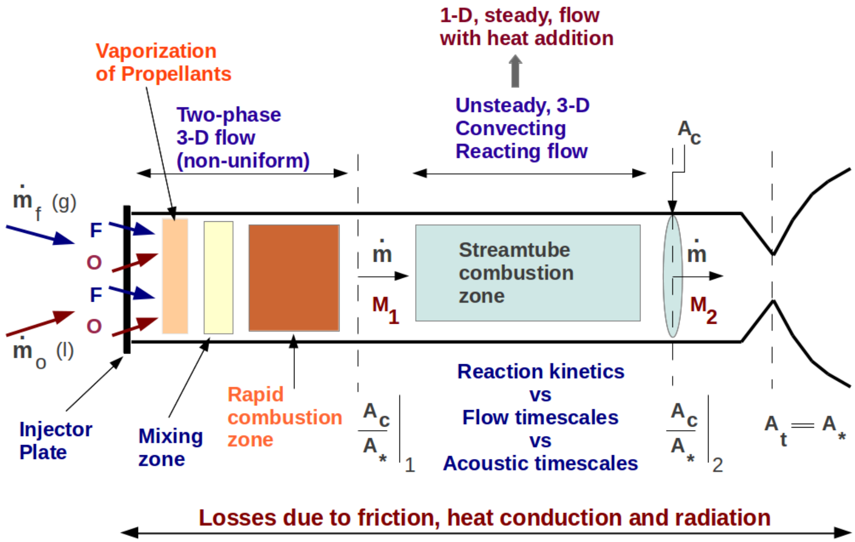
AE 330 Rocket Propulsion

Rocket Performance Parameters & Nozzles

Kowsik Bodi
Aerospace Engineering, IIT Bombay

Physical processes in combustion chamber



Rocket Engine

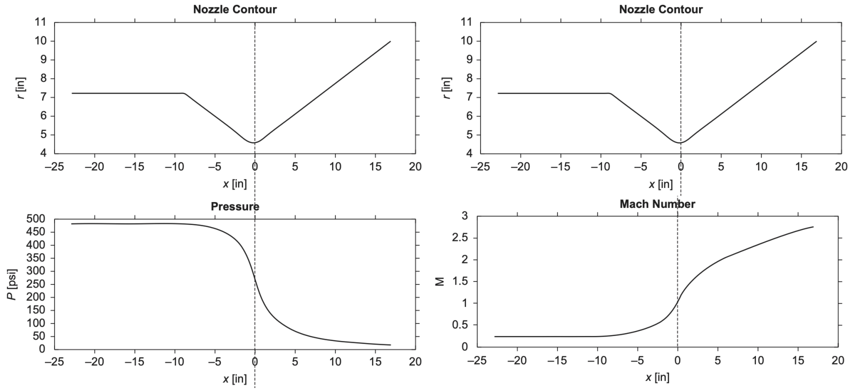
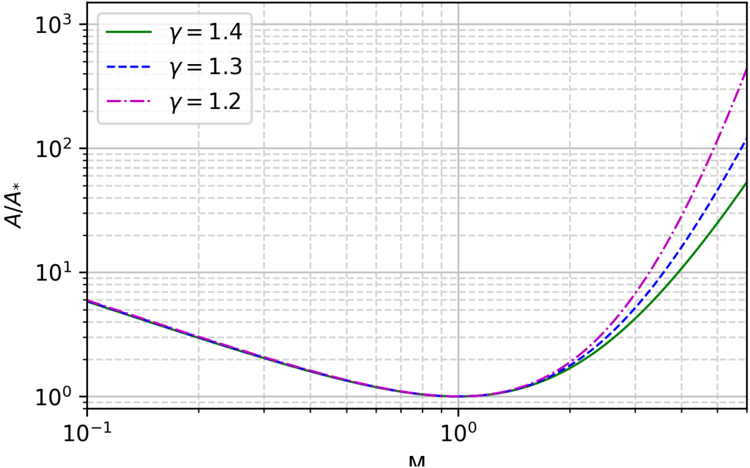
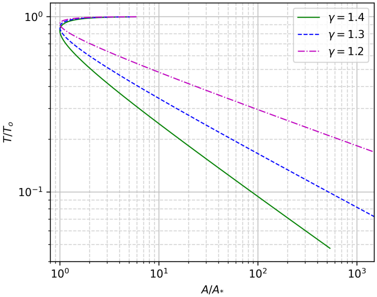


