Lecture 18

Nozzles

Nozzle (Exhaust) Section

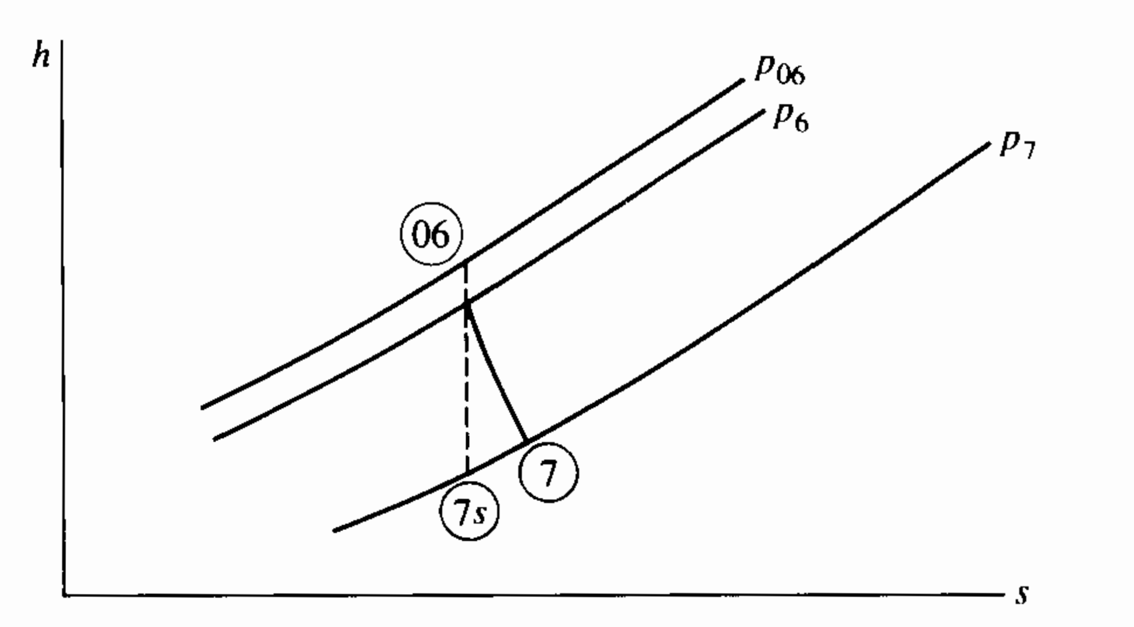
- Exhaust section extends from the rear of the turbine section to the point where the exhaust gases leave the engine.
- Nozzles are relatively easy to design, since the pressure gradient can be favorable all along the wall.
- The mechanical design can be complex if the area of the nozzle needs to be adjustable, especially if a converging-diverging (i.e., super- sonic) configuration is desired.
- Adjustable nozzles are often constructed of a series of segments that can be moved to form a conical fairing of variable outlet area.

https://www.youtube.com/watch?v=ss96tsbG5KY

Main functions of nozzle

- Accelerate flow to required exit velocity to produce thrust (supersonic if need be)
- Thrust vectoring to provide improved pitch, roll, yaw control, V/STOL
- Thrust reversers for deceleration
- Noise reduction of jet exhaust

