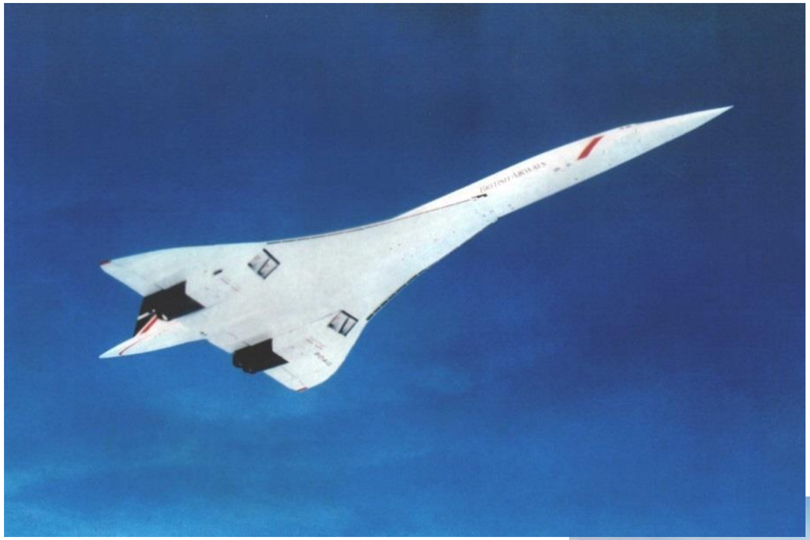
Lecture 9

Propulsion Systems for Super/Hypersonic Flight

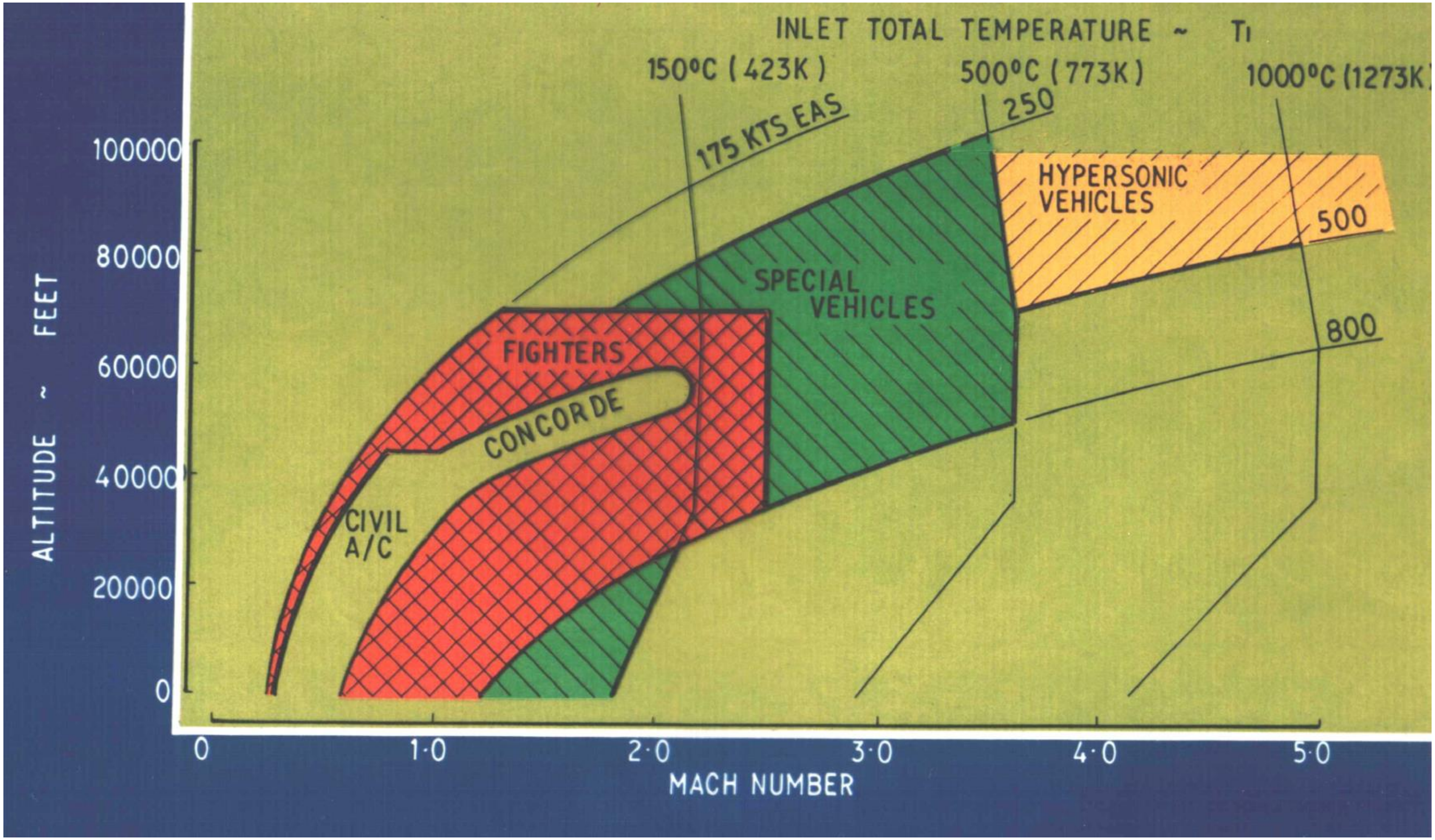
An Overview



High Speed propulsion systems

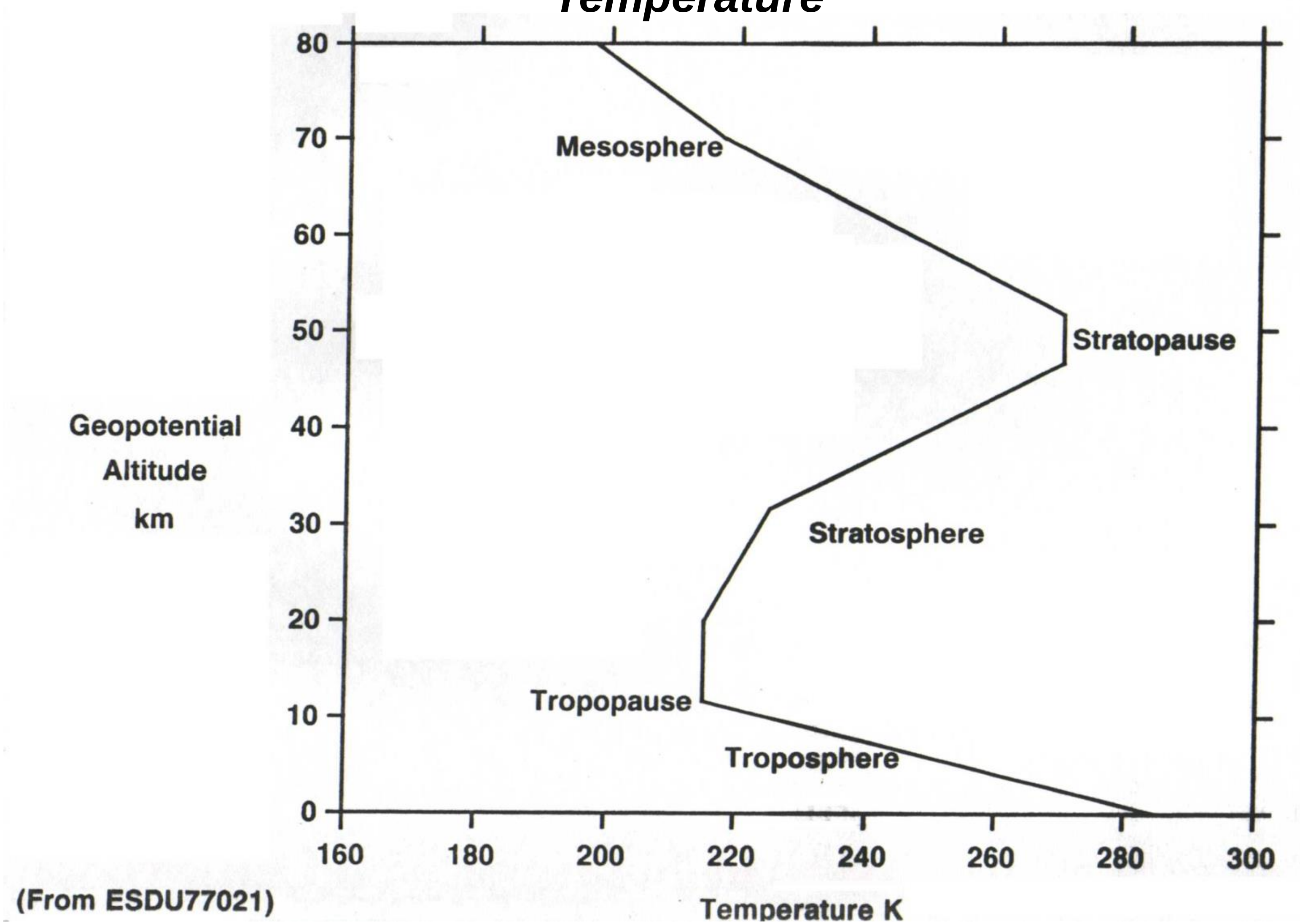
- The course so far has dealt primarily with propulsion systems for Subsonic and Transonic vehicles
- Some applications require higher flight Mach numbers e.g. Combat Aircraft, Supersonic Transport Aircraft, Launch vehicles for placing satellites in orbit etc.
- This presents extra issues in the design of the engine
- This lecture will concentrate mainly on systems, covering the M=1+, to M ~ 6 range.
- This will include such concepts as:
    - Ramjets
    - SCRamjets
    - Rockets and LACE
    - Combined Cycle

Flight Envelope



International Standard Atmosphere ISA

Temperature



What's the Problem?

- As the velocity of flight increases, stagnation properties (i.e. Total Temperature & Total Pressure) increase

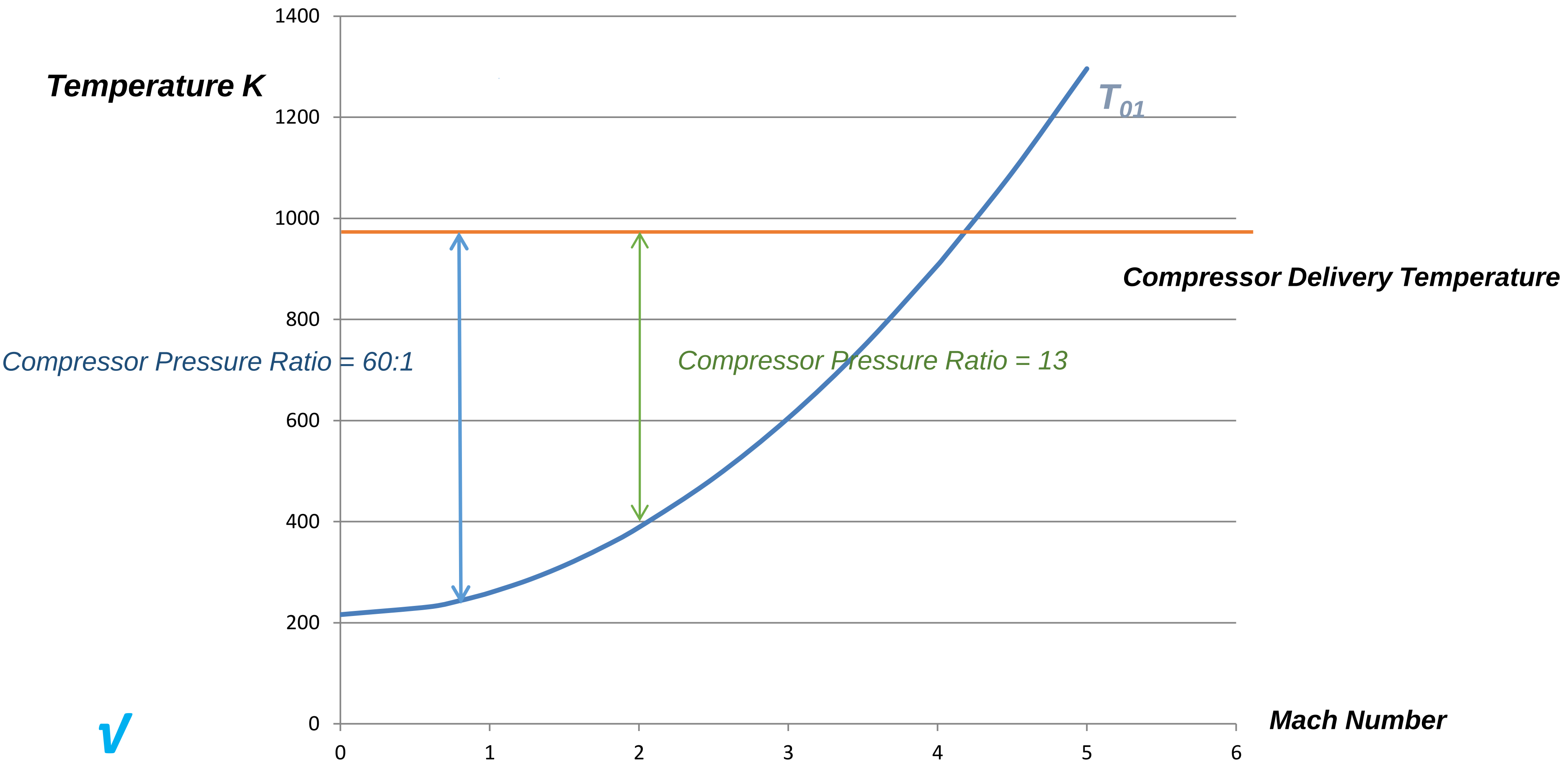
- In the stratosphere, (atmospheric temperature of 217K), the stagnation temperature at Mach 2 (Cruise Mach Number of Concorde) is 390K