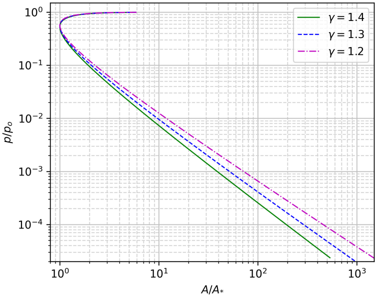
Image from Heister

Effect of γ



Effect of γ





Equilibrium vs Frozen Nozzle Flow

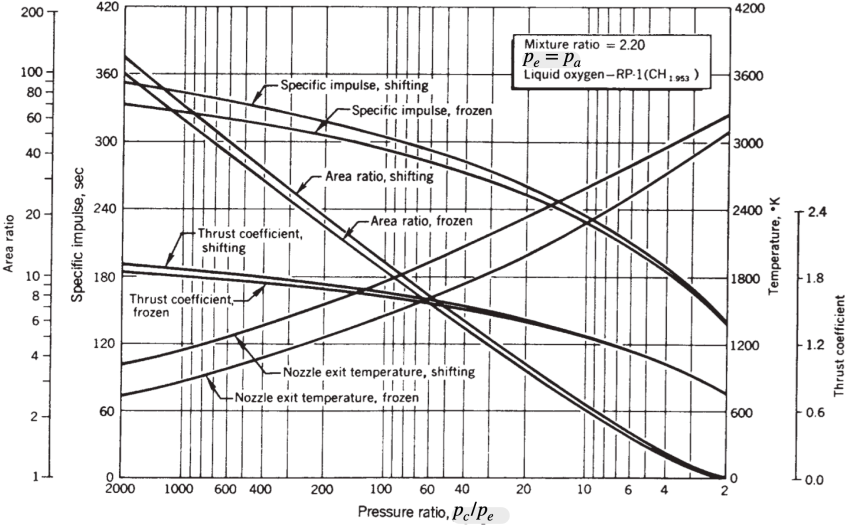
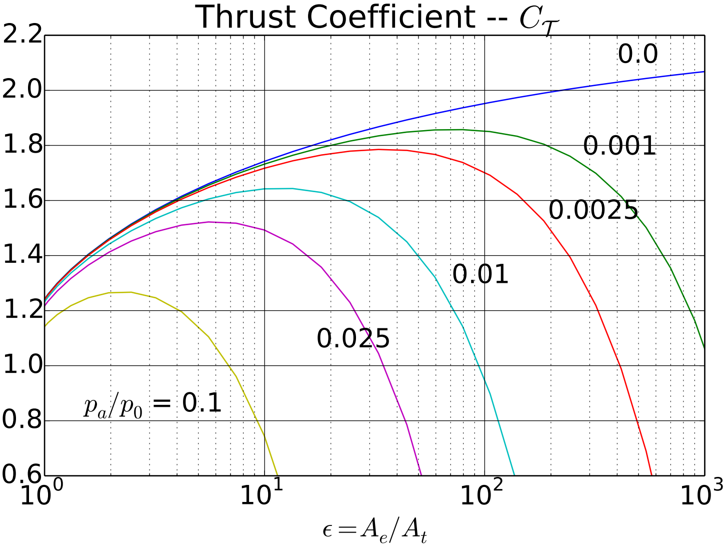


Image from Sutton

Characteristic Velocity

		$\mathcal{M}_w$ (gm/mol)	T_c (K)	c^* (km/s)
Solid		23-26	2,400 - 3,600	1.5-1.8
Liquid	Monopropellant	12-15	1,000 - 1,300	1.2-1.4
	Storable bipropellant	22-24	3,000 - 3,400	1.7-1.9
	Cryogenic bipropellant	12-15	3,000 - 3,400	2.3-2.5

Coefficient of Thrust ($\gamma = 1.2$)