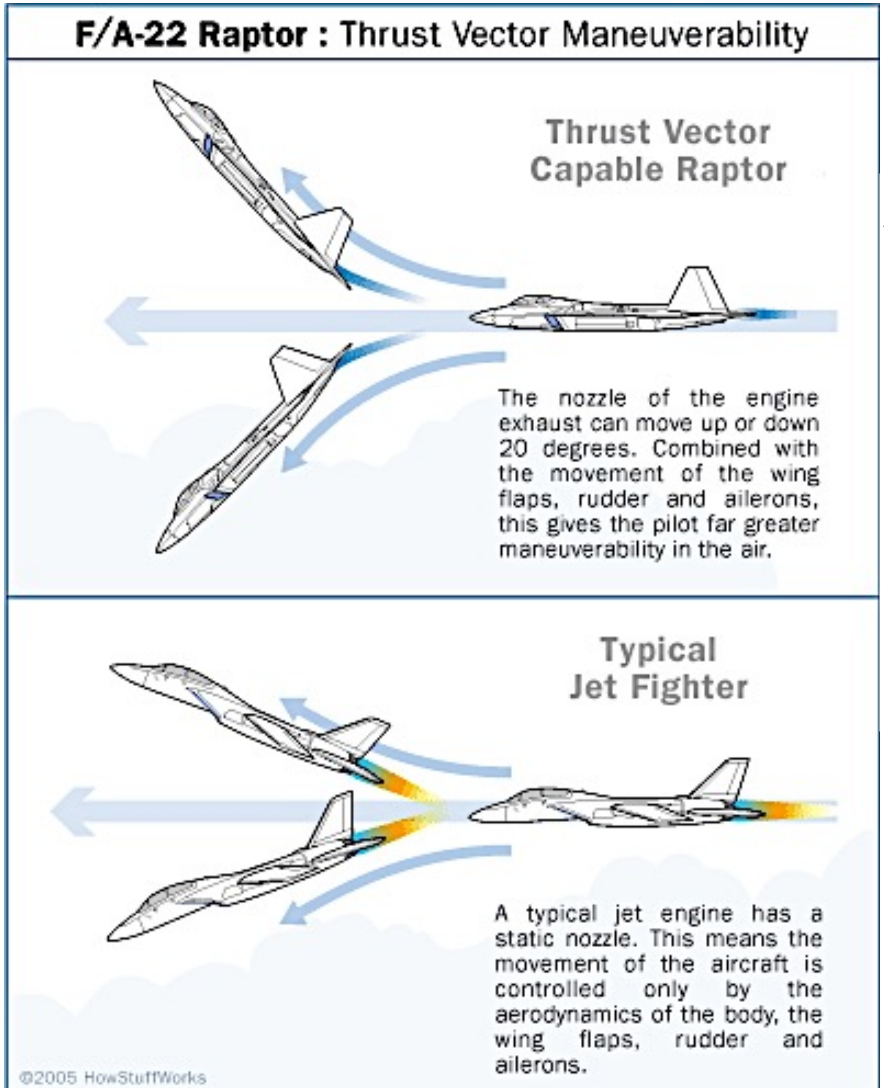
Nozzle T-s Diagram



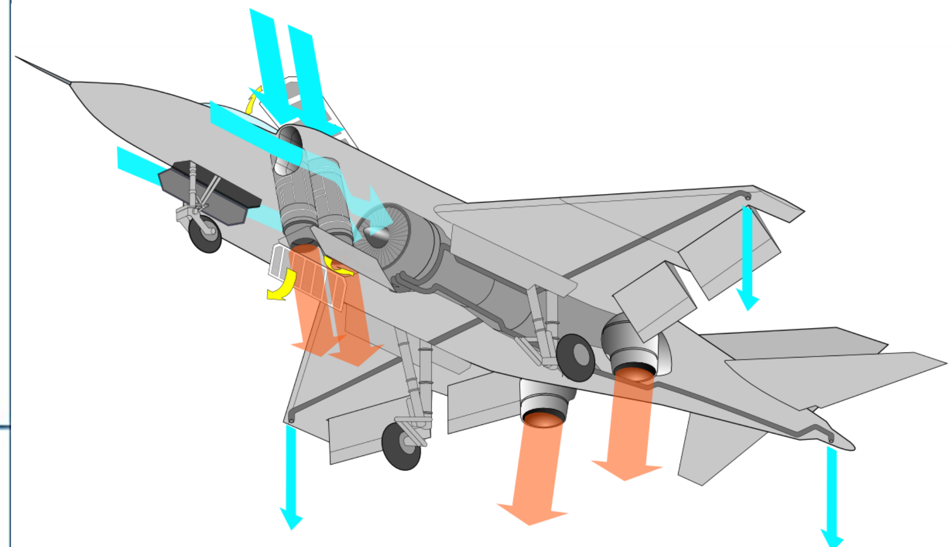
$$\eta_n = \frac{h_{06} - h_7}{h_{06} - h_{7s}};$$ Adiabatic efficiency of nozzle

Flow is accelerated from Station 6 to 7, converting a part of the stagnation enthalpy into Kinetic Energy

Thrust Vectoring



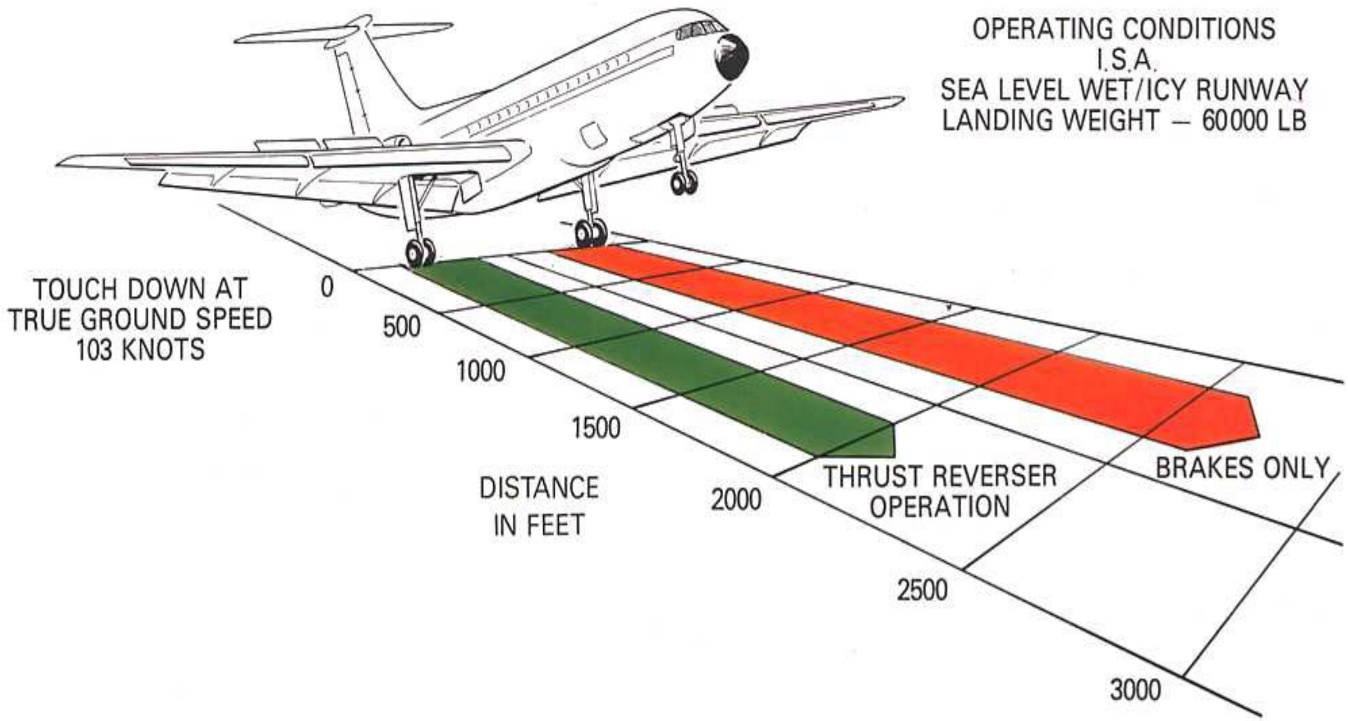
VSTOL – Vertical/Short Take Off and Landing



https://www.youtube.com/watch?v=zW28Mb1YvwY

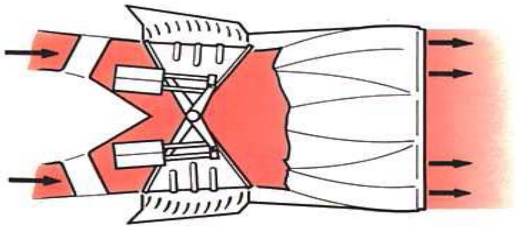
https://www.youtube.com/watch?v=yrDnXEKlSY4