- In the stratosphere, (atmospheric temperature of 217K), the stagnation temperature at Mach 6 is ~ 1800K i.e. equal to the inlet temperature of today's turbines

- There are no current compressor materials which will withstand such an inlet T_0

- With current materials the maximum temperature at the end of compression ~ 1000K

Inlet Total Temperature vs Mach Number



Conditions in stratosphere i.e. Ta = 217K

Consequences

- This suggests that the maximum Mach for a vehicle powered by a turbojet is about 2.5
- Note the Total Temperature T_0 is constant across a stationary normal shock
- This can be improved by using a different kind of intake
  - Normal shocks generate very large changes in Mach number and large total pressure losses (especially above Mach 1)
  - More, weaker shocks can be used to slow the flow before reaching the terminating normal shock, reducing its strength and reducing losses
- There are 3 types of intake External Compression, Internal Compression and Mixed Compression

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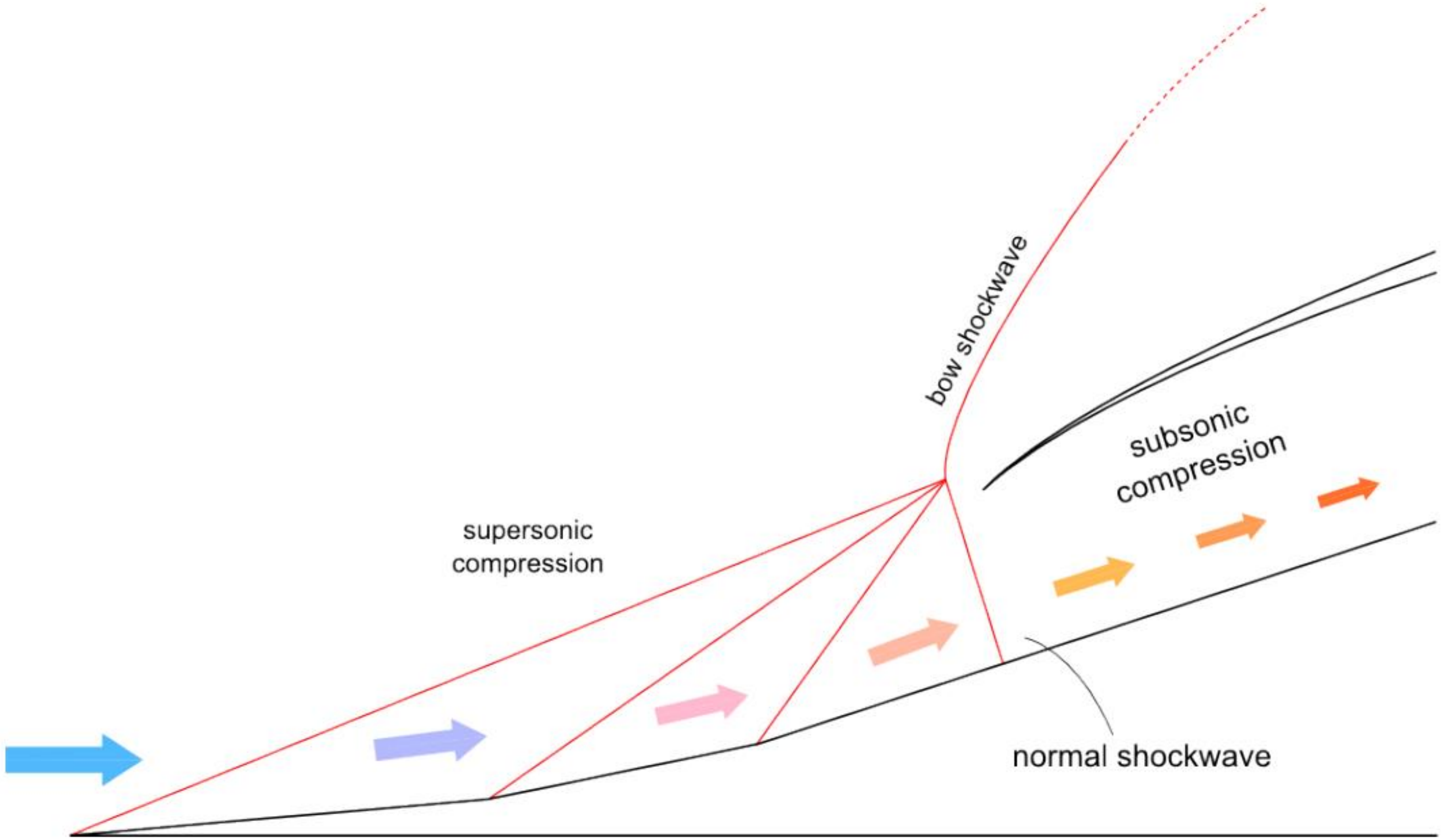
External Compression



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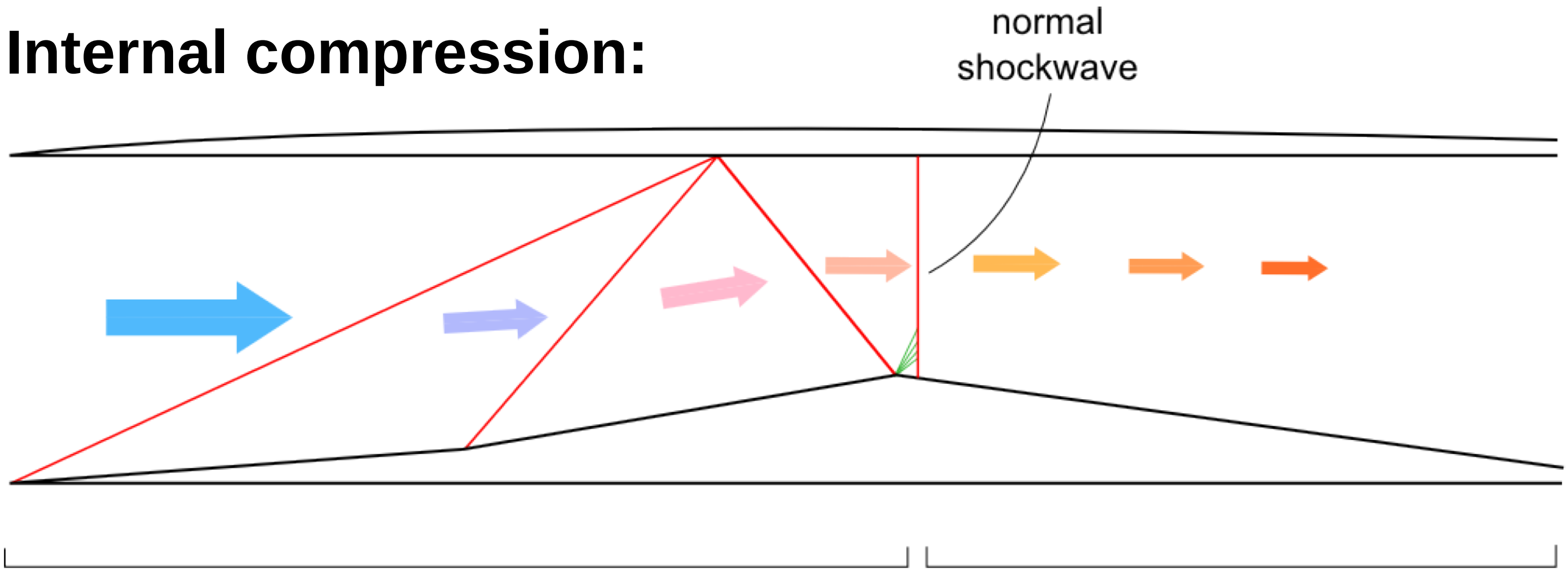
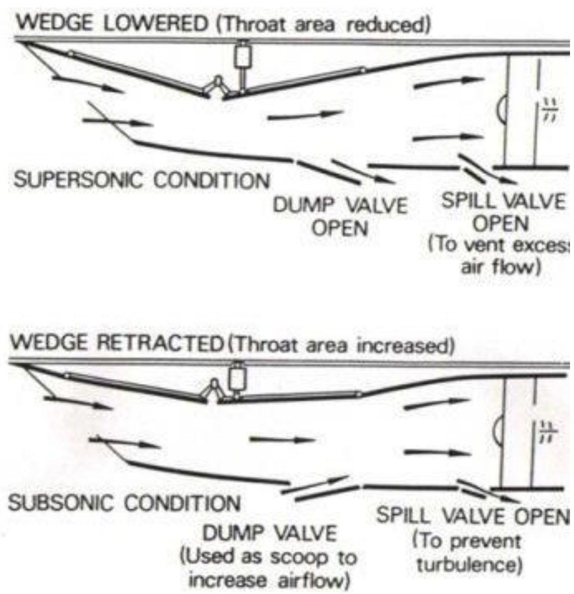
Internal compression:





Concorde Intake

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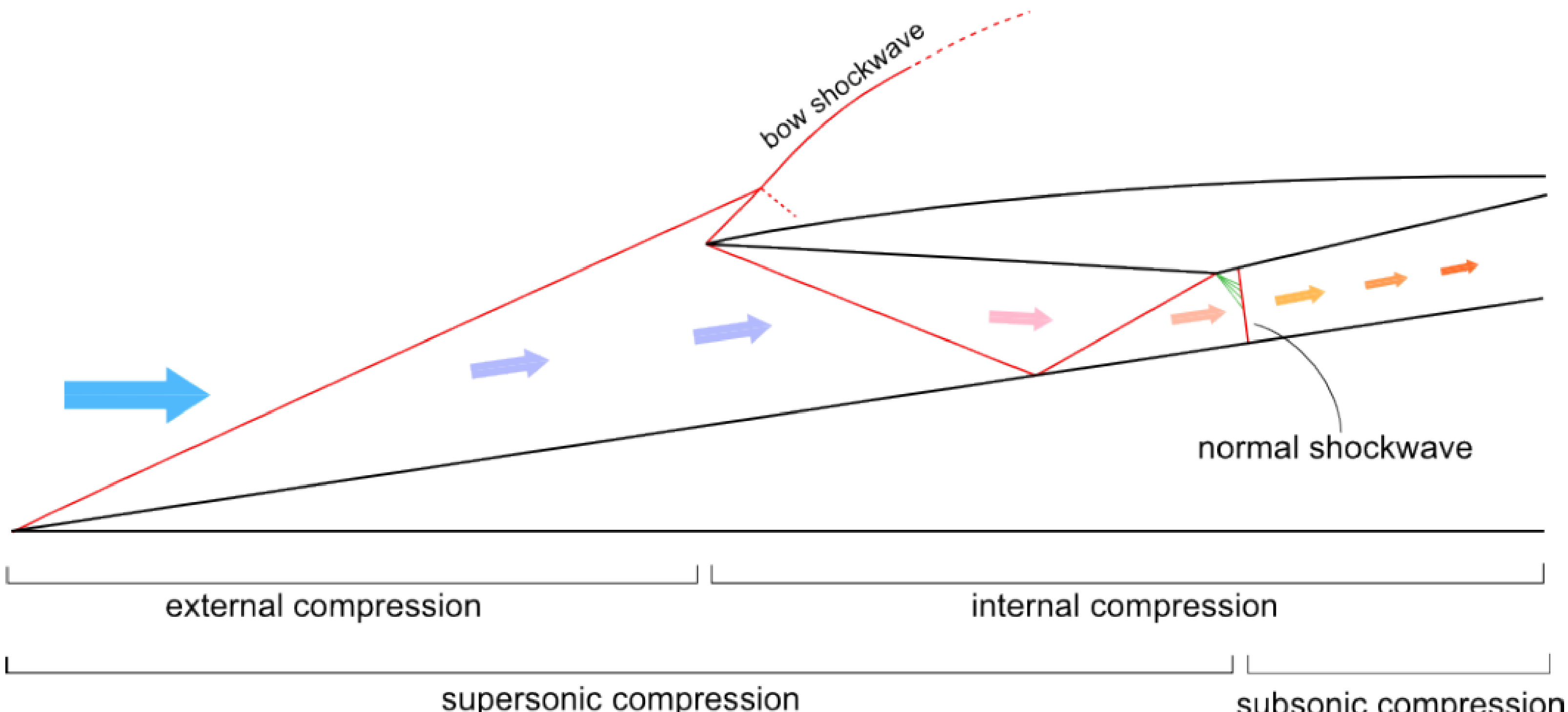
Mixed Compression



Efficiencies and limits

- A compromise must be reached when selecting the number of shocks – more shocks give better efficiency (normally defined as total pressure loss through the intake:) but mean more moving / control surfaces.

$$\eta_e = \frac{p_{oI}}{p_{oa}}$$

- Maximum recovery (for a given number of shocks) is obtained when shocks are of equal strength (i.e. pressure rise is the same through each). This is Oswatitch's Theorum.

