

Propulsion Systems Design

- Rocket engine basics
- Solid rocket motors
- Liquid rocket engines
 - Monopropellants
 - Bipropellants
 - Propellant feed systems
- Hybrid rocket engines
- Auxiliary propulsion systems



Thermal Rocket Exhaust Velocity

- Exhaust velocity is

$$V_e = \sqrt{\frac{2\gamma}{\gamma-1} \frac{\mathfrak{R}T_0}{\bar{M}} \left[1 - \left(\frac{p_e}{p_0} \right)^{\frac{\gamma-1}{\gamma}} \right]}$$

where

\bar{M} \equiv average molecular weight of exhaust

\mathfrak{R} \equiv universal gas const. = $8314.3 \frac{\text{Joules}}{\text{mole}^\circ\text{K}}$

γ \equiv ratio of specific heats ≈ 1.2



Ideal Thermal Rocket Exhaust Velocity

- Ideal exhaust velocity is

$$V_e = \sqrt{\frac{2\gamma}{\gamma-1} \frac{\mathfrak{R}T_0}{\bar{M}}}$$

- This corresponds to an ideally expanded nozzle
- All thermal energy converted to kinetic energy of exhaust
- Only a function of temperature and molecular weight!



Thermal Rocket Performance

- Thrust is

$$T = \dot{m}V_e + (p_e - p_{amb})A_e$$

- Effective exhaust velocity

$$T = \dot{m}c \Rightarrow c = V_e + (p_e - p_{amb}) \frac{A_e}{\dot{m}}$$

$$\left(I_{sp} = \frac{c}{g_0} \right)$$

- Expansion ratio

$$\frac{A_t}{A_e} = \left(\frac{\gamma + 1}{2} \right)^{\frac{1}{\gamma-1}} \left(\frac{p_e}{p_0} \right)^{\frac{1}{\gamma}} \sqrt{\frac{\gamma + 1}{\gamma - 1} \left[1 - \left(\frac{p_e}{p_0} \right)^{\frac{\gamma-1}{\gamma}} \right]}$$



Nozzle Design

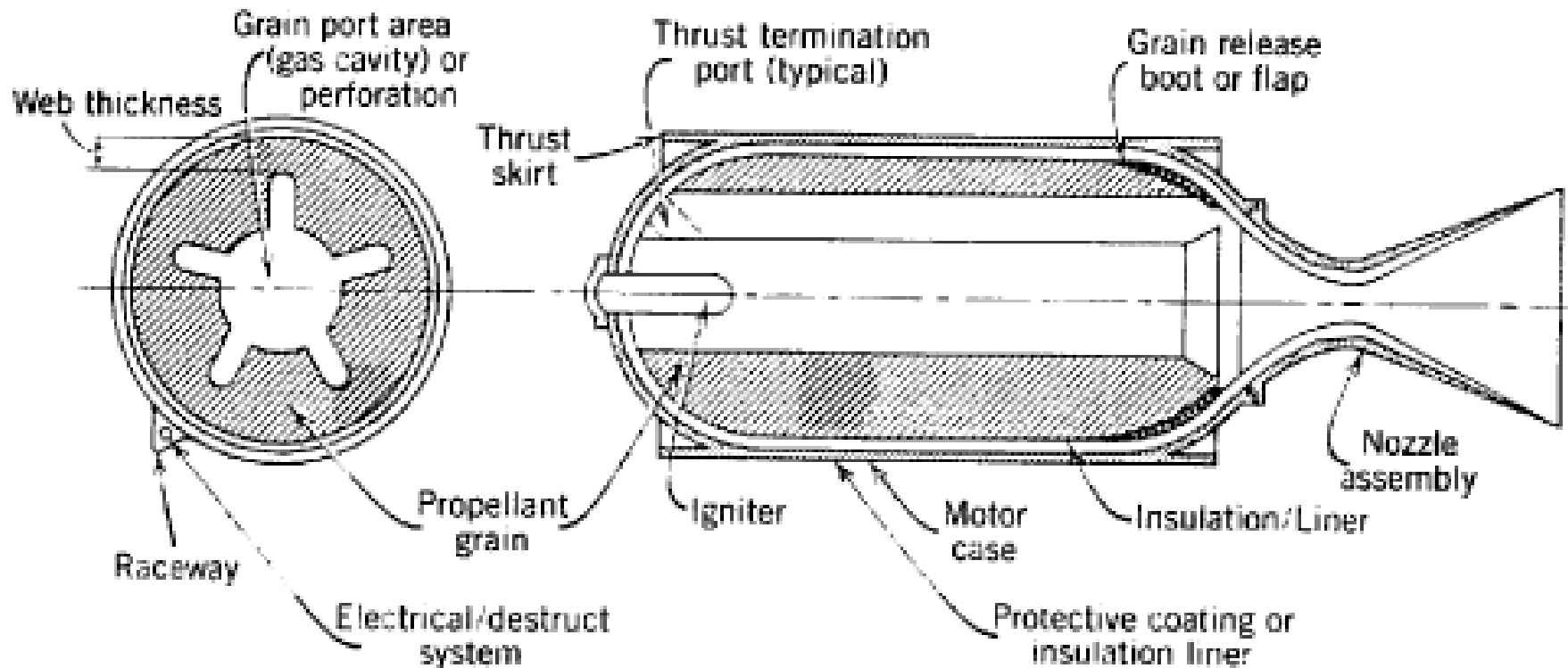
- Pressure ratio $p_0/p_e=100$ (1470 psi-->14.7 psi)
 $A_e/A_t=11.9$
- Pressure ratio $p_0/p_e=1000$ (1470 psi-->1.47 psi)
 $A_e/A_t=71.6$
- Difference between sea level and ideal vacuum V_e