Typical Rocket Performance Parameters

	Ordinary	High
T_c (K)	2,000 - 3,000	3,300 - 3,900
c^* (m/s)	1,200 - 1,500	1,800 - 2,400
$C_{\mathcal{T}}$	1.3 - 1.5	1.7 - 1.9
$\mathcal{M}_w$ (gm/mol)	20 - 25	8 - 20
γ	1.14 - 1.18	1.2 - 1.25

Nozzles: Choice of design altitude

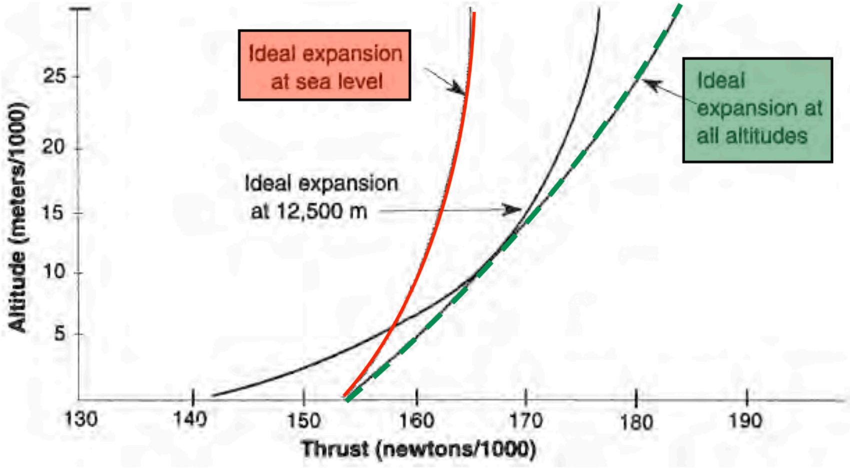


Image from Hrbud

CD Nozzle – Inviscid, Adiabatic

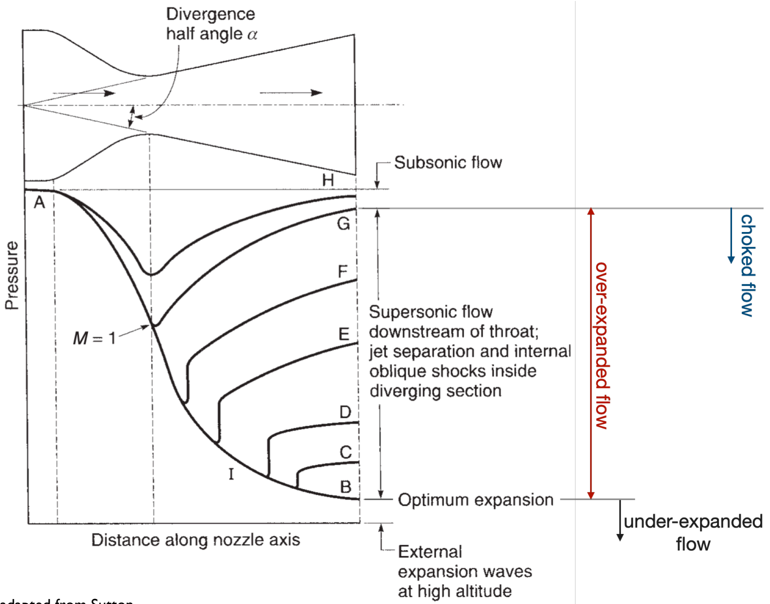


Image adapted from Sutton

Nozzles

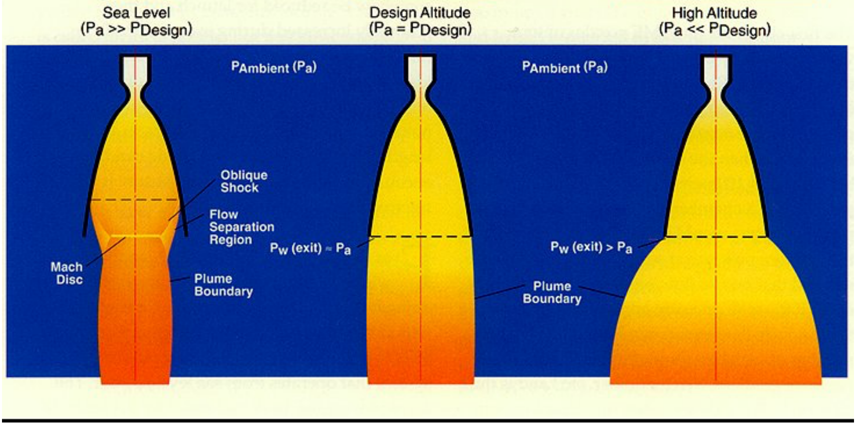
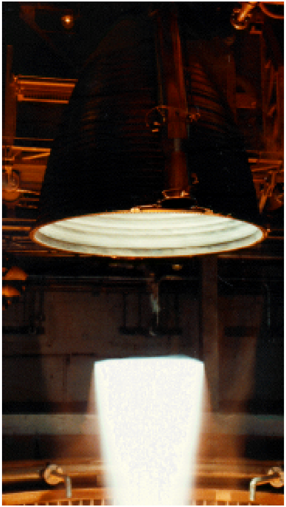
