High Speed Propulsion

KTH Rocket Course 2008

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AEROSPACE PROPULSION

FROM INSECTS TO SPACEFLIGHT

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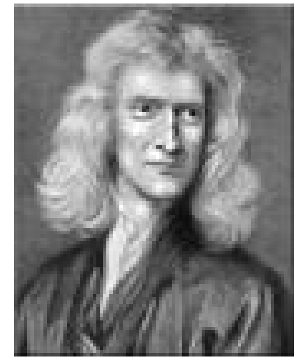
COMPUTERIZED EDUCATIONAL PLATFORM
HEAT AND POWER TECHNOLOGY
Lecture Series Volume No.3

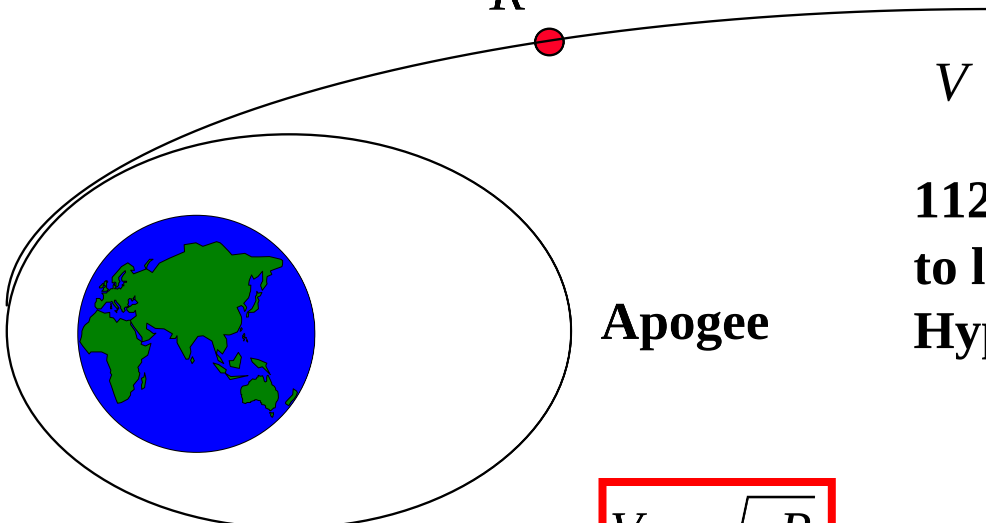
STOCKHOLM 2006

What velocities?



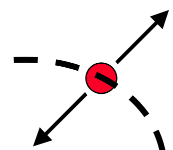
Isaac Newton:
Law of gravity 1687

$$g = g_0 \frac{R_0^2}{R^2}$$



$$V = \sqrt{2gR}$$

11200 m/s
to leave earth.
Hyperbolic velocity.



$$V_0 = \sqrt{gR}$$

Circular velocity 7900 m/s.
Mach 26.


USA

The spaceplane would give more flexible space access. (Eugen Sänger and Irene Bredt 1944).

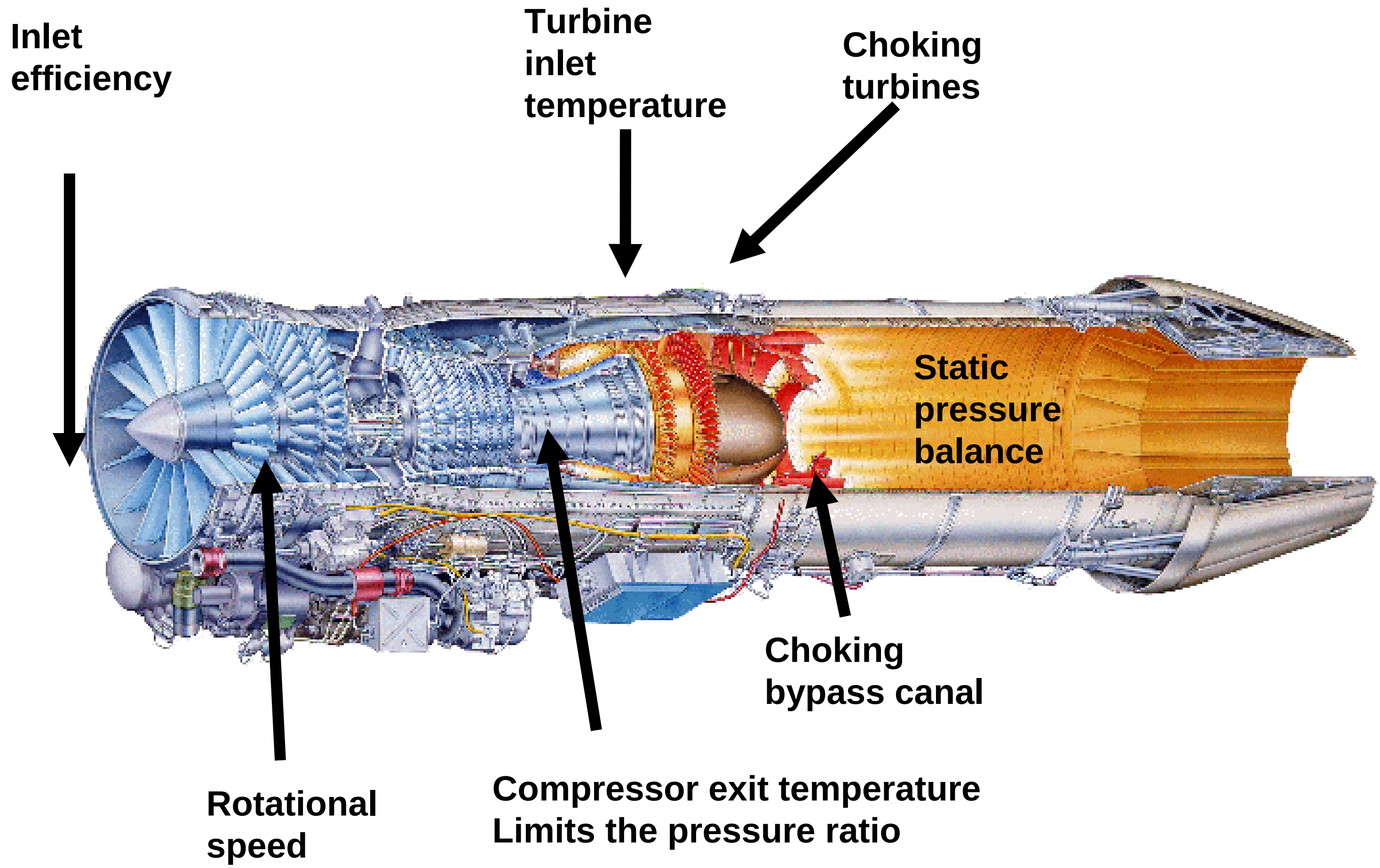
Wings and atmospheric oxygene

The SR71- the highest speed aircraft ever (Mach 3.2)

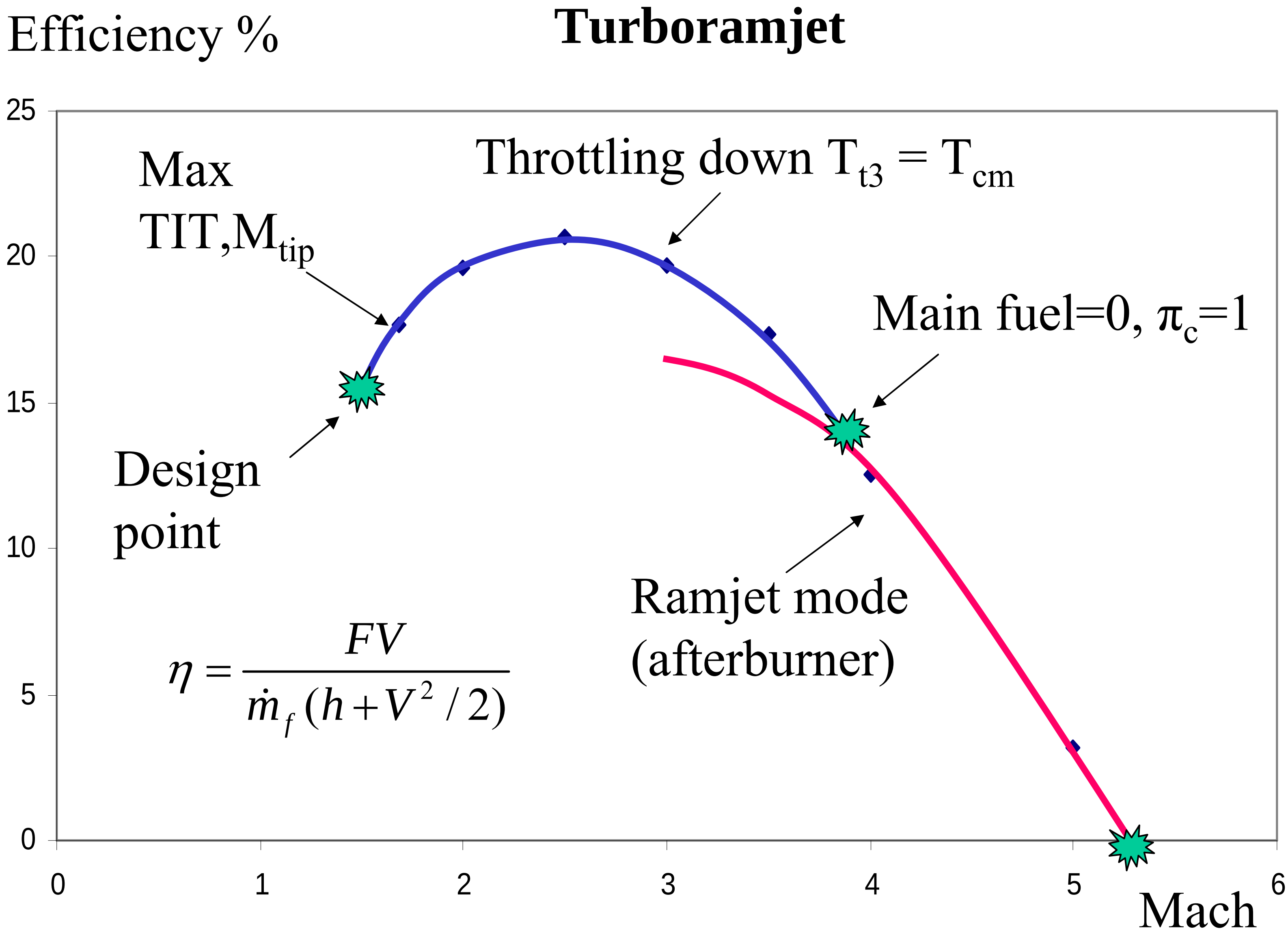
The limits of the turbojet engine $F = \dot{m}(V_j - V)$

The turbine inlet temperature limits the thrust.

$$\frac{F}{\dot{m}a_0} = \sqrt{\frac{2}{\gamma - 1}}\left(\sqrt{T_{t4}/T_0} - 1\right)$$