$$\frac{V_e}{V_{e,ideal}} = \sqrt{1 - \left(\frac{p_e}{p_0}\right)^{\frac{\gamma-1}{\gamma}}}$$

- $I_{sp,vacuum}=455$ sec --> $I_{sp,sl}=333$ sec



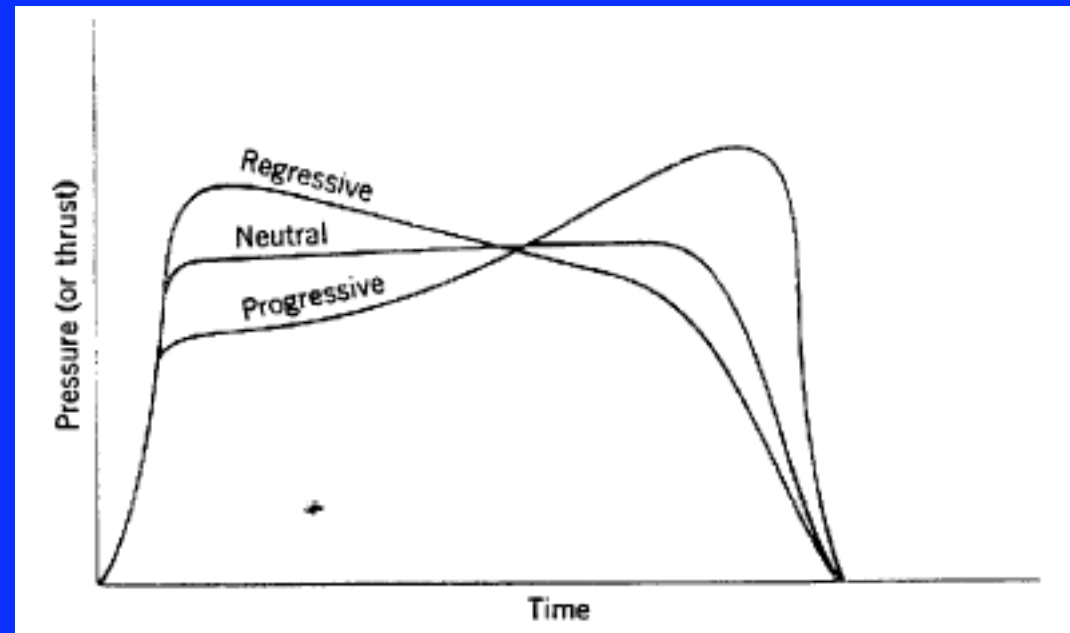
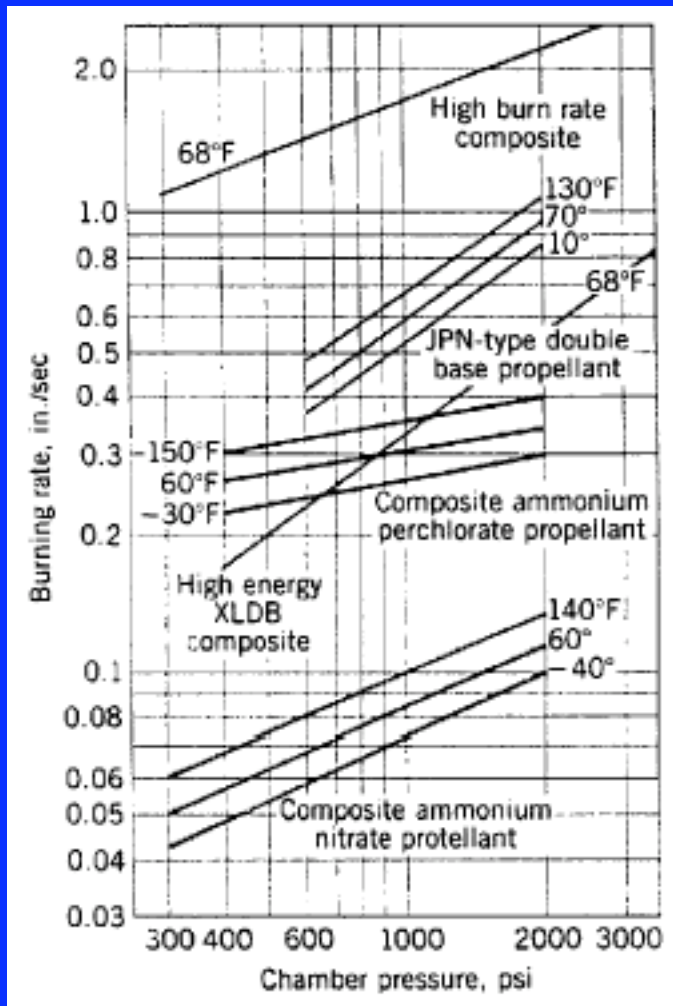