- As on flow Mach number changes, therefore, the values of flow angles change, and the whole intake must be flexible (or flow angle is fixed and losses are accepted at all but one flight condition).

- At Mach Numbers up to about 3.5, where some fighter aircraft fly with turbojets a variable intake is needed e.g. SR 71

- More shocks/adjustable intakes can be used to fly at higher and higher flight Mach numbers
  - but eventually hit a limit (about M = 6/7)

- However, work of compressor is being reduced
  - P_0 after shock waves approaches 10 bar

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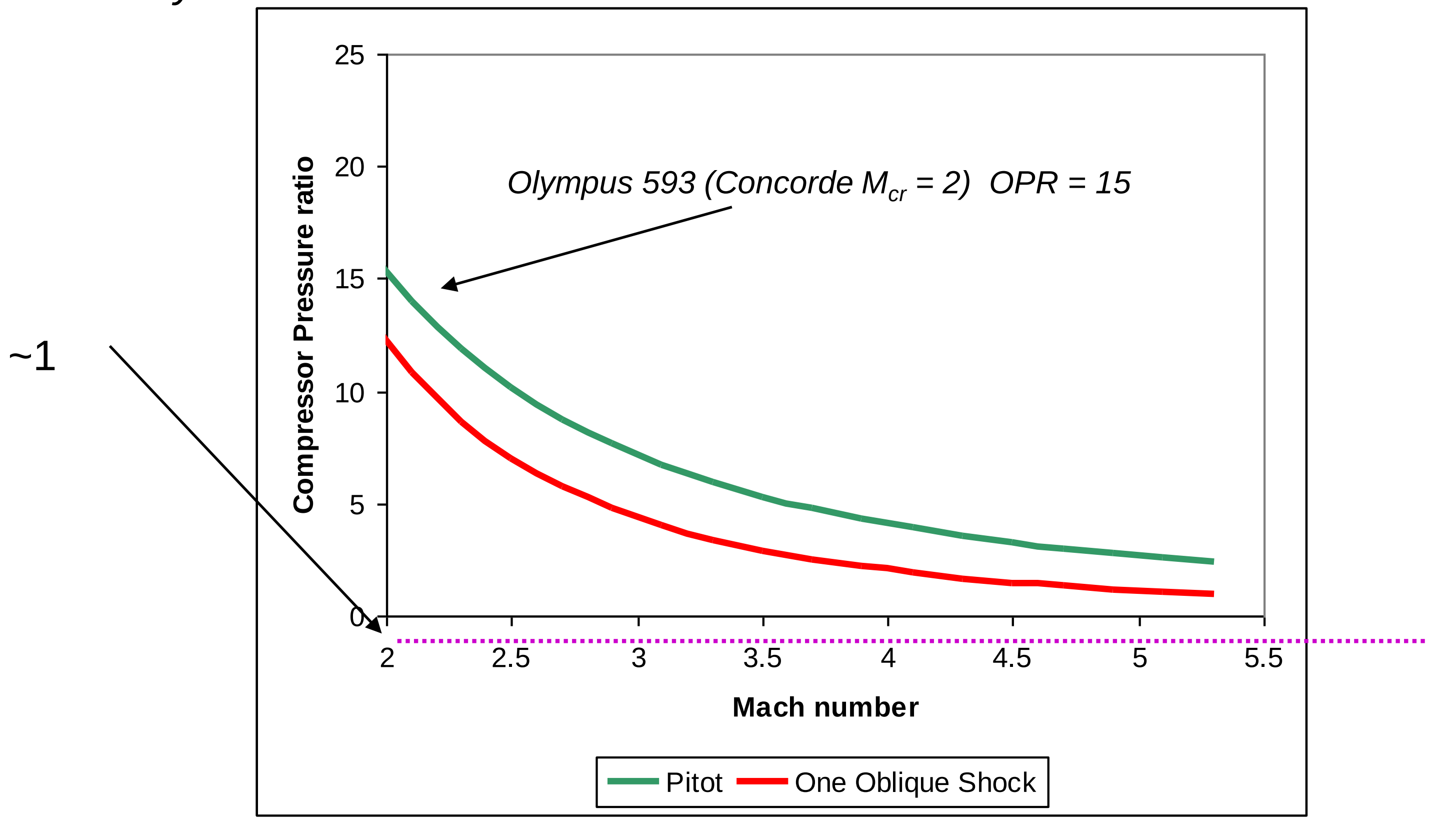
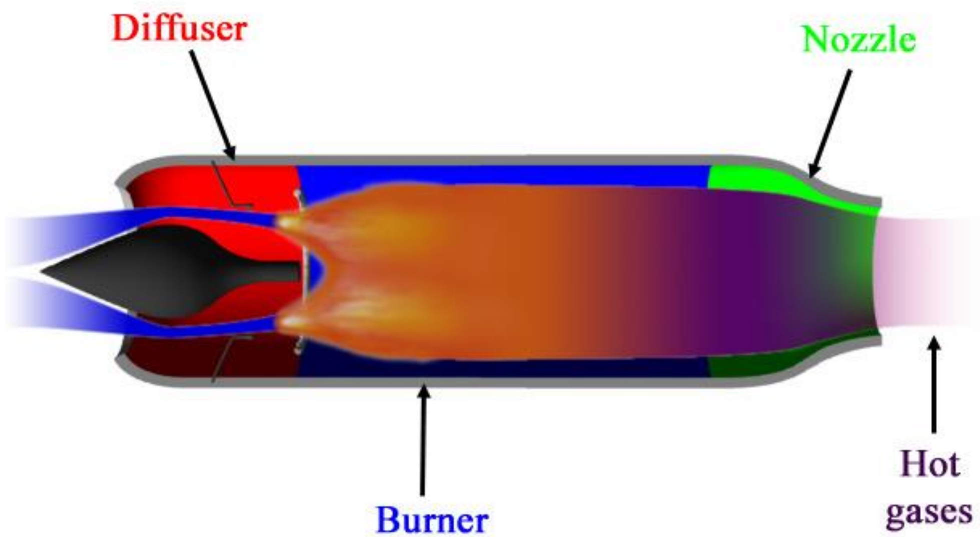
Put another way:



Note that for this oblique shock intake, the compressor does no work at about Mach 4.5, and more careful design would bring this Mach number down further. This means that the compressor is superfluous.



- Very simple engine - no moving parts (except intake?)
- Mach range high subsonic up to M = 6 – below this not enough pressure recovery to sustain combustion.
- So vehicle must be accelerated up to a Mach Number where the engine will operate

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Examples: Bristol Thor

Examples: Bristol Odin

- Odin Ramjet for Sea Dart air to Air Missile
- Mach Number = 2.5

Lockheed SR-71 Blackbird

EC92-1284-1 Photographed 1992
SR-71 Takeoff

Lockheed SR-71 Blackbird
Powerplant

- Pratt and Whitney J58-P4
- Actually a Turbo-Ramjet
  - i.e. could operate in both modes
- Operate up to Mach 3.5
- Demanded a *very* complex intake
  - operating range
  - engine unstart (not considered here)
  - thousands and thousands of wind tunnel tests

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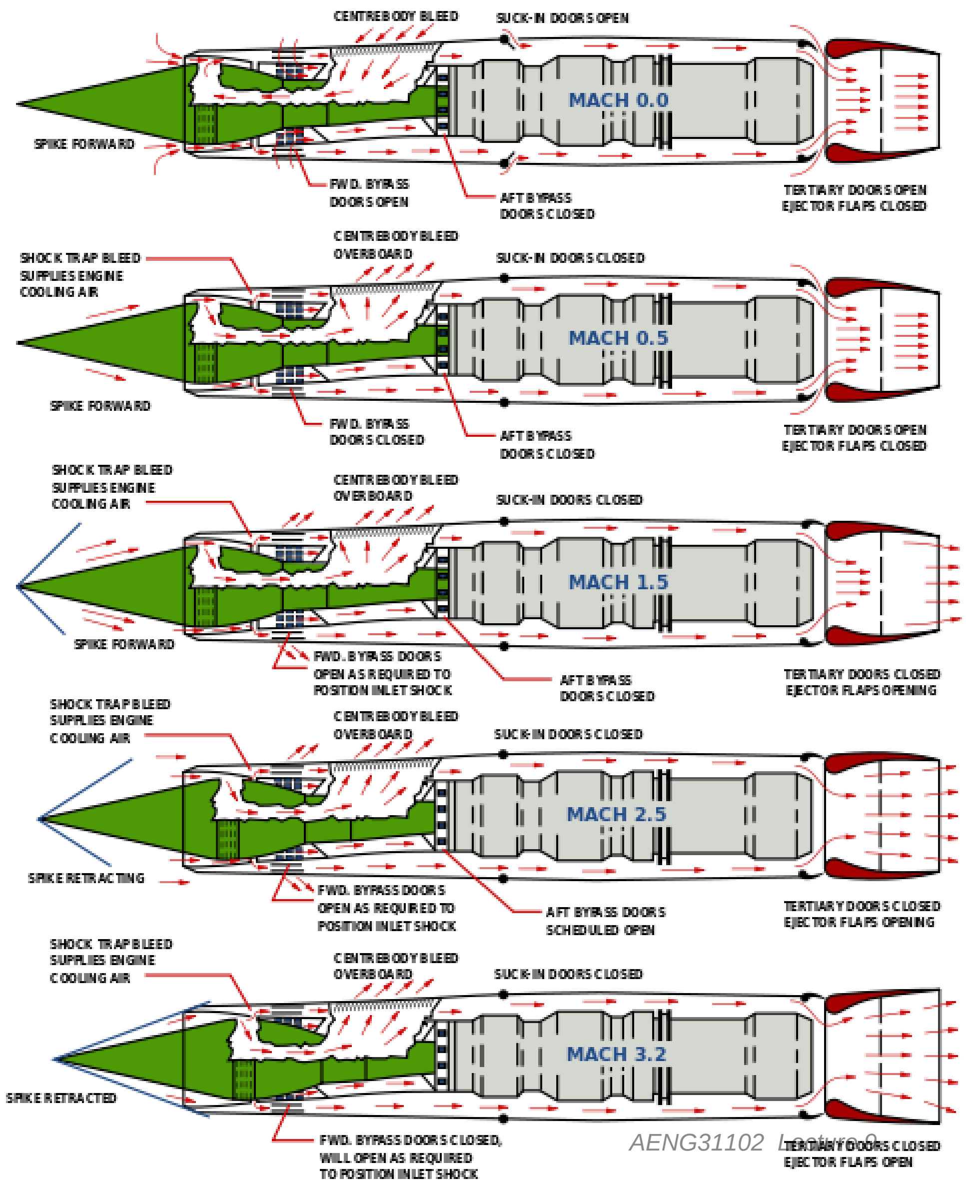
Pratt and Whitney J58-P4

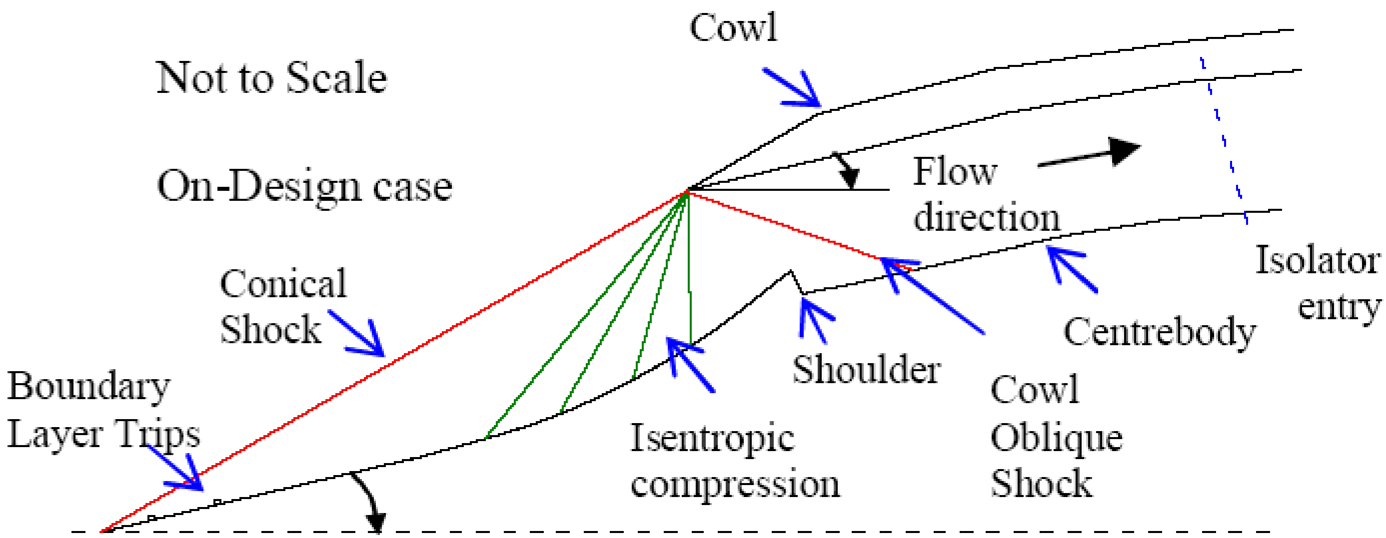


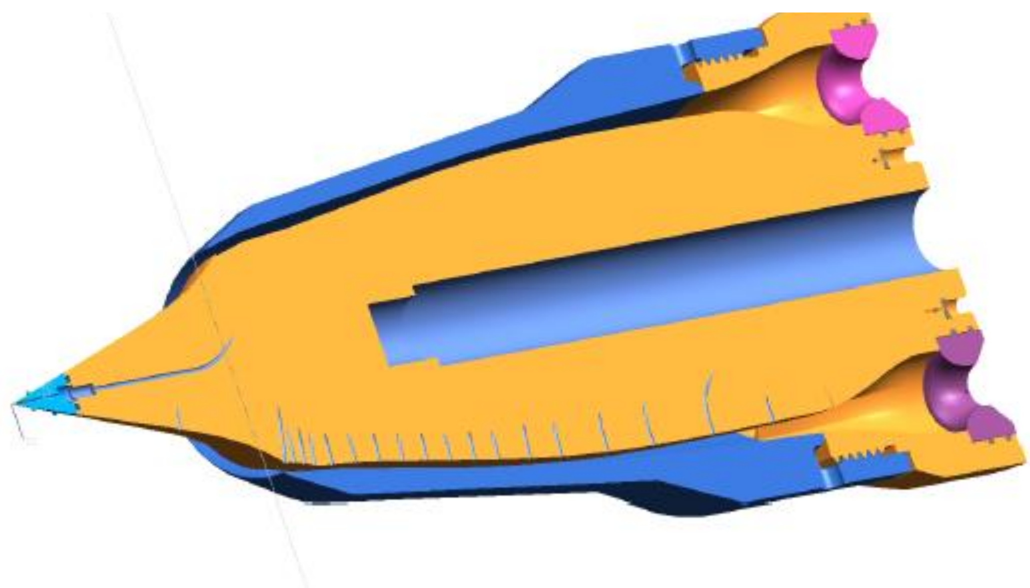
See also YouTube Video:
The Mighty J58 -
The SR-71's Secret Powerhouse