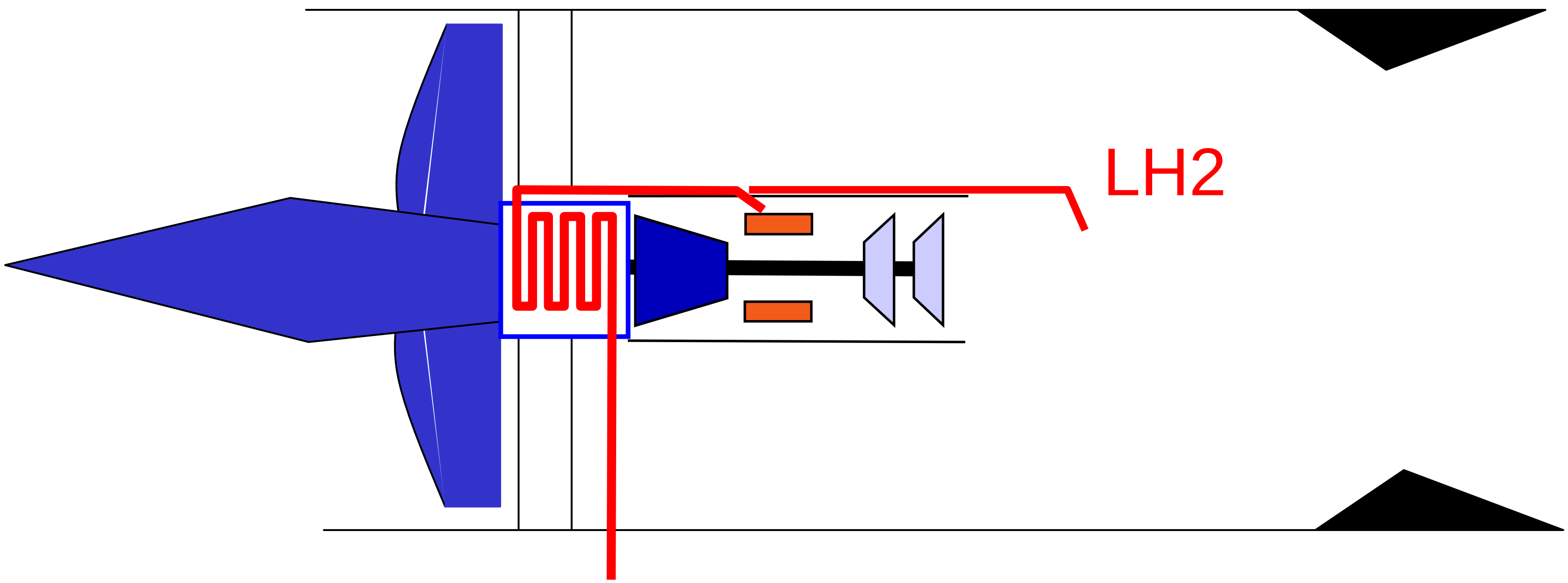


Turboramjet

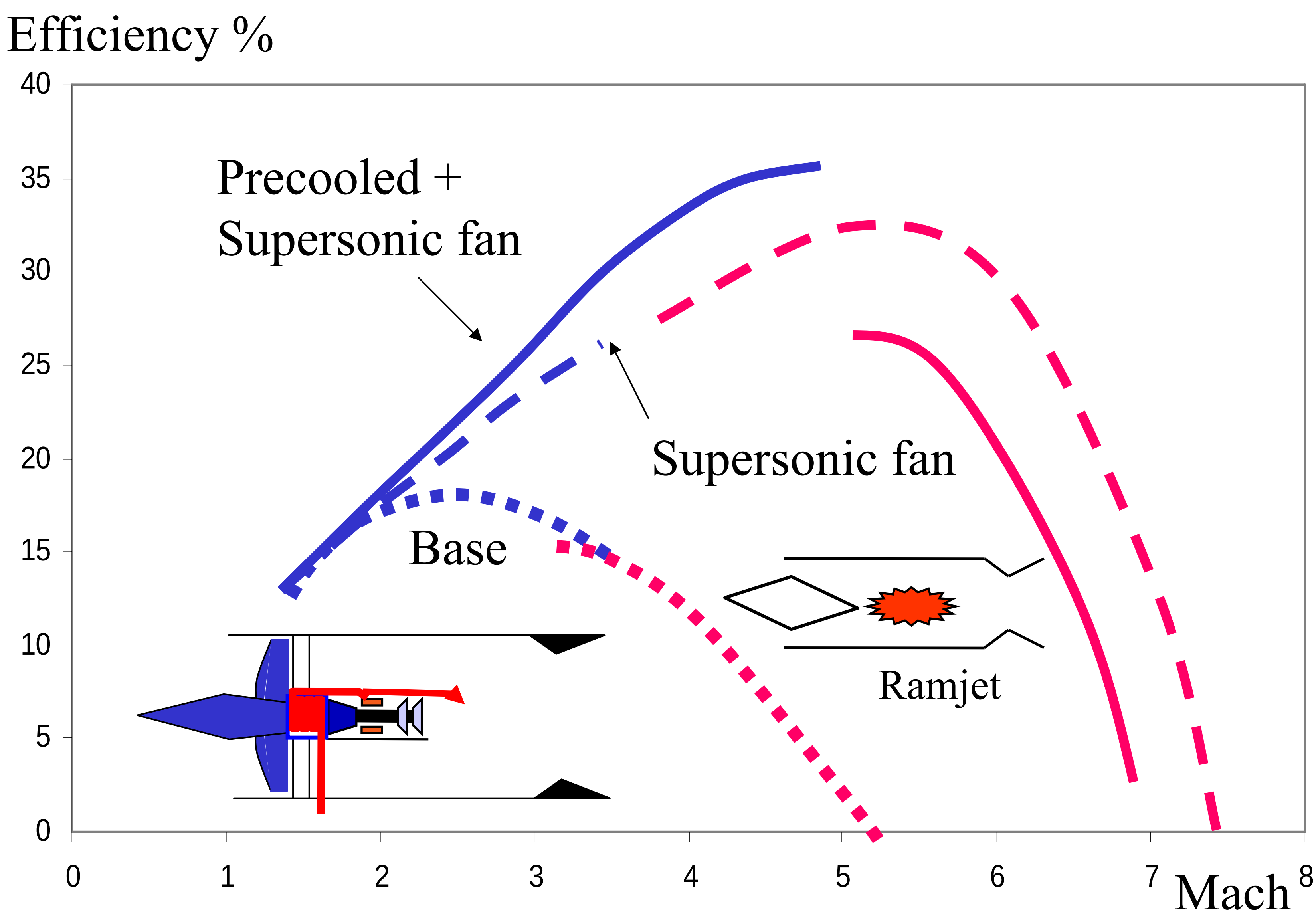


Close down the turbomachine at high speed

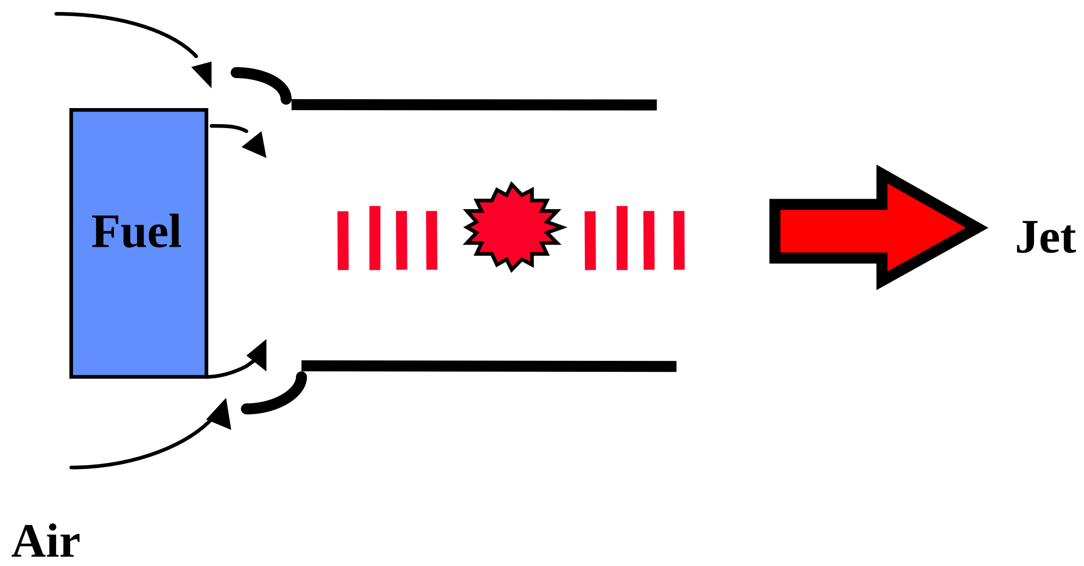
Supersonic fan for less inlet losses



Precooling for extended turbojet operation

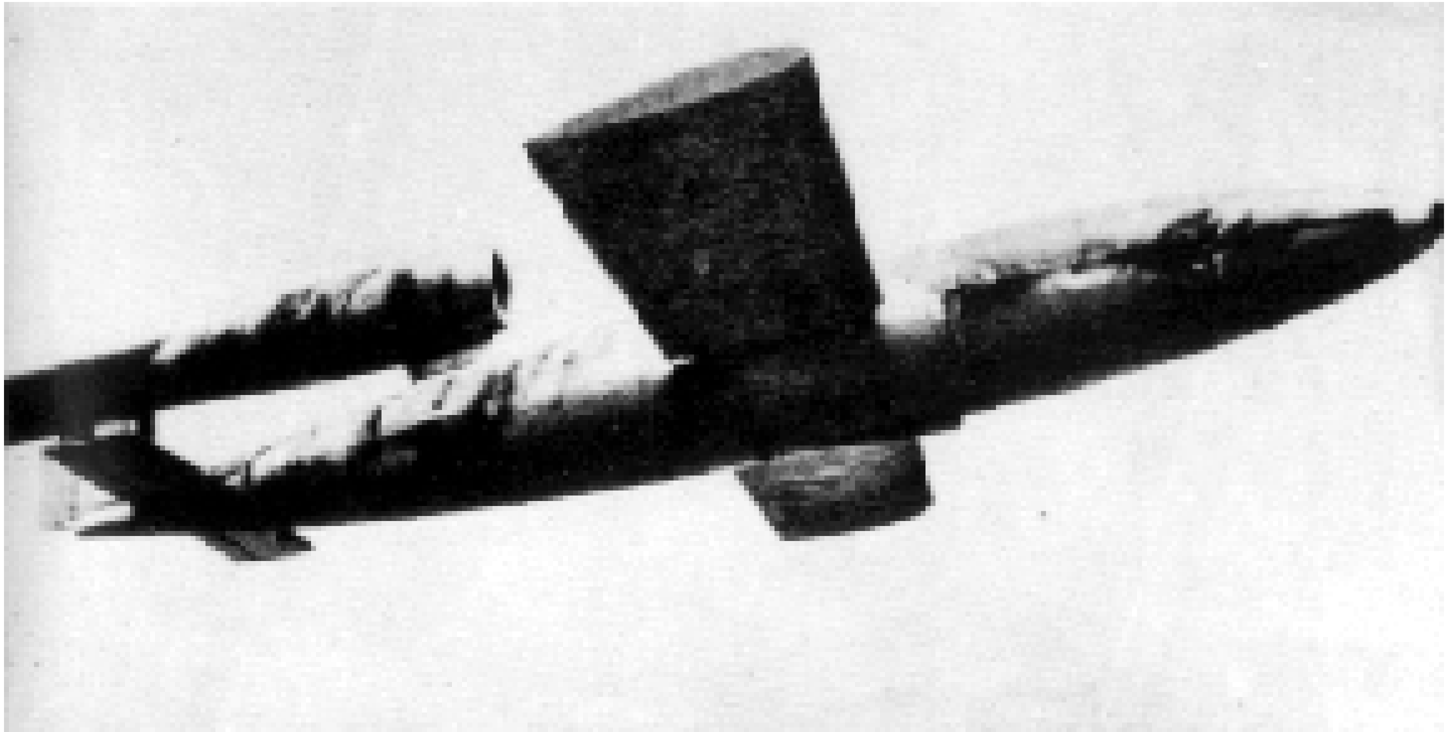


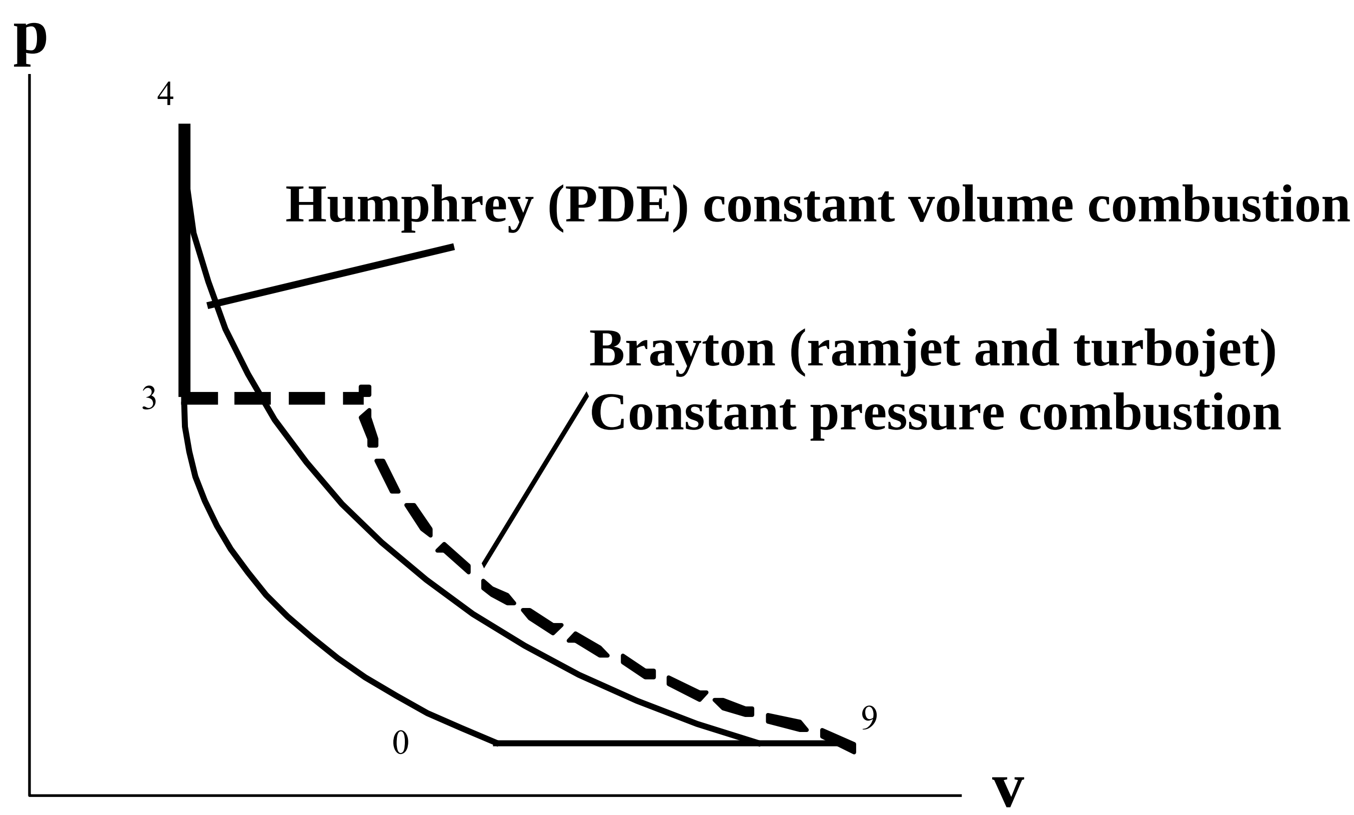
Efficiency %
40
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
Mach
Precooled +
Supersonic fan
Supersonic fan
Base
Ramjet

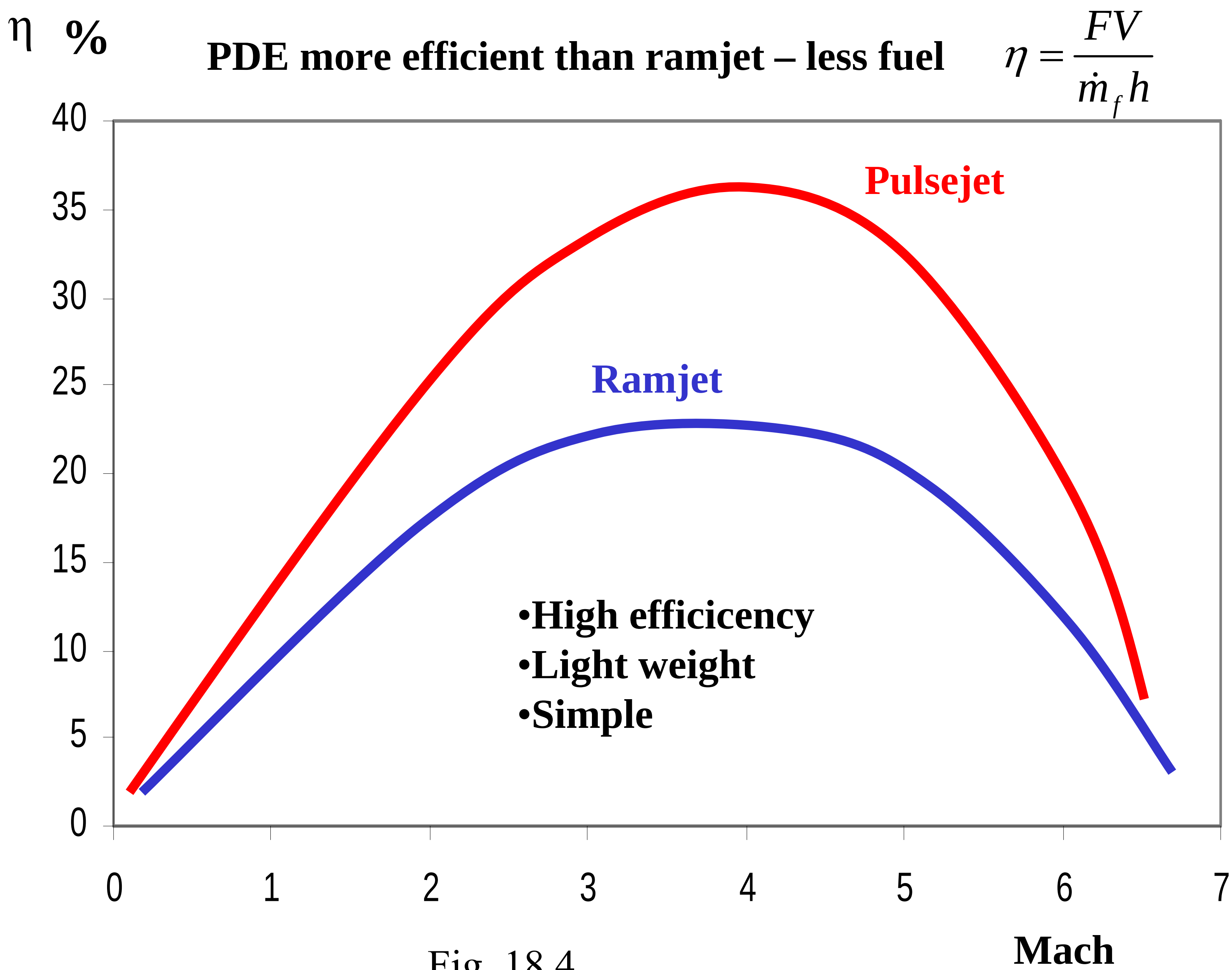


The principle of a Pulse Detonation Engine (PDE)