Solid Rocket Motor



From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



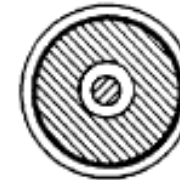
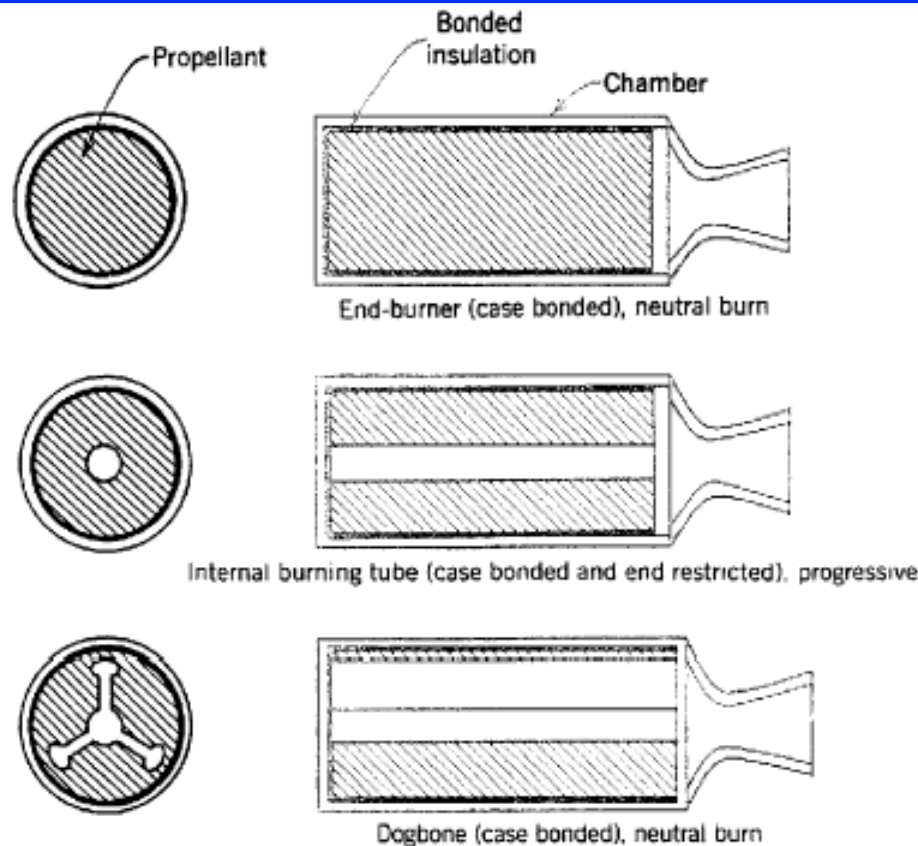
Solid Propellant Combustion Characteristics