U.K. SHyFE

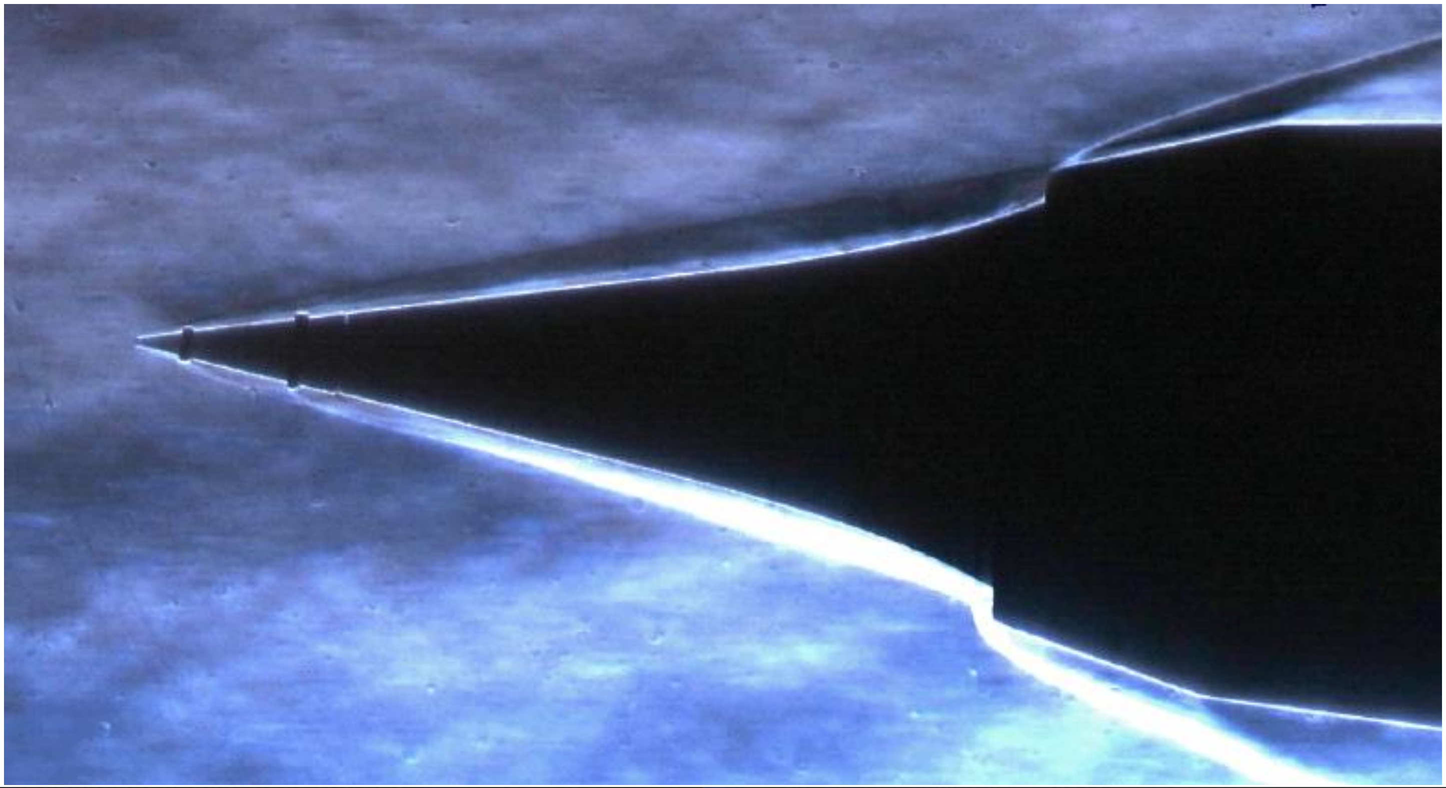
- Sustained Hypersonic Flight Experiment
- An initial 3 year paper study completed in July 2005. There was a second phase, intended to culminate in a flight in Australia (see HiFiRe). This did not happen due to launcher problem
- Aim; to demonstrate upper limit of Ramjets
  - launched at Mach 4, accelerate to Mach 6
  - weighs about 30 Kg
  - Mainly QuinetiQ

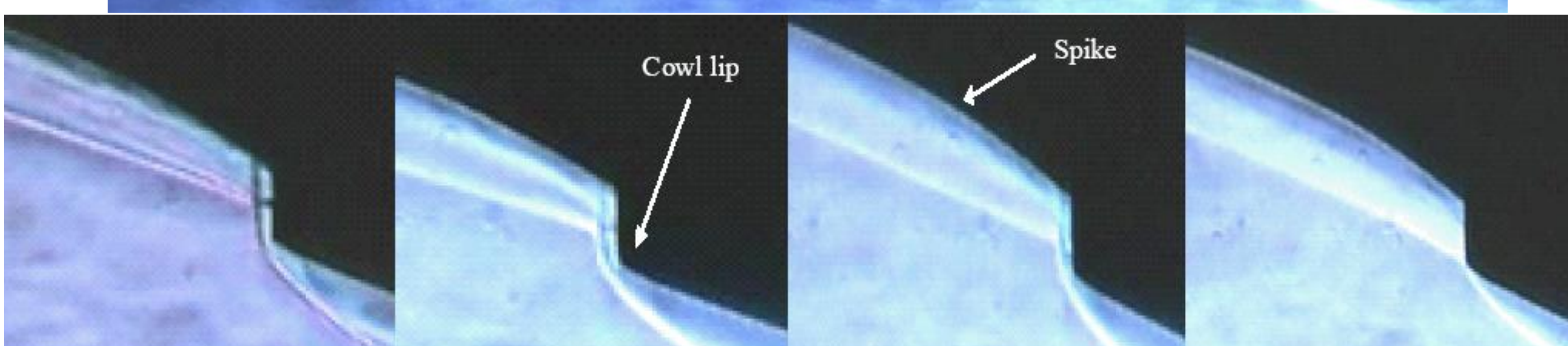
Intake Design





Flow Visualisation





Even Higher Mach Number?

- So far, everything is relatively conventional
- Ramjets are just like conventional engines, except in some ways simpler
- But what if we want to go even faster?
- Can't just stagnate the flow, so have three main options:
  - Scramjets
  - Rockets and derivatives
  - LACE and derivatives

SCRamjets
(Supersonic Combustion Ramjets)

- Basic idea is simple:
  - High temperatures are due to stagnation conditions
  - Avoid stagnation, avoid high temperatures
  - Should be able to operate up to almost any Mach number

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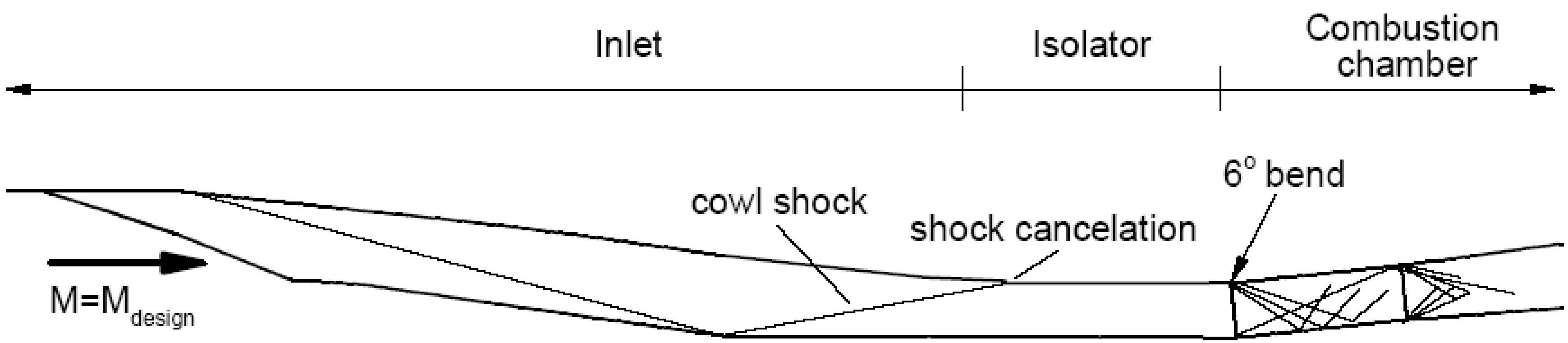
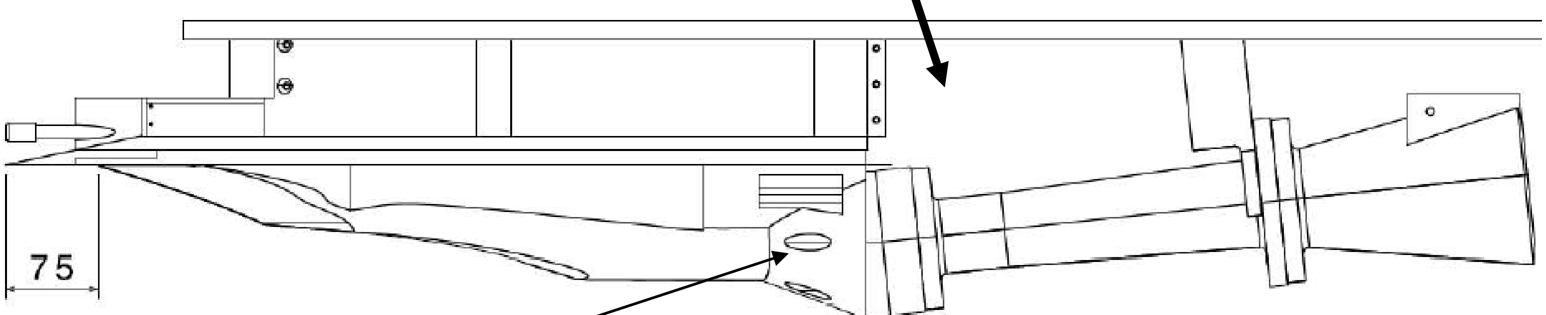
Components:

- Intake
  - As ramjet ~ complex device with multiple shocks for minimising pressure losses at high speeds (even more complexity than ramjet)
- Isolator
  - Channel that separates intake from combustion zone, needed for stability
- Combustor
- Nozzle

Hypersonic International Flight Research (HIFiRE)