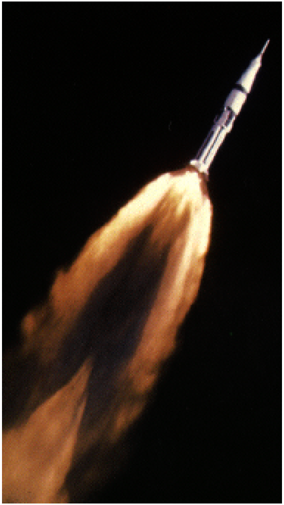


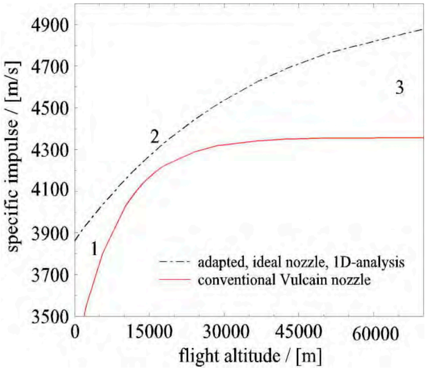
Image from Pratt & Whitney

Nozzles

Over-expanded	Perfectly-expanded	Under-expanded
		
Vulcain Engine	RL-10 Engine	Saturn Rocket

Images from Hrbud

Nozzles: Thrust variation with altitude



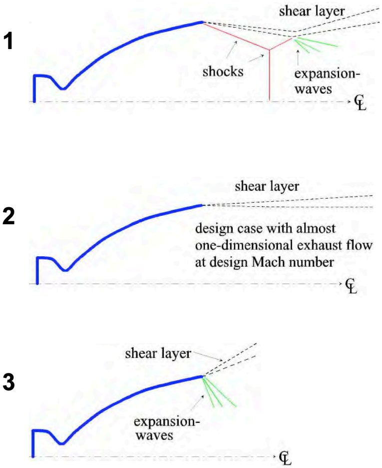
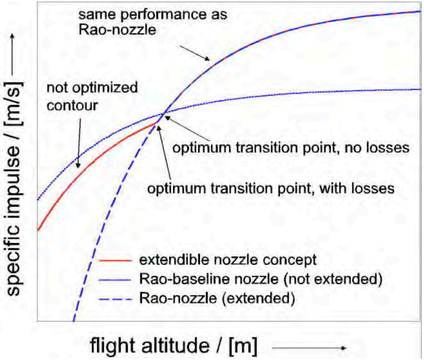


Image from Hrbud

Extendable Nozzle



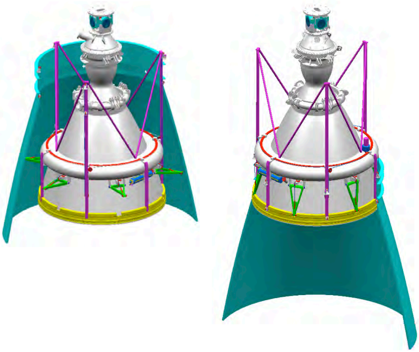
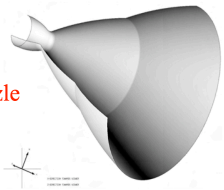


