ME 239: Rocket Propulsion

Over- and Under-expanded Nozzles and Nozzle Configurations

J. M. Meyers, PhD

Over- and Underexpanded Nozzles

Underexpanded Nozzle

- Discharges fluid at an exit pressure greater than the external pressure
- This owes to the exit area being too small for an optimum area ratio
- The expansion of the fluid is incomplete
- Further expansion happens outside of the nozzle
- Nozzle exit pressure is greater than local atmospheric pressure

Overexpanded Nozzle

- Fluid exits at lower pressure than the atmosphere
- This owes to an exit area too large for optimum

Over- and Under-expanded Nozzles

Curve AB:
- variation of axial pressure with optimum back pressure for given nozzle area ratio

Curves AC thru AF:
- Variation of axial pressure for increasingly higher external pressures.
- Sudden rise in pressure represents flow separation.
- This results in shock formation (sharp pressure rise) within the nozzle
- This shock is pushed upstream toward the nozzle as ambient pressure increases

Curve AG:
- Significant back pressure has caused the nozzle to "unstart" meaning the nozzle is no longer choked
- The diverging section now decelerates the flow

Curve AH:
- Further back pressure increase drives reduces the pressure and resulting exit velocity

Overexpanded Nozzle Pressure Traces

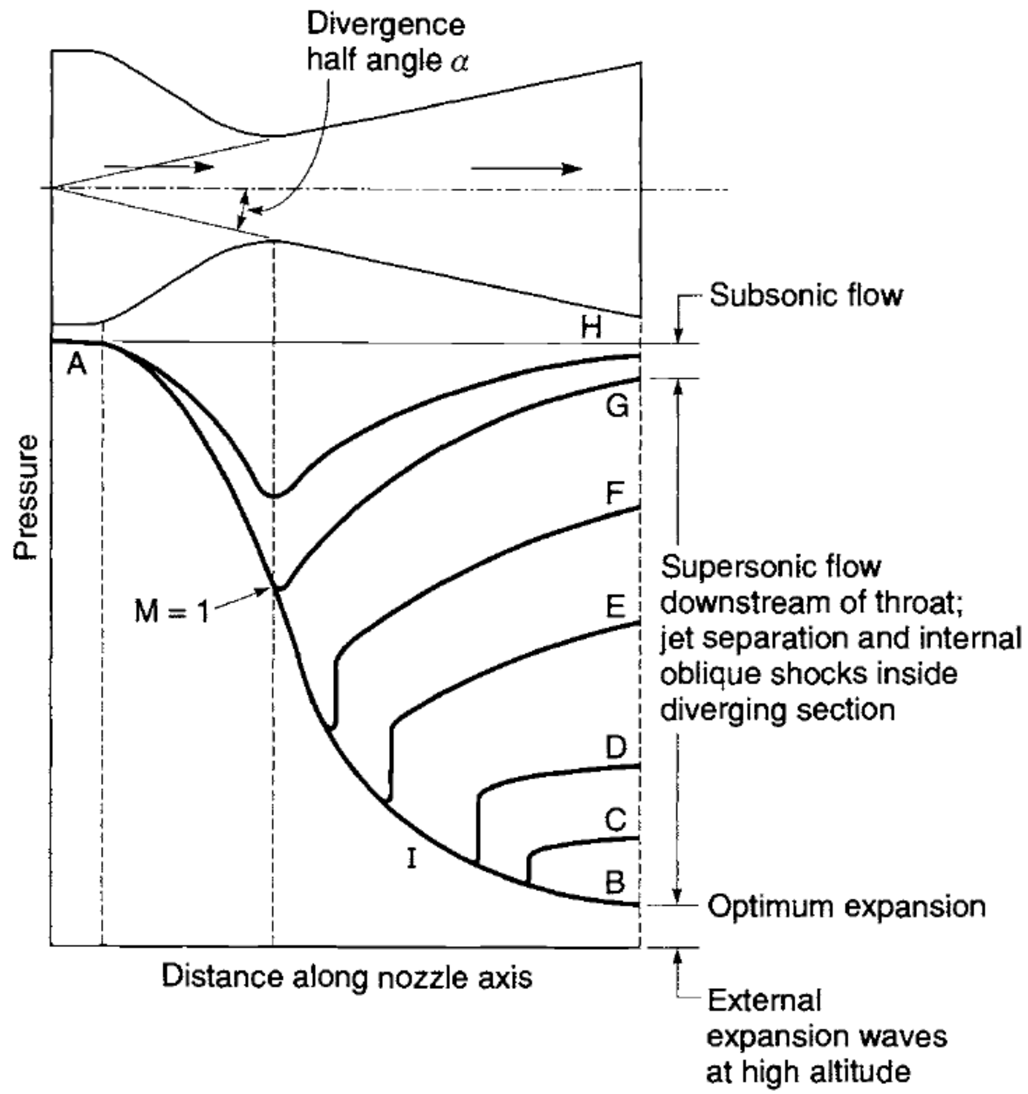
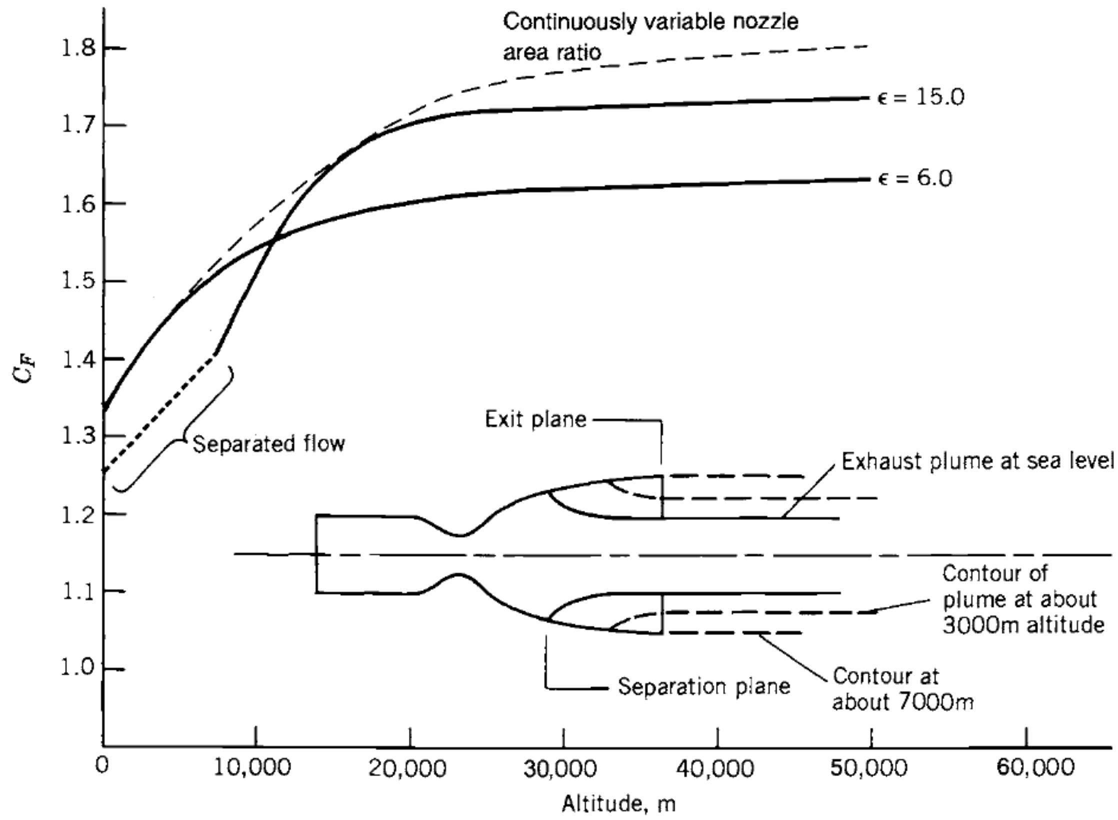


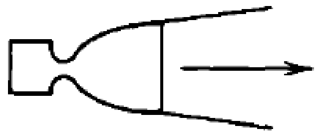
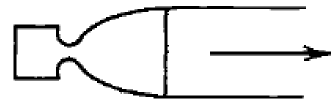
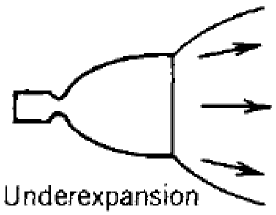
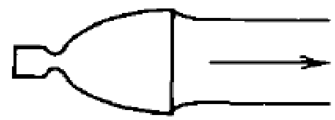
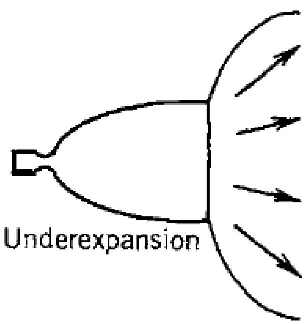
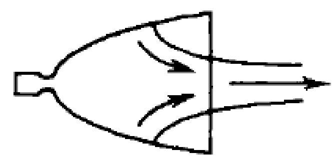
Fig 3-9: Distribution of pressures in a C-D nozzle for different flow conditions. Inlet pressure the same but back pressure (exit pressure) is not.

Over- and Underexpanded Nozzles

- For higher external pressures , separation will occur inside the divergent portion of the nozzle
- The jet diameter will be smaller than that of the nozzle exit diameter
- Separation location depends on local pressure and wall contour
- Decreasing external pressure pushes the separation plane out toward the nozzle (optimal altitude is being approached)



Over- and Underexpanded Nozzles

		During flight			During sealevel static tests		
Stage	A_2/A_t		h(km)	I_s (sec)		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

Over- and Underexpanded Nozzles

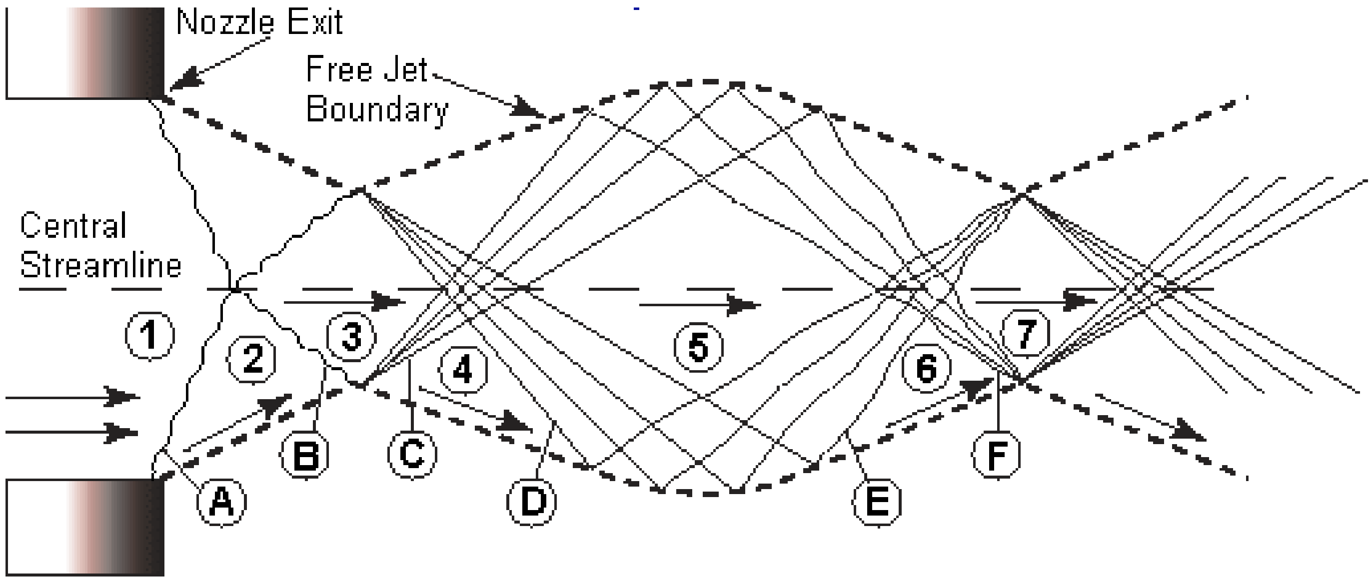
Shuttle Main Engine Test (ε ~ 77)

