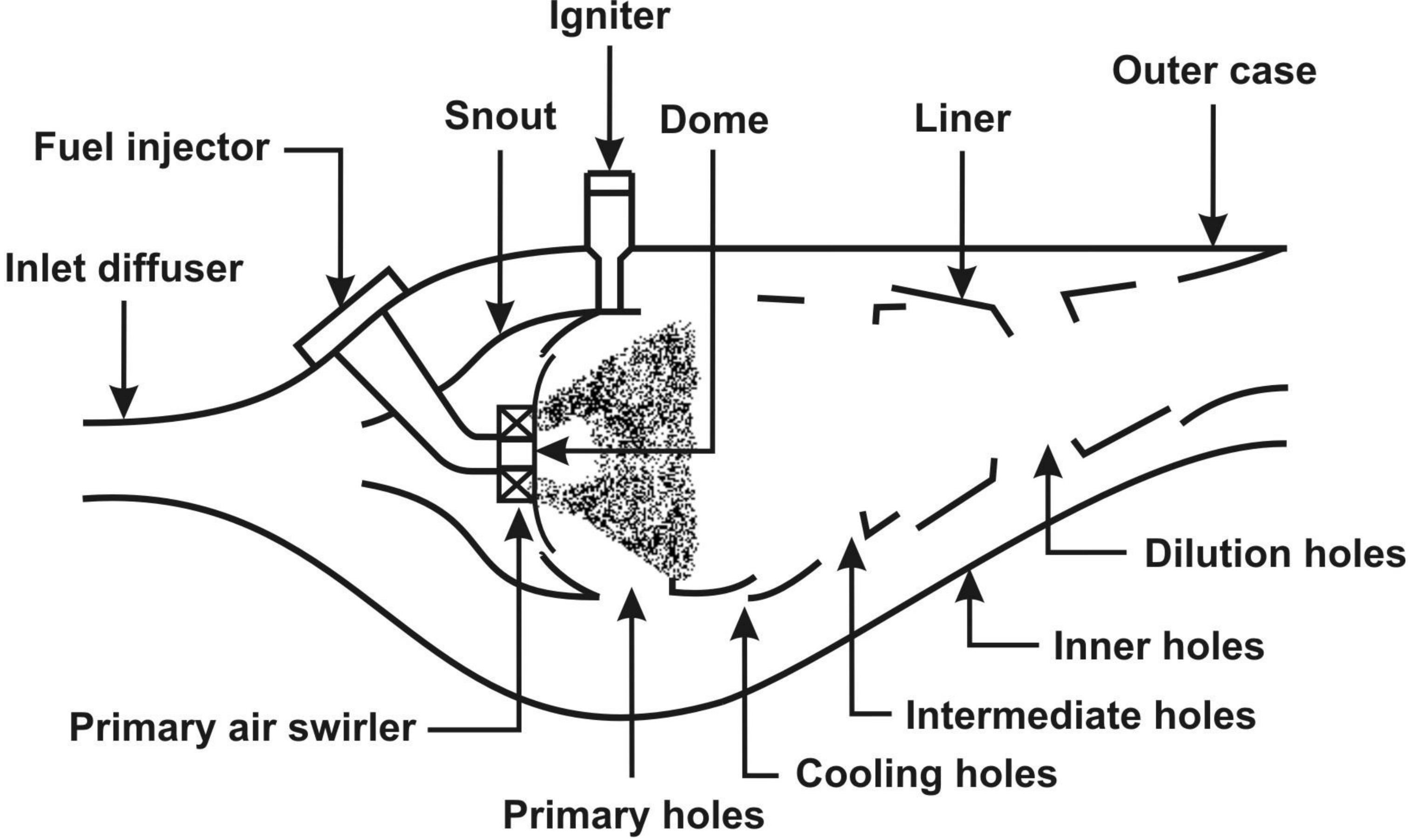
Premixed
/Diffusion

Diffusion flame of Candle

Thus reaction zone
is smaller
for premixed
condition

compared to

Diffusion limited
combustion



Civil aircraft M_0 = 0.85

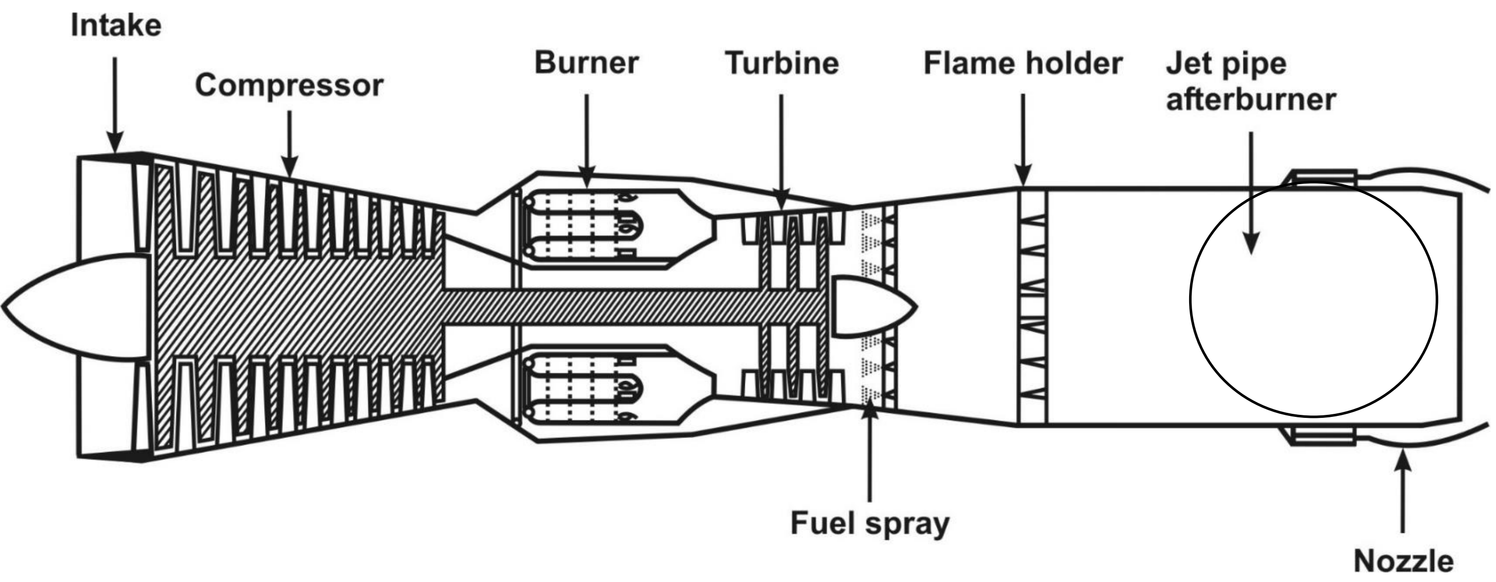
Concorde M_0 ~ 2

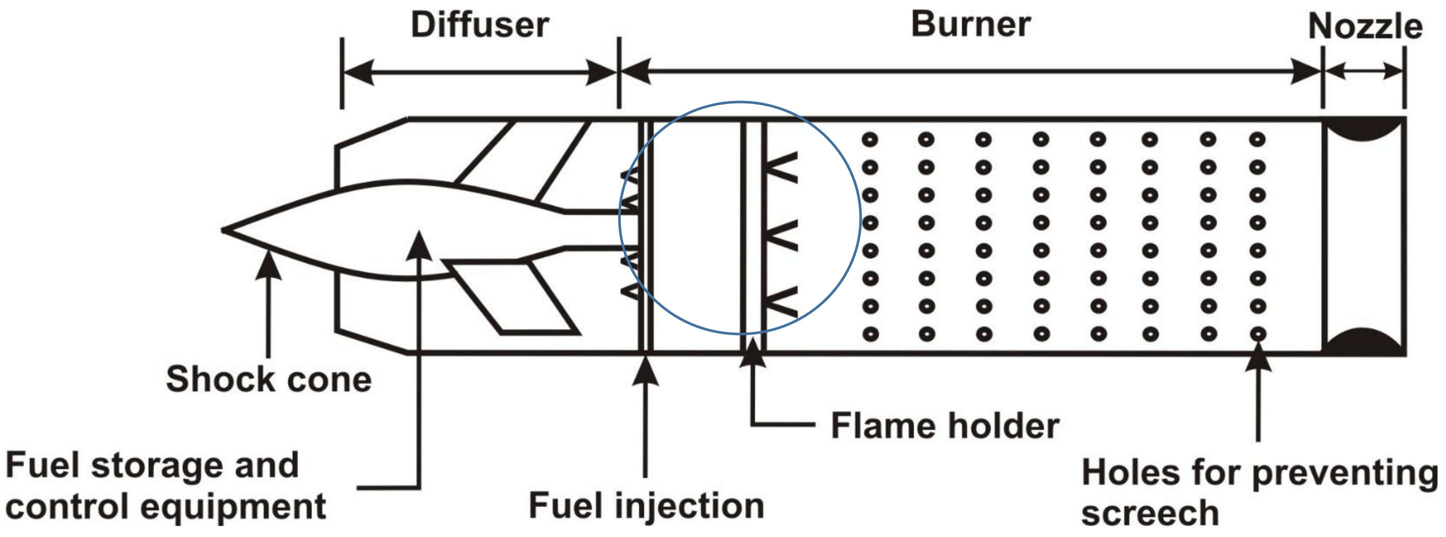
Military aircraft M_0 = 2.5

SR 71 (Skunk Works) M_0 ~ 3

Runs more on afterburner at the outer limit of flight M_0

Gas turbine main combustor used on aircrafts with flight M_0 up to 3