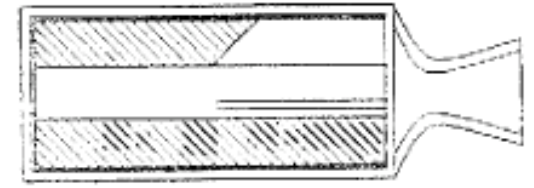
From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



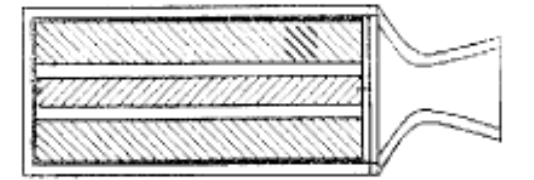
Solid Grain Configurations



Star (neutral)



Slots and tube (case bonded), neutral burn



Rod and tube (case bonded), neutral burn



Wagon Wheel (neutral)



Multiperforated (progressive-regressive)



Dendrite (case bonded)

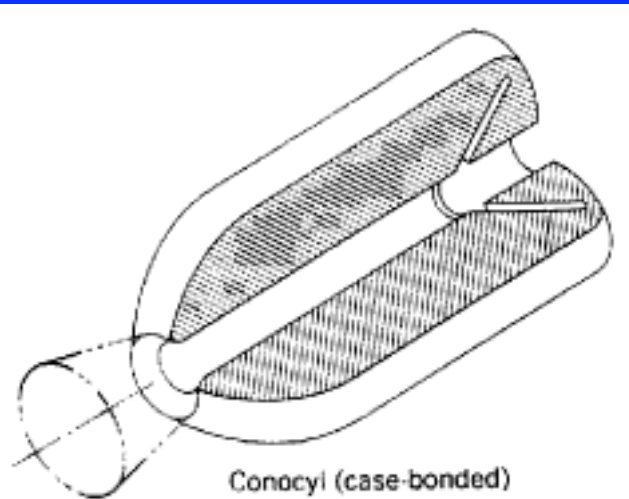
From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