Overexpanded Nozzle

- Static pressure at exit of Space Shuttle Main Engine nozzle is considerably less than ambient pressure at sea level
- Mismatch in pressure gives rise to Mach "disc" in nozzle exhaust
- Extremely strong shock wave that creates a region of subsonic flow and produces a characteristic white luminescent glow
- Flow in picture is over-expanded (lift-off)

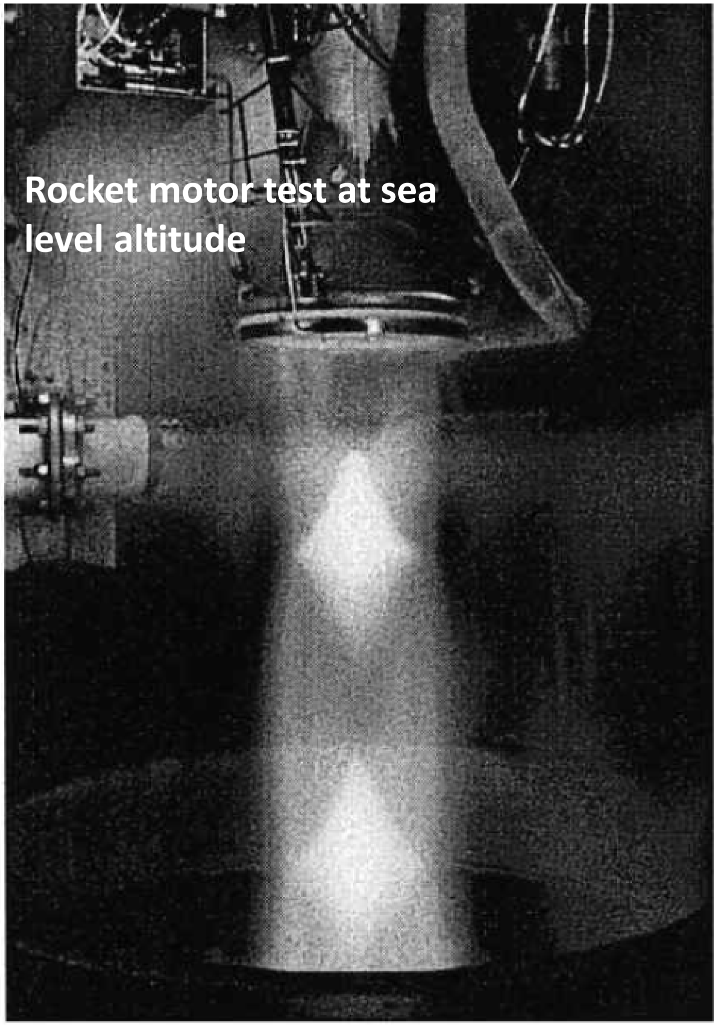
Over- and Underexpanded Nozzles

Overexpanded Nozzle



Over- and Underexpanded Nozzles

Overexpanded Nozzle



a)

Underexpanded Nozzle

b)

Over- and Underexpanded Nozzles

$$F = \dot{m}v_2 + A_2(P_2 - P_3)$$

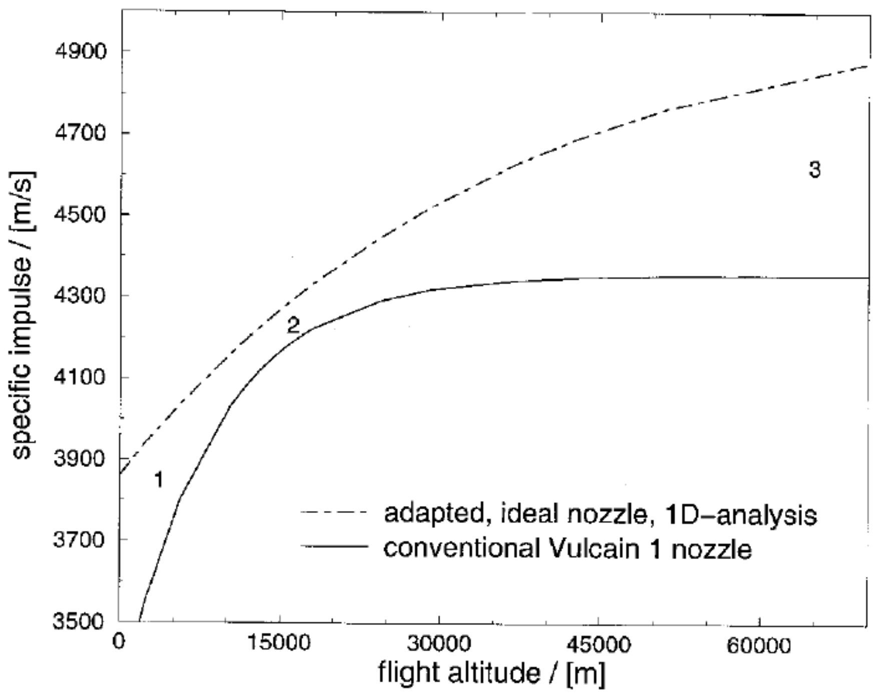
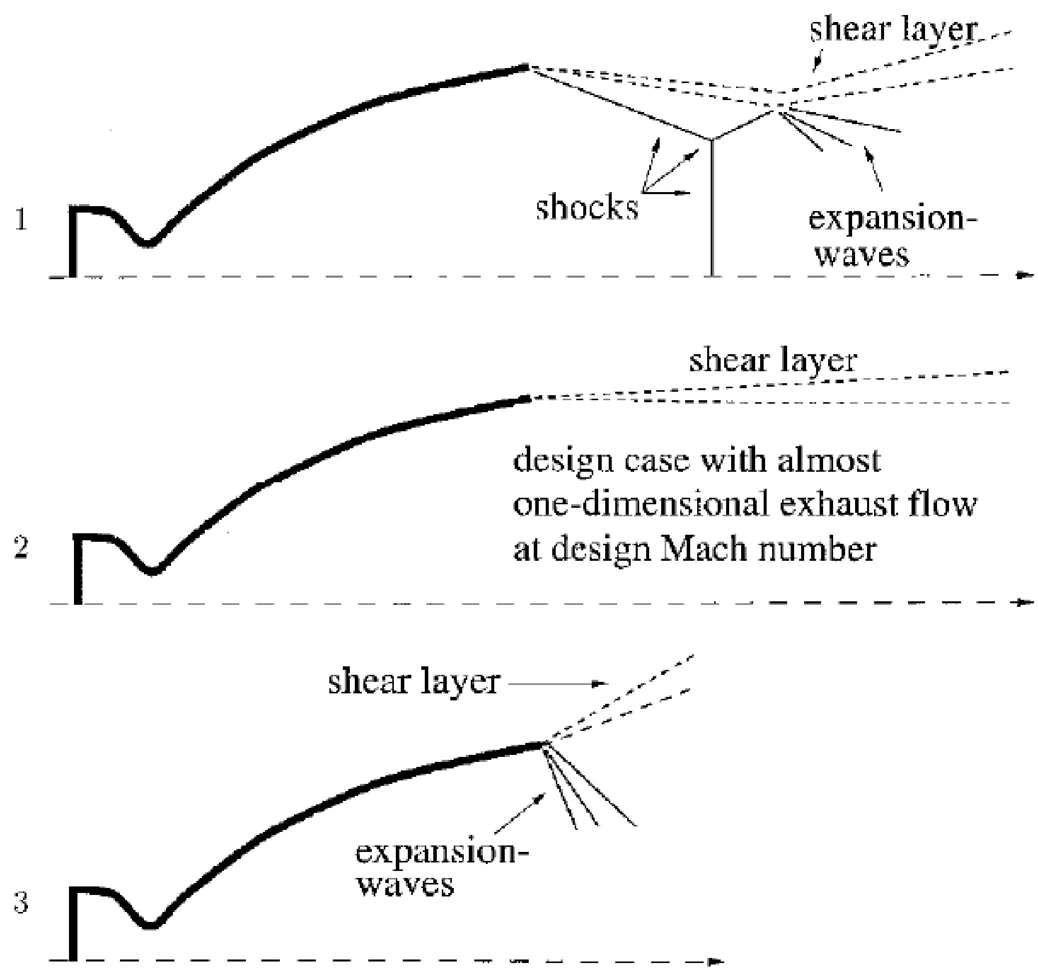


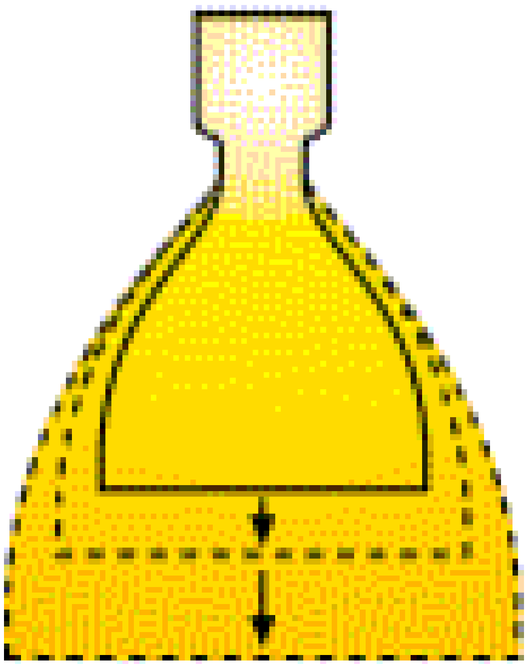
Fig. 3 Performance data for nozzle of Vulcain 1 engine (design parameters of Vulcain 1 nozzle: $\varepsilon = 45$, $p_c/p_{amb} = 555$, $\bar{r} = 5.89$).