Support structure for test model

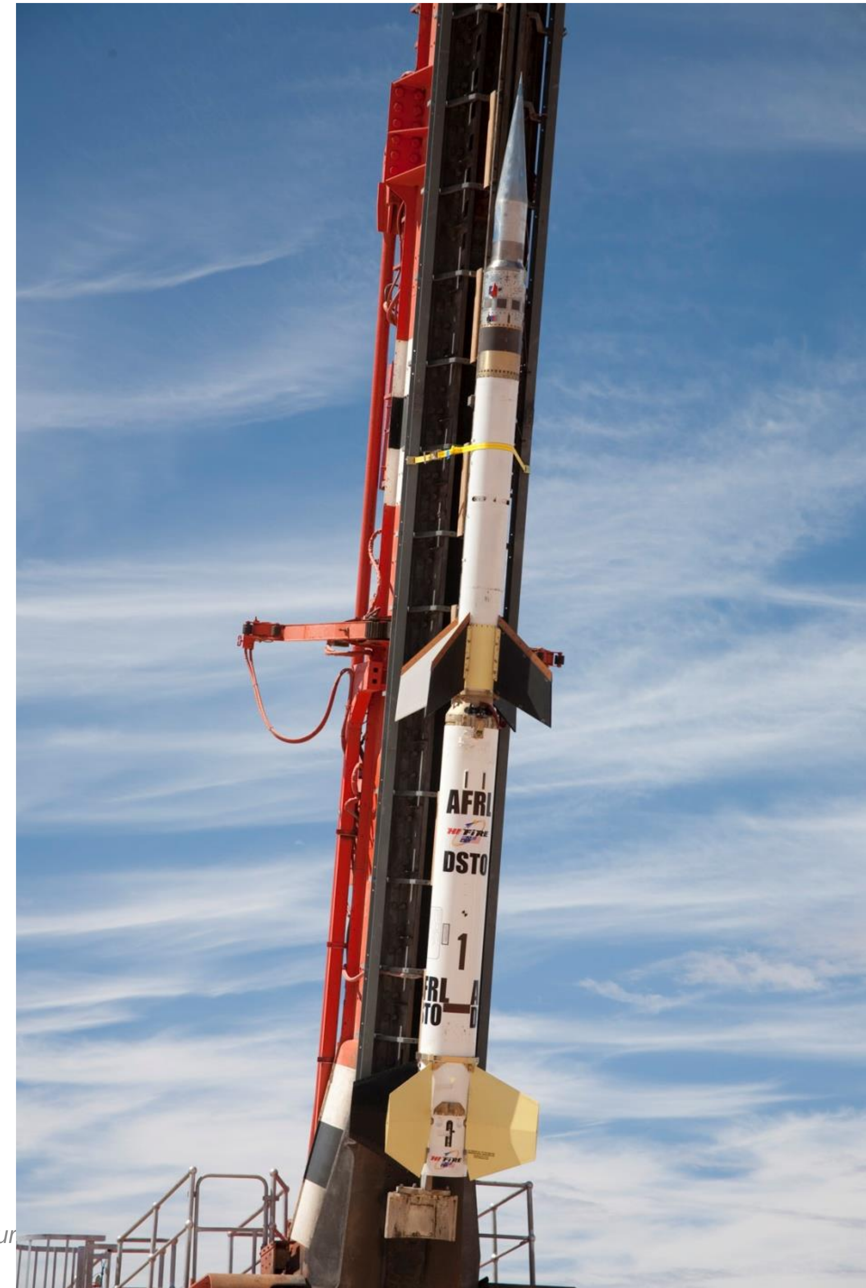


Engine

NASA

HIFiRE


NAVY


AFRL
DSTO
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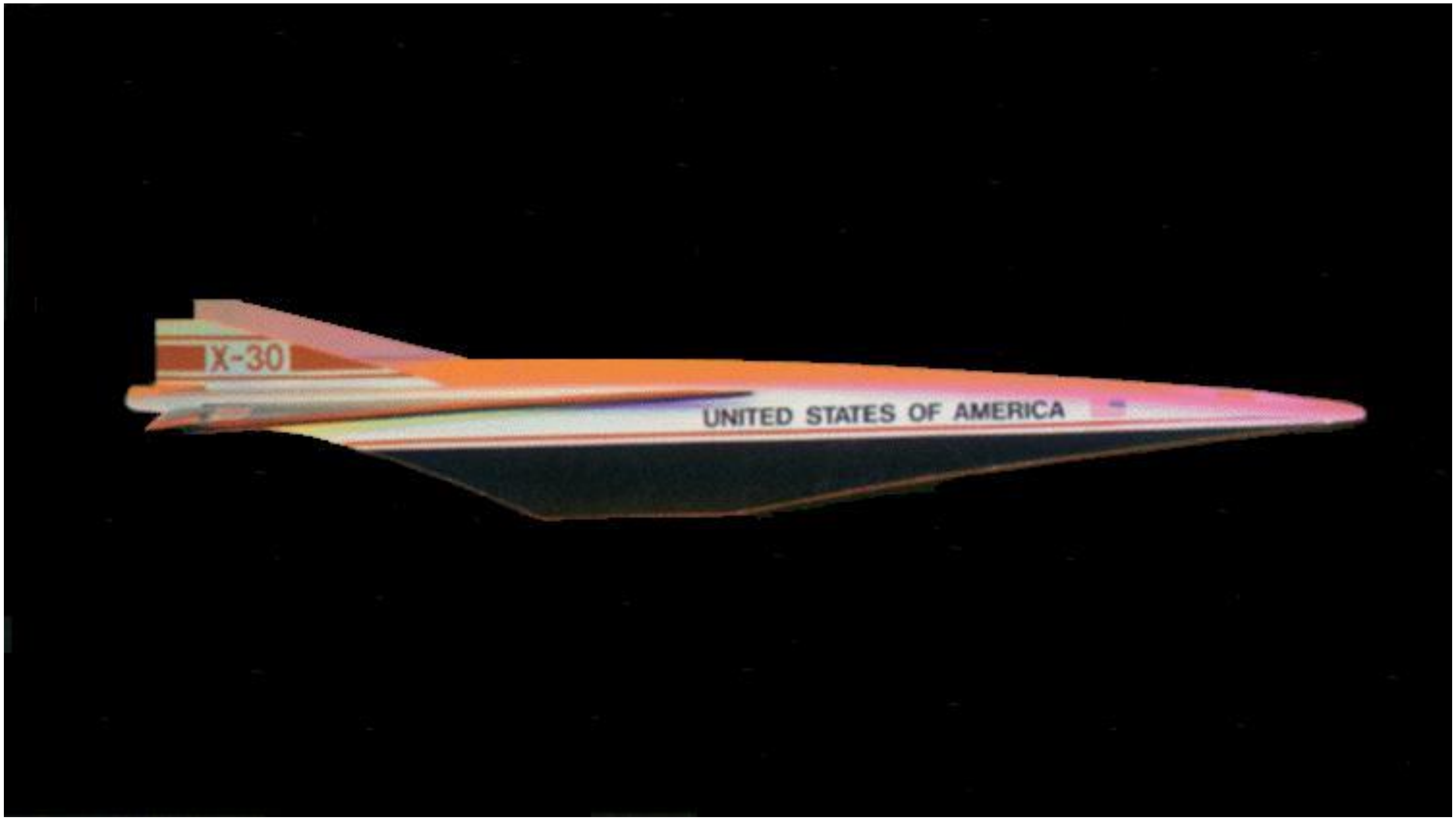
Problems

- Despite a huge amount of effort over many years, scramjet technology is still ‘just around the corner’
- Main problem is contrary requirements of flow for combustion
  - need good mixing – turbulence
- and efficiency
  - need low losses – no turbulence
- Also inlet behaves poorly at off design conditions

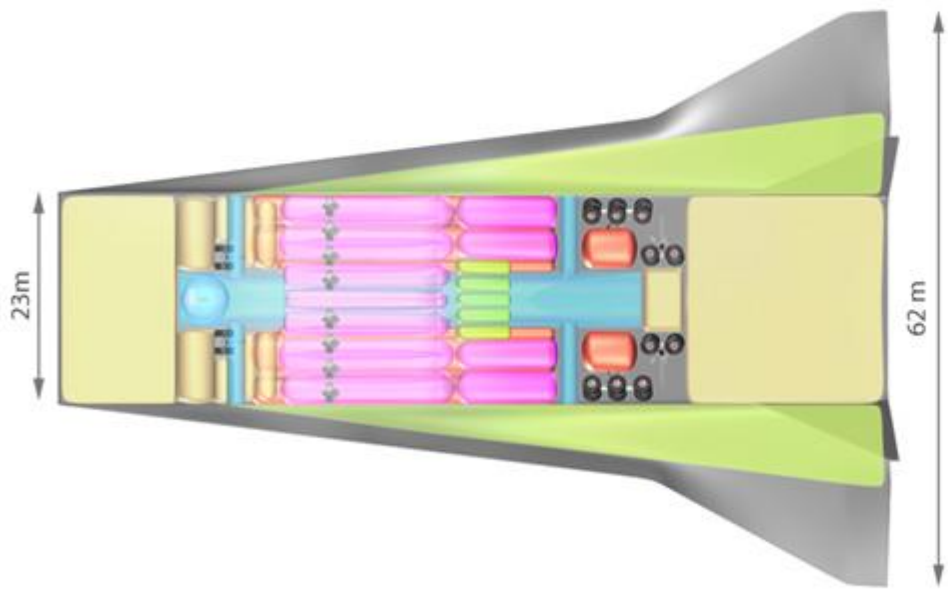
North American SpacePlane

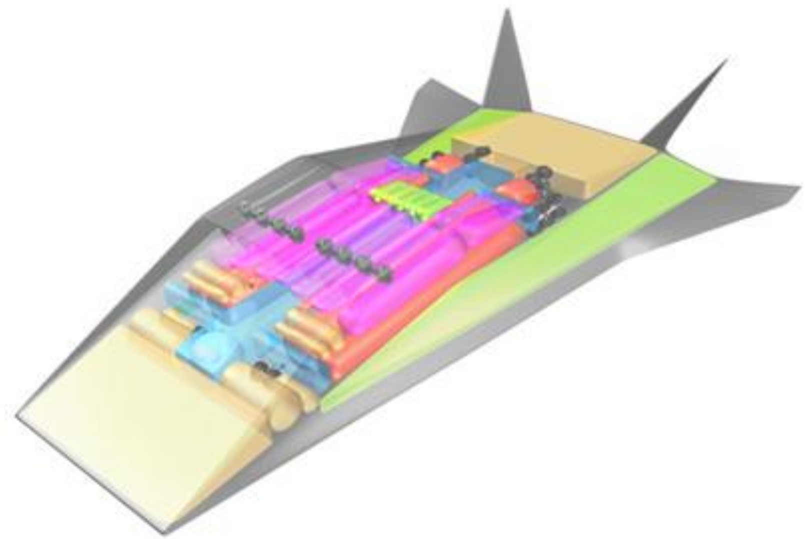


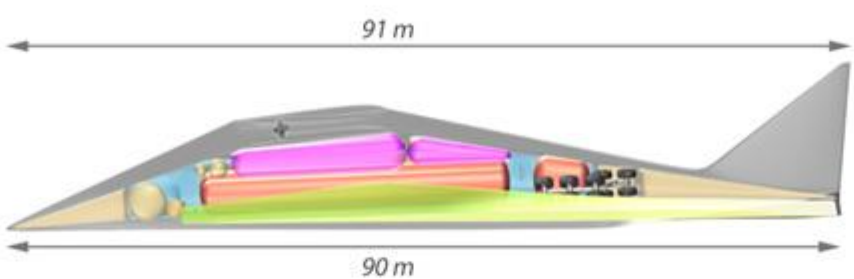
(early to mid 90's)

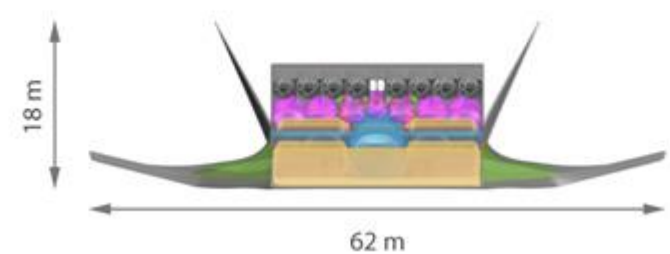
EU Lapcat I Mach 8

EU Lapcat I Mach 8





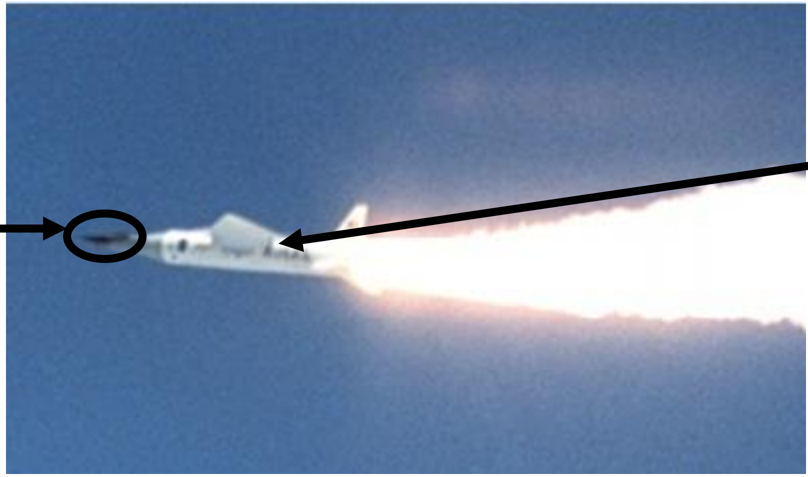




Issues

- Have a problem in that they only work at high enough speeds, generally above turbojet maximum
- So, need at least 2 forms of propulsion before it gets going (or can use a rocket, as per X43/HiFire (below), but these are test vehicles