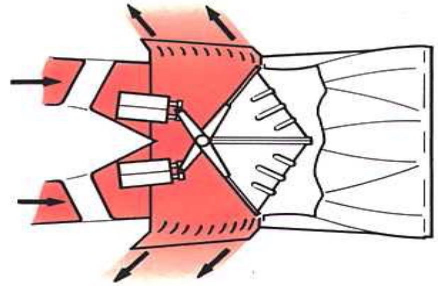
THRUST REVERSERS

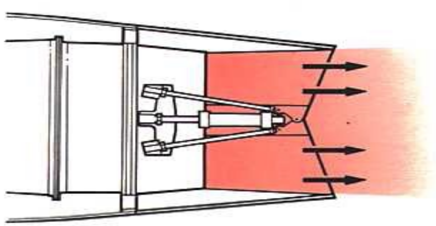


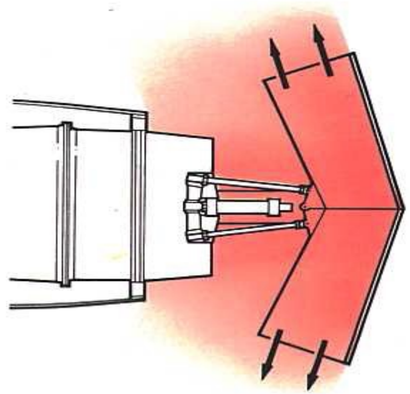
- Brakes are unable to slow larger A/C adequately during landing (need a longer runway)
- Brake wear would be prohibitive and heat buildup could lead to brake fire.
- Most turbojet and turbofan powered A/C are fitted with thrust reversers to assist in braking.
- Thrust reversers redirect the flow of gases to provide thrust in the opposite direction.