p ~ 10 to 40 atm, T_0 ~ 450 to 650 K
M_{comb} ~ (100 m/s)/(400 m/s) = 0.25
Combustor flow residence time ~ 5 ms





After burner of gas turbine

M_0 ~ from 0 to 2

p ~ 3 to 5 atm, T0 ~ 1000 K
M_{comb} ~ (150 m/s) / (450 m/s) = 0.33

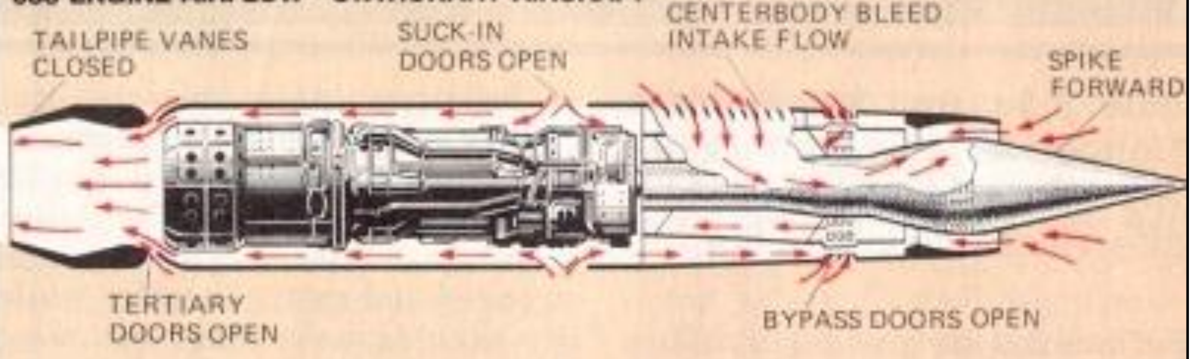
Ramjet – M_0 from ~ 2 to 3

Not self-starting

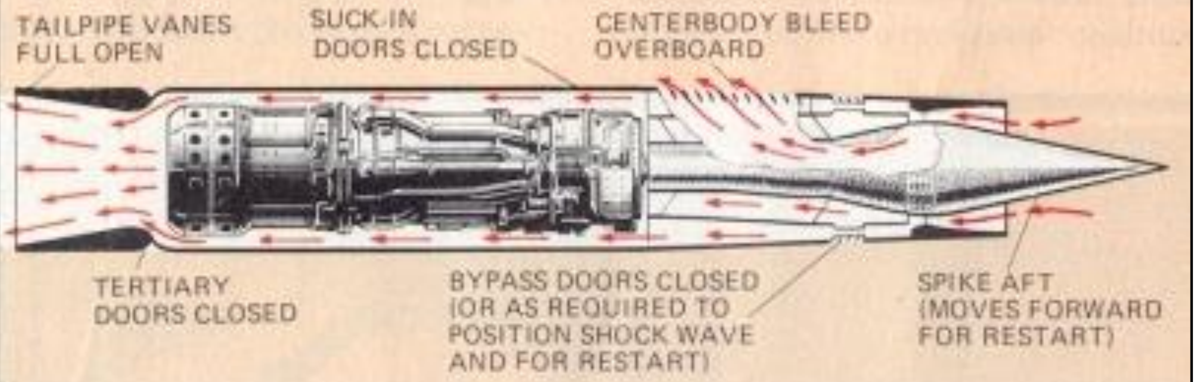
P_{stag} ~ 11 to 15 p_{amb}; Air inlet shocks bring down the pressure to about
p_{comb} ~ 3 to 5 atm
T_{comb} ~ 500 to 750 K,
M_{comb} ~ (200 m/s) / (500 m/s) = 0.4