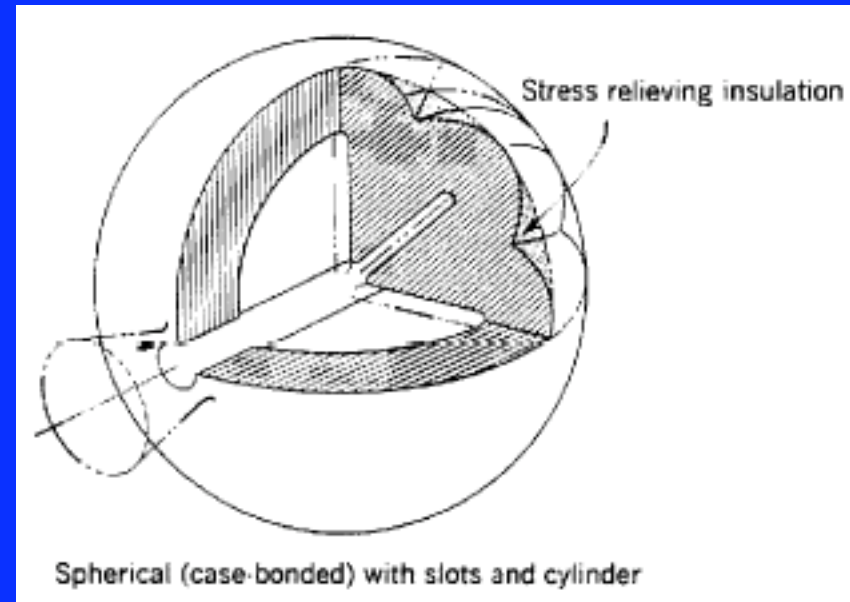
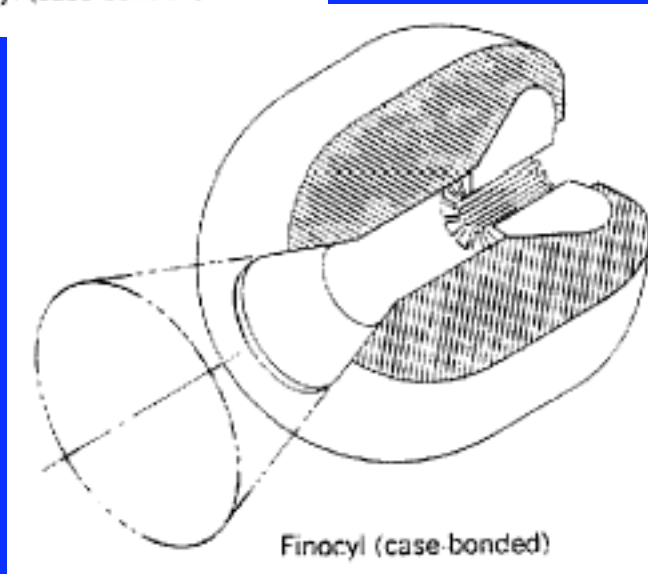
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Rocket Propulsion Launch and Entry Vehicle Design