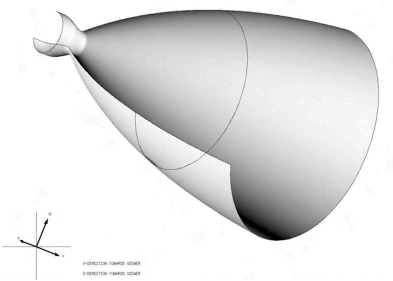
Image from Hrbud

Altitude-adjusting Nozzles

Dual-bell nozzle



Bell nozzle



Extendible nozzle

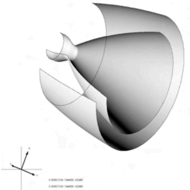
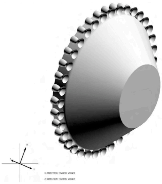


Image from Hrbud

Plug nozzle
("Aerospike")



Conical Nozzle

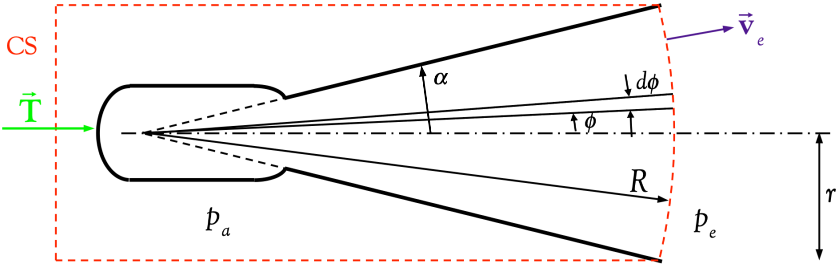


Image from Hrbud

- Axial Component of exit velocity: $v_{e_x} = v_e \cos\phi$
- Exit Area: $A_e = \pi r_e^2 \equiv \pi R^2 \sin^2\alpha$
- Exit Area (Spherical):

  $A_{e_{sph}} = \int_0^\alpha 2\pi R^2 \sin\phi \,\mathrm{d}\phi \equiv 2\pi R^2 (1 - \cos\alpha)$

Conical Nozzle

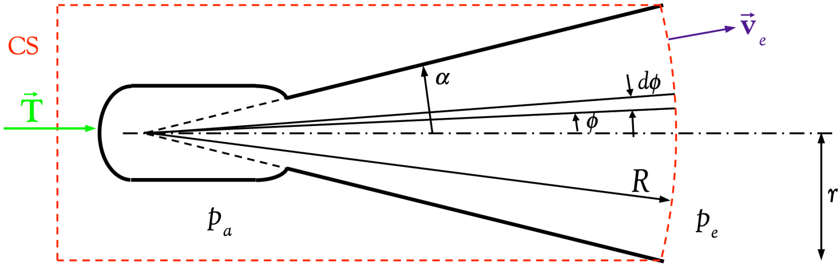


Image from Hrbud

- Axial Component of exit velocity: $v_{e_x} = v_e \cos\phi$
- Mass flow-rate:
  $\dot{m} = \int_0^\alpha \rho_e v_e 2\pi R^2 \sin\phi \mathbf{d}\phi \equiv 2\pi R^2 \rho_e v_e \left(1 - \cos\alpha\right)$
- Thrust: $\mathcal{T} = \int_0^\alpha \rho_e v_e v_e \cos\phi 2\pi R^2 \sin\phi \mathbf{d}\phi \equiv \rho_e v_e^2 \pi R^2 \sin^2\alpha$
- $\mathcal{T} = \lambda \dot{m} v_e$, where, $\lambda = \left(1 + \cos\alpha\right)/2$