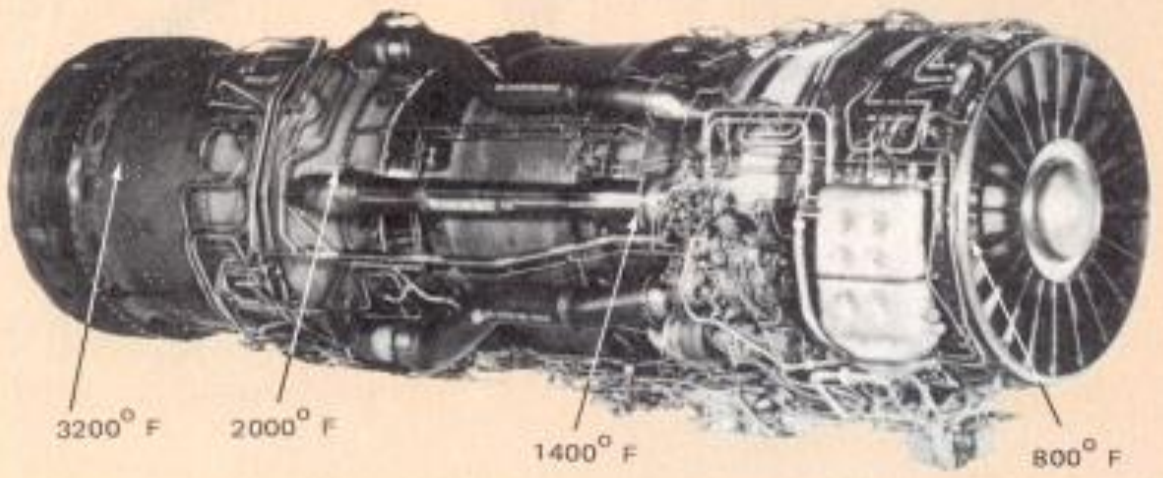
Combustor residence time ~ 4 – 5 ms

J58 ENGINE AIRFLOW—STATIONARY AIRCRAFT

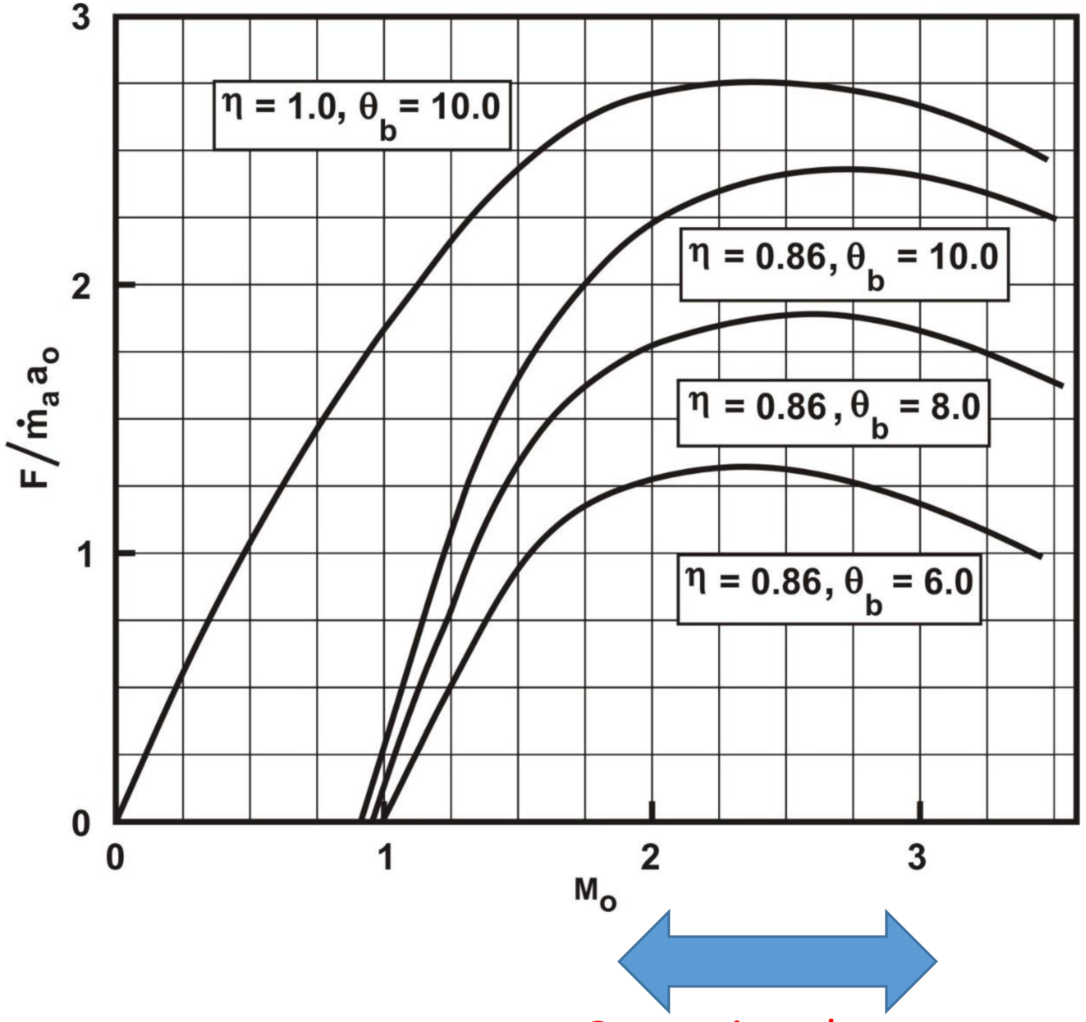


J58 ENGINE AIRFLOW—AT HIGH SPEED





Ramjet operational range – to - scramjets



Operational range

Best operating M ~ 2.5

$$[M_o]_{min} \sim \sqrt{\frac{2(\frac{1}{\eta}-1)(1+f)^2\theta_b}{(\gamma-1)[\theta_b(1+f)^2-1]}}$$

As M_0 increases, bringing down the Mach number through shocks to subsonic conditions at the combustion chamber will become more and more inefficient, adequate energy addition difficult to have an efficient propulsion engine and hence the Mach number should not be brought down.

This leads to Scramjet – Combustion chamber Mach number will be supersonic and hence One must burn the fuels under these conditions

Scramjets - issues

- Flight boundary
- Geometry
- Aerodynamics
- Fuels
- Injection system
- Ignition
- Mixing
- Combustion performance

Flight boundary

- Since ramjets and scramjets are not self-starting, they need to be brought to speed.
- In both cases, one can conceive of air drop from an aircraft with maximum speed of drop of M = 2 (usually lesser is desirable). Even in this case, subsonic ramjet taking the system to M~ 5 to 6 or beyond is essential.
- However, rocket as the propelling system is considered vastly simpler. The rocket delivers the scramjet vehicle to the altitude and attitude. Altitude is typically 30 to 40 km, Mach numbers of 6 to 7 or even up to 100 km at M ~ 10.
- Generally, the scramjet operates at a single altitude over the duration since change in altitude changes the combustor conditions significantly.
- Assuming that the system has been tuned for one flight condition sensitively, increase in altitude at the same Mach number reduces the combustion chamber pressure and degrades the reaction time; lowering the altitude causes increased pressures as well more hostile thermal conditions.
- However, with the availability of fast response control systems, changes may be possible.