V1-German WW1 pulsejet




p
4
Humphrey (PDE) constant volume combustion
Brayton (ramjet and turbojet)
Constant pressure combustion
3
0
9
v

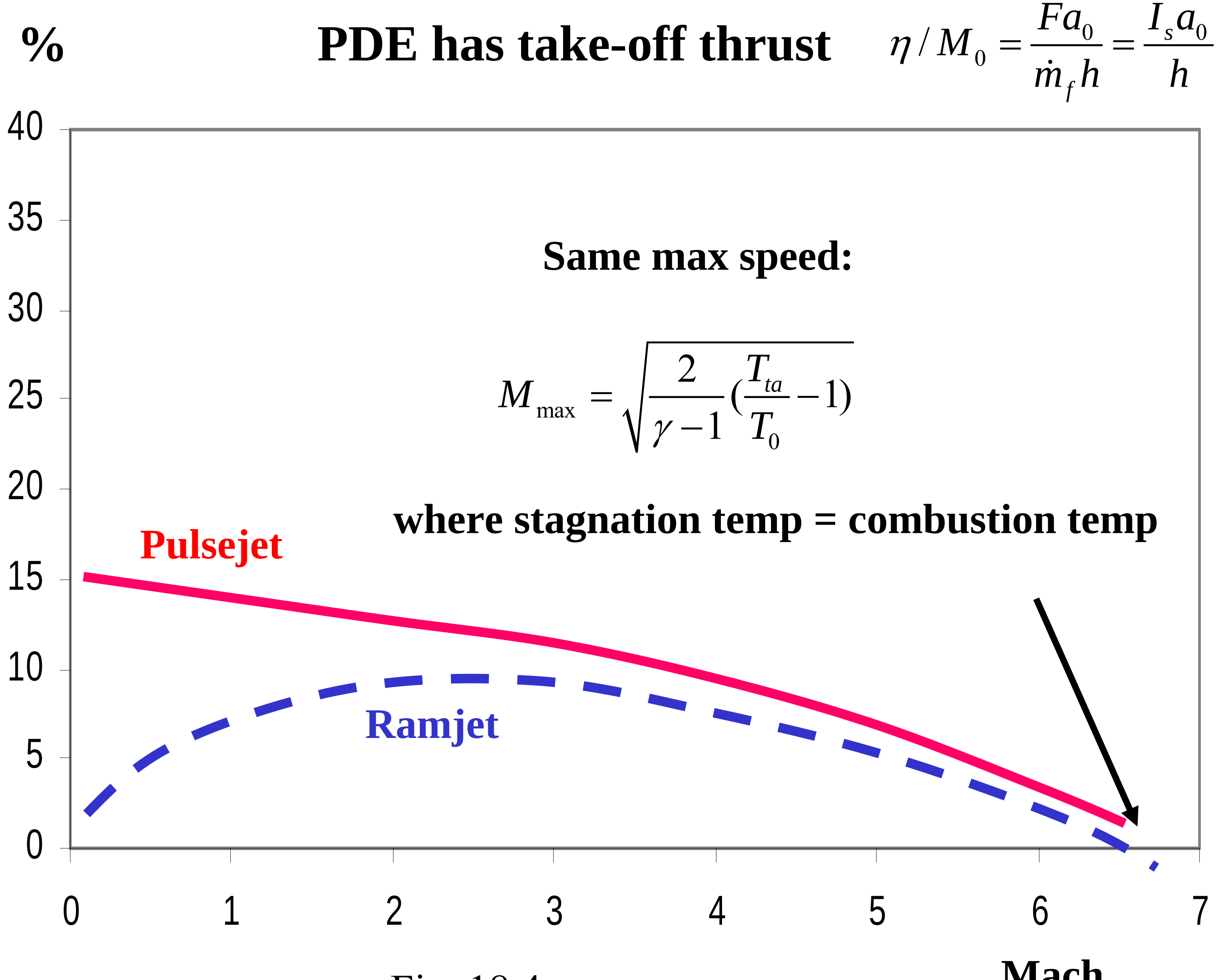


η %
PDE more efficient than ramjet – less fuel
$\eta = \frac{FV}{\dot{m}_f h}$
40
35
30
25
20
15
10
5
0
Pulsejet
Ramjet
•High efficicency
•Light weight
•Simple
0
1
2
3
4
5
6
7
Mach

Fig. 18.4

PDE has take-off thrust

$$\eta / M_0 = \frac{Fa_0}{\dot{m}_f h} = \frac{I_s a_0}{h}$$



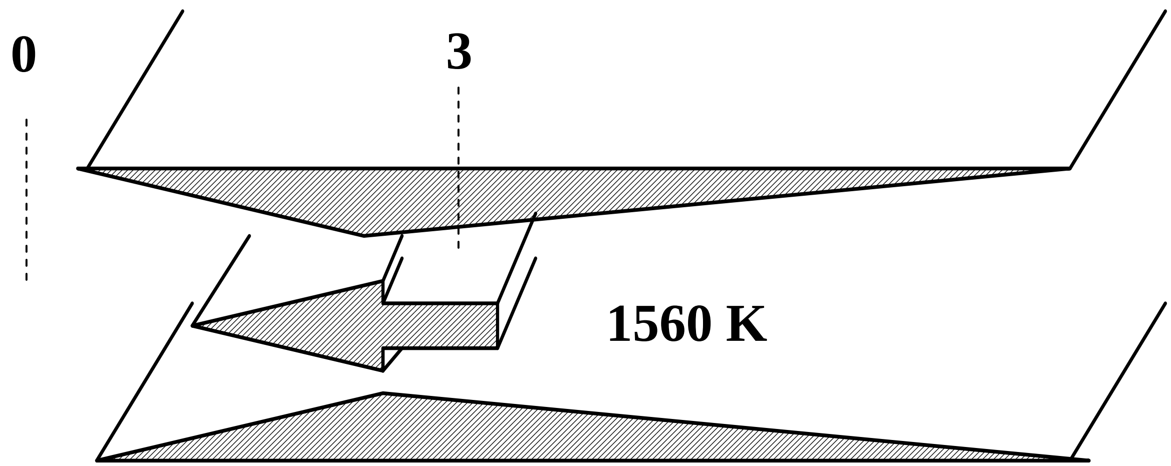
$$M_{\max} = \sqrt{\frac{2}{\gamma - 1}\left(\frac{T_{ta}}{T_0} - 1\right)}$$