Short-Grain Solid Configurations

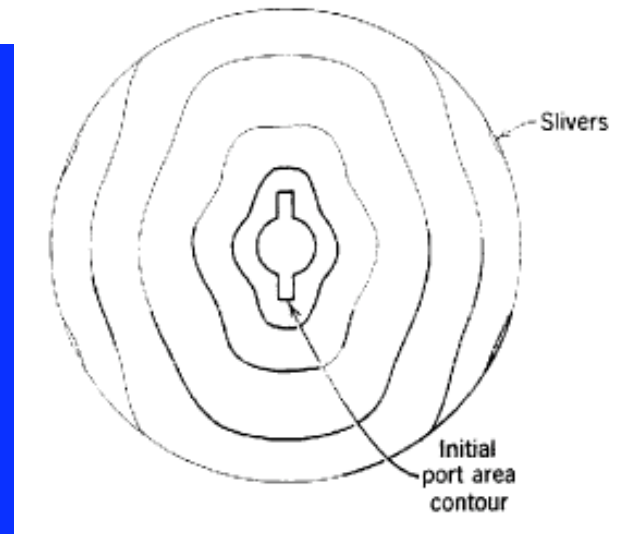
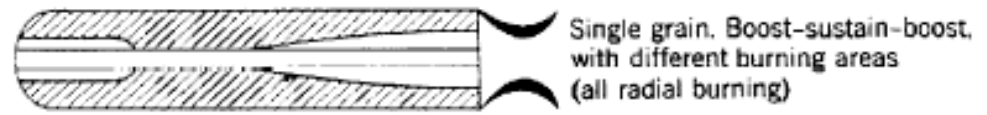
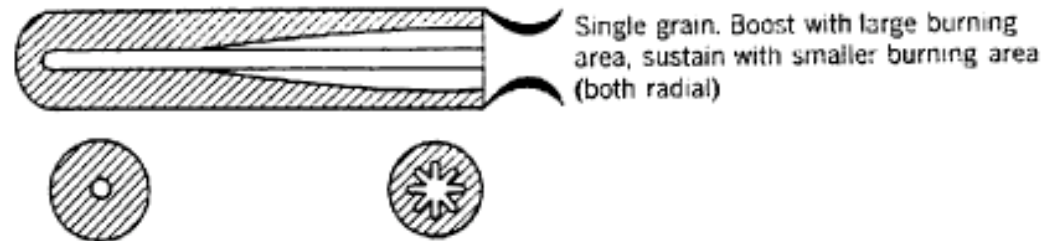
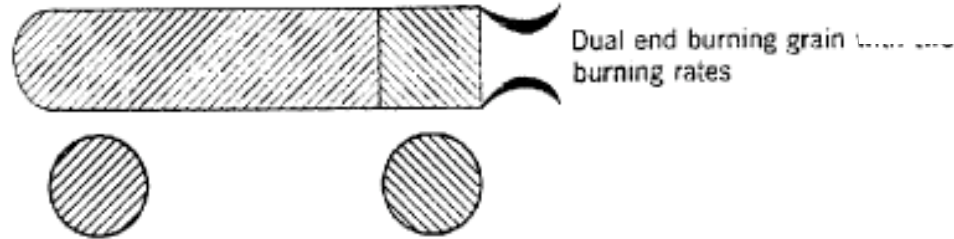
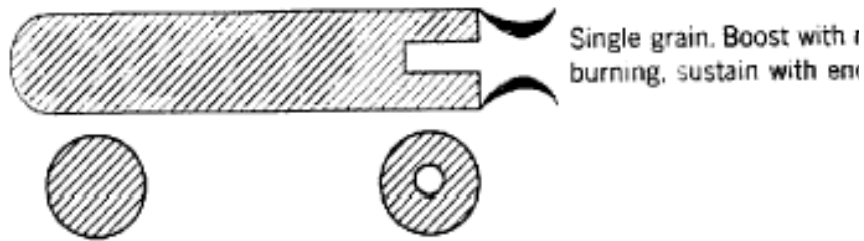


From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.)
John Wiley and Sons, 1986