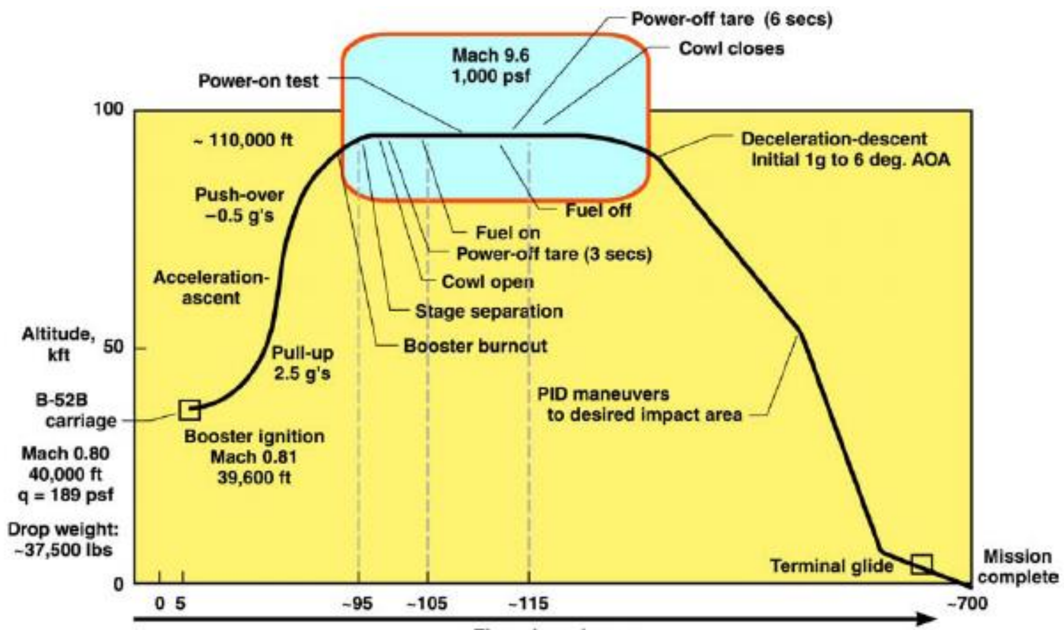
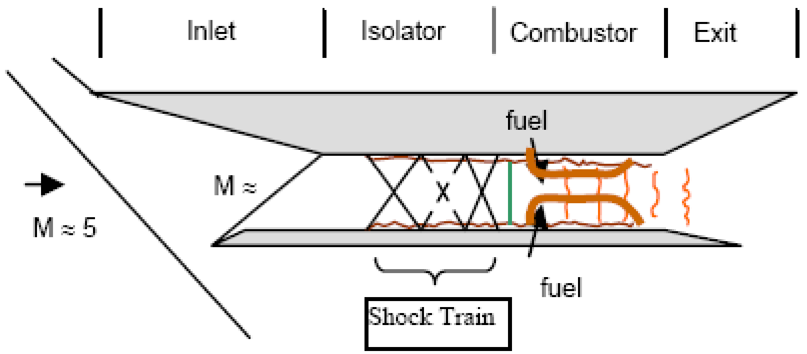
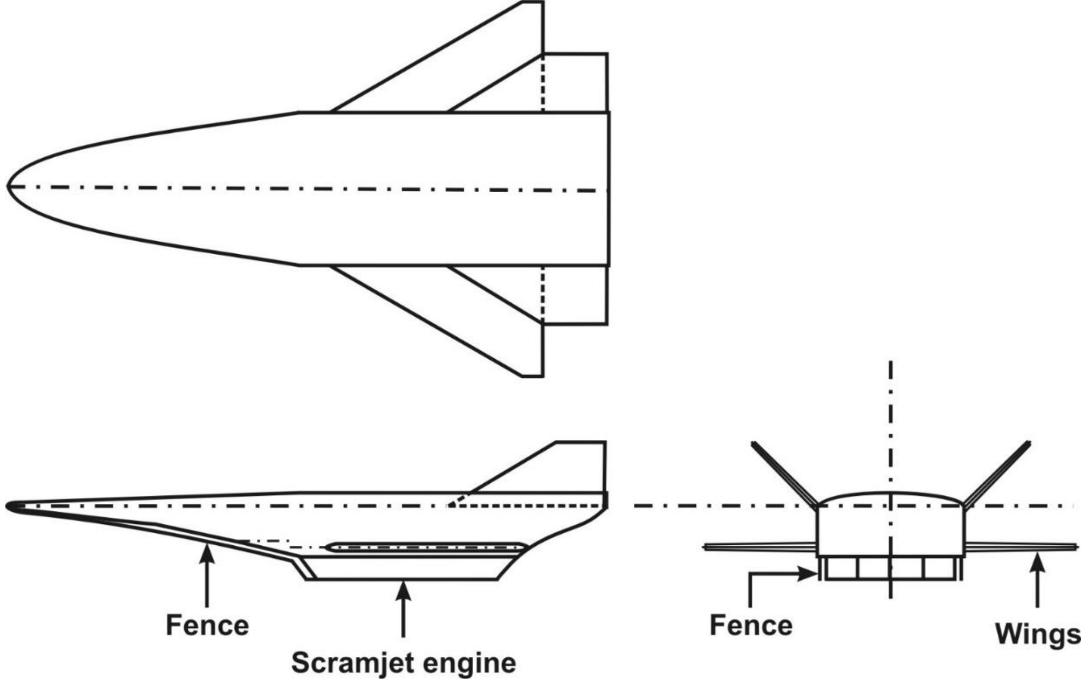


Figure 2. Mach 10 mission profile.

Scramjet vehicle - Geometry



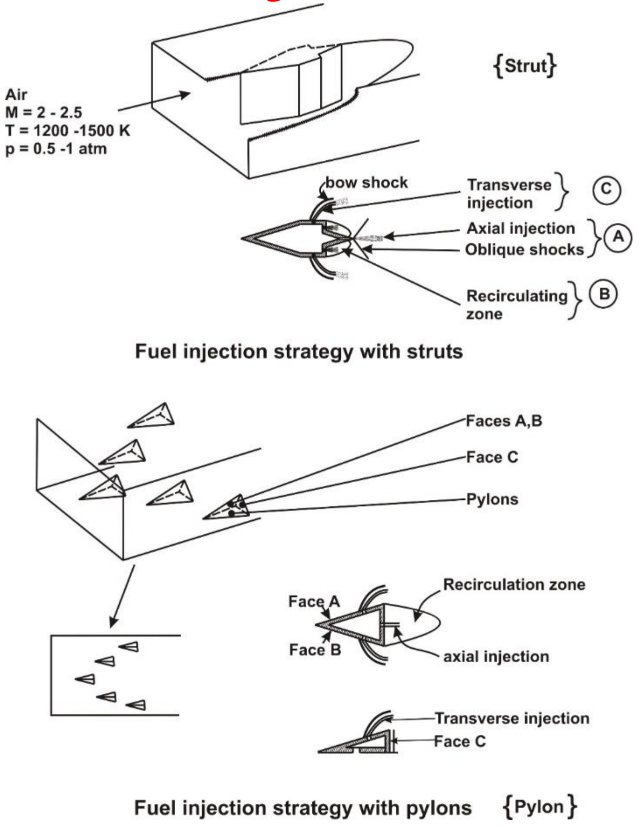


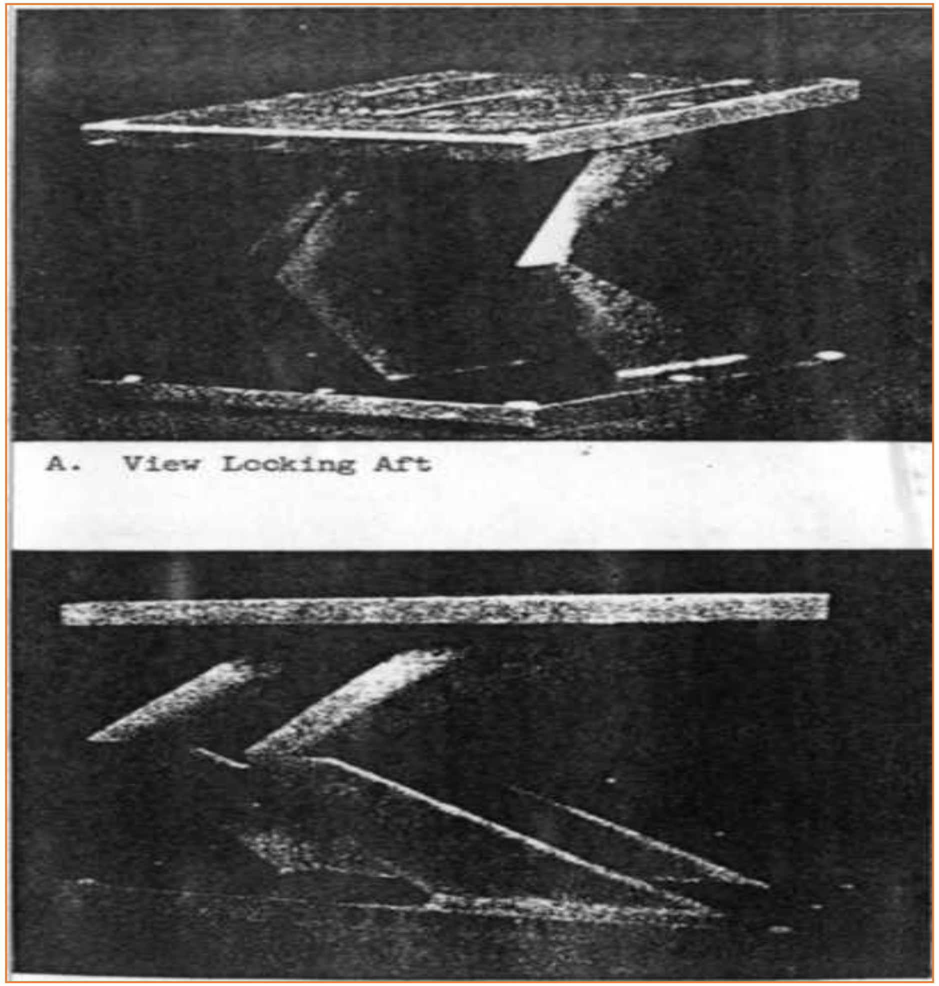
While *combustors in gas turbines* – both main and afterburner as well as ramjets are *circular or annular axisymmetric in shape*, the shapes for scramjets are rectangular …….why?