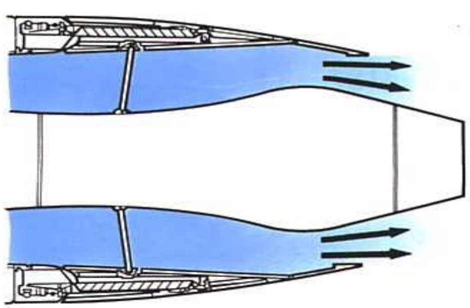
THRUST REVERSERS

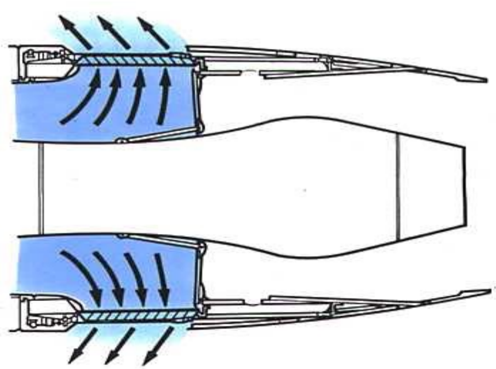

CLAMSHELL DOORS IN FORWARD THRUST POSITION


CLAMSHELL DOORS IN REVERSE THRUST POSITION

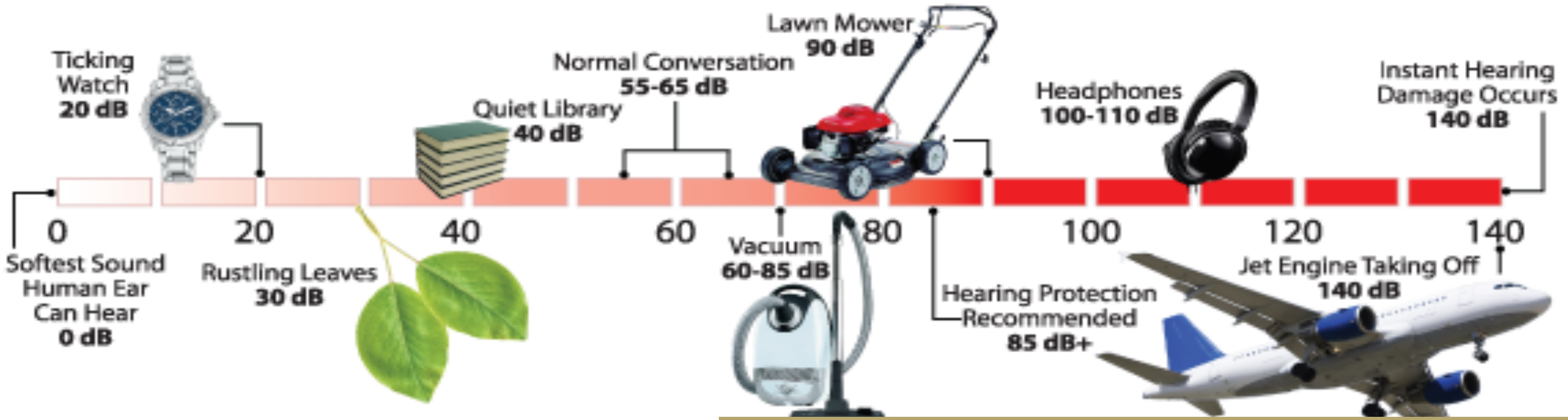

ACTUATOR EXTENDED AND BUCKET DOORS IN FORWARD THRUST POSITION


ACTUATOR AND BUCKET DOORS IN REVERSE THRUST POSITION

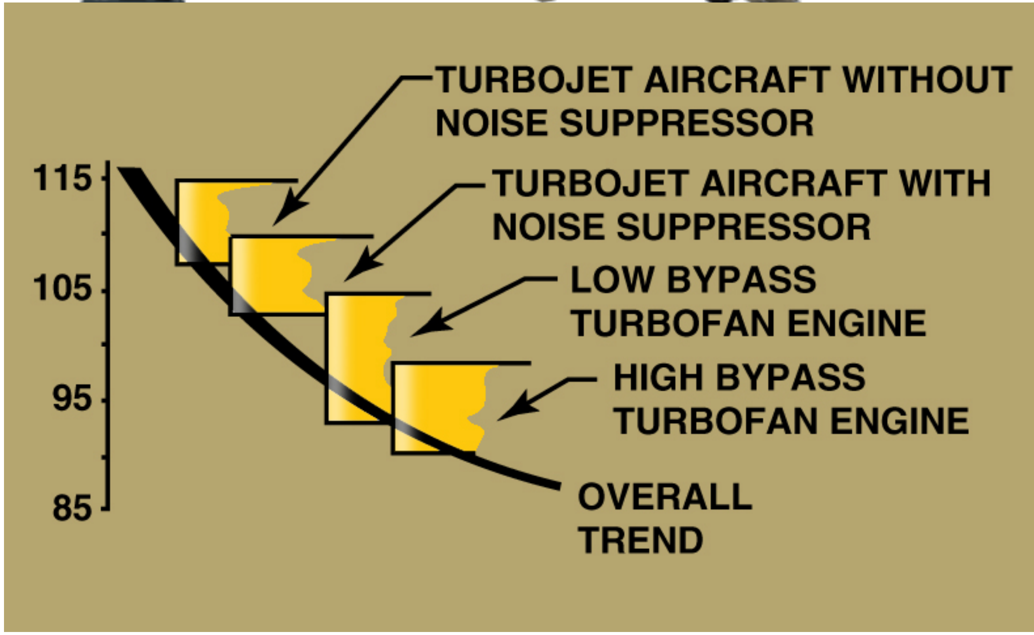

COLD STREAM REVERSER IN FORWARD THRUST POSITION


COLD STREAM REVERSER IN REVERSE THRUST POSITION

JET NOISE SUPPRESSION

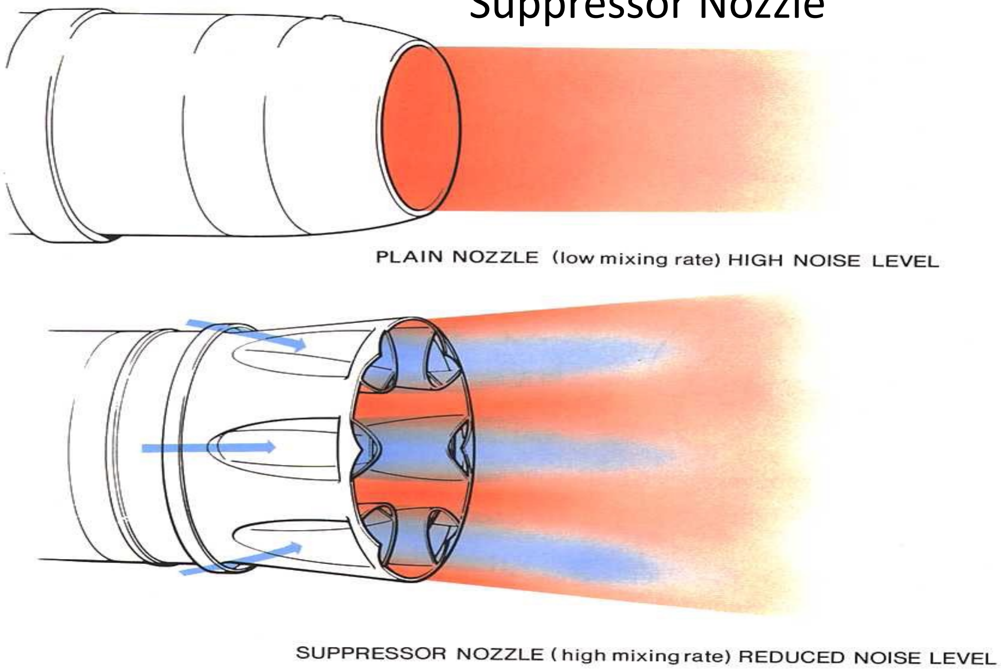


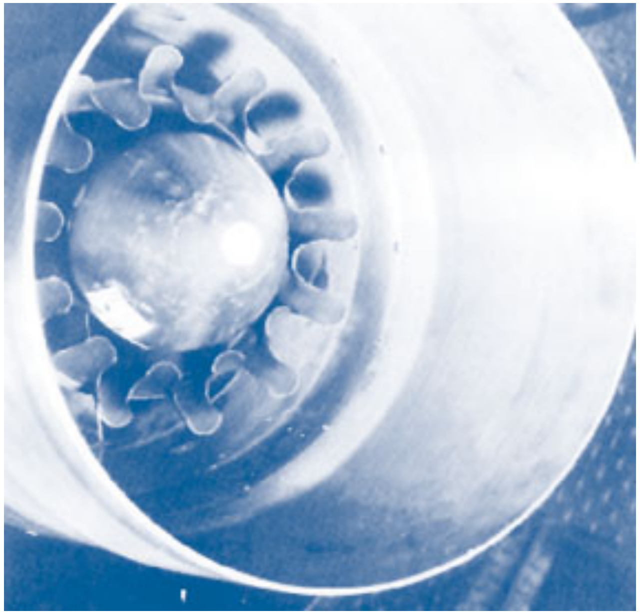
- Jet noise is produced by a turbine engine when hot, high velocity gases mix with cold, low velocity atmospheric air surrounding the engine.
- FAA establish rules for aircraft operators that specify maximum noise levels.