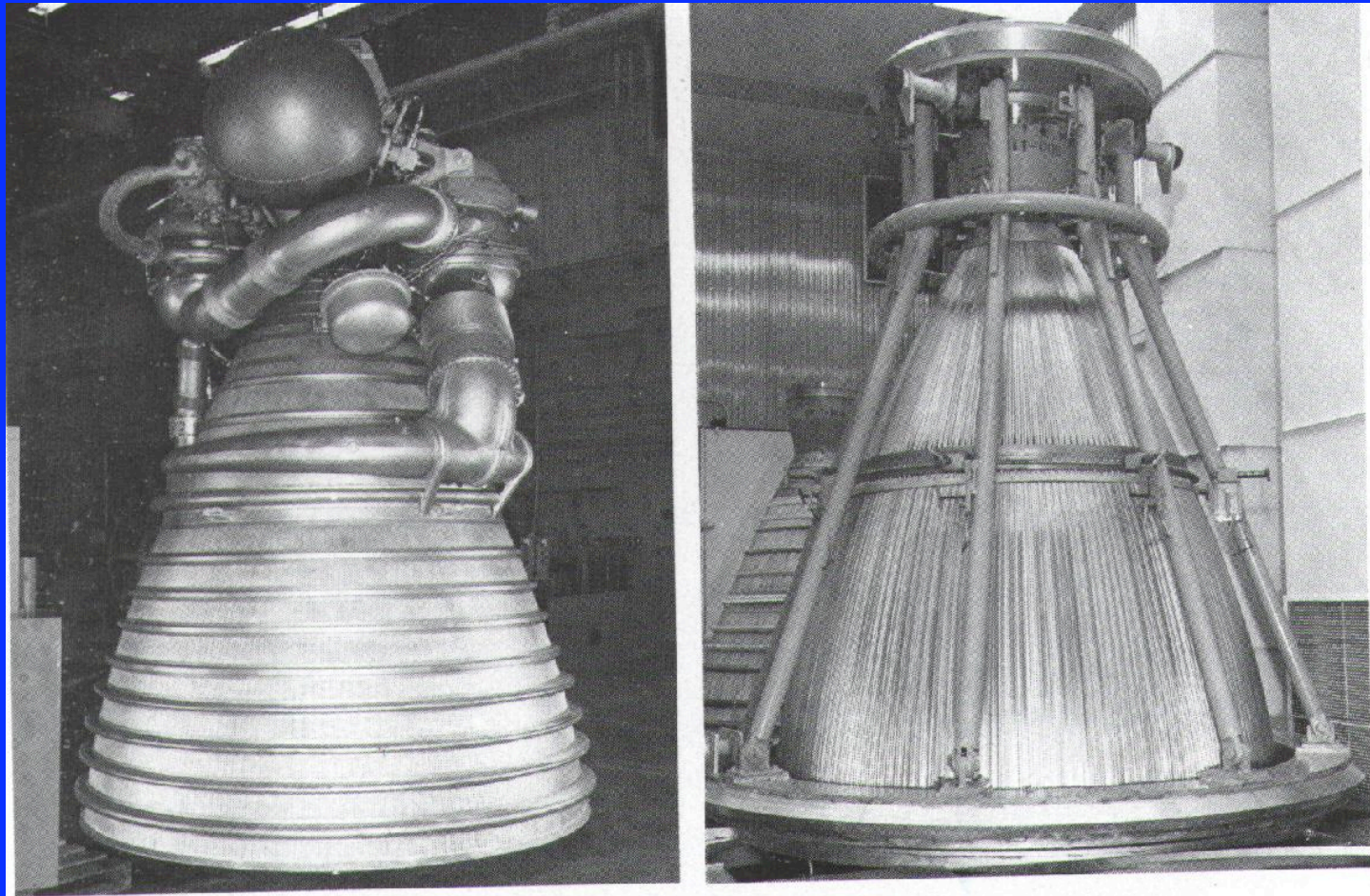


Advanced Grain Configurations

From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



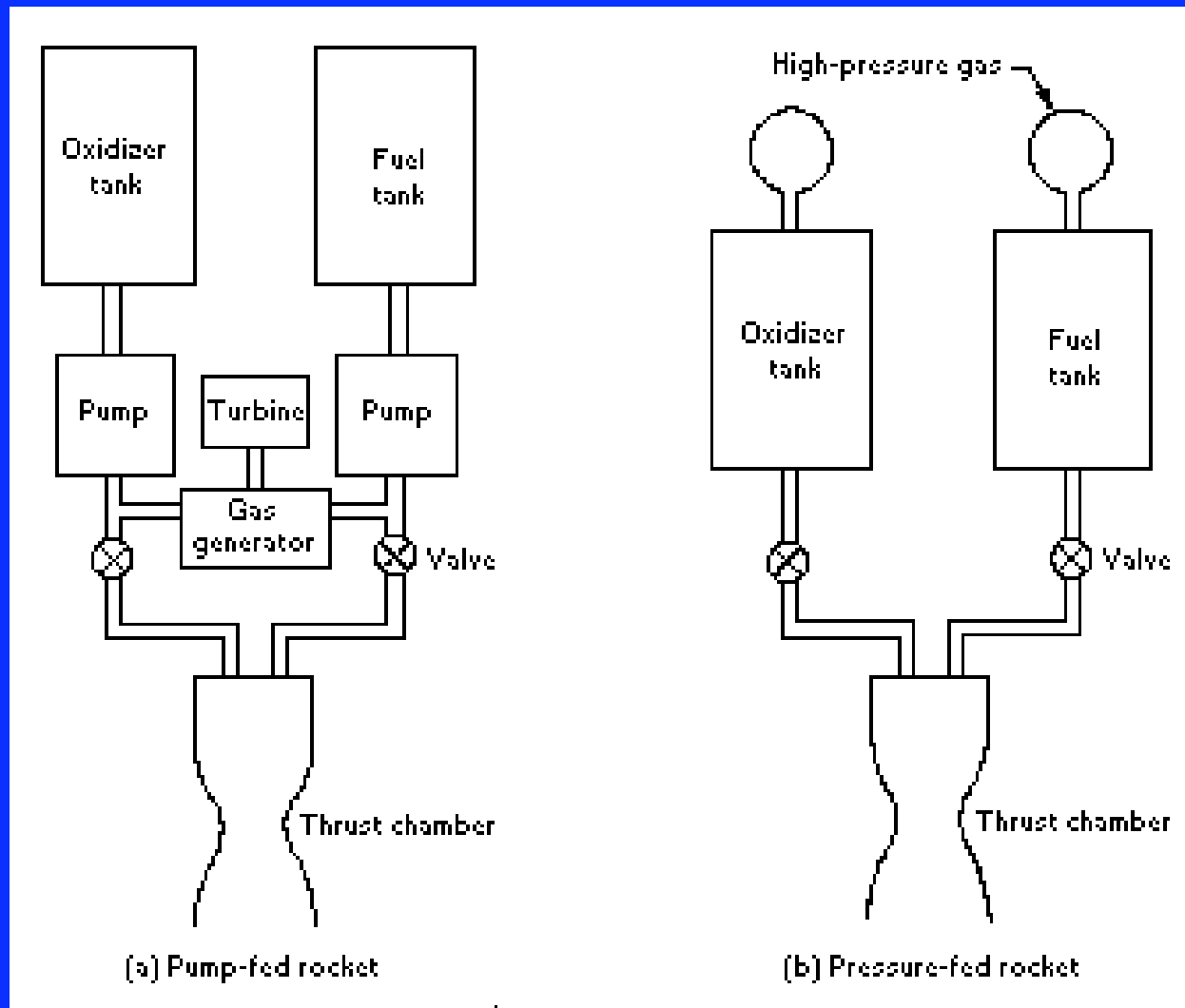
Liquid Rocket Engine