Fig. 18.4

The idea of the scramjet

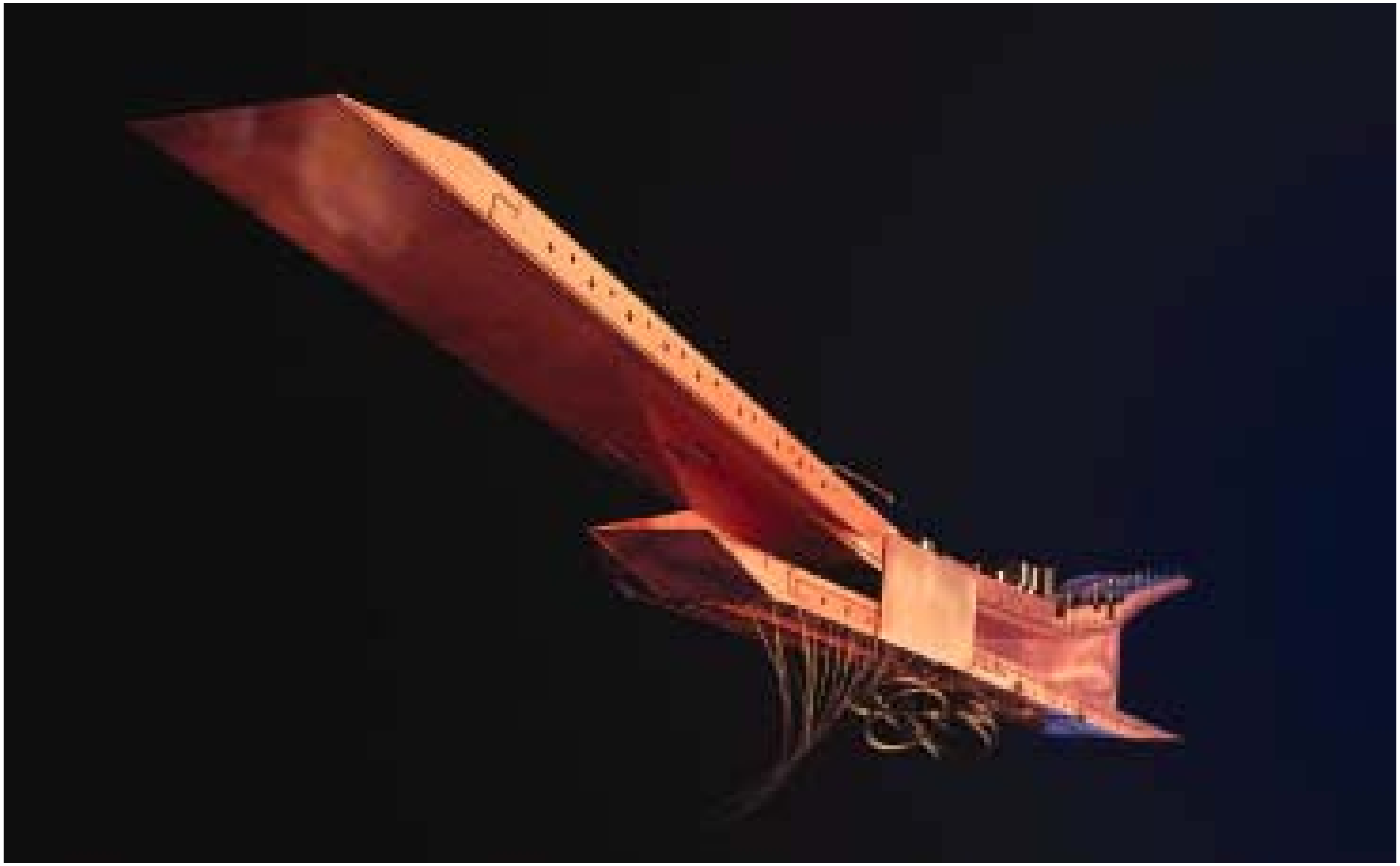
Increase M_3 to keep T_3 low to prevent dissociation (1560 K)

$$T_t = T_0\left(1+\frac{\gamma-1}{2}M_0^2\right) = T_3\left(1+\frac{\gamma-1}{2}M_3^2\right)$$

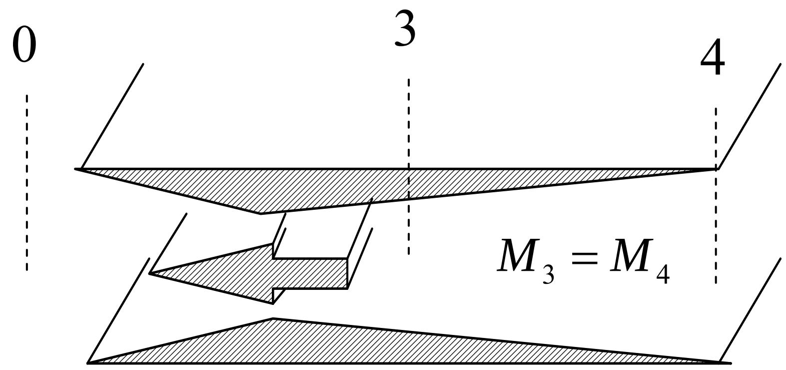


Scramjet M_3 >1 if $M_0 > \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{\gamma+1}{2}\right)\frac{T_3}{T_0}-1\right]}$ **=6**

US scramjet test hardware



The jet speed of a scramjet



Constant Mach in combustor

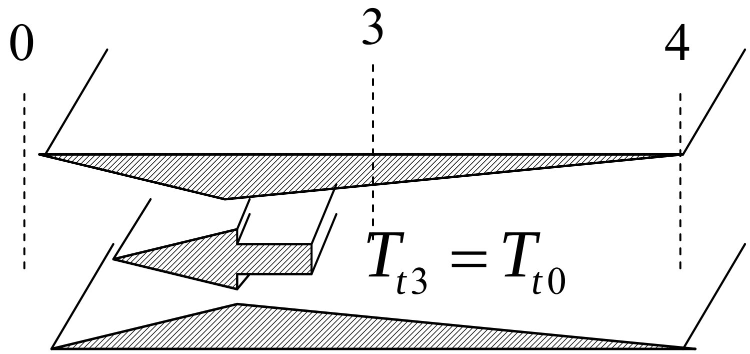
Kinetic efficiencies

$$V_3 = V_0 \sqrt{\eta_{ki}}$$

$$\frac{V_4}{V_3} = \frac{M_4 a_4}{M_3 a_3} = \sqrt{\frac{T_4}{T_3}} = \sqrt{\frac{T_{t4}}{T_{t3}}}$$

$$V_j = V_0 \sqrt{\frac{T_{t4}}{T_{t3}} \eta_{ki} \eta_{kc} \eta_{kn}}$$

The scramjet performance



Jet speed:

$$V_j = V_0 \sqrt{\frac{T_{t4}}{T_{t3}} \eta_{ki} \eta_{kc} \eta_{kn}}$$

Note max stoich f=0.0291 for hydrogen

Heat release: $$(1+f)C_p T_{t4} - C_p T_{t3} = \eta_b f h$$

Specific thrust: $$\frac{F}{\dot{m}} = (1+f)V_j - V_0$$

There is a max flight speed of the scramjet at F=0

The maximum Mach number of the scramjet

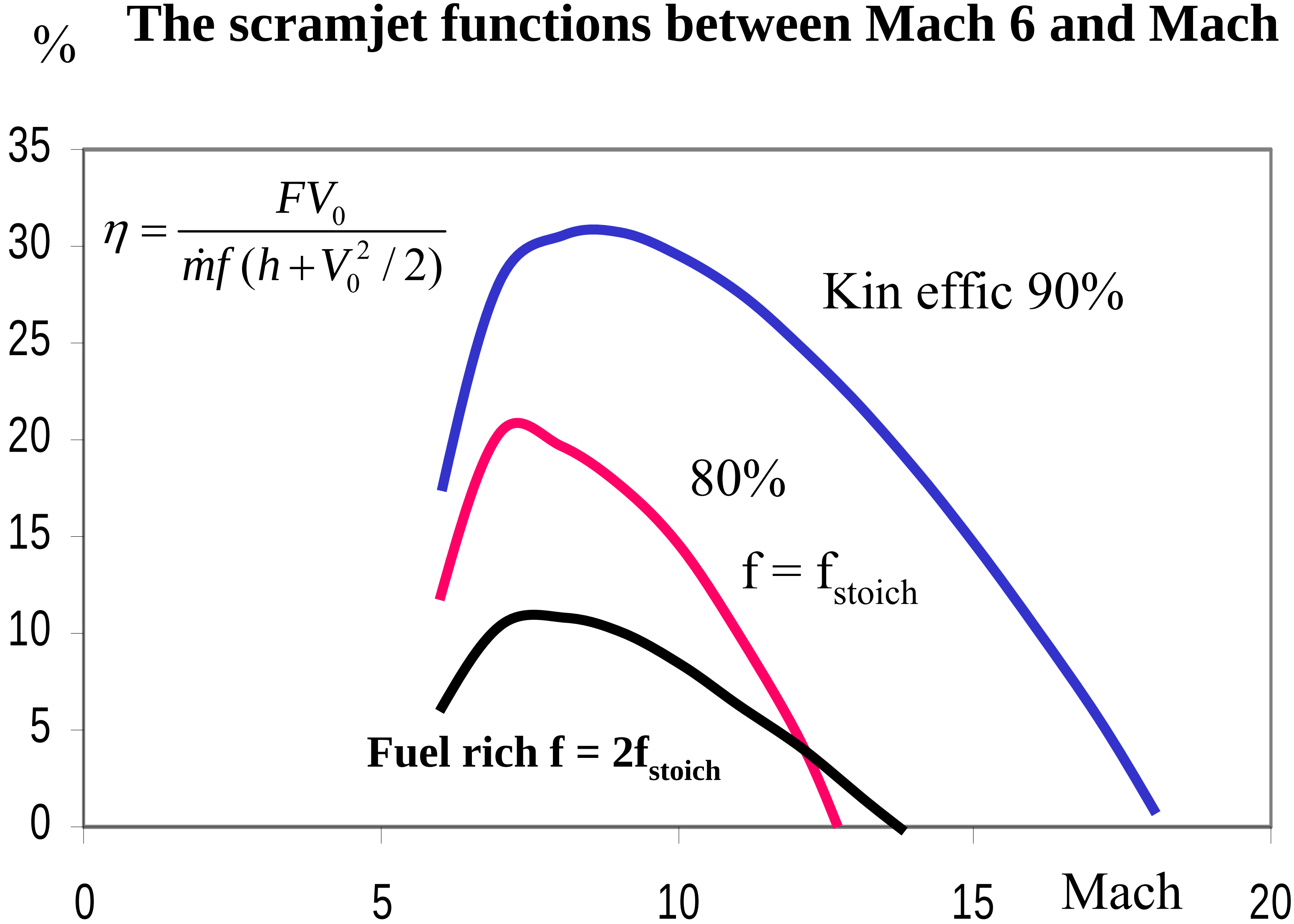
F=0 at:

$$M_{\max} = \sqrt{\frac{2}{\gamma - 1}\left[\frac{\eta_b h f_s}{C_p T_0}\frac{\eta_{\mathrm{ke}}\left(1+f\right)}{1\text{-}\eta_{\mathrm{ke}}\left(1+f\right)} - 1\right]}$$

Kinetic efficiency 65-75% gives max Mach number 10-15.