NOISE SUPPRESSION METHODS

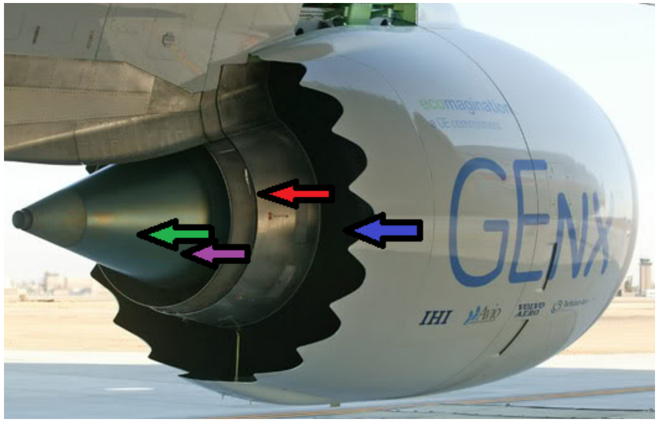
Suppressor Nozzle





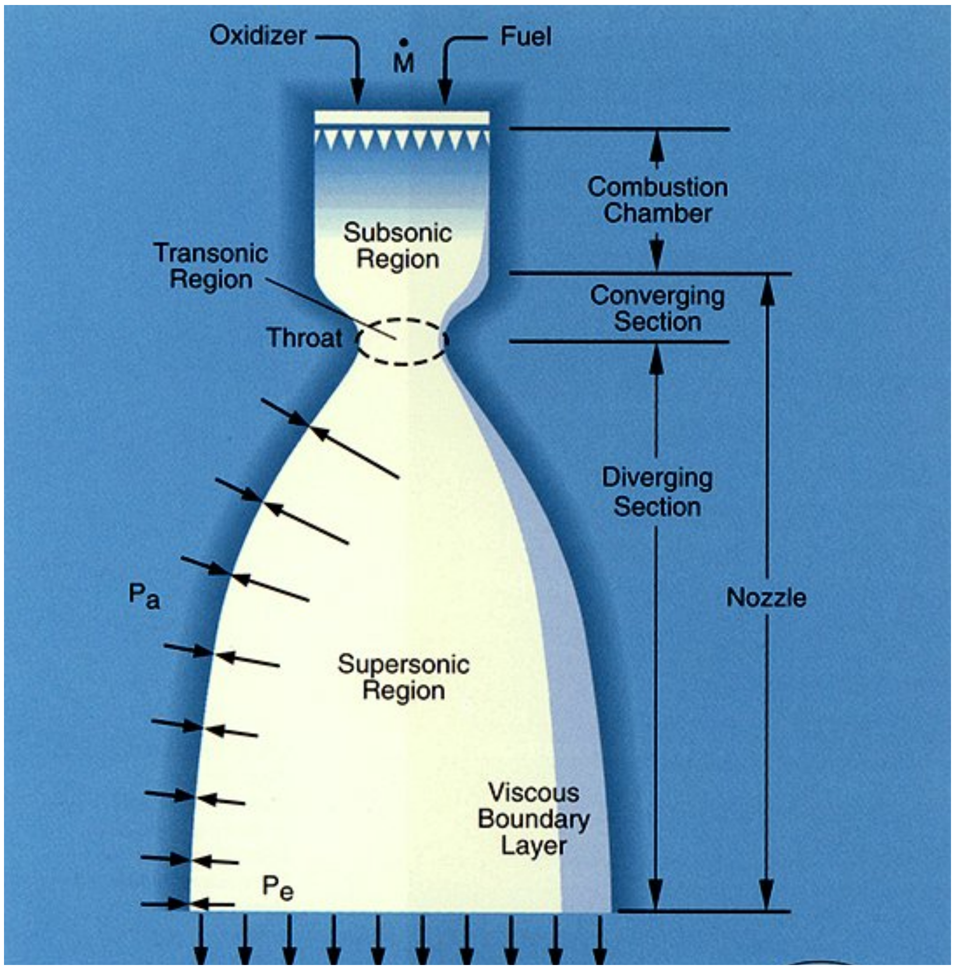
Corrugated internal nozzle

Chevron



Goal is to increase turbulence prior to leaving the nozzle

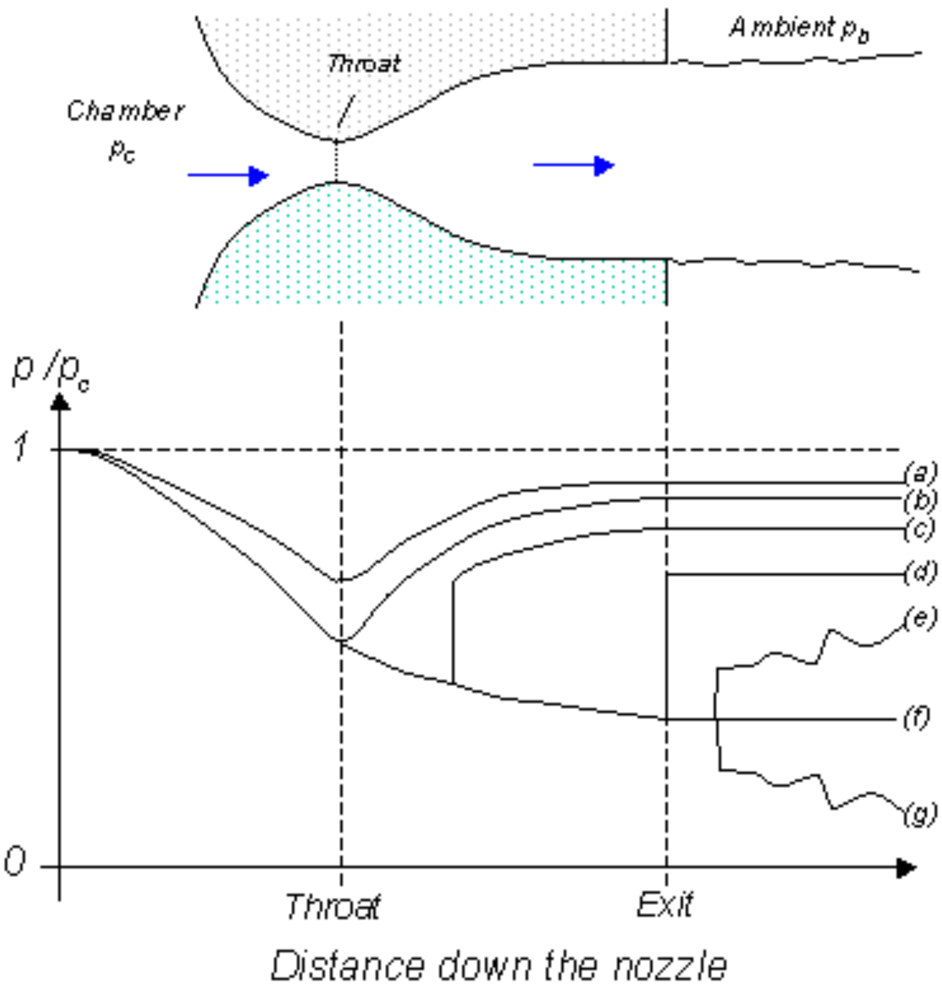
CD NOZZLE BASICS REVIEW

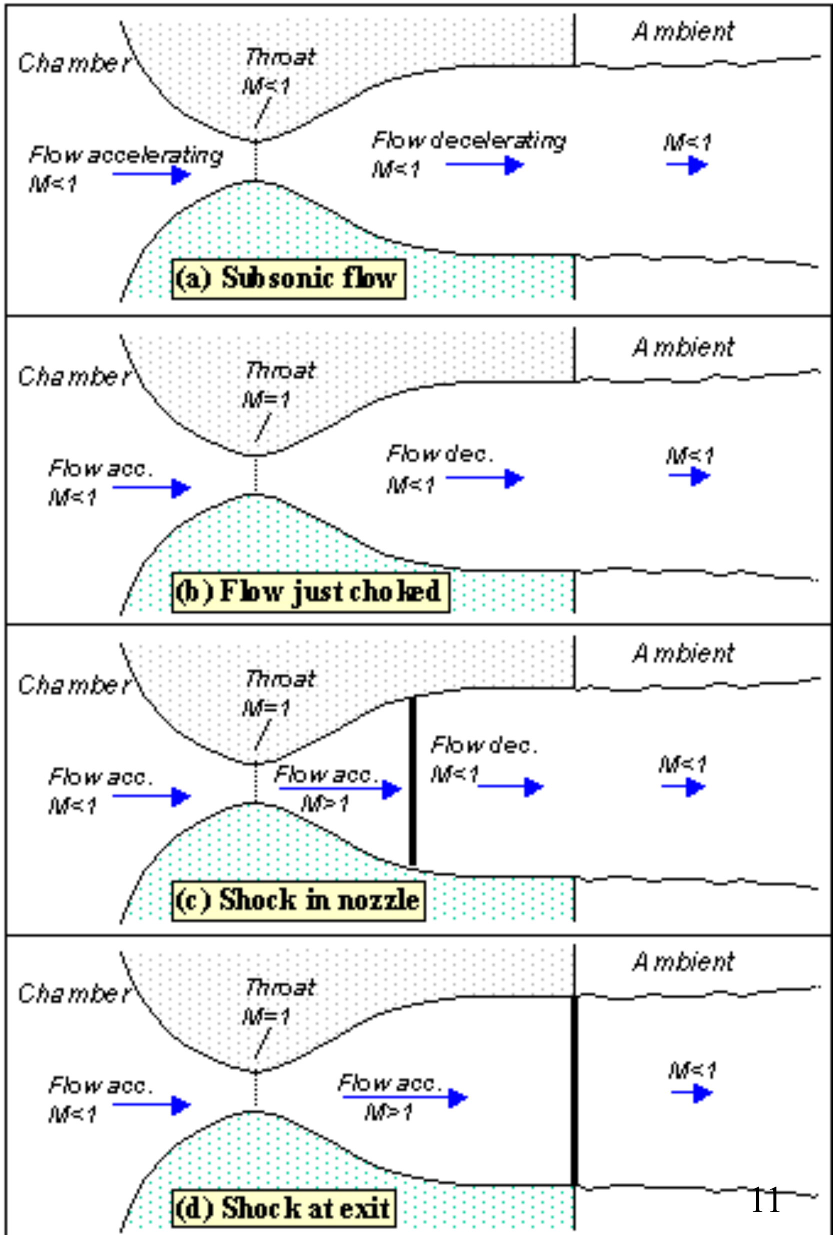


- Convert thermal energy of hot chamber gases into kinetic energy and direct that energy along nozzle axis
- Exhaust gases from combustion are pushed into throat region of nozzle
- Throat is smaller cross-sectional area than rest of engine → gases are compressed to high pressure
- Under right conditions, CD nozzles can accelerate flow to supersonic
- Ultimate purpose of nozzle is to expand gases as efficiently as possible so as to maximize exit velocity