Nozzle Lengths

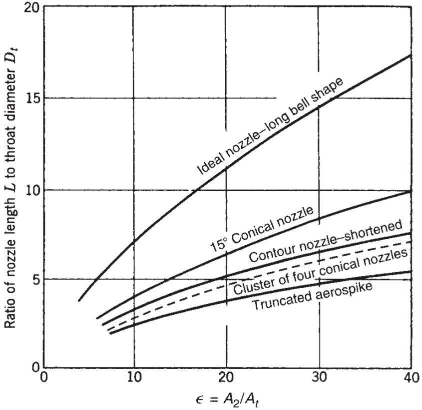


Image from Sutton

Nozzles: Bell Contour (Rao) Nozzle

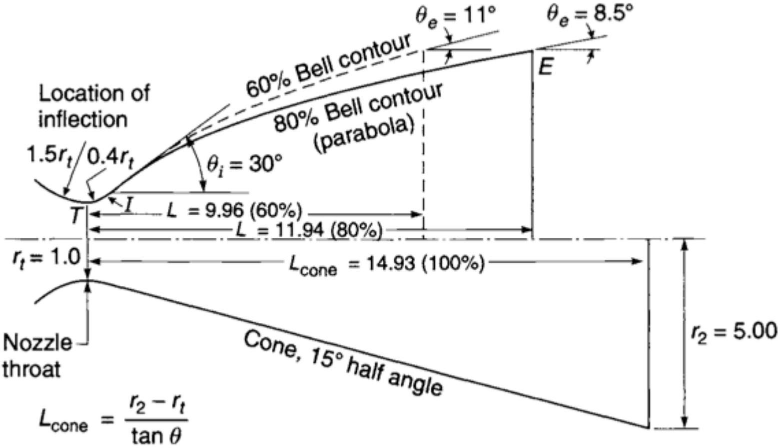
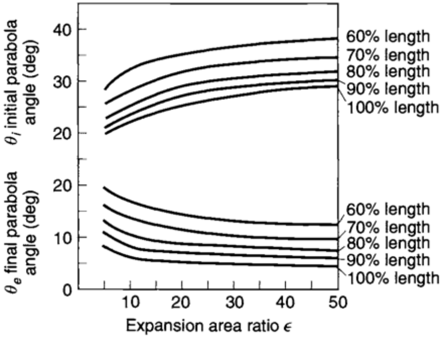
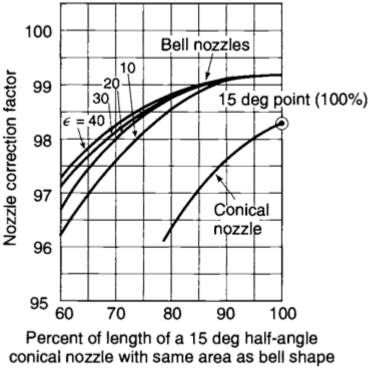


Image from Sutton

Nozzle Lengths





Images from Sutton

Nozzles: Bell Contour (Rao) Nozzle

TABLE 3–4. Data on Several Bell-Shaped Nozzles

Area Ratio	10	25	50
Cone (15° *Half Angle*)			
Length (100%)[a]	8.07	14.93	22.66
Correction factor λ	0.9829	0.9829	0.9829
80% Bell Contour			
Length[a]	6.45	11.94	18.12
Correction factor λ	0.985	0.987	0.988
Approximate half angle at inflection point and exit (degrees)	25/10	30/8	32/7.5
60% Bell Contour			
Length[a]	4.84	9.96	13.59
Correction factor λ	0.961	0.968	0.974
Approximate half angle at inflection point and exit (degrees)	32.5/17	36/14	39/18

[a]The length is given in dimensionless form as a multiple of the throat radius, which is one.