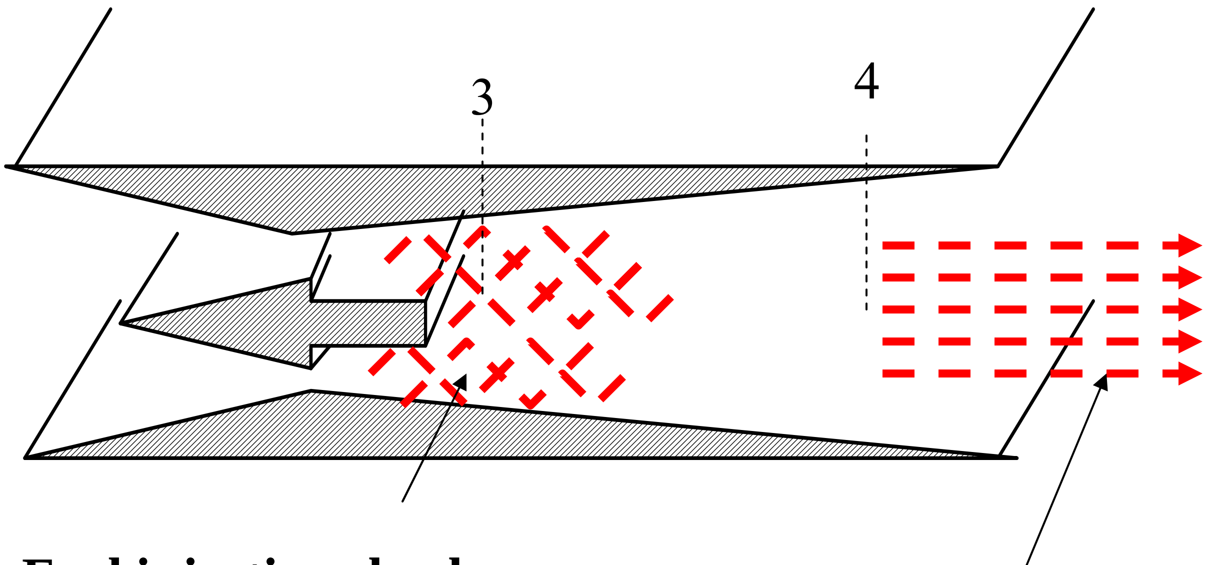
Run fuel rich to reach a higher Mach number:

The scramjet functions between Mach 6 and Mach 15



The efficiency of a Scramjet

Problems with the scramjet



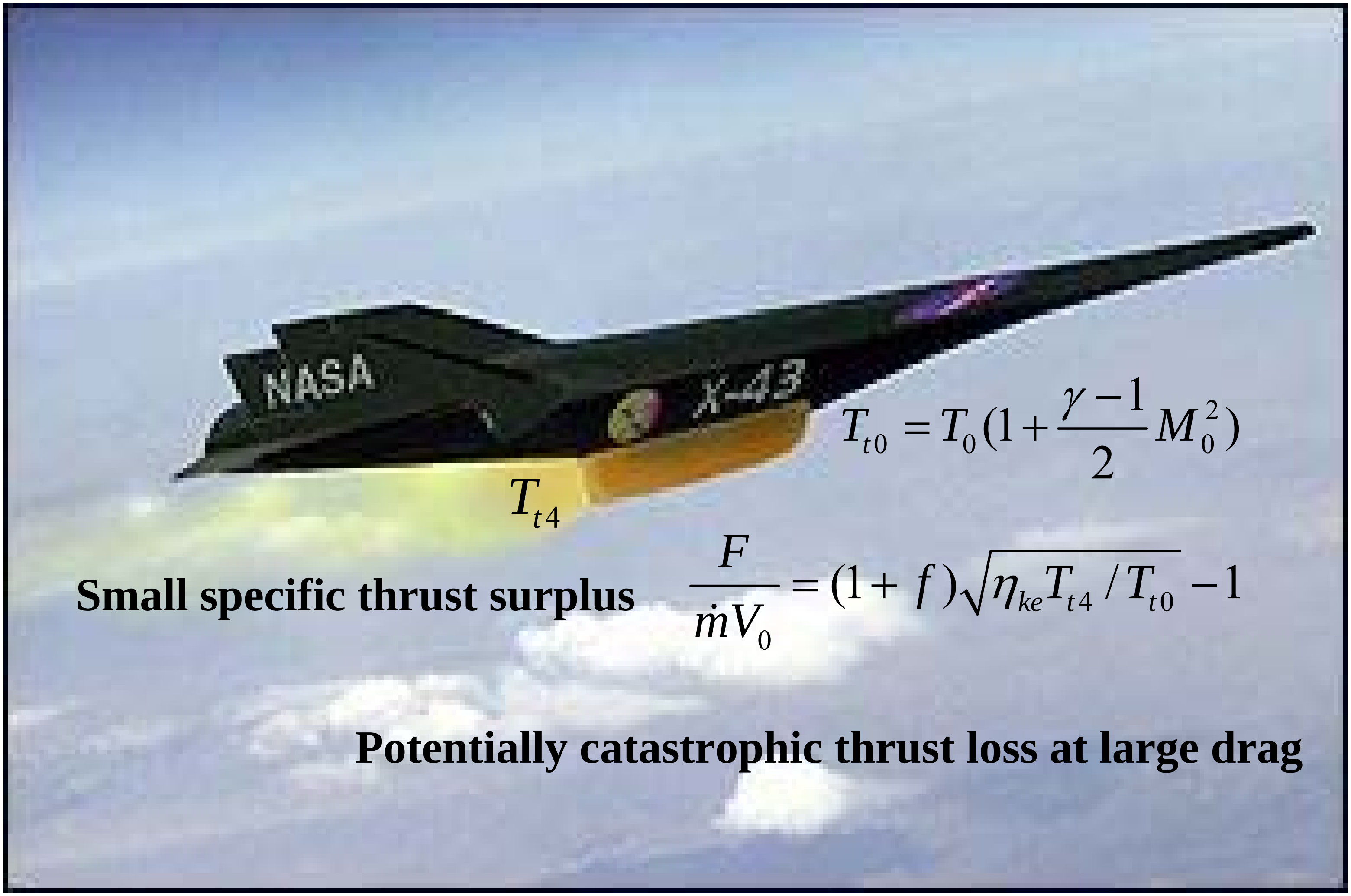
Fuel injection shock waves

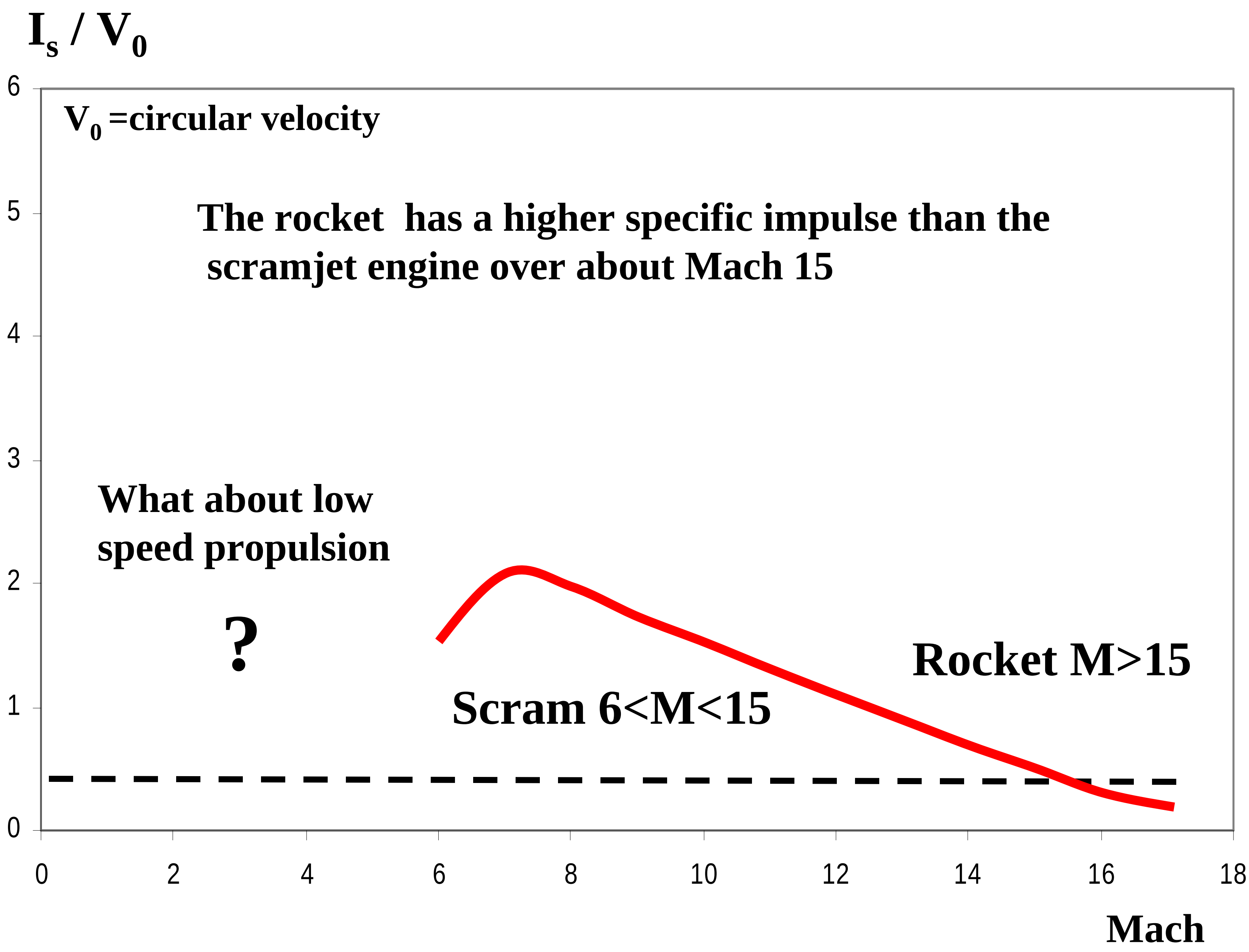
Incomplete combustion

Note: $\frac{M_3}{M_0} \approx \sqrt{\frac{T_0}{T_3}}$ **High combustor Mach numbers**

Very sensitive to kinetic efficiencies $V_j = V_0 \sqrt{\frac{T_{t4}}{T_{t3}} \eta_{ki} \eta_{kc} \eta_{kn}}$

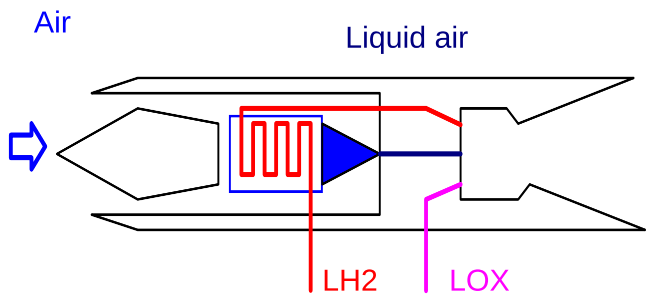
Scramjet powered spaceplane


NASA
X-43
$T_{t0} = T_0 (1 + \frac{\gamma - 1}{2} M_0^2)$
T_{t4}
Small specific thrust surplus
$\frac{F}{\dot{m} V_0} = (1 + f) \sqrt{\eta_{ke} T_{t4} / T_{t0}} - 1$
Potentially catastrophic thrust loss at large drag