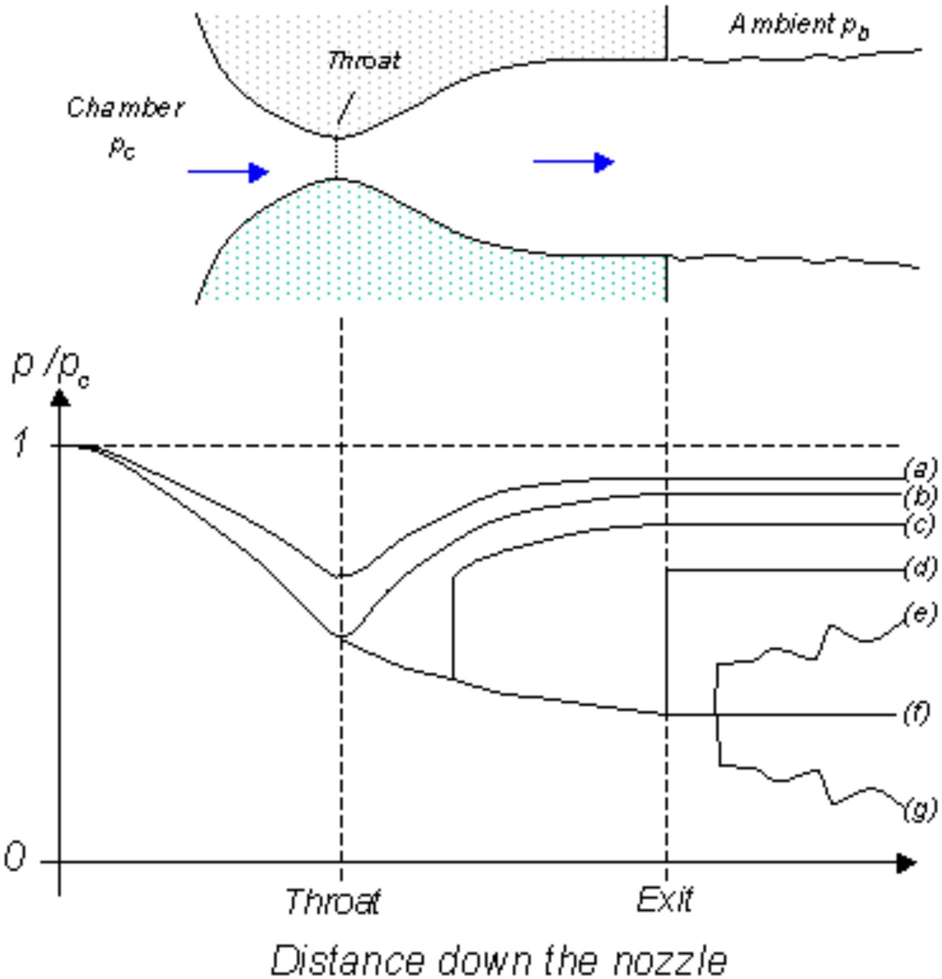
$$F = \dot{m}_e V_e + (P_e - P_a) A_e$$

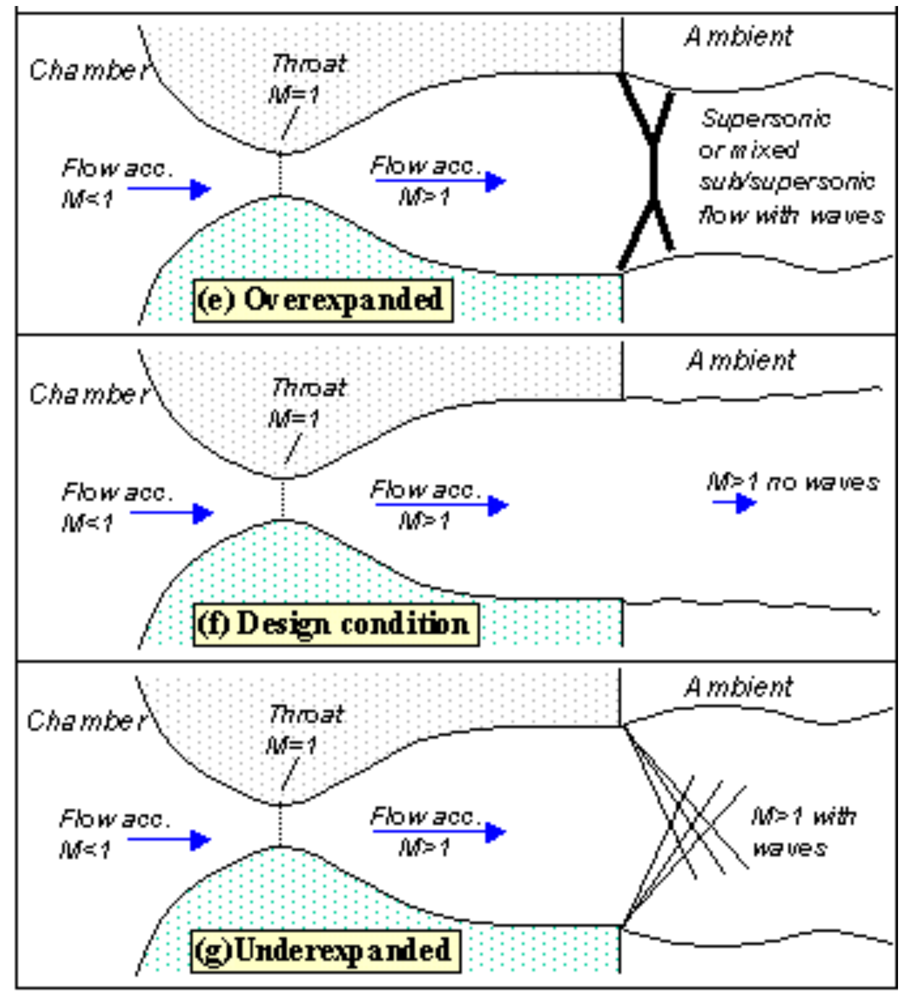
OPERATION OF CD NOZZLES





OPERATION OF CD NOZZLES





All practical rockets operate in regimes (e)-(g)

When does maximum thrust occur

Eliminating velocity from the thrust equation, we can write

$$F_R = p_c A^* \left\{ \frac{2\gamma^2}{\gamma - 1} \left(\frac{2}{\gamma + 1} \right)^{(\gamma+1)/(\gamma-1)} \left[1 - \left(\frac{p_e}{p_c} \right)^{(\gamma-1)/\gamma} \right] \right\}^{1/2} + p_e A_e - p_a A_e$$