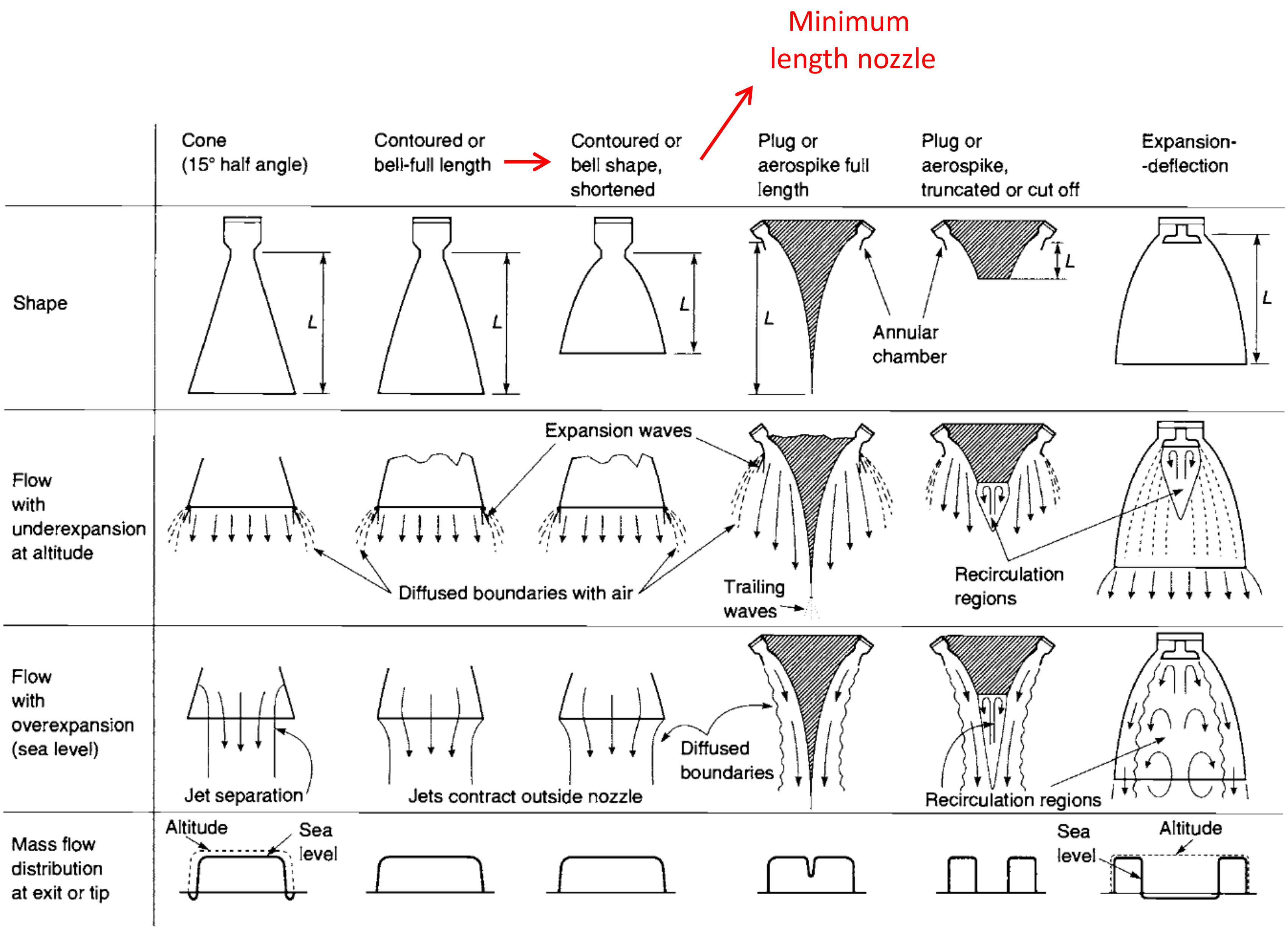
Core engine of European Ariane-5 launcher

G. Hagemann et al., "Advanced Rocket Nozzles," JOURNAL OF PROPULSION AND POWER, Vol. 14, No. 5, September –October 1998

- Ideal situation would be to have size of nozzle bell increase as altitude increases
- Altitude Adaptive Nozzles:
  - Dual-Bell Nozzle
  - Inserts, fixed and ejectable
  - Gas injection
  - Variable geometry (two-position)



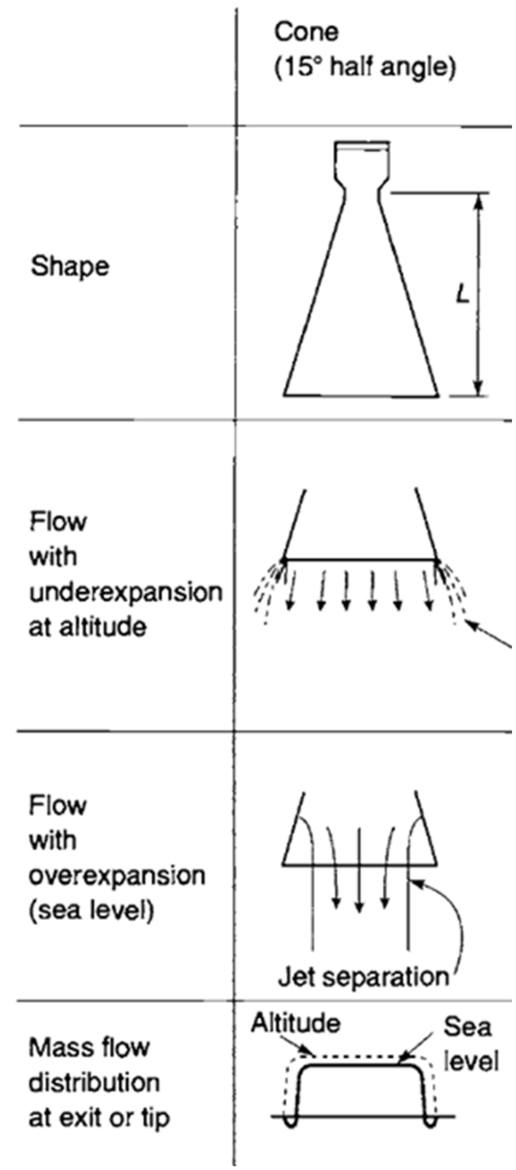
Nozzle Configurations



Nozzle Configurations: Conical Nozzles

- Oldest nozzle type for rocket applications due to simplicity and ease of construction
- Cone gets its name from the fact that the walls diverge at a constant angle
- A small angle produces greater thrust, because it maximizes the axial component of exit velocity and produces a high specific impulse
- Penalty is longer and heavier nozzle that is more complex to build
- At the other extreme, size and weight are minimized by a large nozzle wall angle
  - Large angles reduce performance at low altitude because high ambient pressure causes overexpansion and flow separation
- Primary Metric of Characterization: Divergence Loss