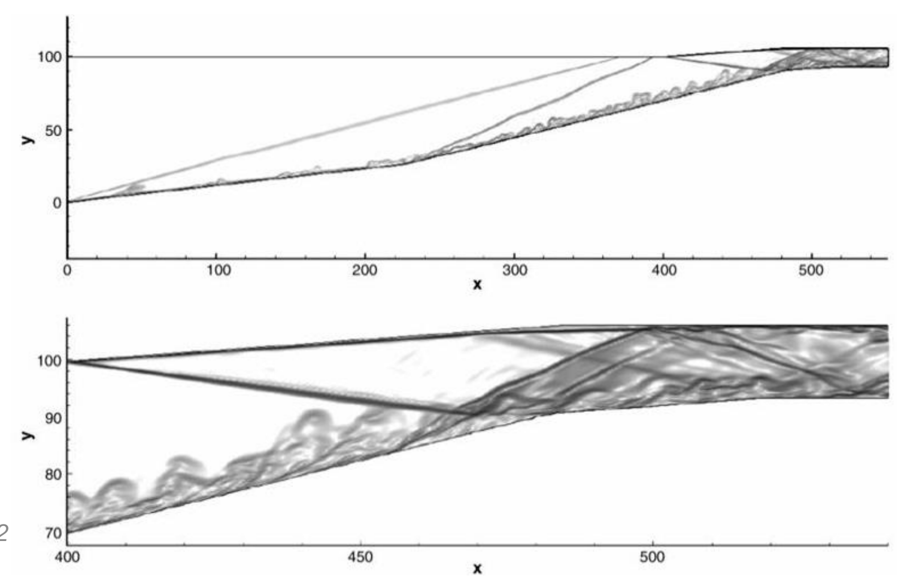
X-43



Pegasus rocket

- Despite this, they are attractive and are being researched in numerous places
- Huge number of papers - search of AIAA database for papers using title keyword ‘scramjet’ gives 94 results (17 for ‘ramjet’)
- Papers on combustion, combustor design, intakes, nozzles, vehicles

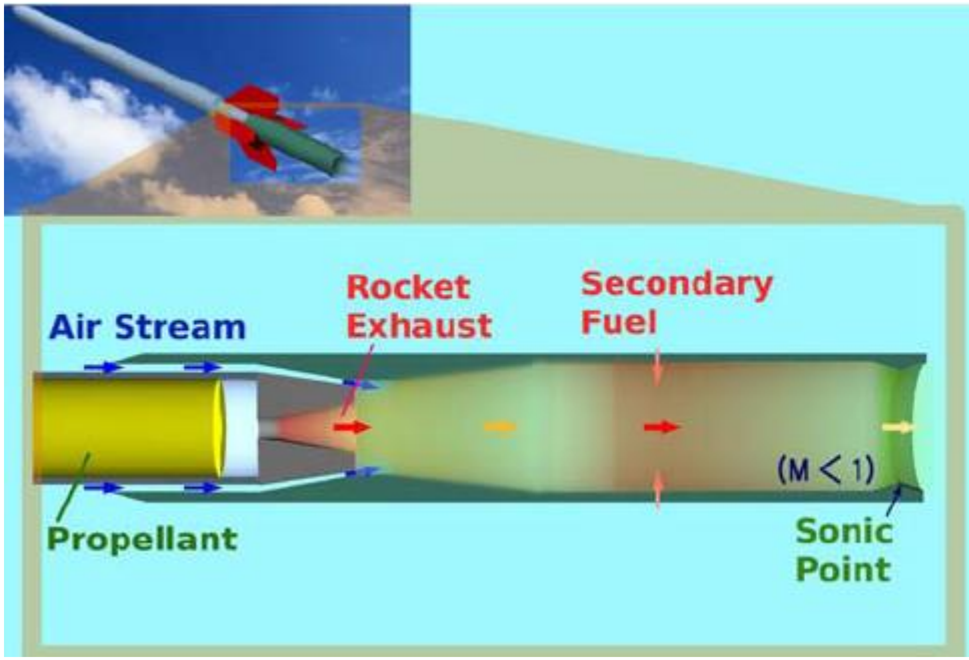
(NASA X-51)

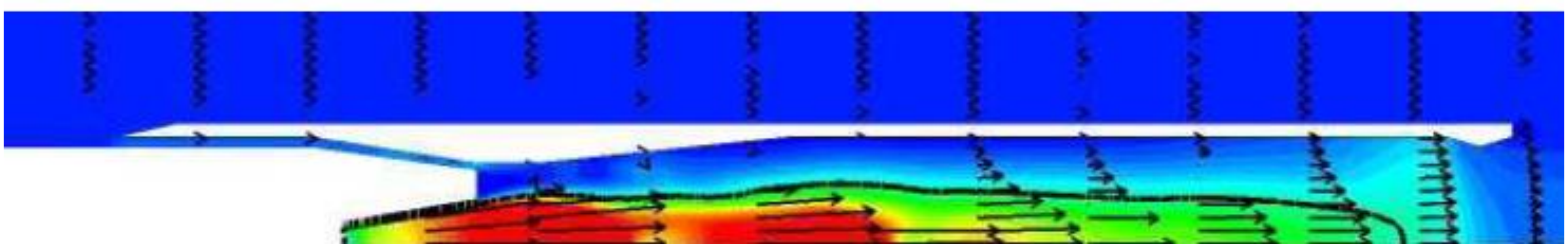


Rocket Engines

- Can just use a rocket
  - Work at all velocities from 0 – 10000+ m/s
  - However, carry all oxidiser and reaction mass, not very efficient
- Can augment the performance by ducting the flow, i.e. entraining atmospheric flows around the engine.
- Think of it a bit like a bypass turbofan, but with a rocket. Gives performance similar to turbojet/ramjet, but can fly at all speeds

JAXA CAMUI


Air Stream
Rocket Exhaust
Secondary Fuel
(M < 1)
Propellant
Sonic Point



LACE (also rocket based)

- Stands for Liquid Air Cycle Engines
  - similar ACE (Air Collection Engines)

- Most high speed propulsions systems (particularly Launch vehicles) have lots of liquid hydrogen on tap, which would be better warm
  - idea is use the cold hydrogen to cool the air, and simultaneously warm the hydrogen
  - if you can liquefy the air, then you have rocket fuel.

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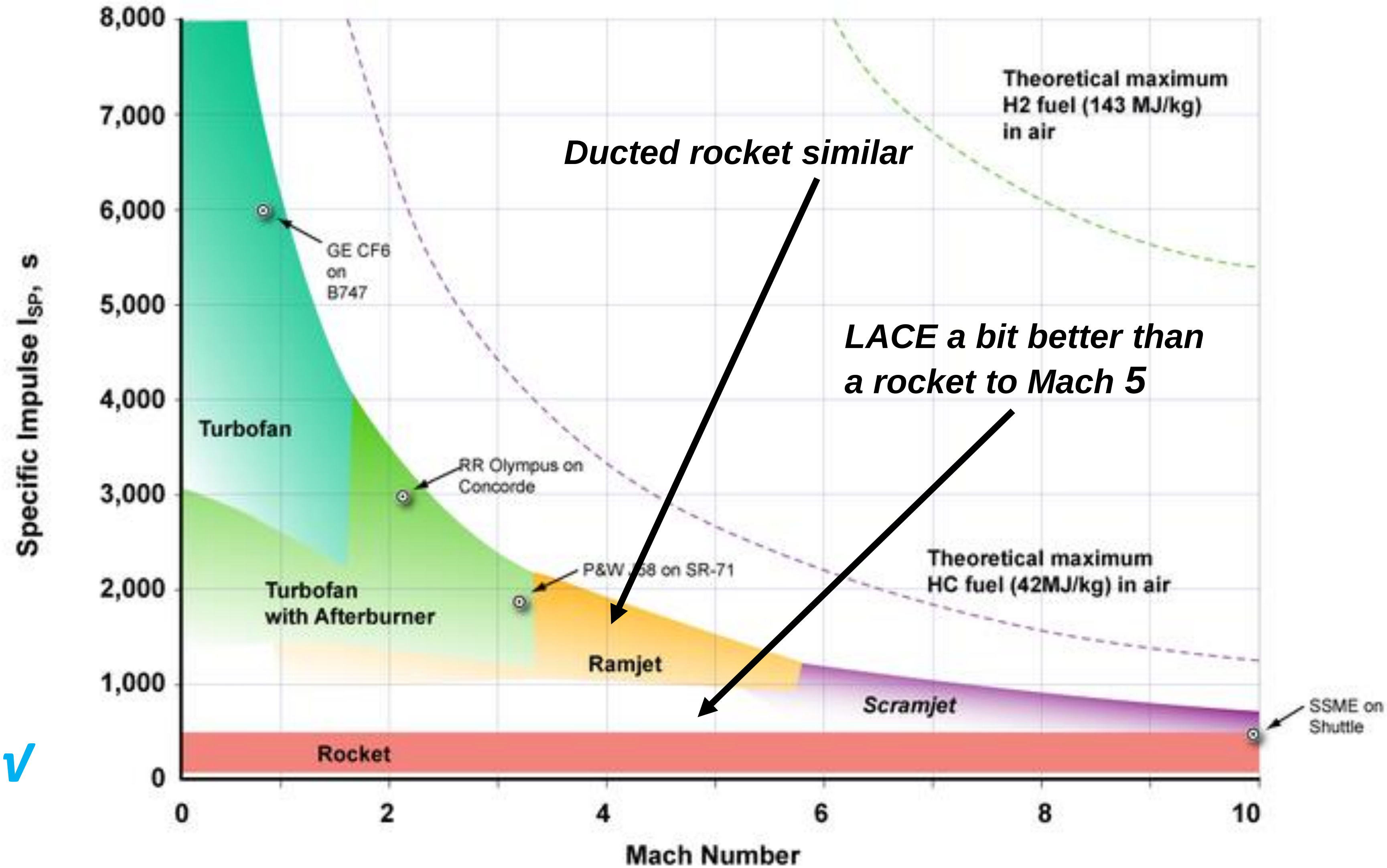
Problems

- Need to cool air down from ~1500K to 77K
- Then liquefy the air
- This requires a big heat sink, and the hydrogen flow needed is more than the engines need – i.e. throwing warm hydrogen overboard
- Also have the problem of heat exchanger weight and design
- and ice formation
- and hydrogen embitterment, and, and…

Propulsion Performance



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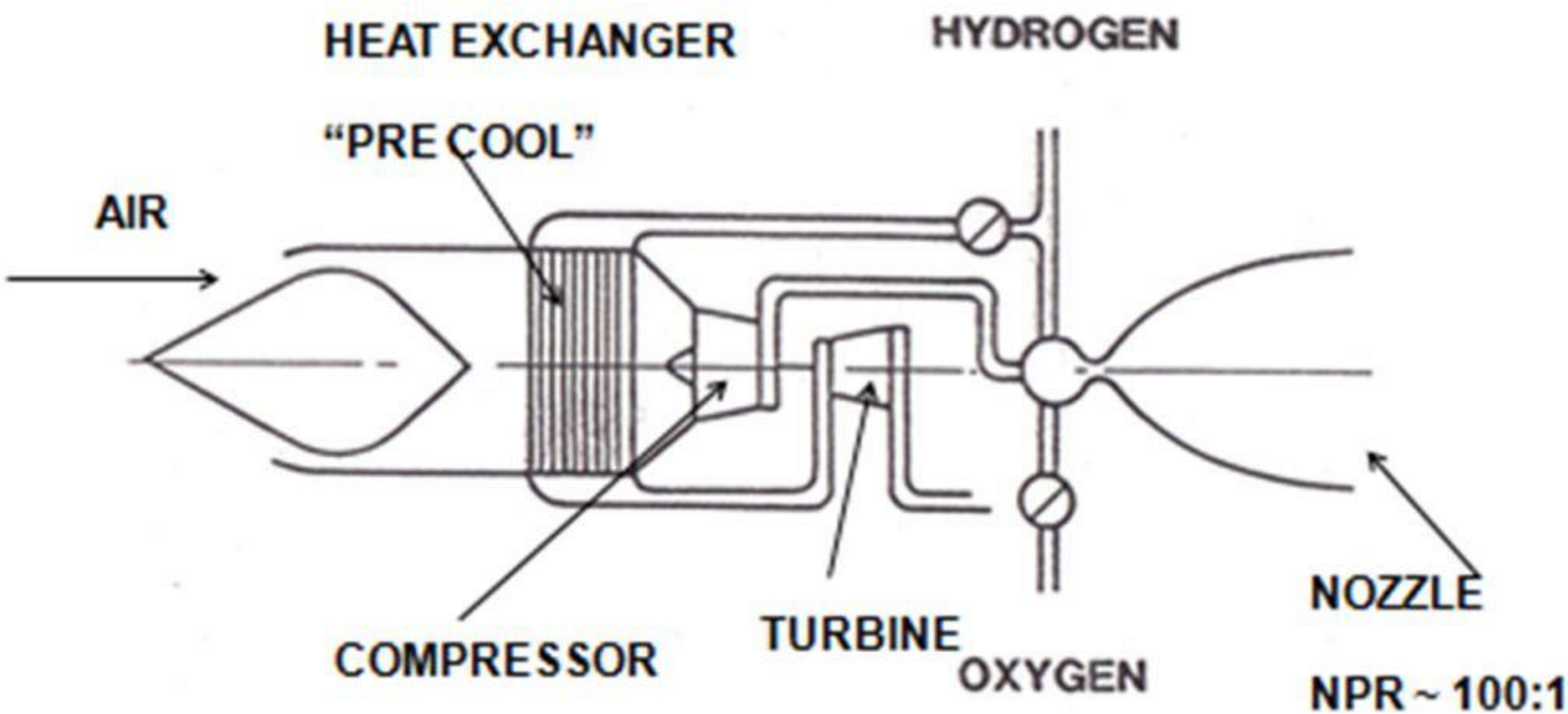
Specific Impulse = 1/ (SFC x g_o) Example GE CF6 SFC_{cruise} = 0.06 kg/hr/N SI = 3600 / (9.81 x 0.06) = 6000 seconds