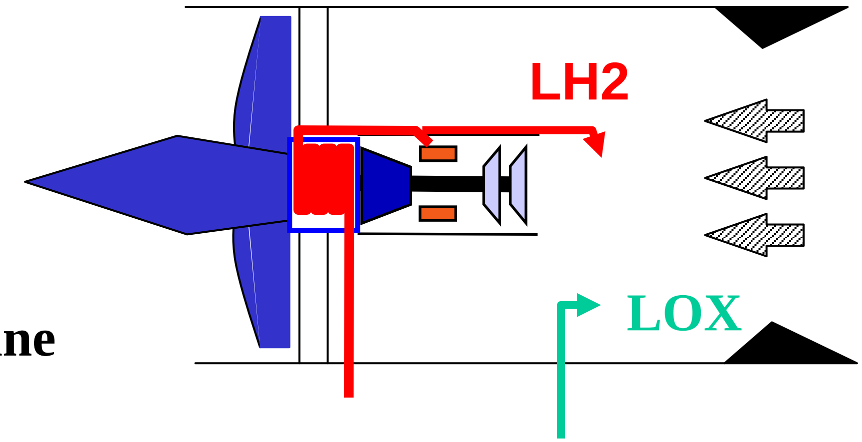


Is / V0
V0 =circular velocity
The rocket has a higher specific impulse than the scramjet engine over about Mach 15
What about low speed propulsion
?
Rocket M>15
Scram 6<M<15
0
1
2
3
4
5
6
0
2
4
6
8
10
12
14
16
18
Mach

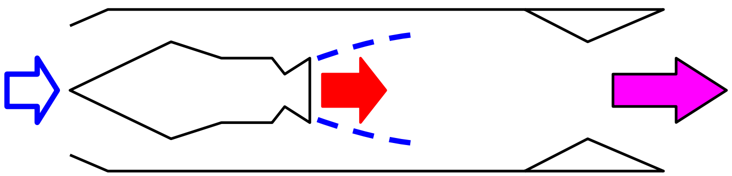
Combined engines



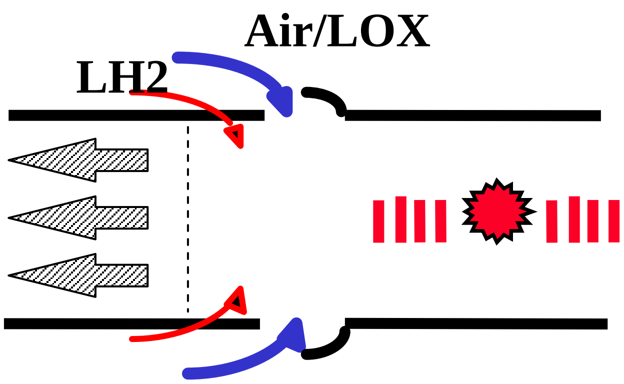
LACE-Liquid Air Combustion Engine



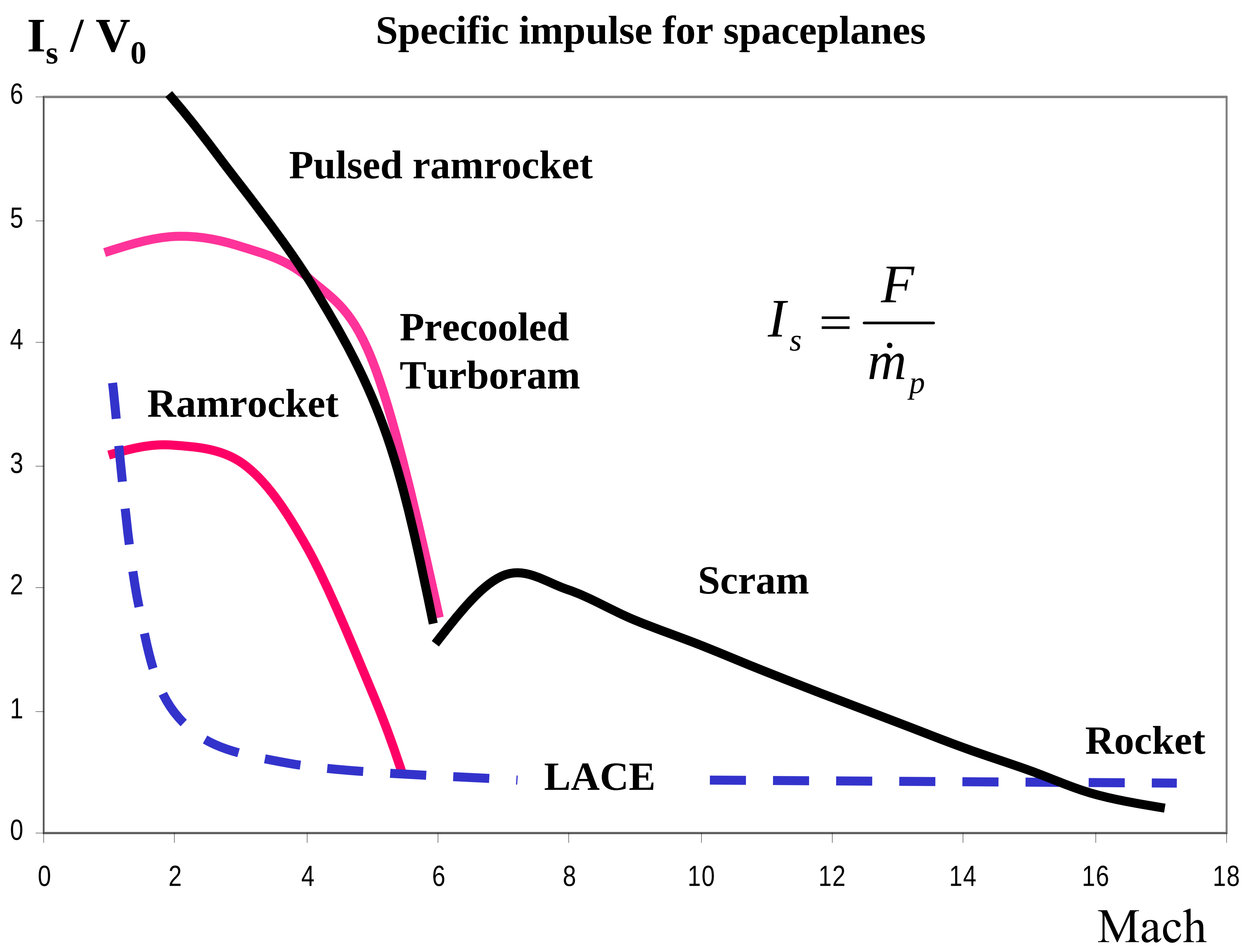
Precooled turboram-rocket



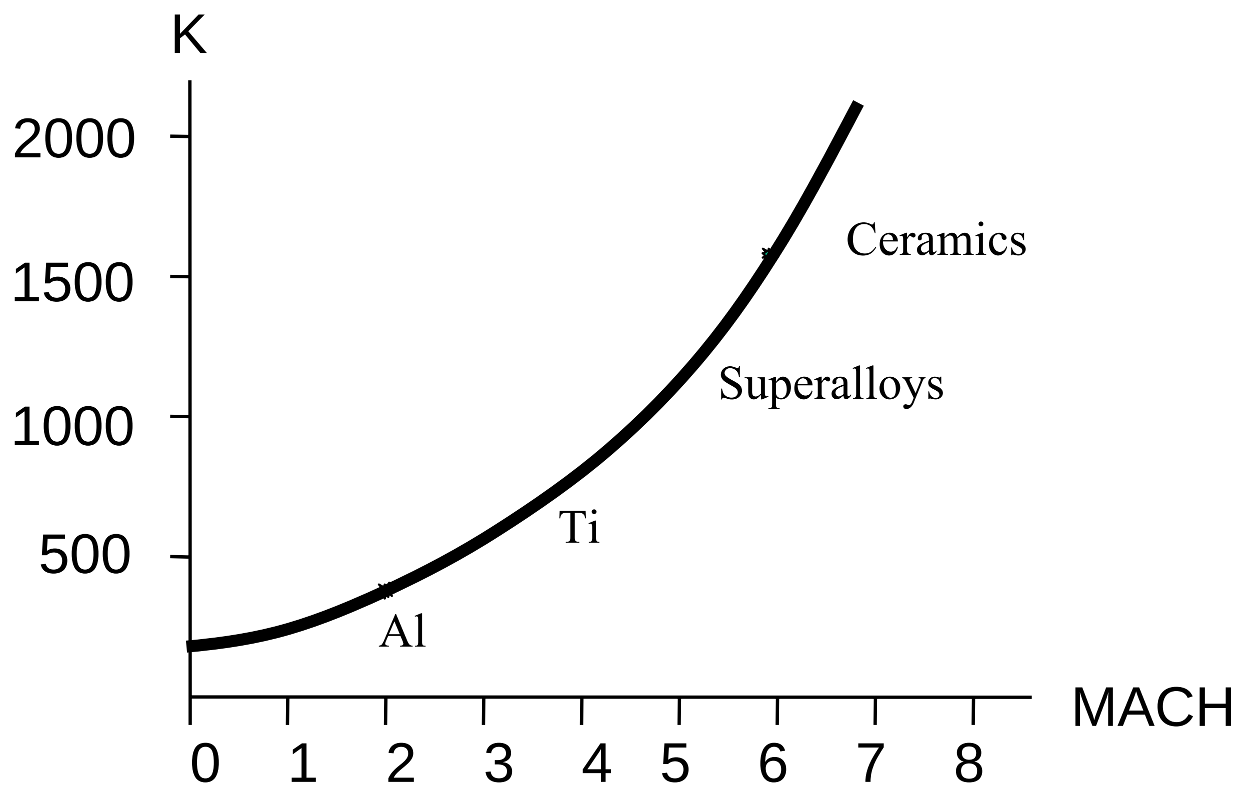
Ramrocket



Pulsed ramrocket

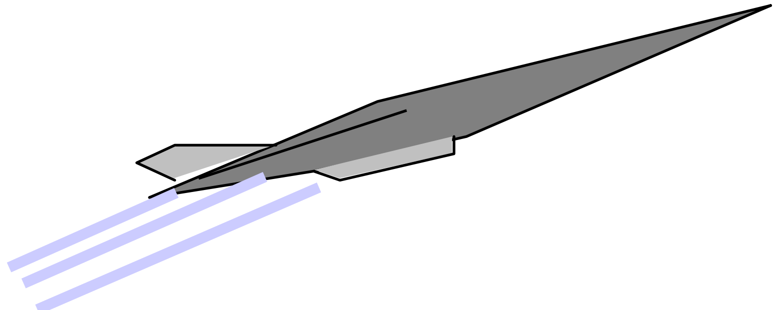

Specific impulse for spaceplanes
I_s / V_0
Pulsed ramrocket
Precooled
Turboram
Ramrocket
Scram
LACE
Rocket
$I_s = \frac{F}{\dot{m}_p}$
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
18
Mach

Heat protection is a big problem



Stagnation temperature and materials

Tsiolkovsky equation with gravity and atmosphere



Konstantin Tsiolkovsky

Ordinary Tsiolkovsky:

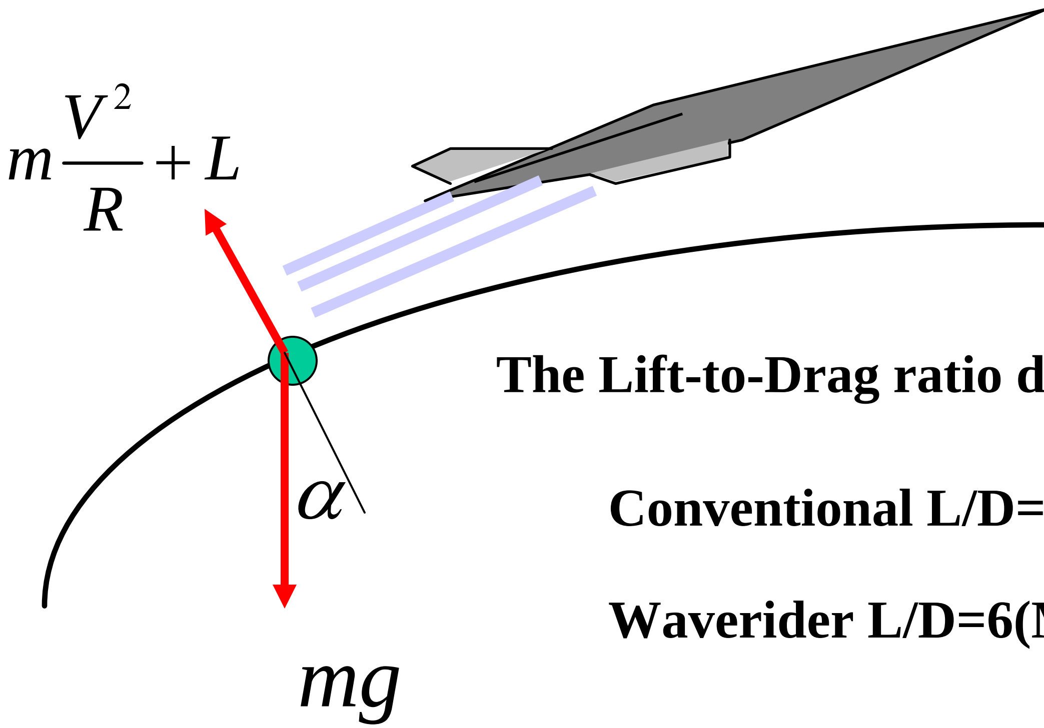
$$\frac{m_c}{m_0} = e^{-V/I_s}$$

Modified for aero and gravity losses:

$$\frac{m_c}{m_0} = 1 - \frac{m_p}{m_0} = \exp\left(-\int_0^V \frac{dV}{\eta_f I_s}\right)$$

Flight efficiency

Flight efficiency



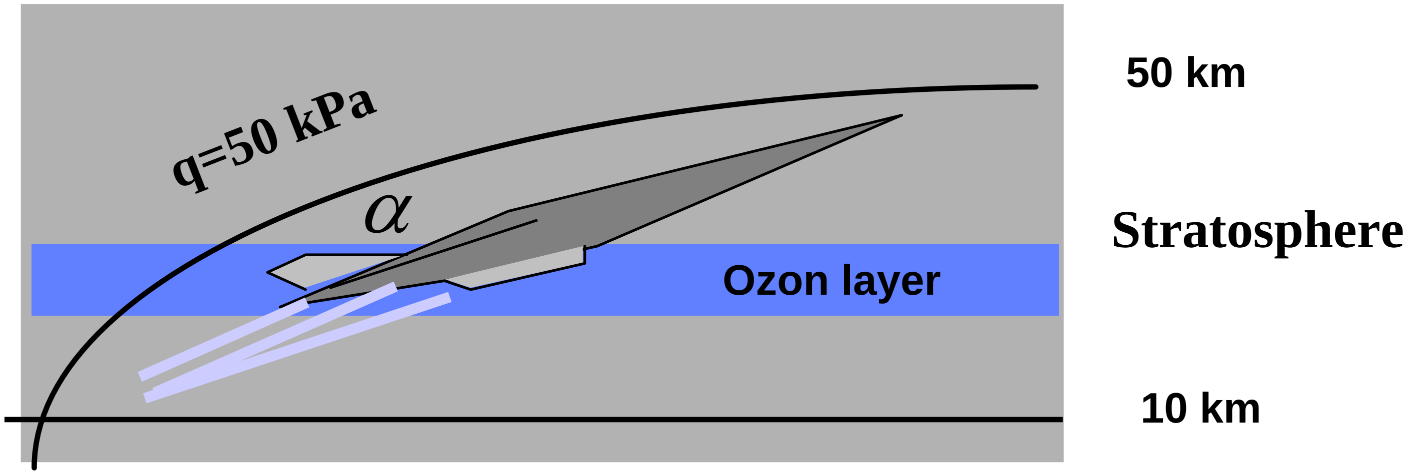
The Lift-to-Drag ratio decreases with speed

Conventional L/D=4(M+3)/M

Waverider L/D=6(M+2)/M

$$\eta_f = 1/(1 + \frac{D}{L}\left(\cos\alpha - \frac{V^2}{gR}\right)\frac{g}{a} + \frac{g}{a}\sin\alpha)$$

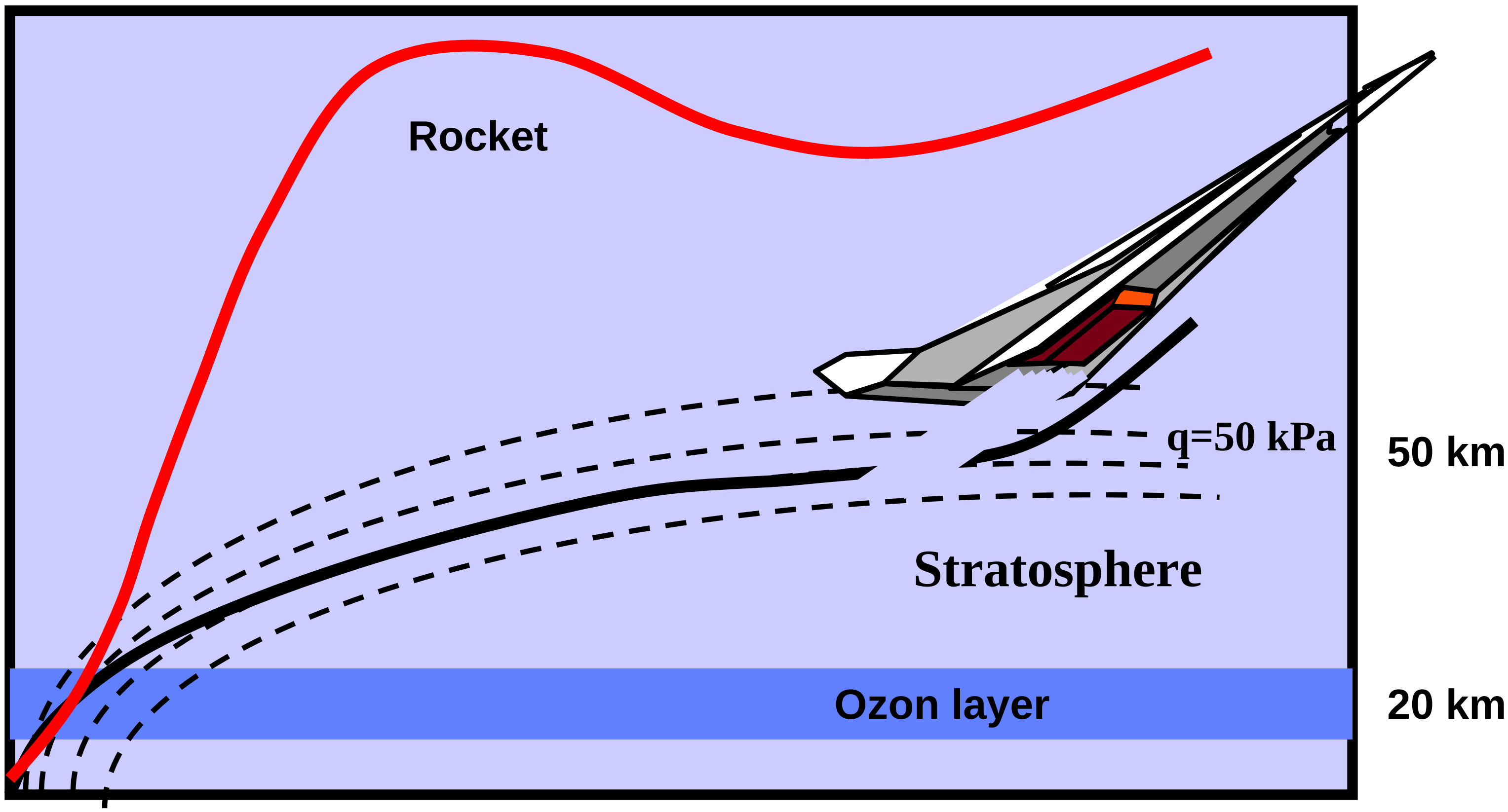
Spaceplane trajectory



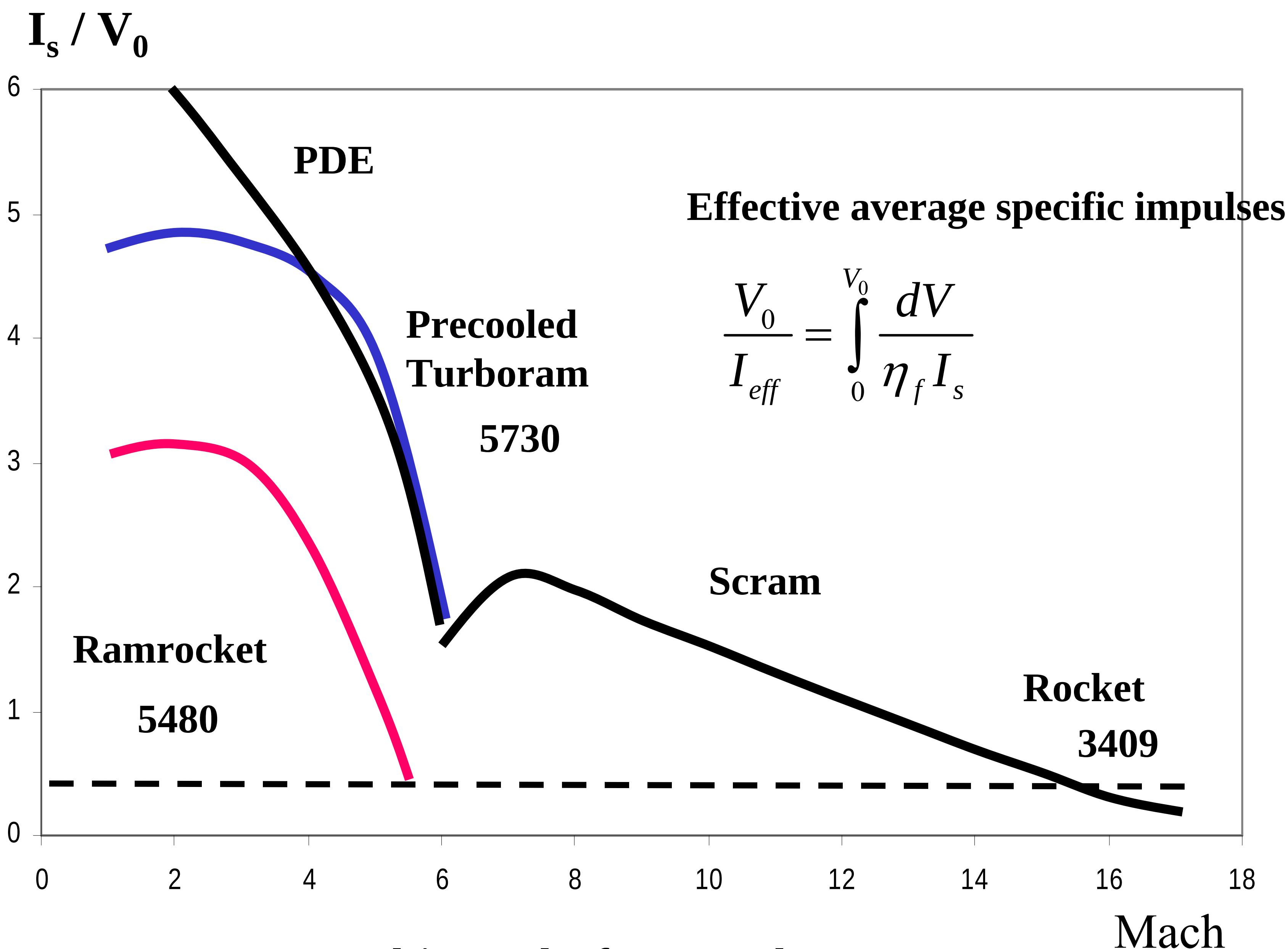
Atmospheric pressure: $\frac{p}{p_{sl}} = e^{-h/h_0}$ **h_0 =6670 m**

$$q = \frac{1}{2}\rho V^2 = \frac{1}{2}\frac{p}{RT}V^2 = \frac{\gamma p}{2}M^2 \qquad M = \sqrt{\frac{2q}{\gamma p_{sl} e^{-h/h_0}}}$$