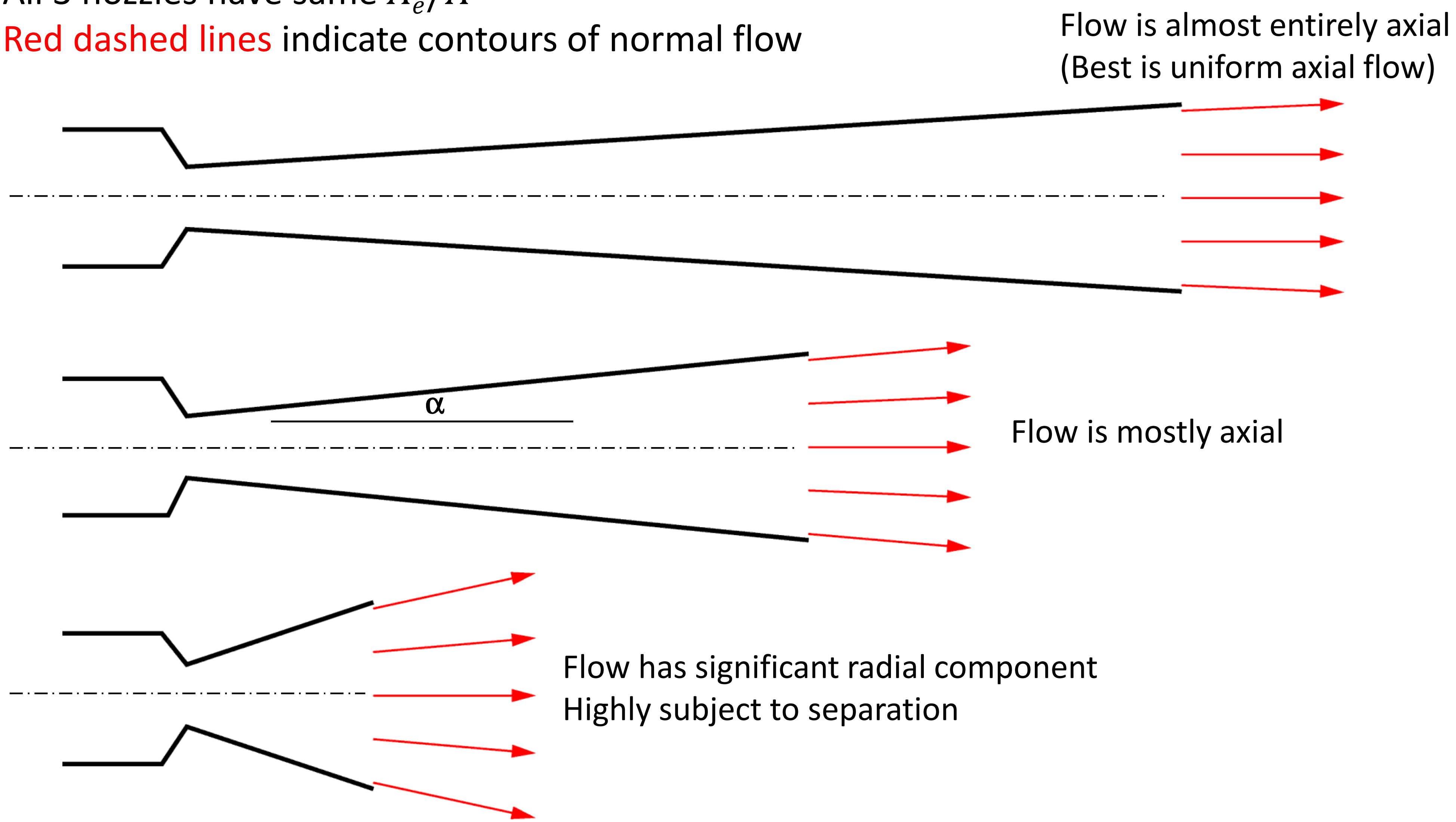
$$\lambda = \frac{1+\cos\alpha}{2}$$



Nozzle Configurations: Conical Nozzles

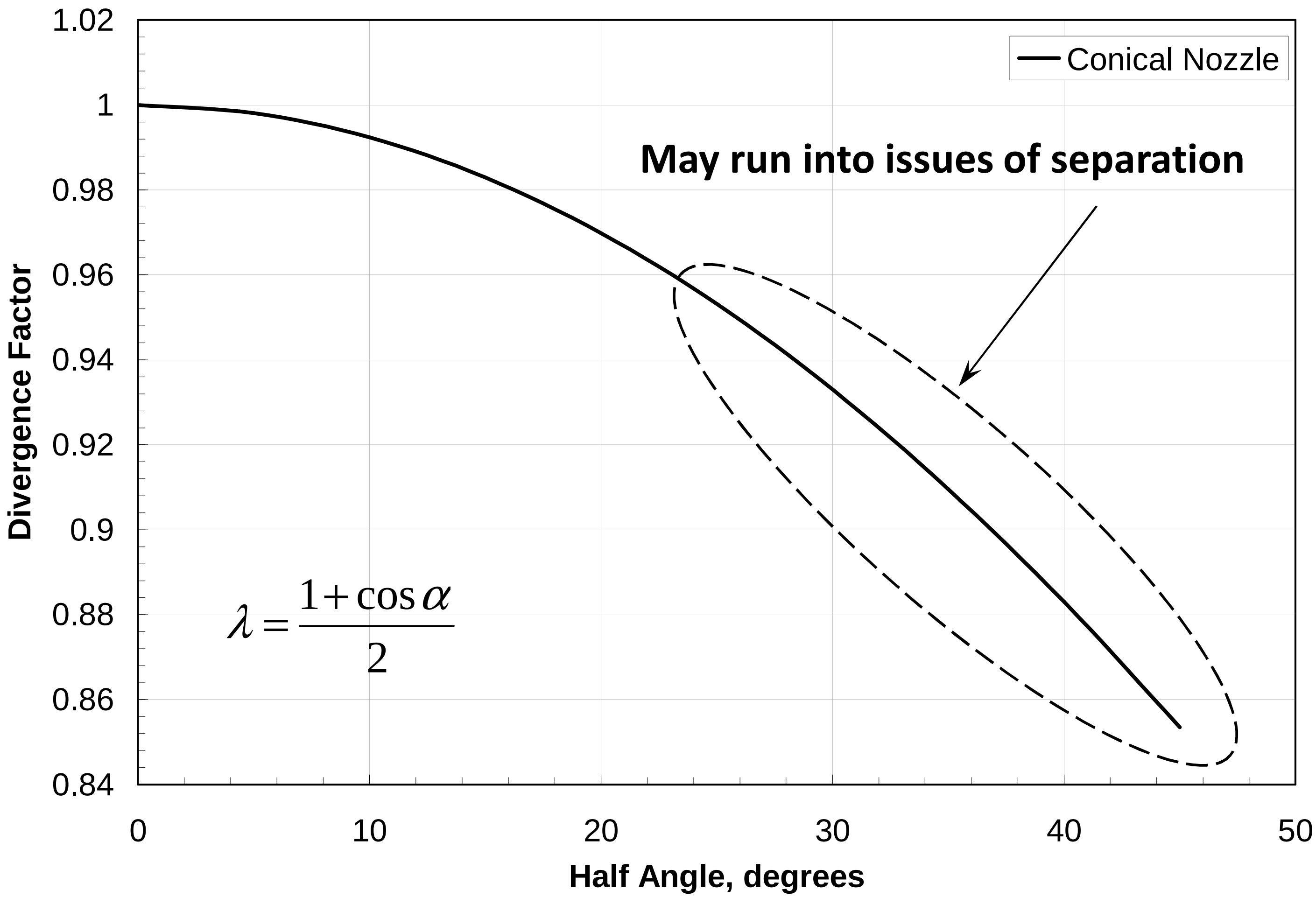
All 3 nozzles have same A_e/A^*

Red dashed lines indicate contours of normal flow



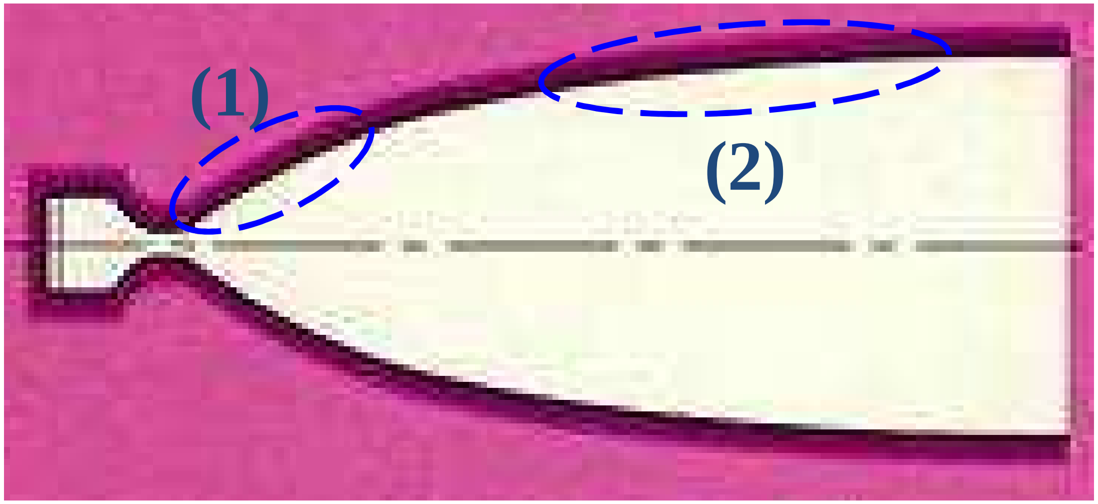
Nozzle Configurations: Conical Nozzles

- Deviation of flow from axial (thrust direction) is called the divergence factor
- Longer Nozzle → Higher Thrust and Increased Weight



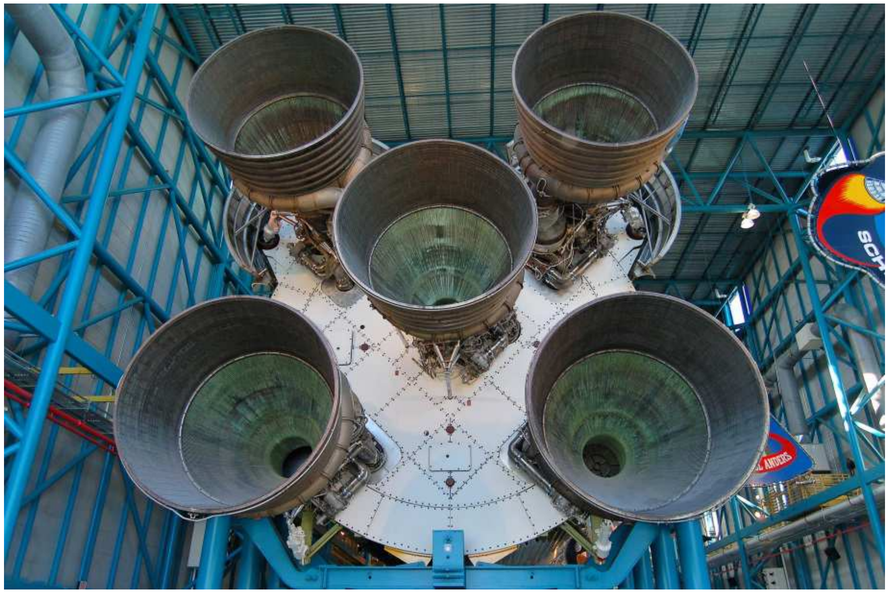
Nozzle Configurations: Contoured Nozzles

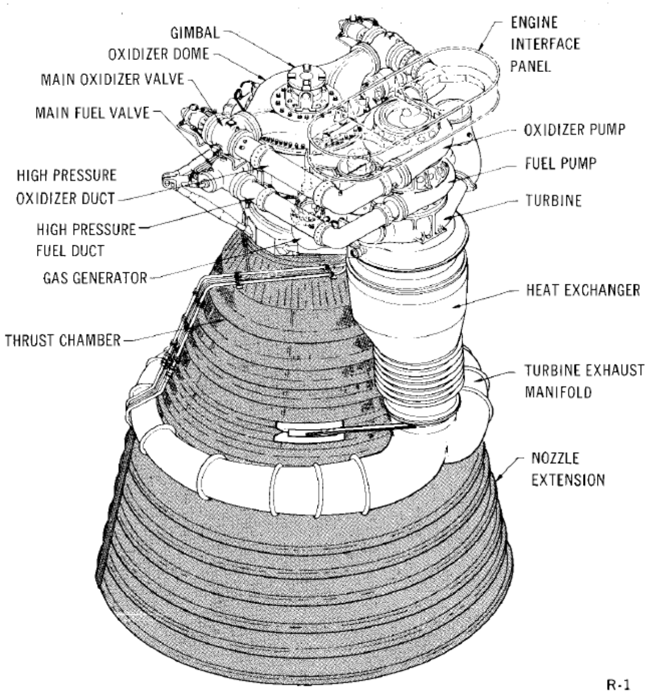
- Contoured nozzles are most common
- Offers significant advantages over conical nozzle, both in size and performance
- Bell consists of two sections
  - Near throat, nozzle diverges at relatively large angle, **(1)**
  - Degree of divergence tapers off further downstream
  - Near nozzle exit, divergence angle is very small ~2º-8º, **(2)**
  - Minimize weight / maximize performance ~10-25% shorter than conic
- Issue is to contour nozzle to avoid oblique shocks and maximize performance
- Remember: Shape only optimum at one altitude



Further Subclasses
- Contoured Full Length
- Contoured Shortened
- Contoured Minimum Length

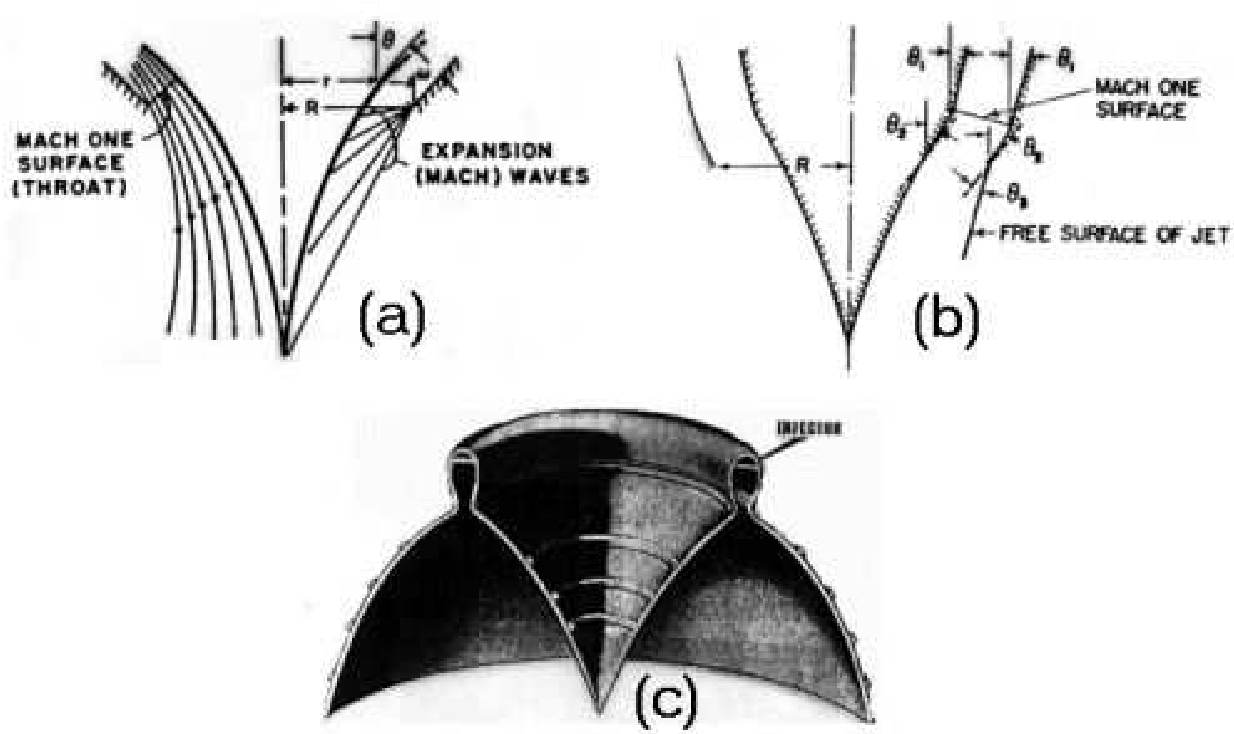
Nozzle Configurations: Contoured Nozzles