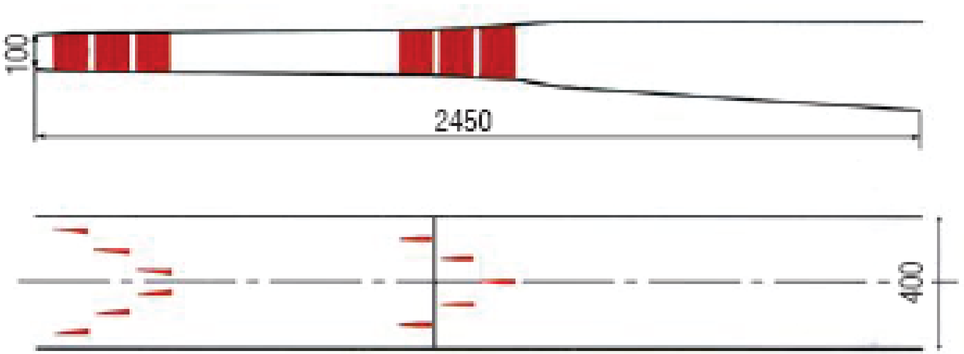
While gas turbine engines can be chosen from several choices and integrated with aircraft, engines for hypersonic vehicles have to conceived with the vehicle that needs a certain L/D with wing like shapes, and supersonic aerodynamics at the front end can enhance or spoil propulsion very significantly. The engine has to be hugging the vehicle and it helps to design a scable unit system to help reduce development. Thrust and drag are close to each other and any reduction in drag can be thought of as having generated more thrust!

Hypersonic vehicle is like …….. "Ardha naareeshawara"!

Scramjet - Geometry







Strut design experimented by Marquardt company in 1964 !

Scramjets - Aerodynamics - Propulsion

- The flow is decelerated to low supersonic Mach numbers, *typically one- third the flight M (or slightly more)* and combustion process initiated at these conditions.
- Typical *static temperatures will be about 1200 to 1600 K* and *pressures about 0.5 to 0.75 atm*. The static pressure crucially decides the combustion process
- While the higher static temperatures are appropriate for ignition, the low pressures may hinder the ignition process and the steady combustion demand larger combustion volume, a feature that may be critical for the scramjet.
- Ignition can be helped by several means including pyrophoric kind, but steady combustion demands the combination of the distributing the fuel injection over the cross section and a small subsonic zone that hold the flame steadily

Scramjet fuels

- Early and space centered efforts used Hydrogen as a fuel (as a gas, mostly) as its combustion process is simpler and achieved far more easily than hydrocarbons. It is very low in density and can be used for short missions only
- However, use of liquid hydrocarbon, say Kerosene calls for attention to atomization and tracking vaporization processes through the combustor.
- Some higher density fuels like JP-10 have been tried out when available.
- Some endothermic fuels – fuels that decompose on heating without going sooty – allow cooling the scramjet engine that has little possibility of dissipating heat due to very intense aerodynamic heating

Scramjet – fuel injection

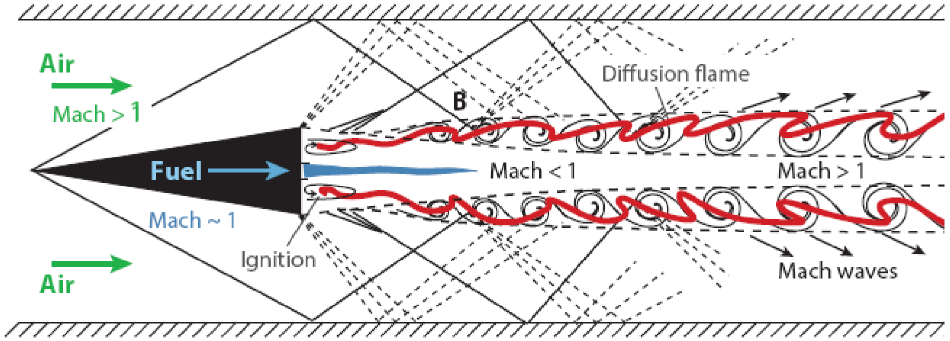
- Fuel needs to be injected into the combustor that has supersonic flow inside with large enough static temperatures, and much larger stagnation temperatures.
- Avoidance of hot pockets near the walls implies that the fuel be injected from centrally located struts.
- Typical velocities in the combustion chamber are about 1 to 1.5 km/s and the Mach numbers will be 1.4 to 2.2 for a typical combustor entry Mach number of 2.2.
- It is to be ensured that combustion occurs in a graded manner – not too fast nor too slow. If too fast, the pressure rise rate may cause the inlet flow to be influenced – causing a detached shock structure and subsonic flow. If too slow, the heat release process would lead to poor combustion efficiency.

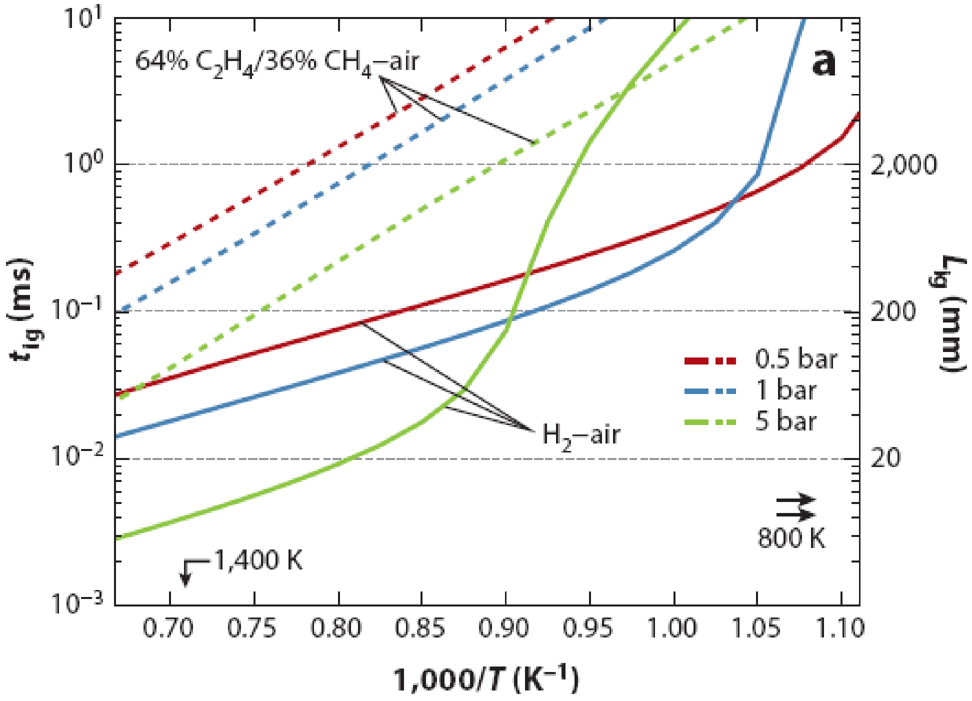
Summary of mixing data

Author/s	(x/d) for 90 % mixing	
• Gerlinger et al	700	(parallel Inj.)
• Uneshi et al	120	(perpendicular Inj.)
• Gruineg et al	284 to 450	(perpendicular Inj)
• Wilhelmi et al	40	(perpendicular Inj.)
• Guoskov et al	110	(perpendicular Inj.)
• Henry	40 to100	