Flight at constant dynamic pressure q

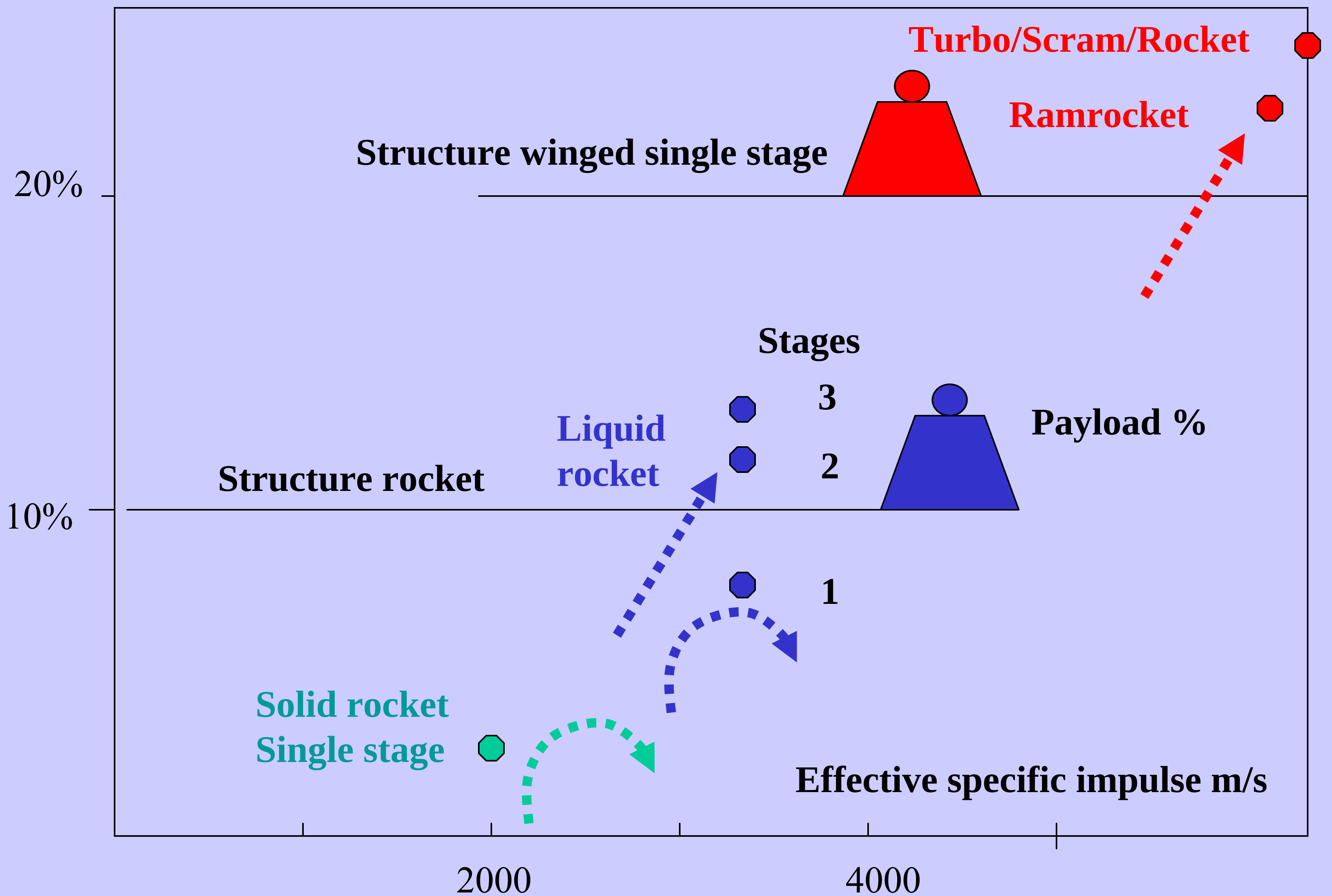


Spaceplane and rocket trajectories

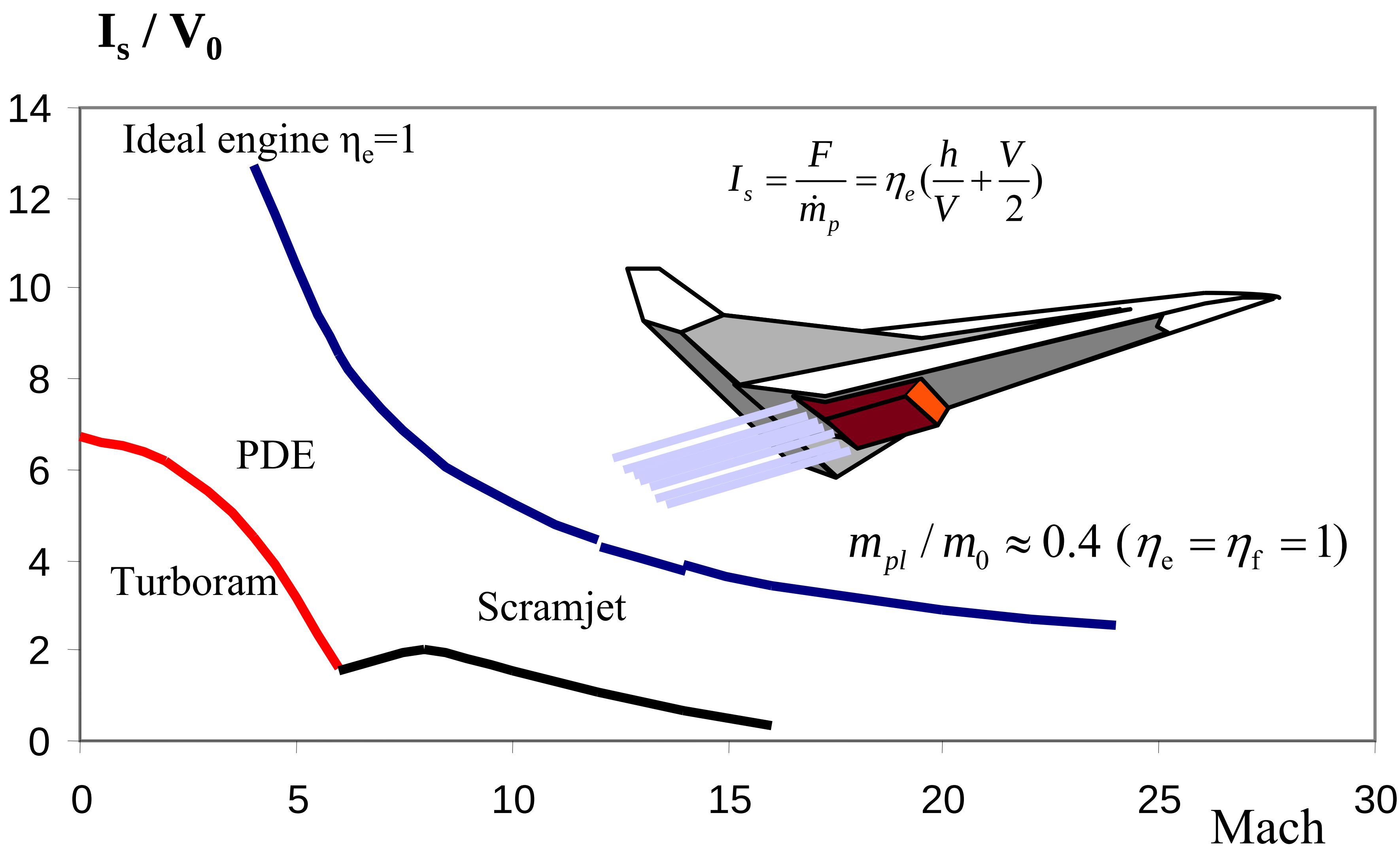


Propulsion cycles for spaceplanes

% take-off weight to satellite orbit $m_c / m_0 = e^{-V_0 / I_{eff}}$



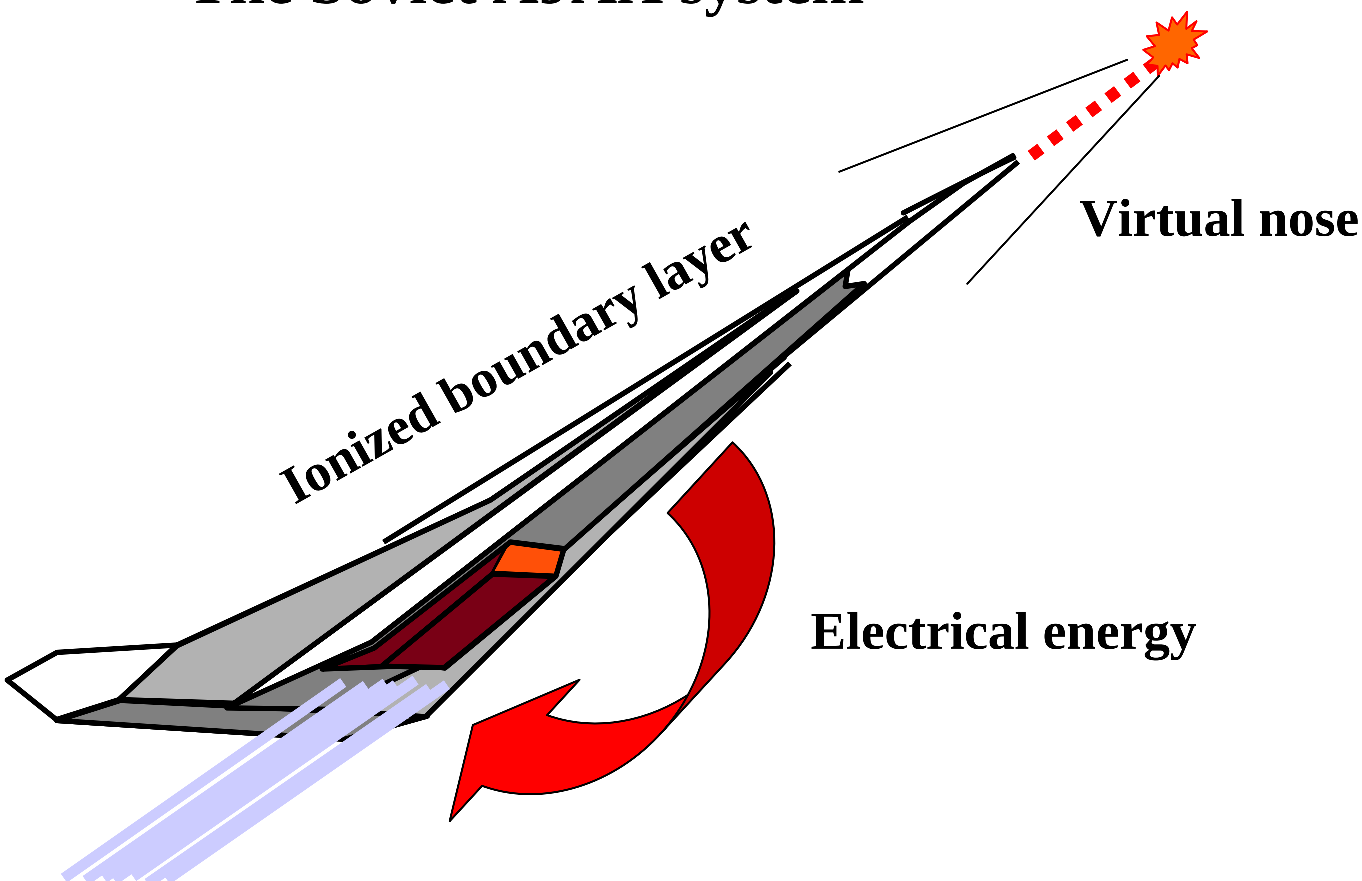
A jumbo to space? Yes, but how?



Limits to airbreathing propulsion

Electricity; Magnetohydrodynamics

The Soviet AJAX system



Magnetohydrodynamic airbreathing vehicle

Most powerful of all engines

Ariane 20000 W/kg.

Gripen 2500 W/kg.

Humming bird 300 W/kg.

Man 3 W/kg.

Insect 60 W/kg.