Image from Sutton

Nozzle Contours

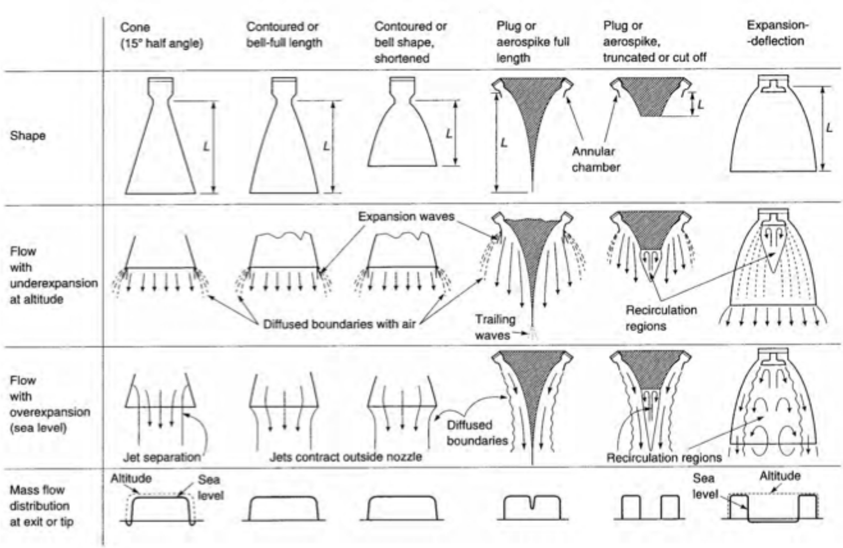
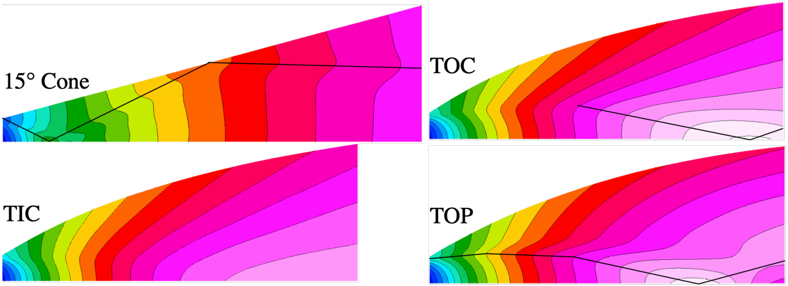


Image from Hrbud

Comparing Nozzles



Contour plots of Mach number from Ostlund

Flow Separation - Correlations

Summerfield: $$\frac{p_{sep}}{p_a} = 0.4$$

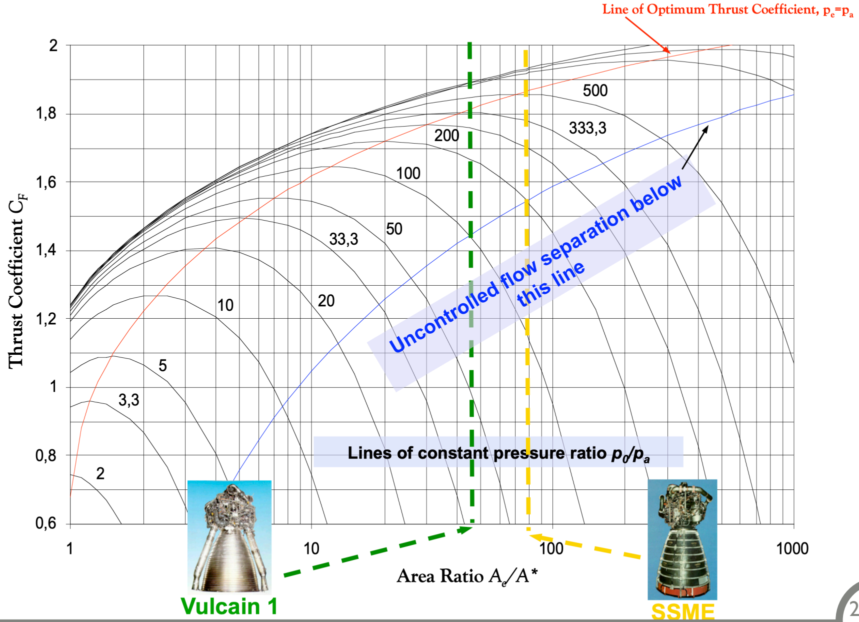
Schilling: $$\frac{p_{sep}}{p_a} = k_1 \left(\frac{p_c}{p_a}\right)^{k2}$$

		k_1	k_2
Schilling	Contoured	0.582	-0.195
	Conical	0.541	-0.136
Kalt & Bendall		2/3	-0.2