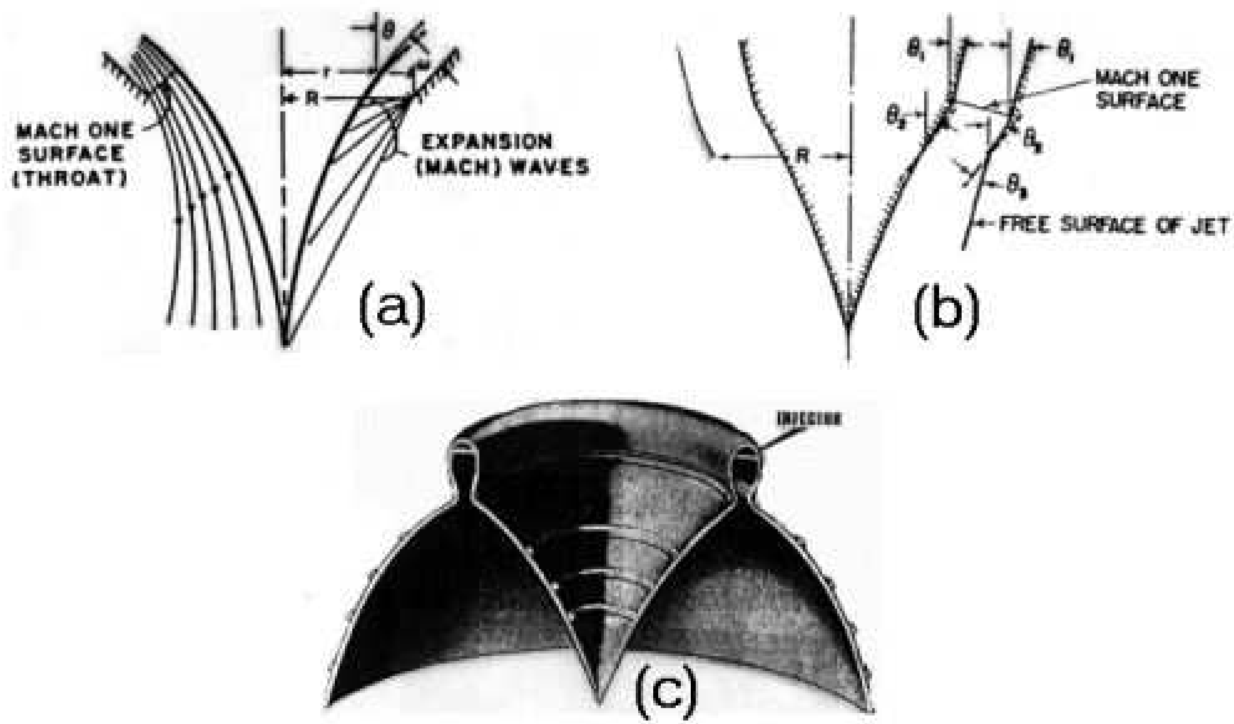
Nozzle Configurations: Aerospike Nozzles

- Often referred to as spike nozzles
  - Named for prominent spike centerbody
  - May be thought of as a contoured nozzleturned inside out
  - Nozzle is only one of many possible spike configurations
    - (a) traditional curved spike with completely external supersonic expansion
    - (b) similar shape in which part of the expansion occurs internally
    - (c) design similar to E-D nozzle in which all expansion occurs internally

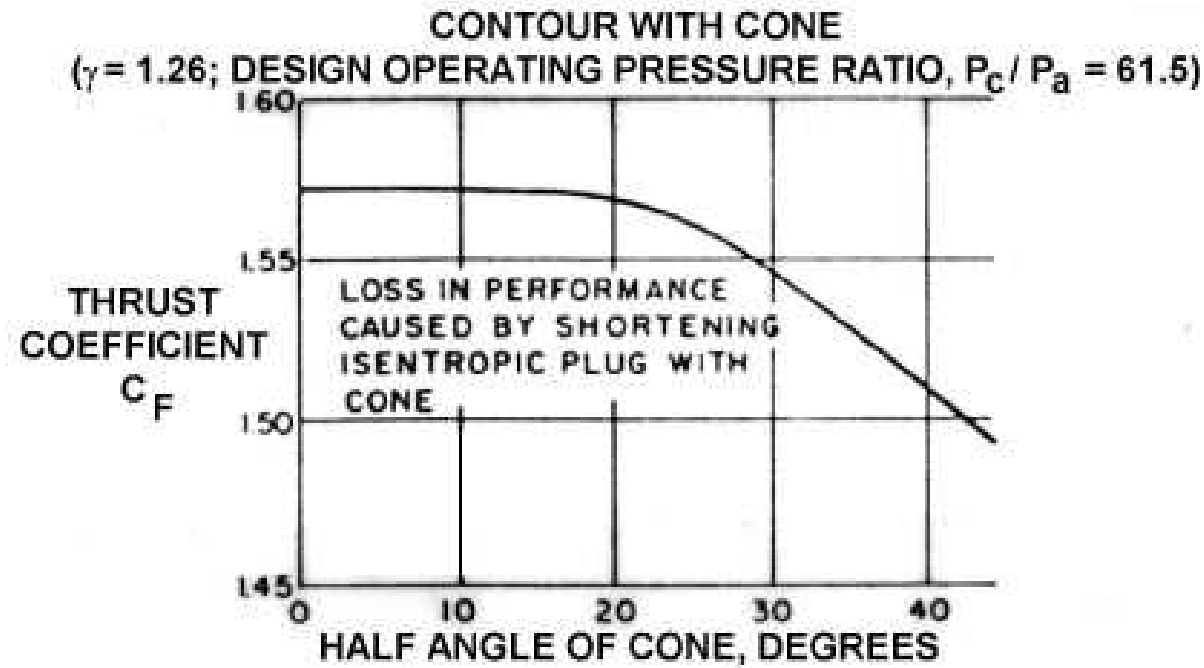


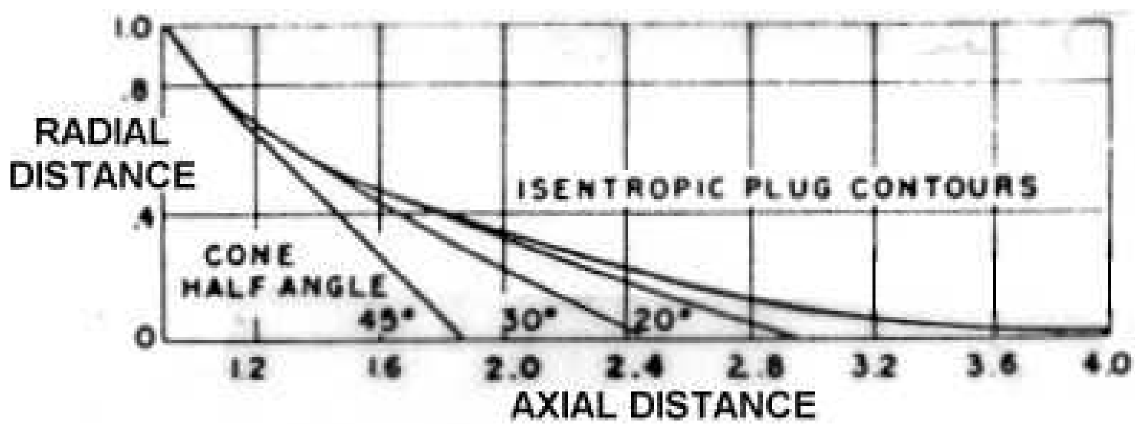
Nozzle Configurations: Aerospike Nozzles

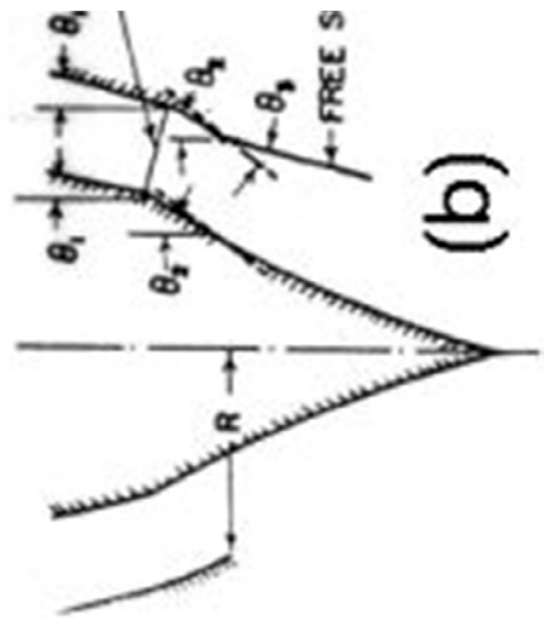
- Each of spike nozzles features a curved, pointed spike
  - Most ideal shape
- Spike shape allows exhaust gases to expand through isentropic process
- Nozzle efficiency is maximized and no energy is lost because of turbulent mixing
- Isentropic spike may be most efficient but tends to be prohibitively long and heavy
- Replace curve shape by shorter and easier to construct cone ~1% performance loss
- Can be **linear** or **axisymmetric**



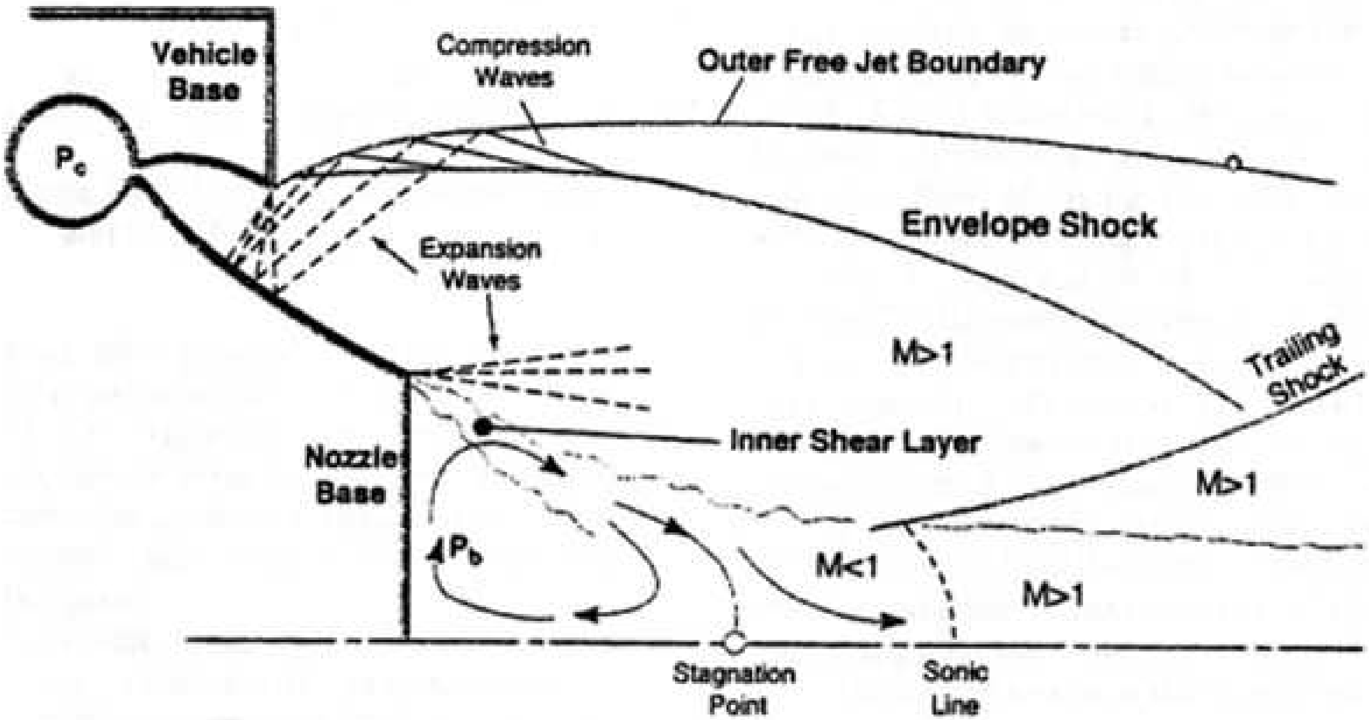
Nozzle Configurations: Aerospike Nozzles