Mixing distances in perpendicular injection vary from x/d ~ 100. By reducing the injector diameter, one can reduce the mixing Distance. If d is chosen as 0.5 mm, one would need a distance not exceeding 75 mm for mixing for perpendicular injection and about 300 mm for parallel injection.

Analysis of processes inside the combustor





To accommodate the time required for ignition, a recirculation zone behind the strut is employed

Once ignition has occurred, the flame is stabilized in the recirculation zone, typical Length scales for this zone ~ 15 to 20 mm

$$t_{combustion} = t_{ignition} + t_{vaporization} + t_{mixing} + t_{reaction}$$

$t_{ignition} \sim 0.01$ ms

$t_{ignition} \sim (1/p^2)\exp(-E_{ign}/RT)$ $\quad t_{vaporization} \sim d^2/K_{evp}$

$t_{mixing} \sim \delta_{mixing\ layer}/v' \sim \delta_{mixing\ layer}/(U_1 - U_2)$ **Where U1 and U2 are stream velocities across the mixing layer**

$t_{reaction} \sim (1/p^2)\exp(-E_g/RT)$ **For high temperature reactions like in scramjet E_{ign}/R and E_g/R are both relatively small ~ 3000 – 5000 K**

$t_{vaporization}$ is the key time scale for liquid based scramjets; the drop diameter must be ~ 15 - 20 microns

Operational experience
M ~ 5, 7, 10

NASA, (USA),
VSSC, India
China, Australia,
France-Russia

- HyFly program was initiated in 2002 by DARPA (Defense Advanced Research Projects Agency) and U.S. Navy's ONR (Office of Naval Research) to develop and test a demonstrator for a hypersonic Mach 6+ ramjet-powered cruise missile
- Engine runs on conventional liquid hydrocarbon fuel (JP-10)
- Sustainer engine of HyFly is a dual-combustion ramjet (DCR) (very complex)
  - Two different air inlet systems
    - Operate as a "conventional" ramjet with subsonic combustion
    - Operate at hypersonic speeds as a scramjet

- X 51 – successfully flown in 2010
- 200 Secs powered flight
- Successful boost
- a= 0.17g uphill to Mach ~5
- Ethylene to JP-7

Further on Boeing X51 A

- A Boeing X-51A WaveRider unmanned hypersonic vehicle achieved the longest air-breathing, scramjet-powered hypersonic flight in history May 1, flying for three and a half minutes on scramjet power at a top speed of Mach 5.1. It's called Waverider because it rides its own shockwave at hypersonic speeds in excess of Mach 5 (6125 km/hr).

- The 7.62 m long vehicle is a combination of a wingless cruise vehicle powered by a scramjet engine built by Pratt & Whitney and a modified Army Tactical Missile used to boost it to near-hypersonic speeds 26 seconds after being dropped from a B-52 bomber – The third flight that failed was analyzed as due to a fin failure. Corrected and was later flown successfully.

- On the fourth flight, U.S. Air Force B-52H released the X-51A from 50,000 feet above the Point Mugu Naval Air Warfare Center Sea Range.

- After the B-52 released the X-51A, a solid rocket booster accelerated the vehicle to about Mach 4.8 before the booster and a connecting inter-stage were jettisoned.

- The vehicle reached Mach 5.1 powered by its supersonic combustion scramjet engine, which burned all its JP-7 jet fuel. The flight was the fourth X-51A test flight completed for the U.S. Air Force Research Laboratory. It exceeded the previous record set by the program in 2010.

- The X-51A program is a collaborative effort of the Air Force Research Laboratory and the Defense Advanced Research Projects Agency, with industry partners Boeing and Pratt & Whitney Rocketdyne.

https://boeing.mediaroom.com/2013-05-03-Boeing-X-51A-WaveRider-Sets-Record-with-Successful-4th-Flight

On X 43 A flight

from: Overview with results and lessons learned of the X-43A Mach 10 flight, Marshall, L A., Bahm, C., Corpening, G. P and Sherill, R., AIAA J.

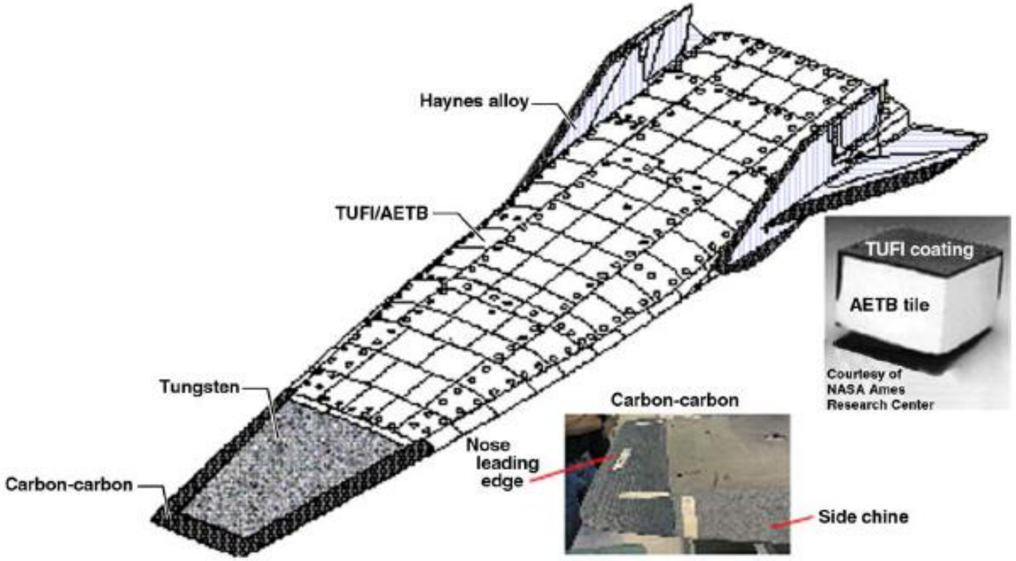
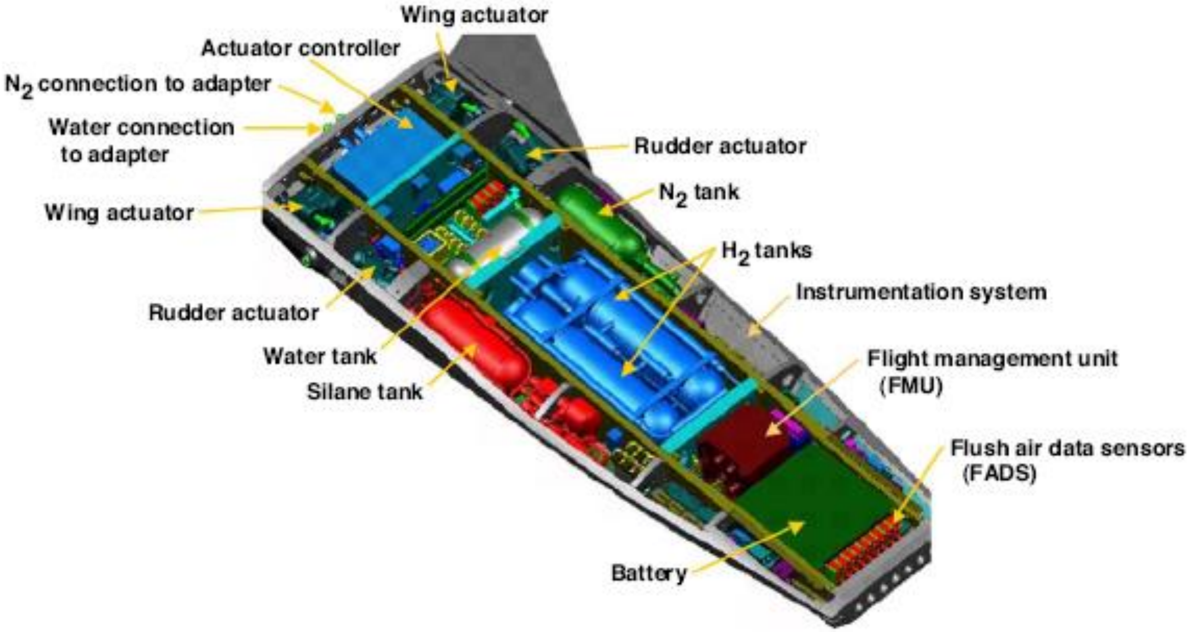