Schmucker proposed the following empirical critierion

$$\frac{p_{sep}}{p_a} = (1.88M_{sep} - 1)^{-0.64}$$

Nozzles: Thrust Coefficient



Nozzles: Thrust Coefficient

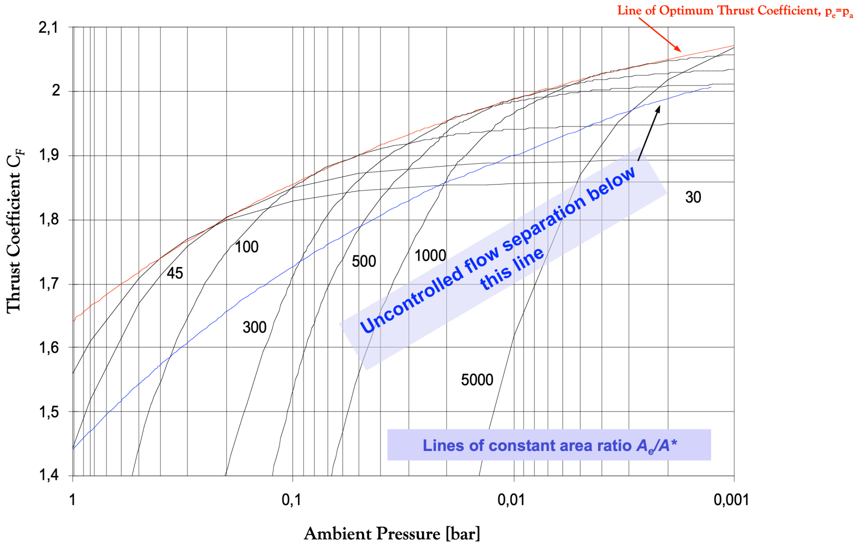


Image from Hrbud

Nozzles: Thrust Coefficient – Separated Flow

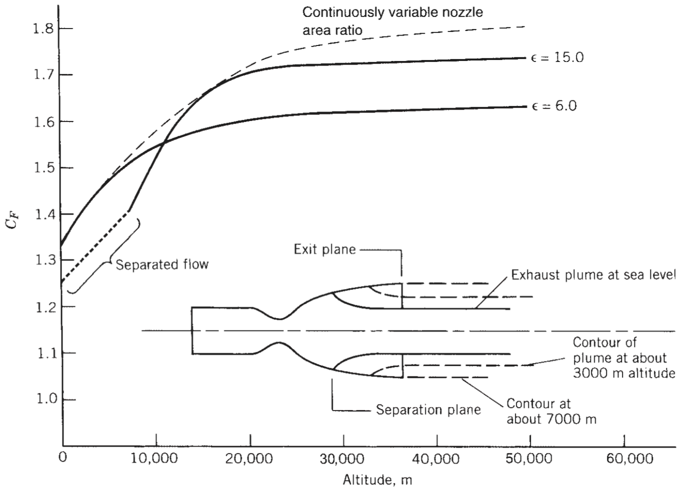


Image from Sutton

Nozzles: Thrust variation with altitude

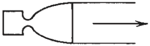
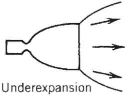
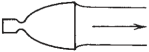
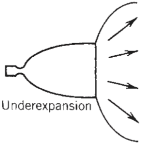
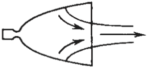
Stage	A_2/A_t	During flight	h (km)	I_s (sec)	During sea level static tests	h (km)	I_s (sec)
Booster or first stage	6	 Nozzle flows full, slight underexpansion	0	267	 Nozzle flows full	0	267
Second stage	10	 Underexpansion	24	312	 Overexpansion, slight contraction	0	254
Third stage	40	 Underexpansion	100	334	 Flow separation caused by overexpansion	0	245

Image from Sutton

Nozzles: Thrust variation with altitude

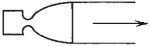
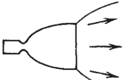
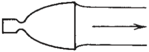
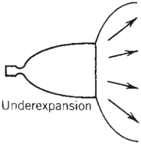
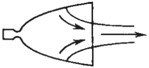
Stage	A_2/A_t	During flight	h (km)	I_s (sec)	During sea level static tests	h (km)	I_s (sec)
Booster or first stage	6	 Nozzle flows full, slight underexpansion	0	267	 Nozzle flows full	0	267
Second stage	10	 Underexpansion	24	312	 Overexpansion, slight contraction	0	254
Third stage	40	 Underexpansion	100	334	 Flow separation caused by overexpansion	0	245

Image from Sutton