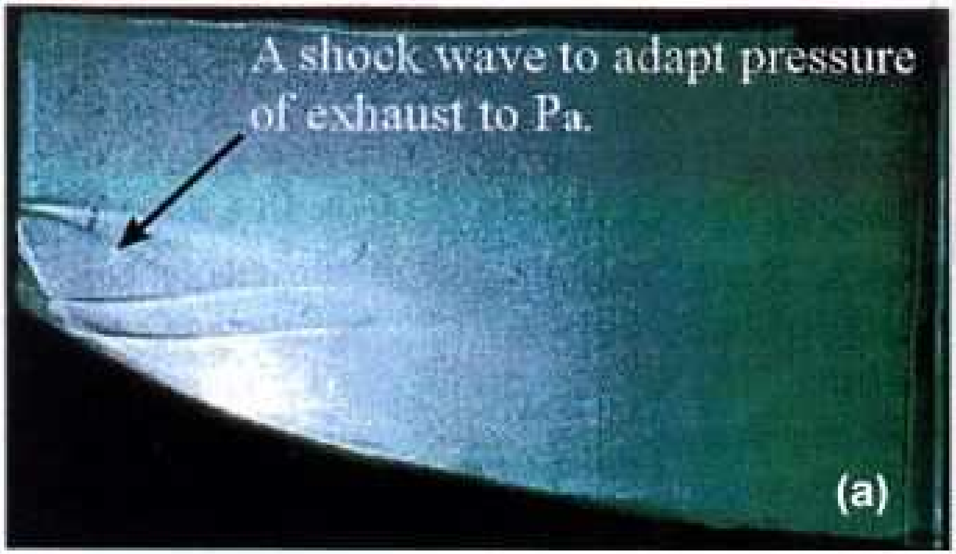


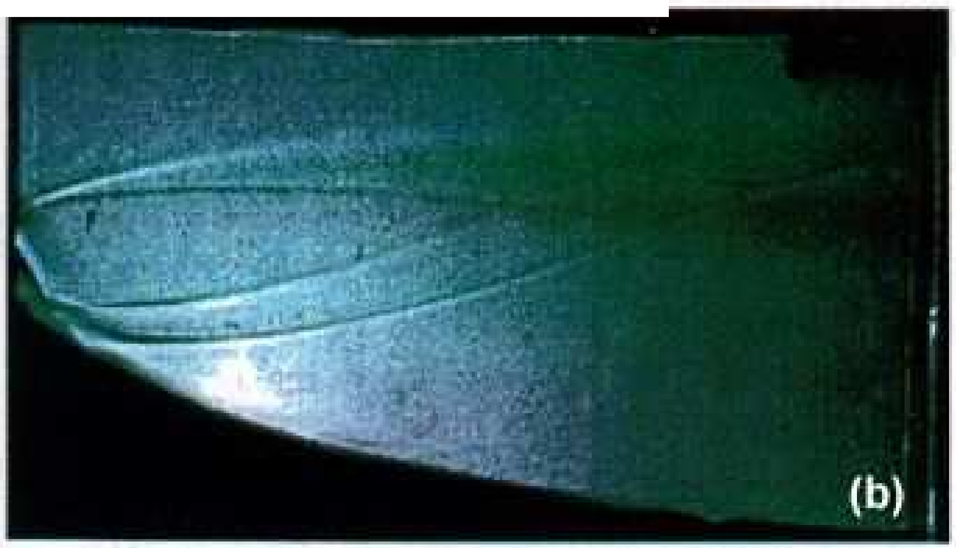




Nozzle Configurations: Aerospike Nozzles



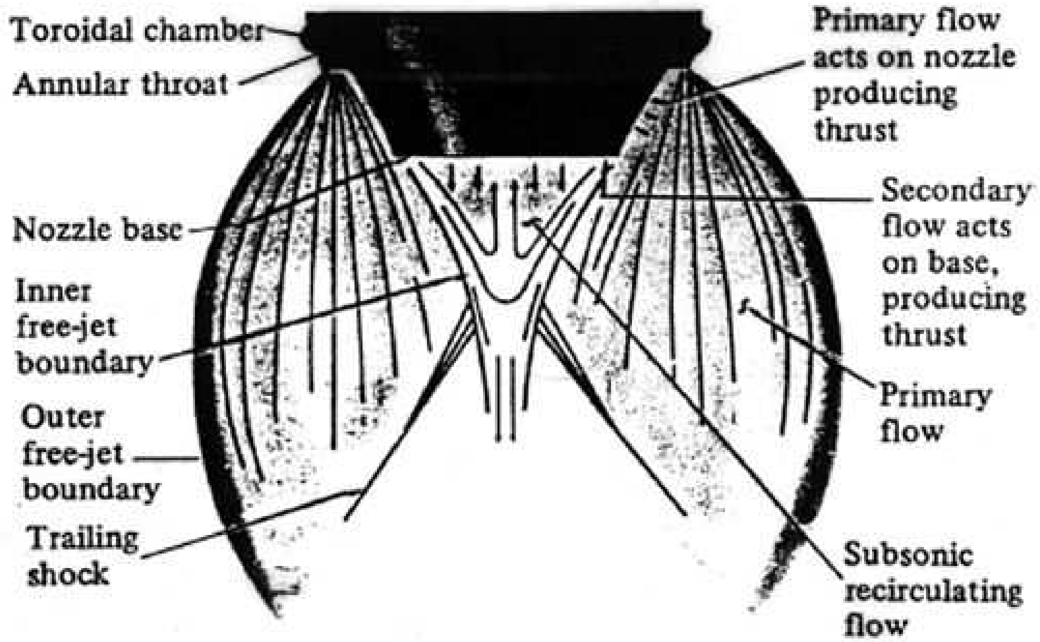


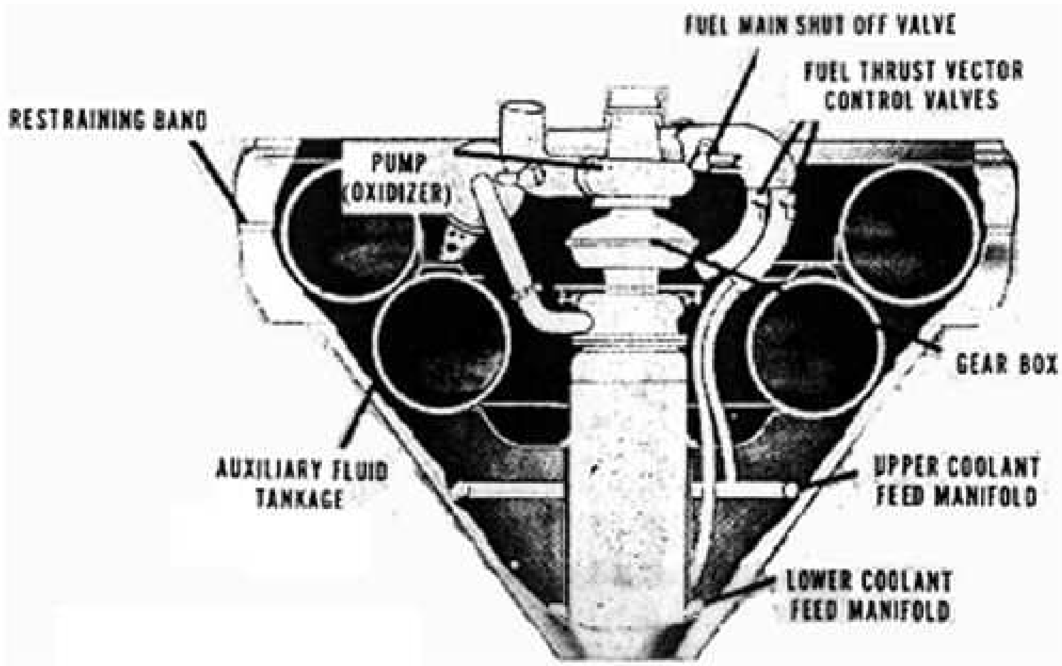


Nozzle Configurations: Truncated Aerospike

- Go even further by removing pointed spike altogether and replace with a flat base
  - This configuration is known as a truncated spike

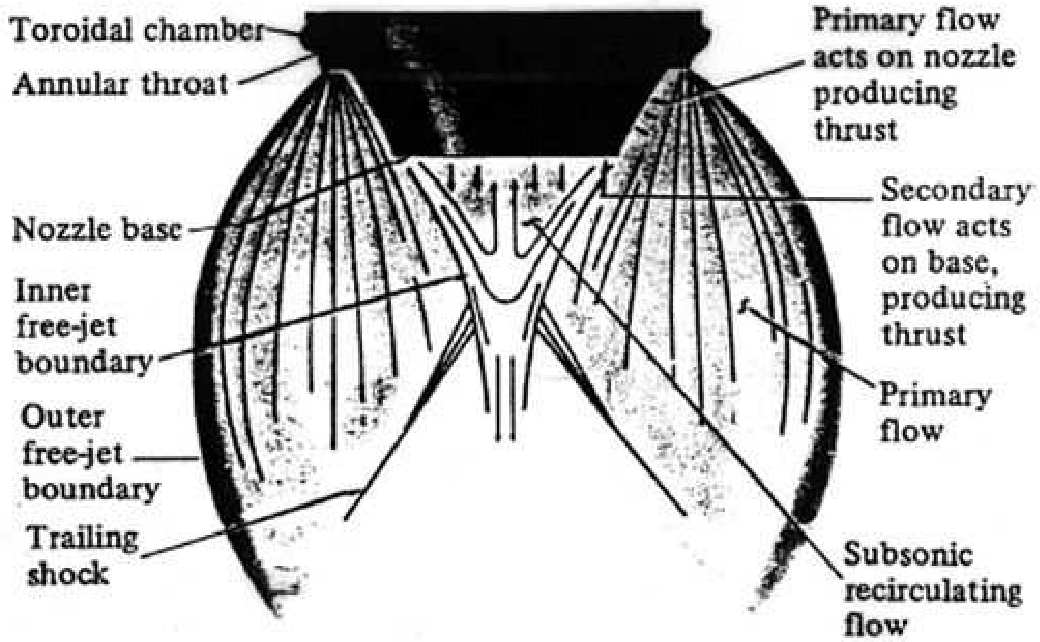
- Disadvantage of "flat" plug is turbulent wake forms aft of base at high altitudes resulting in high base drag and reduced efficiency