Normalizing by combustion chamber pressure and critical area, A*

$$C_F = \left\{ \frac{2\gamma^2}{\gamma - 1} \left(\frac{2}{\gamma + 1} \right)^{(\gamma+1)/(\gamma-1)} \left[1 - \left(\frac{p_e}{p_c} \right)^{(\gamma-1)/\gamma} \right] \right\}^{1/2} + \left(\frac{p_e}{p_c} - \frac{p_a}{p_c} \right) \frac{A_e}{A^*}$$

For a given p_e and p_c, C_F is a function of A_e/A^*., therefore,

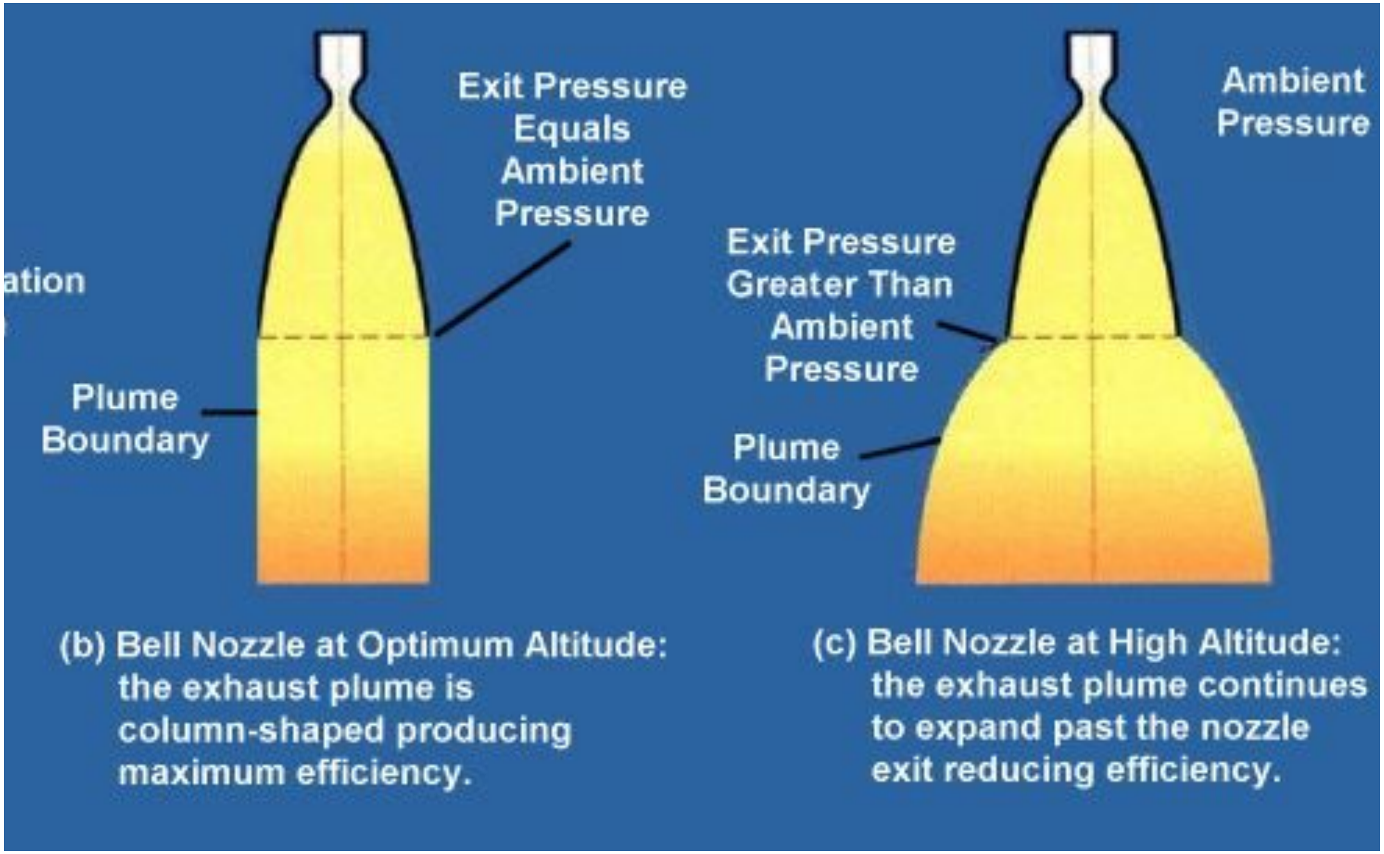
$dC_F/d(A_e/A^*) = 0$ gives condition of maximum thrust.