Combined Cycle engines

- Basically any dual mode engine
- Generally mission specific
  - Particularly Space Transport, either SSTO or TSTO
  - Cruise vehicles which use extra engine for acceleration to SCRamjet speeds
- Former generally aim to compromise between high SFC, and low mass of components
- Latter defined by cruise engine requirements

Air Breathing Rocket



HOTOL

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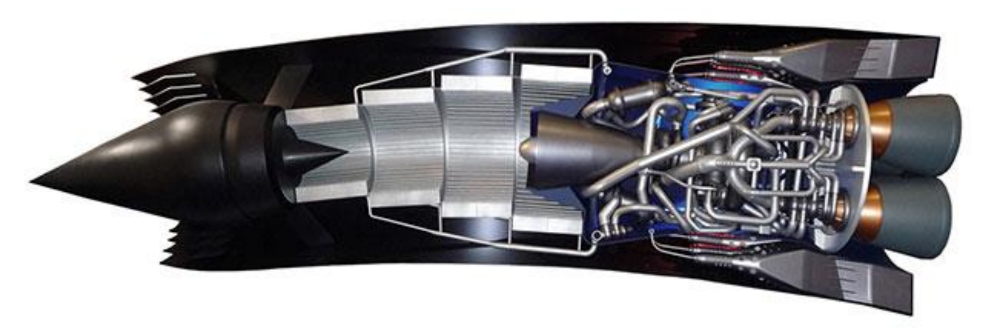
Reaction Engines - SABRE

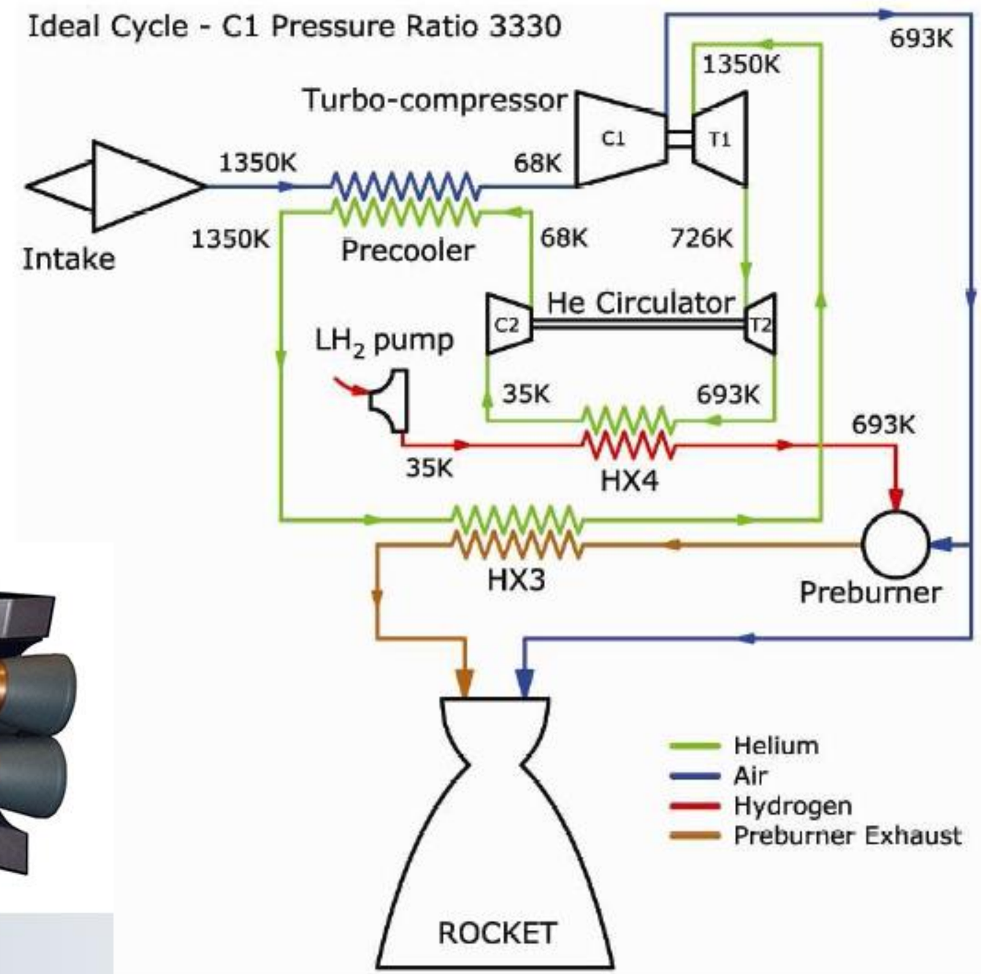
- Synergetic Air Breathing Rocket Engine
- Similar to LACE, except doesn't liquefy the air, just uses it to feed a turbojet
- Still needs very lightweight heat exchanger to keep air temperature down before high compression into rocket engine chamber
- Minimises extra components and weight
- Most of the work still done by the rocket (air breathing stops at Mach 5, for various reasons but partly to keep temperatures down)