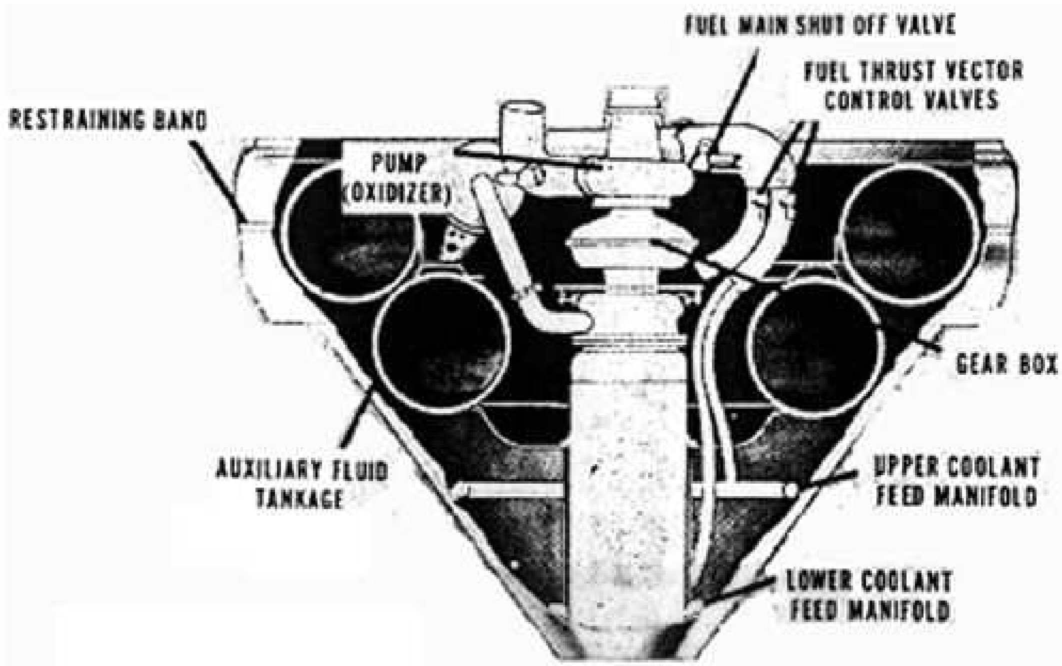




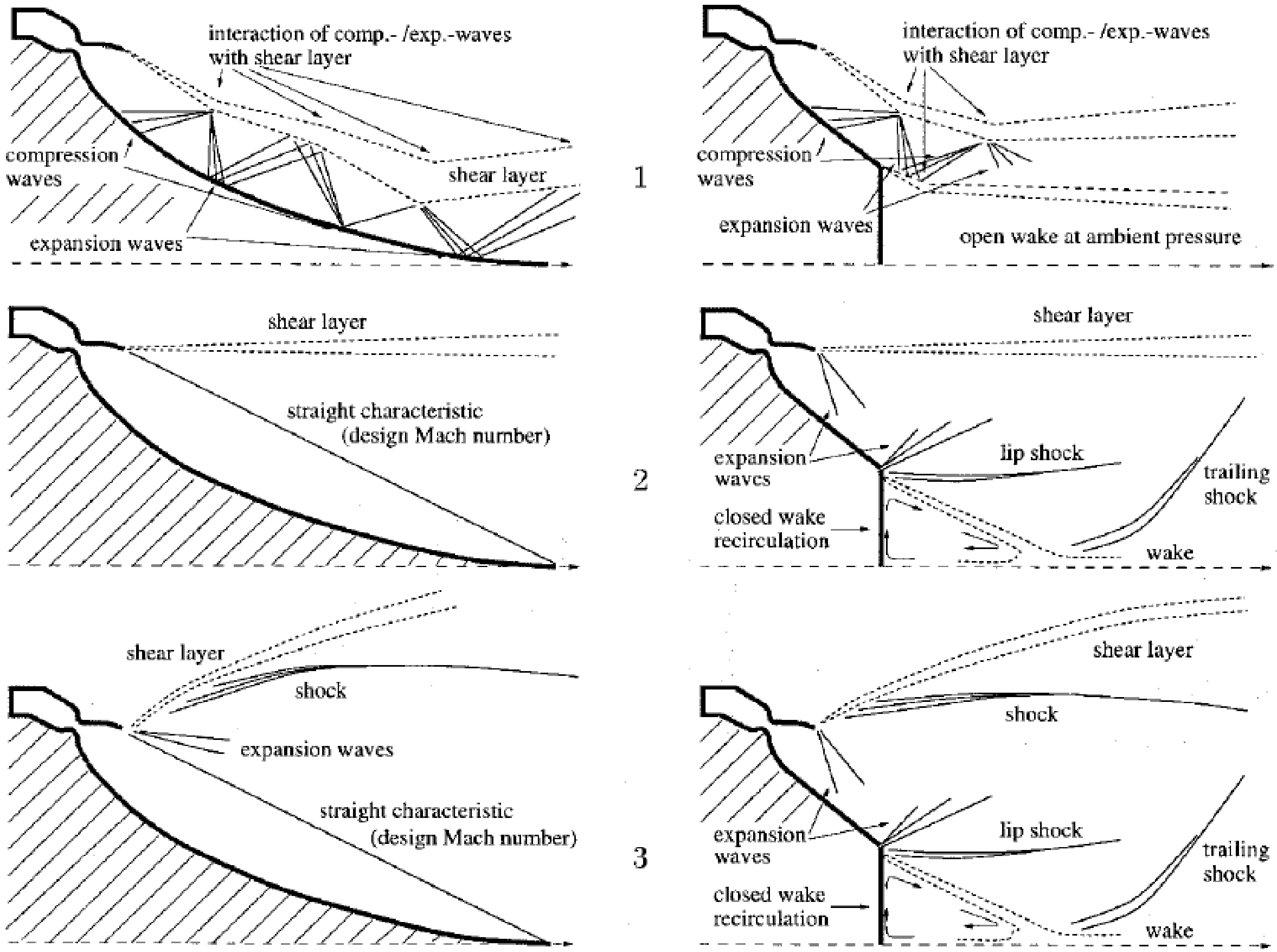
Nozzle Configurations: Truncated Aerospike

- Reduced energy results from high kinetic energy being transformed to thermal energy in the separation process resulting in the need for significant thermal management at the truncation location
- Alleviated by introducing a "base bleed," or secondary subsonic flow
- Circulation of this secondary flow and its interaction with the engine exhaust creates an "aerodynamic spike" that behaves much like the ideal, isentropic spike
- Secondary flow re-circulates upward pushing on base to produce additional thrust





Nozzle Configurations: Truncated Aerospike Nozzles



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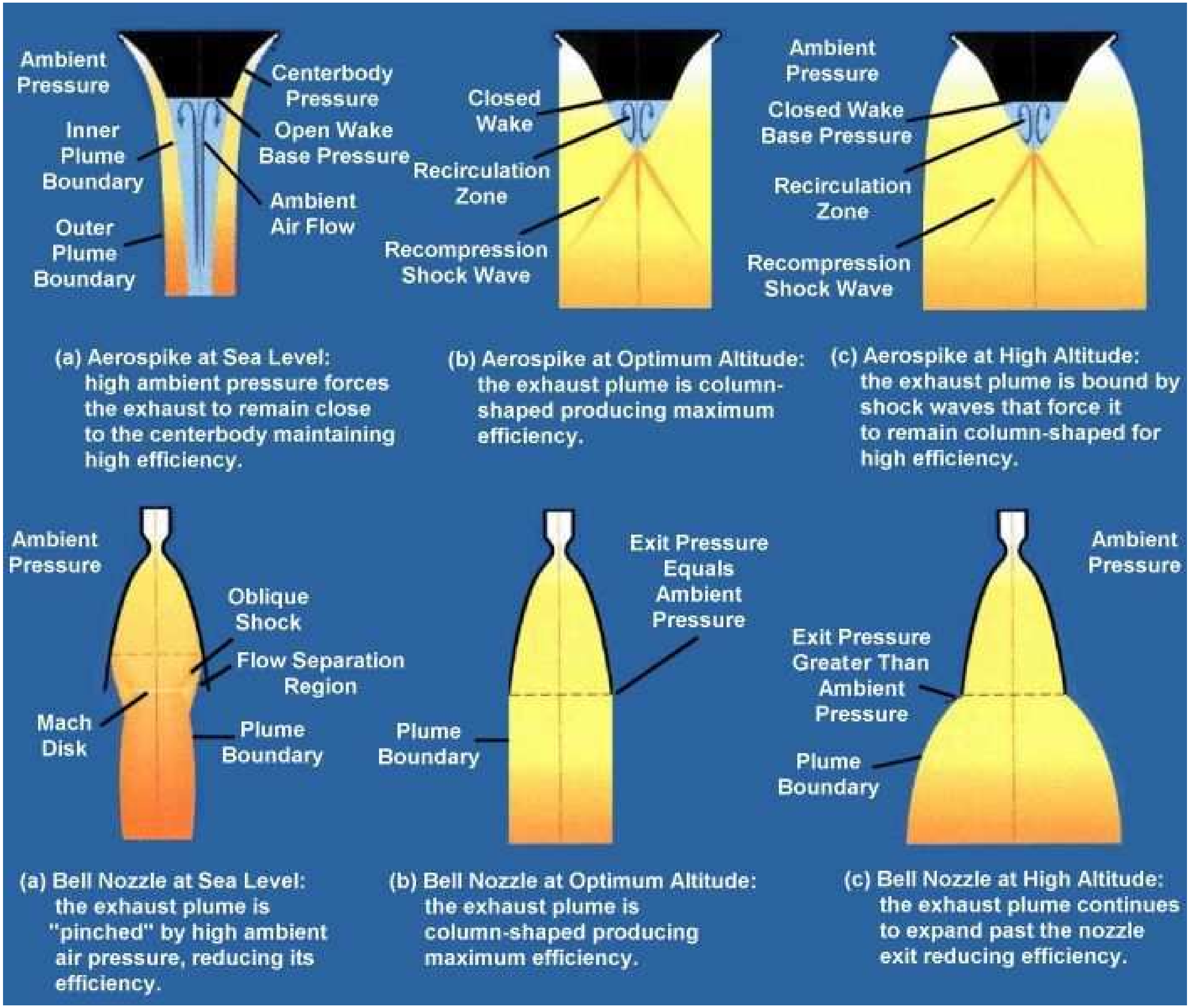
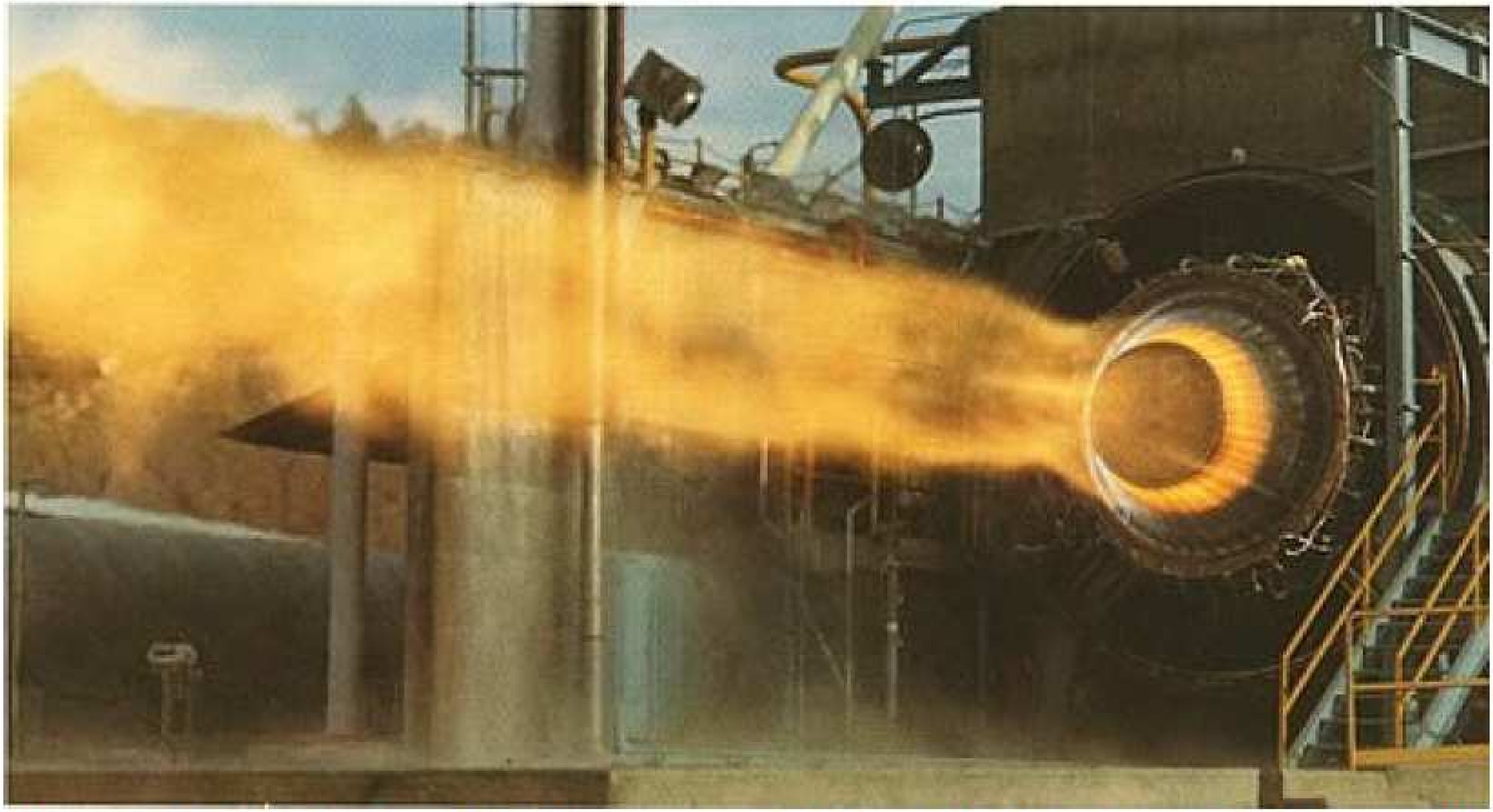
Nozzle Configurations: Aerospike Nozzles