Which gives us, $p_e=p_a$

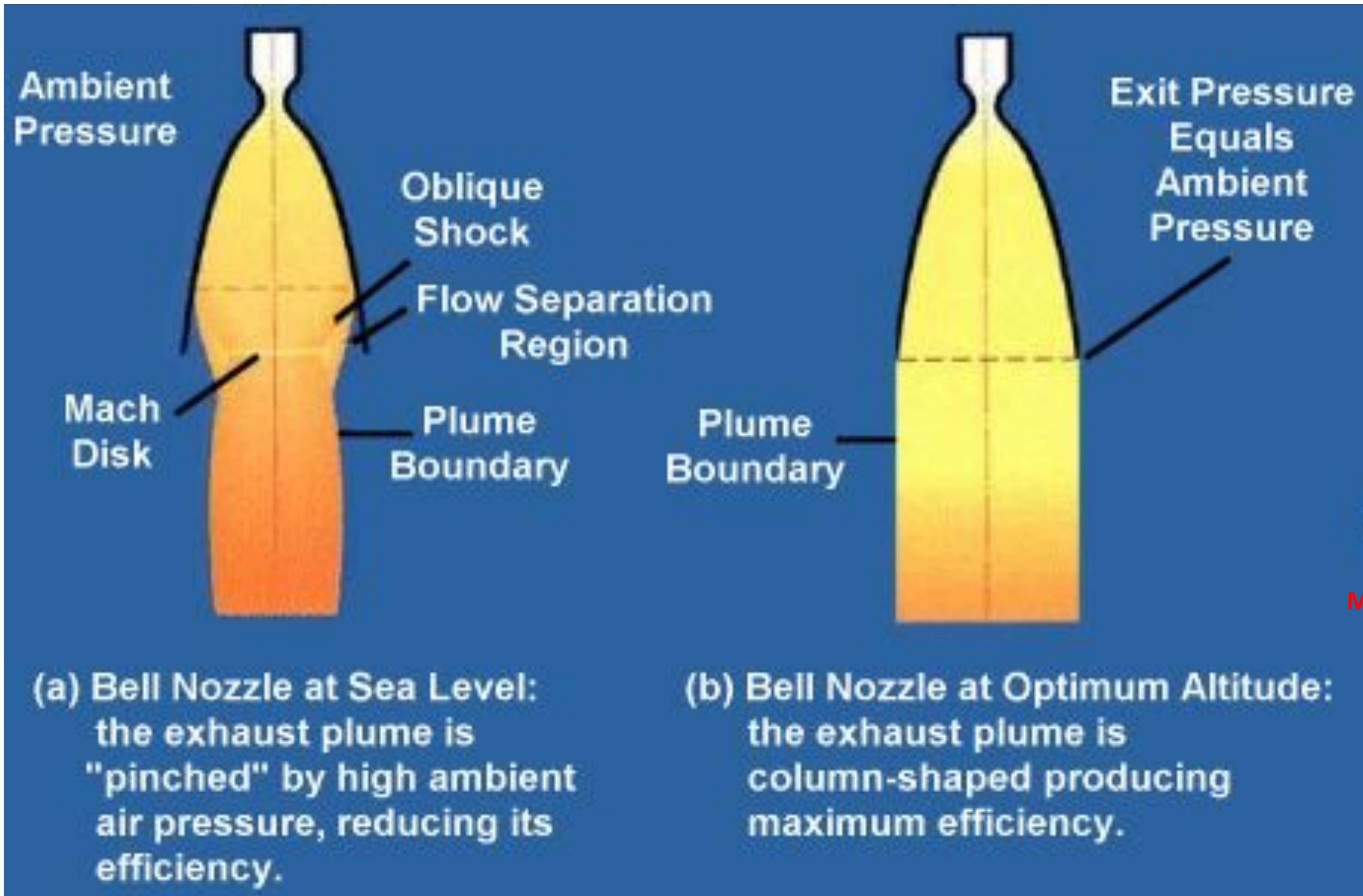
But that is not the entire story

- Since rockets operate in a wide range of atmospheric conditions, the design point of the rocket is critical to designing the rocket nozzle
- For a single stage rocket motor, lift-off from the ground is the most critical, so $p_e=p_a$ at S.L. is usually preferred, so the rocket nozzle is short, but as the rocket starts ascending $p_e>p_a$, resulting in an under- expanded condition.
- Multi-stage motors might be designed to different points, depending on which altitude condition they are fired at.
- Another criterion that the equation doesn't comprehend is aerodynamic drag on the nozzle while still in the atmosphere (installed drag)
  - Installed drag minimization calls for a shorter nozzle
  - Weight requirements also call for a shorter nozzle

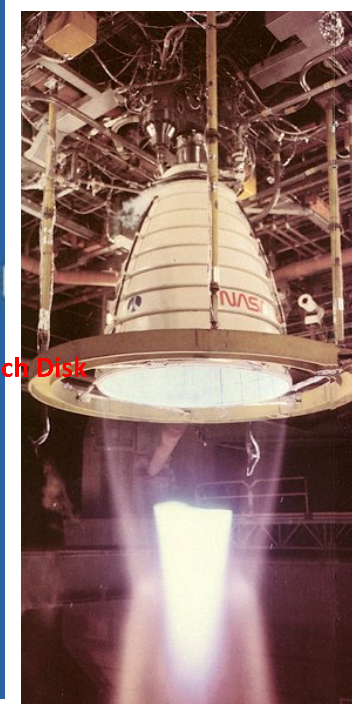
Under-Expanded Rocket Nozzle



Over-Expanded Rocket Nozzle



SPACE SHUTTLE MAIN ENGINE



http://www.aerospaceweb.org/question/propulsion/q0220.shtml