Reaction Engines SABRE

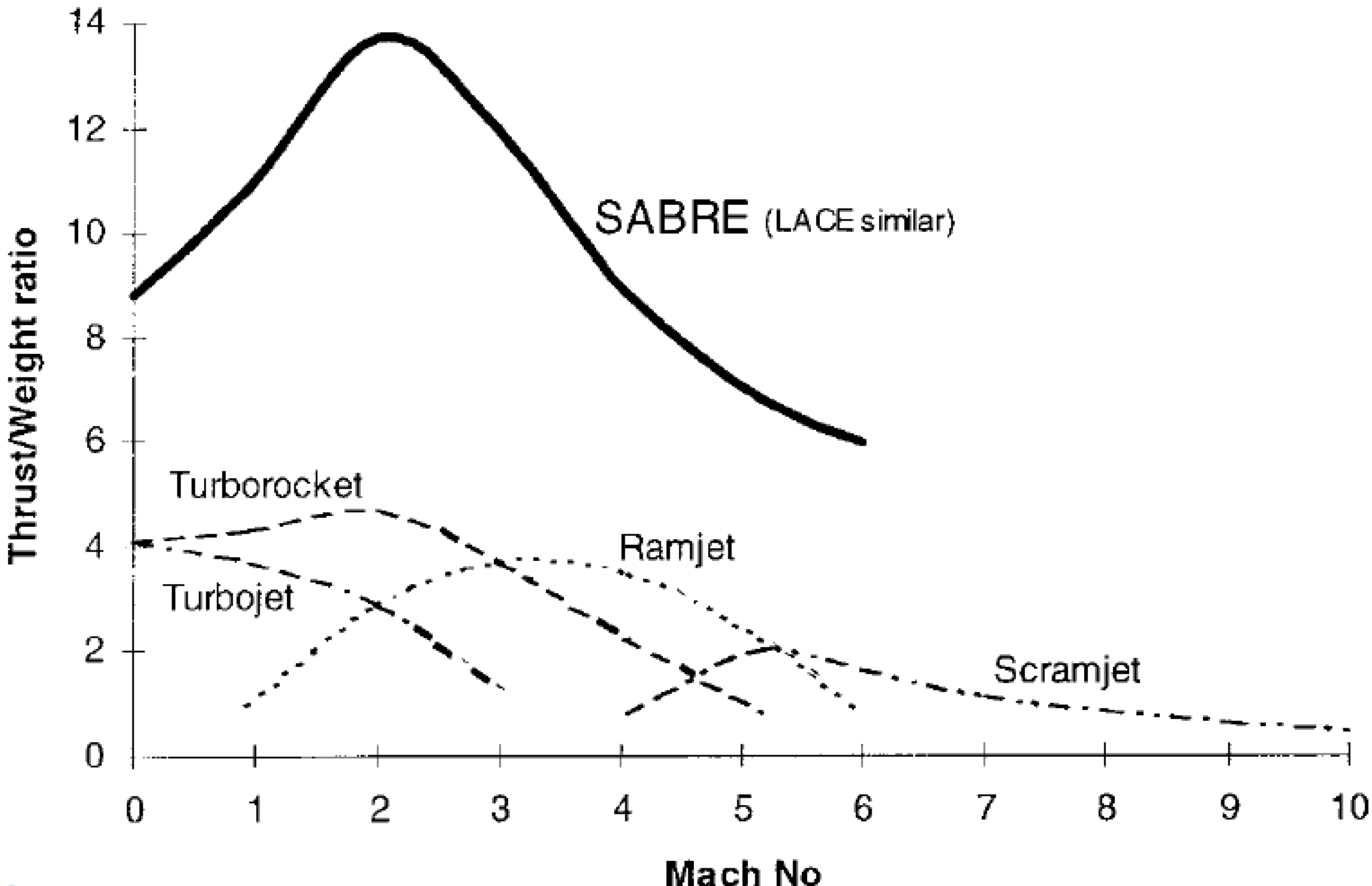
Skylon



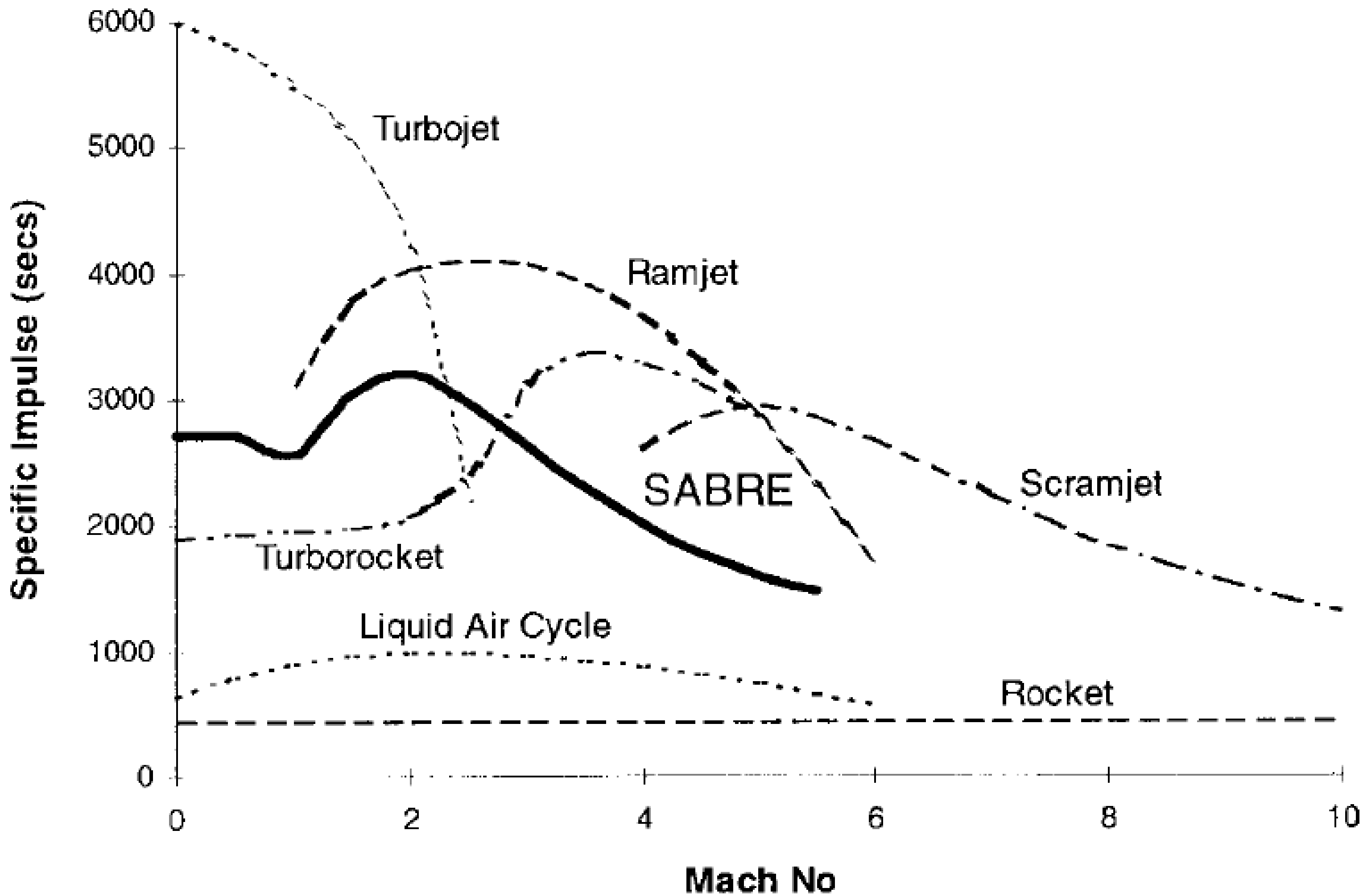
Model of the Sabre Engine



Comparison of T/W



Comparison of Performance



JAXA example, rocket based CC

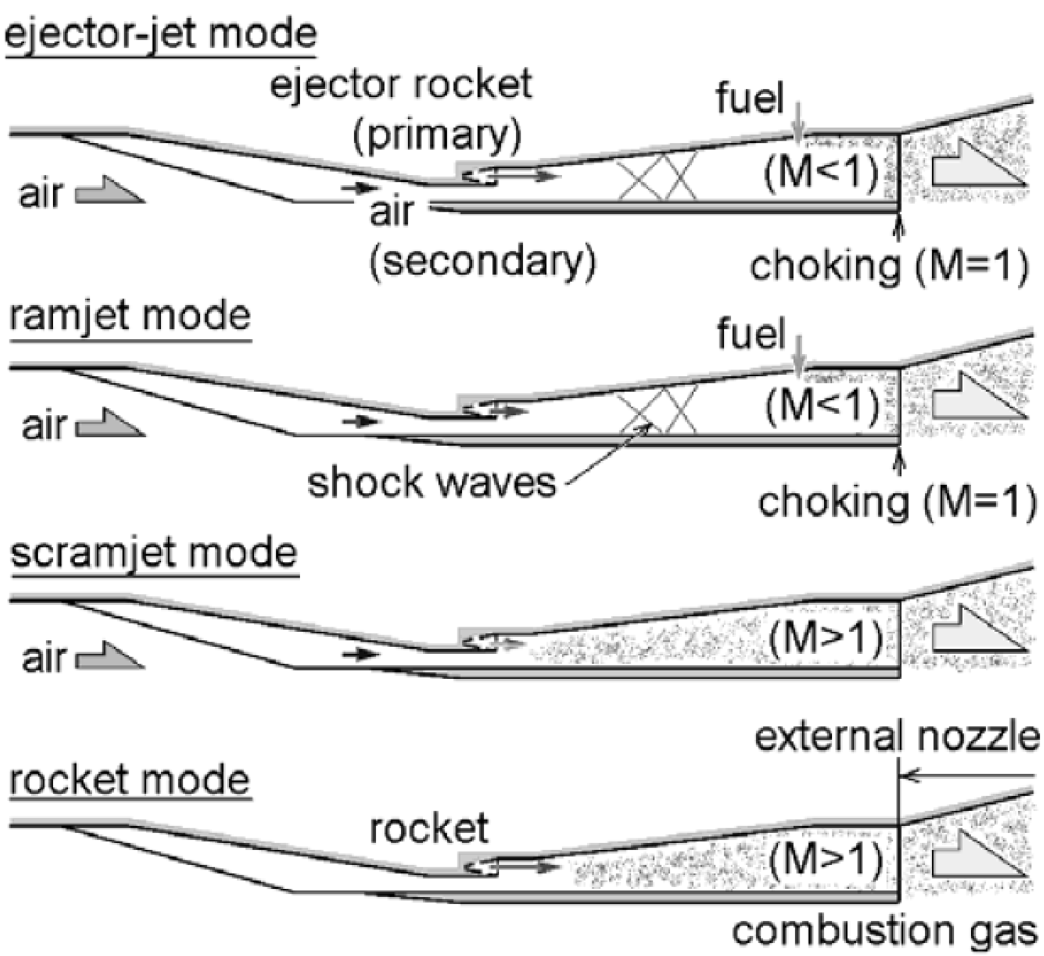


Figure 2. Conceptual Operating modes of RBCC engine.

Take off to modest supersonic

M~1 to M~5/6

M~5/6 to M~12?

M~12 to space

U.S. concept for Cruise Vehicle: Turbine Based

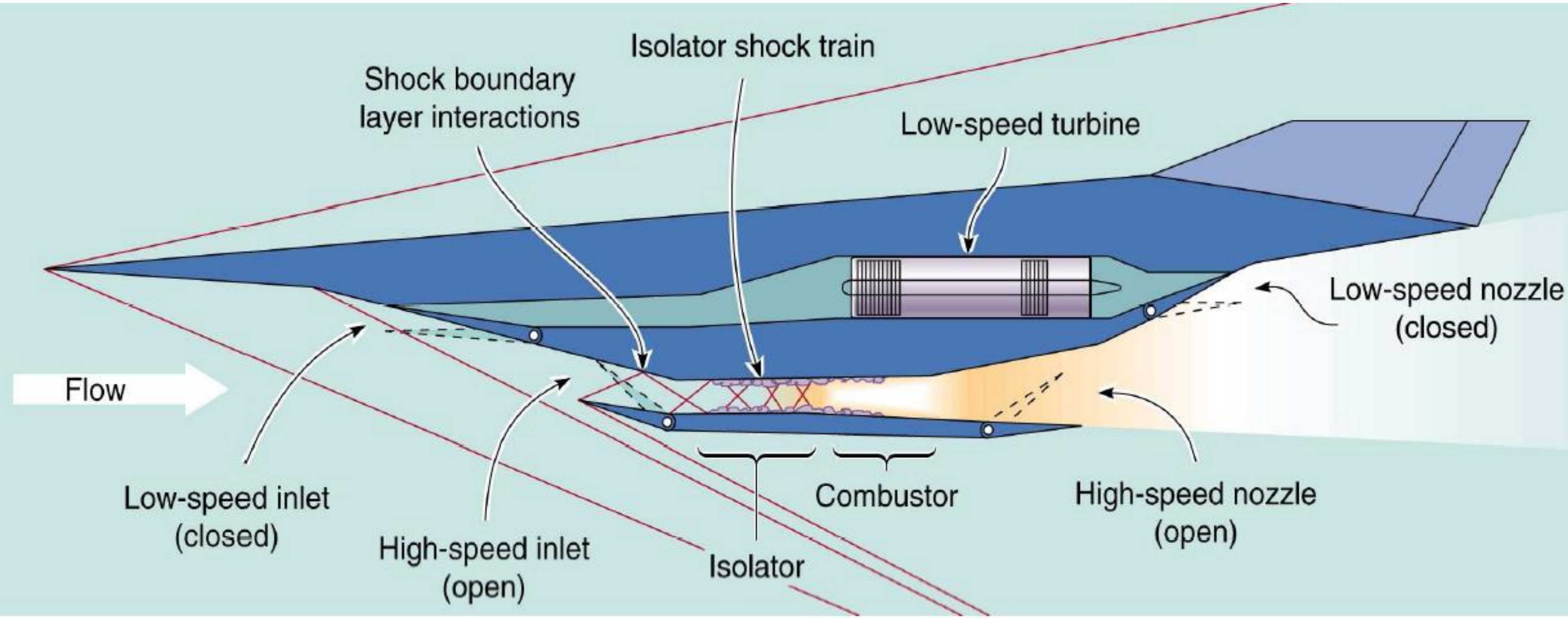
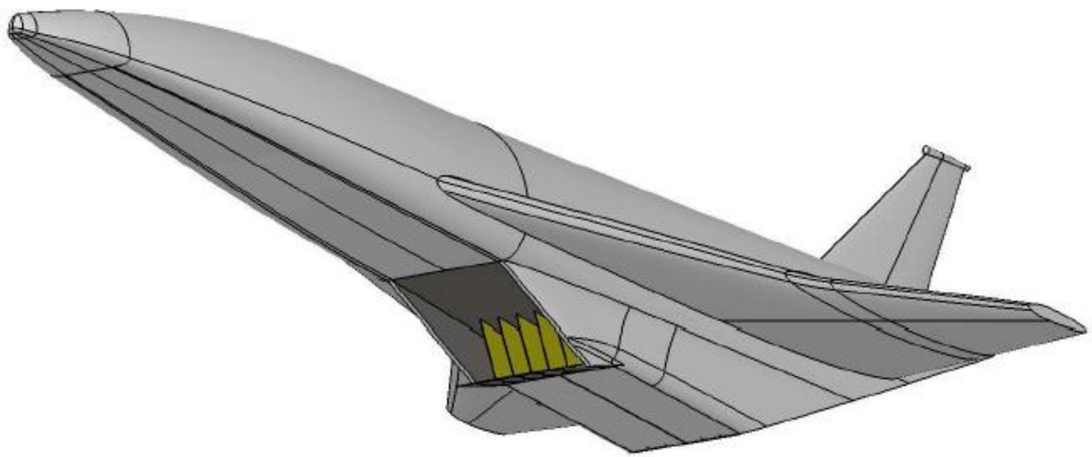


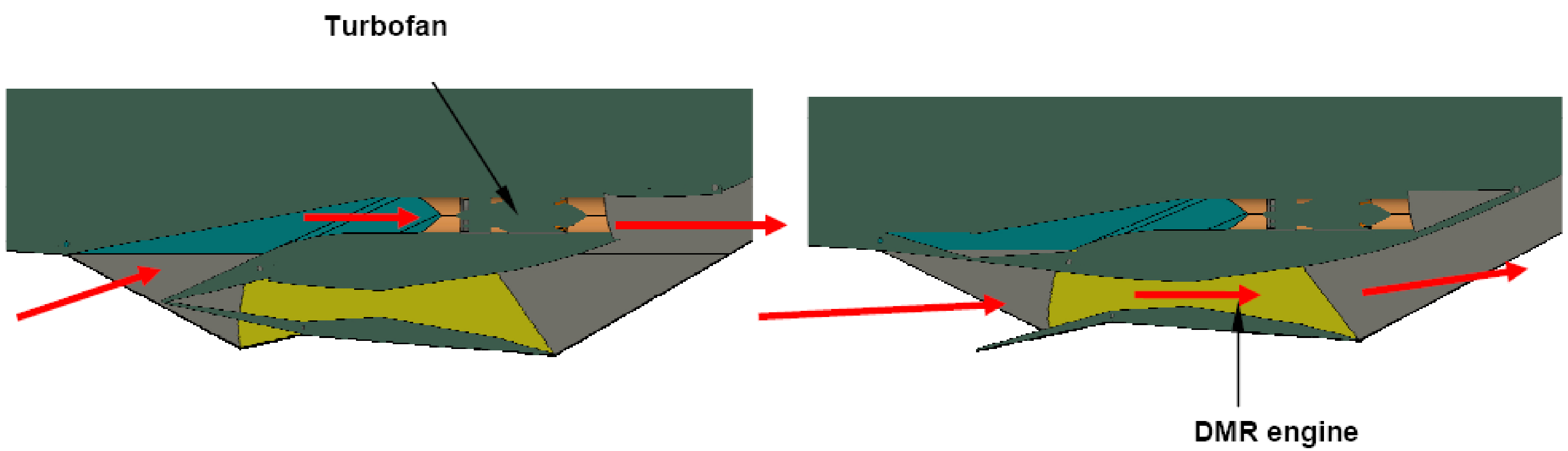
Figure 1: "Over and under" TBCC concept.

Basic design dominated by high speed engine. May be an issue in terms of engine speed range overlap

E.U. concepts: TBCC with Ramjet



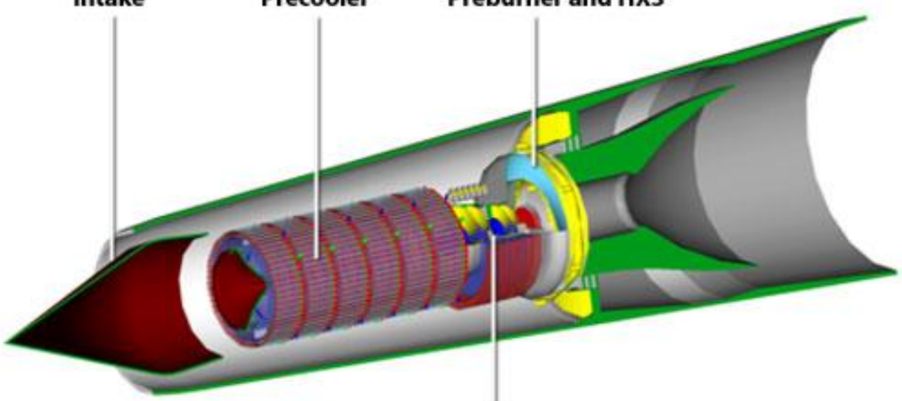
From LAPCAT 2 programme, uses pre-coolers on turbofans

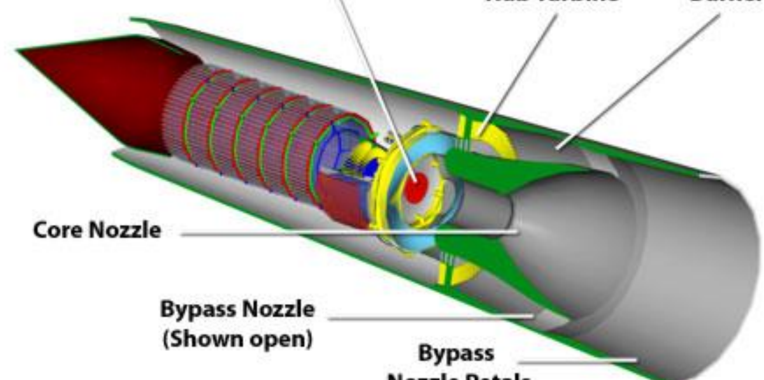


And U.K. (also LAPCAT)

REL again, engine sort of similar to SABRE, but more complex (basically a pre cooled TBCC).

Mach 5 vehicle, Brussels to Sydney in 5 hours. Note engine size





Key Lessons from Lecture 9

- Overall, high speed propulsion is still not a settled issue

- Different groups advocate different engines
  - Scramjet currently king, but ducted rockets looking more common internationally
  - In the U.K. pre-cooled engine technology looking very promising

- In most cases, the size of the engine dictates that the vehicle & propulsion system need to be considered together.

- Cruise a *very* different problem to acceleration!

Lecture 10

Axial Compressors

Objective: A "simple" analysis of an Axial Compressor