Figure 4. Vehicle material layout.



b) Internal.

Figure 3. Concluded.

Table 1. Instrumentation summary.

Measurement type	HXRV	
Embedded time code	6	
Pressures	175	
Strain gages	15	
Temperatures	128	
Miscellaneous analog	13	
1553 data bus (450 16-bit words)	788	(unique parameters)
Total	1125	

The X-43A vehicle was approximately 12 feet (3.66 m) long, 5 feet (1.52 m) wide, 2 feet (0.61m) high, and weighed approximately 3000 pounds (13,345 N). Figure 3 shows both the external (Fig. 3(a)) and internal (Fig. 3(b)) vehicle configuration. The X-43A was powered by a hydrogen-fueled, airframe-integrated scramjet propulsion system. The engine uses gaseous silane (SiH4) as the ignition source for the hydrogen fuel. In order to prevent oxygen intrusion within the vehicle, nitrogen gas was used to maintain an inert environment and to pressurize the X-43A internal cavities. The nitrogen gas was stored in tanks in the RV adapter for use during boost and within the X-43A for use during the engine test. The high heat loads experienced during these portions of the flight, required that the engine leading edges be kept cool. The stored nitrogen gas was also used as a coolant pressurant to move coolant to the engine leading edges. An ethylene glycol-water mixture in the RV adapter served as the coolant during boost, while water only, located in the HXRV, was used as coolant during the engine test.

X 43A Test data

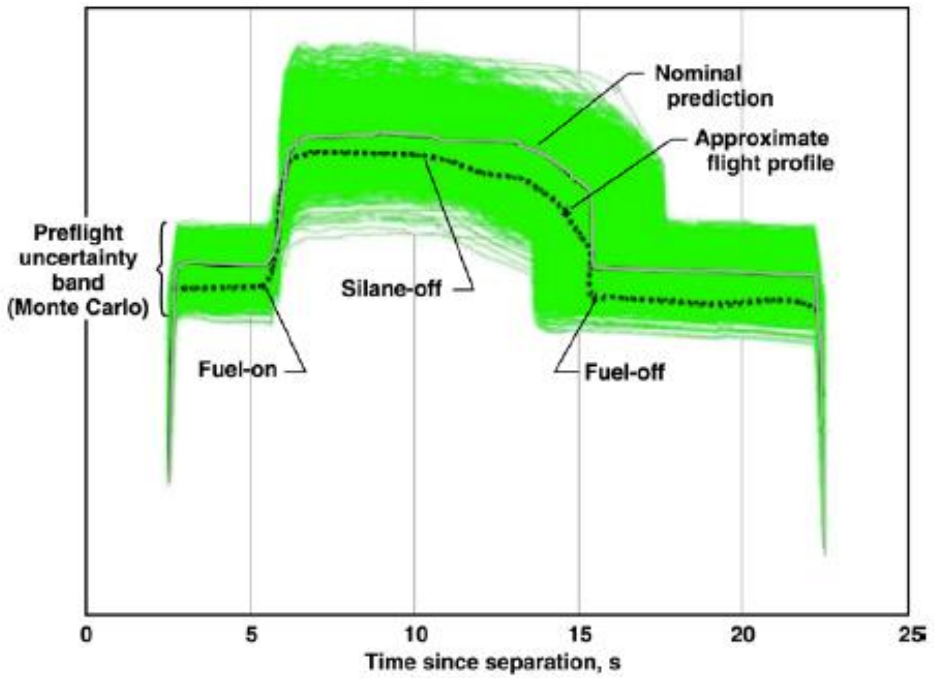


Figure 9. Axial acceleration profile during engine test.