Nozzle Configurations: Aerospike



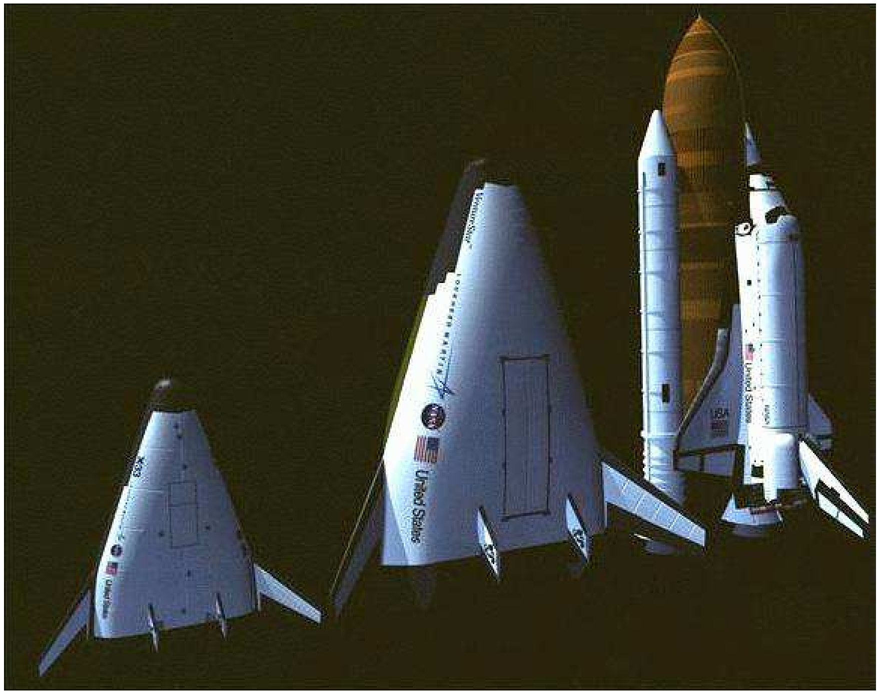
During the 1960s, Pratt & Whitney Rocketdyne tested numerous aerospike engines, ranging in size from subscale, cold-flow models to this 250,000-pound-thrust oxygen/ hydrogen engine shown at a test stand in Nevada.

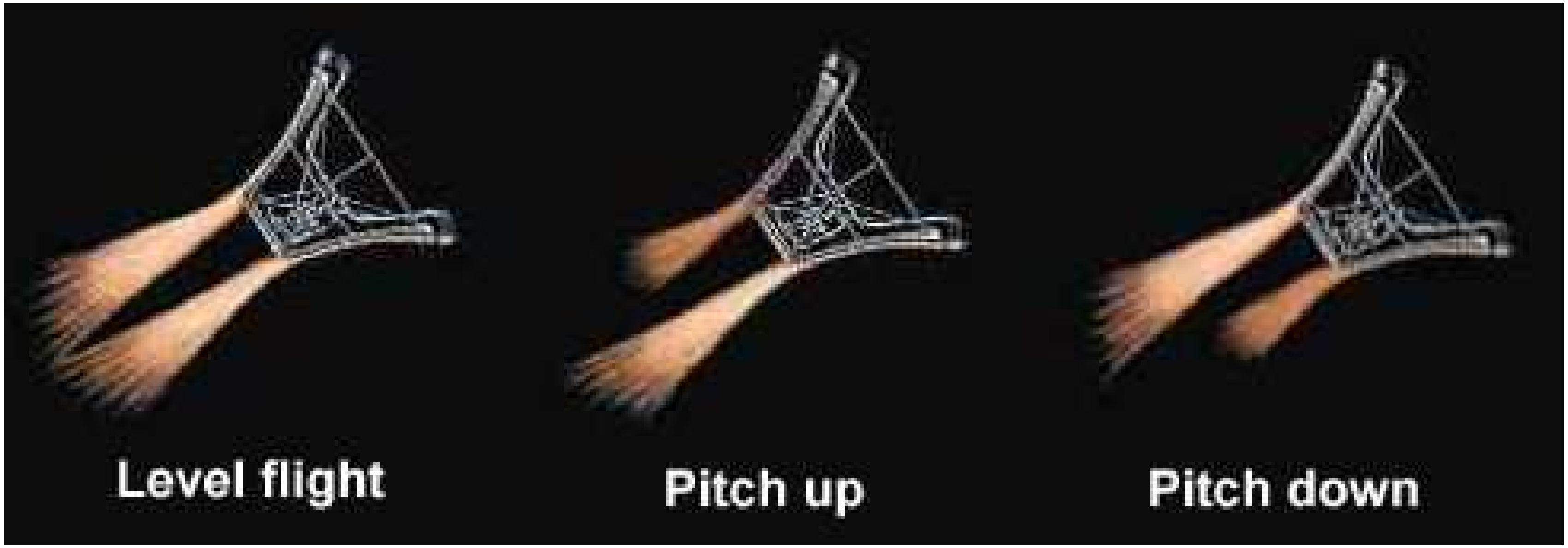
Nozzle Configurations: Linear Aerospike

- Still another variation of aerospike nozzle is linear (instead of annular)
- Linear Aerospike pioneered by Rocketdyne (now division of Boeing) in 1970's
- Places combustion chambers in a line along two sides of nozzle
- Approach results in more versatile design
  - Use of lower-cost modular combustors
  - Modules can be combined in varying configurations depending on application.

Nozzle Configurations: Linear Aerospike

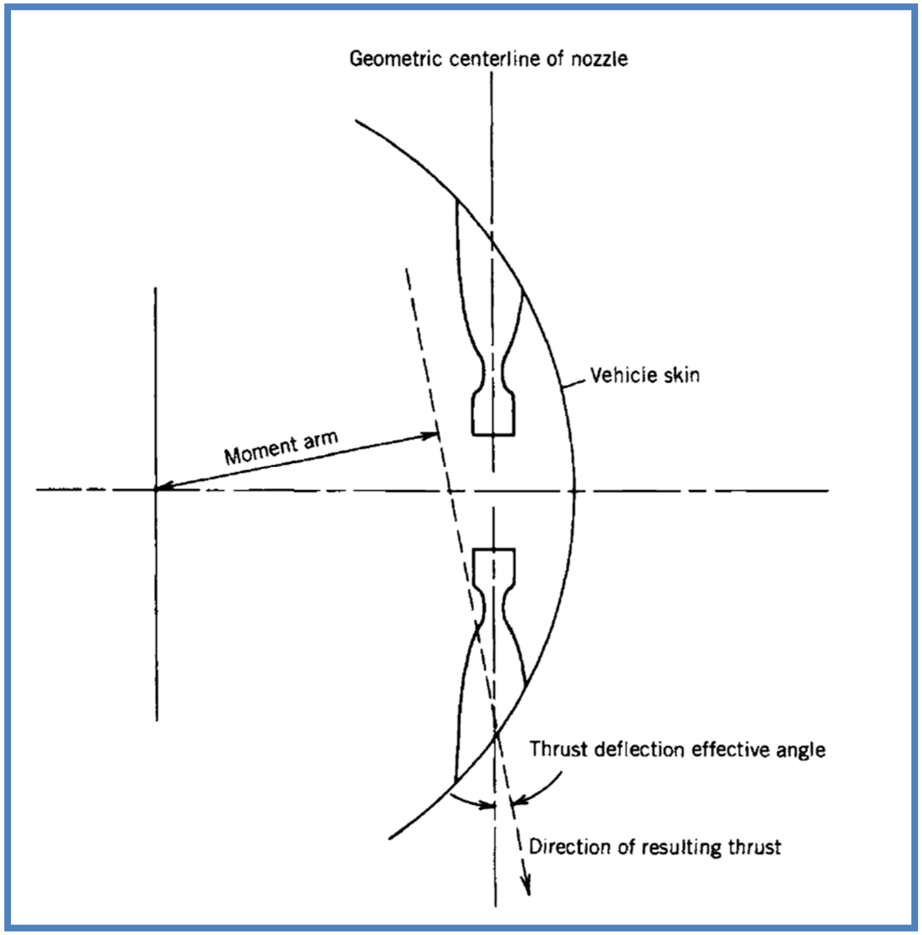
Nozzle Configurations: Linear Aerospike





Nozzle Alignment

- When the motor thrust does not align with the vehicle's mass center a turning moment will be generated
- This turning moment will cause the vehicle to rotate
- This can be undesirable for conditions where altitude gain is desired (boost and upper stage)
- It can also be useful for attitude adjustment. If these motors can be placed far from the body's CG providing improved mechanical advantage



Exit of nozzles for Shuttle attitude adjustment motors