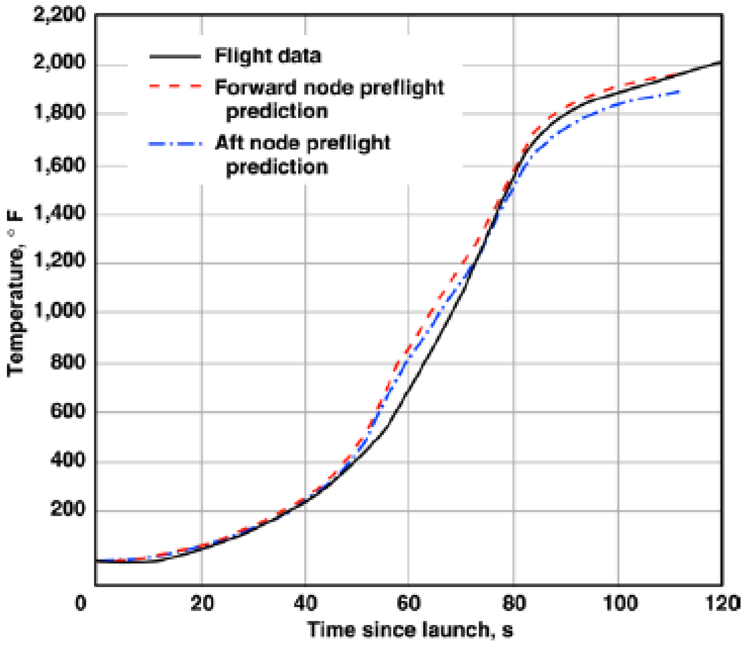
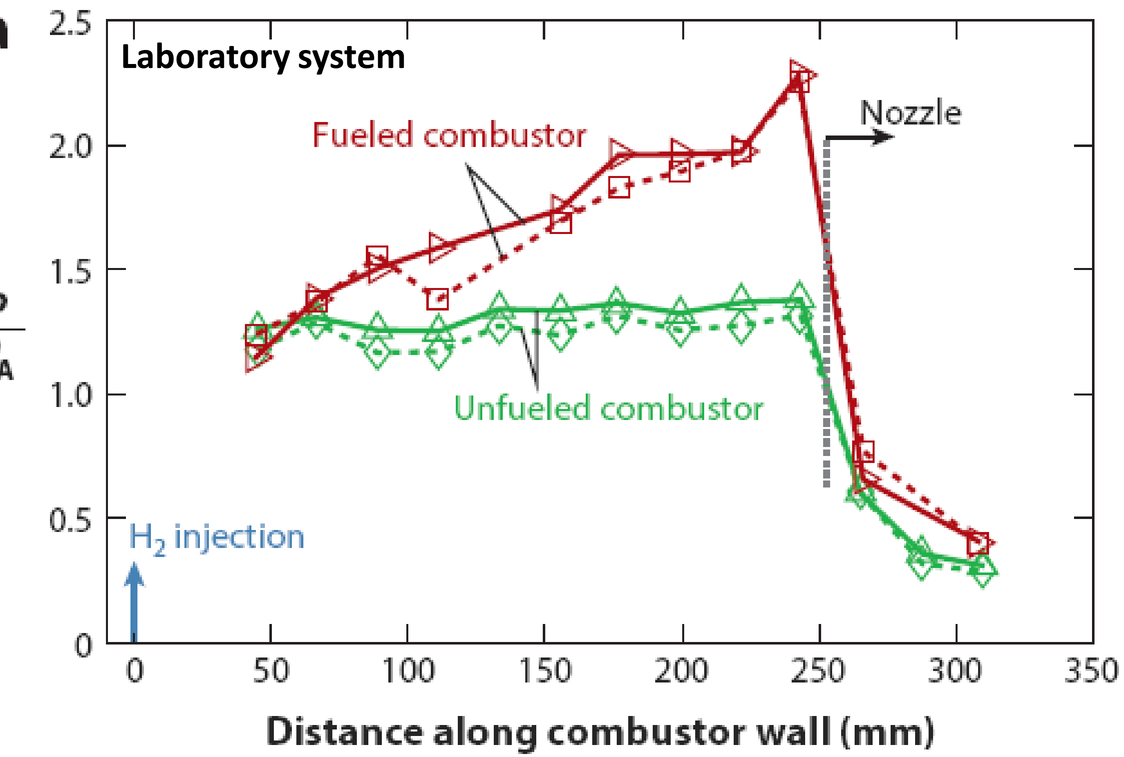


Figure 12. Nose temperature.

Wall pressure plots to derive information on engine thrust



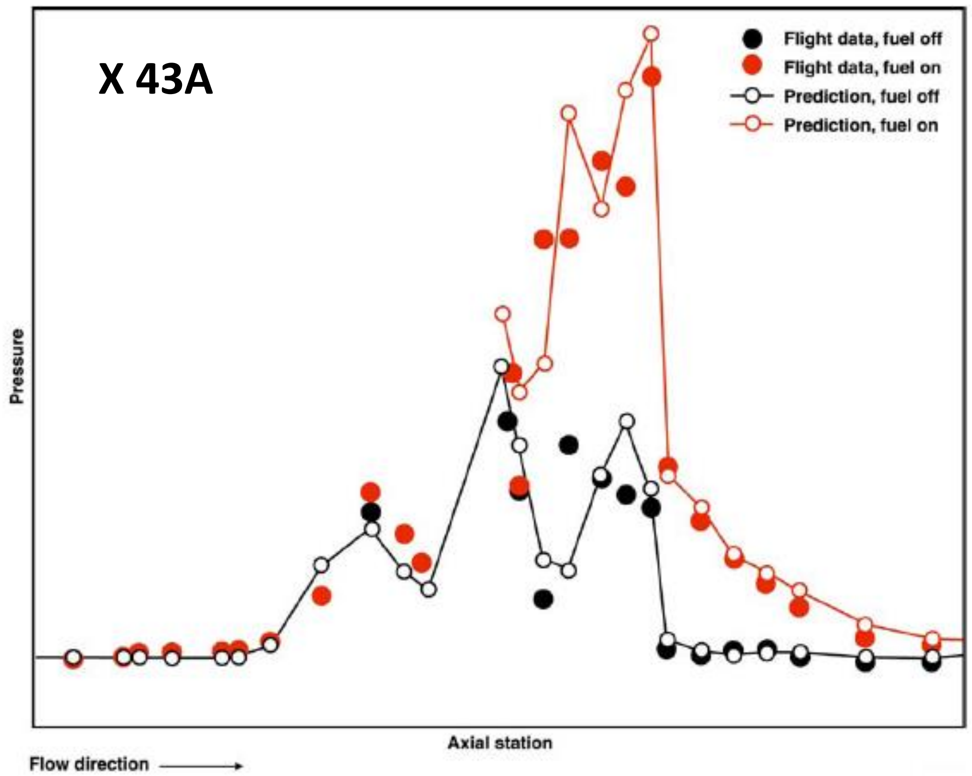


Figure 11. Flight as a function of preflight propulsion database.

Computational techniques will be used to explore the performance on the full geometry under many conditions, including combustion for varying equivalence ratios. In India, both at VSSC and DRDL, much excellent work has been done to combine computational techniques and experiments – connected mode, free jet to ensure that the combustion process predictions match with experimental data – like what you see above. VSSC system has been flown successfully and DRDL system has been successfully free-jet tested.

On performance related aspects

- Local heat release leads to enhanced temperatures.
- This increase causes increased acoustic velocity ($\sim \sqrt{T}$) and reduction in Mach number even if the local speed is unaltered.
- This means that the gas dynamics is intimately coupled to heat release.
- They interact with each other in an opposite sense. Increase in heat release raises the temperature that reduces local M. and so enhanced shock losses that may partly be overcome by expansion of the flow and this adds to the hardware.
- This is the reason why expecting very high combustion efficiency in a supersonic combustion system would be considered unwise.
- About 85 % is considered satisfactory in an overall optimization

Comparison of performance between different propulsion systems

Table 6.7: Comparison of various combustion devices; GT MC = Gas turbine main combustor, AB = Afterburner, RJ = ramjet, LR = Liquid Rocket

Type	GT MC	AB/ RJ	LR	Scramjet
Pressure, atm.	2 – 40	2 – 5	20 – 200	0.5 – 1.5
Temperature, K	500 – 750	600 – 2000	2500 – 3500	1200 – 1500
Mach number	0.2 – 0.4	0.3 – 0.5	0.5 – 0.7	1.5 – 3.5
Mean velocity, m/s	150 – 300	200 – 350	800 – 1000	700 – 1500
Reaction time, ms	0.3 – 1	3 – 4	1 – 2	1 – 1.5
Residence time, ms	3.5 – 5	4 – 5	2 – 3	0.7 – 1.0
Damkohler number	1 – 5	1 – 2	1 – 3	0.5 – 1.0
Pressure loss, %	6 – 8	4 – 5	5 – 20	15 – 25

Comments: Pressure that affects the combustion process is widely different between Rocket engines and air breathing engines. Further, in the air breathing engine whether for civil aircraft, high altitude flight conditions provide lower end of the pressure for combustion. Residence time considerations are most difficult for supersonic combustion (Damkohler number = residence time/conversion time).

Finally,

- One would plan to fly the vehicle on a computer before contemplating initiating the fabrication activities because of complex interactions between flow field and reaction processes

- Hypersonic propulsion could not have been built in an era where RCFD tools could not be used unless the designer (or design team) is extremely intuitive in terms of understanding of a complex balance of physics and chemistry .

- In the last ten years several supersonic flight vehicles have been built an done has already flown interestingly by ISRO making this area with a higher growth potential.