A completed J-2 rocket engine (left), with its pumps and lines installed. The basic engine structure is built up from a series of hollow tubes (right).

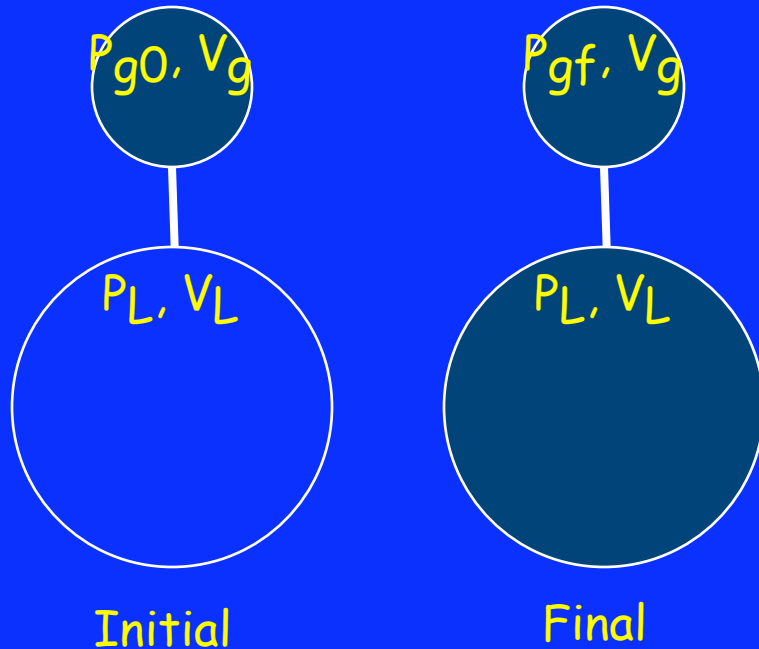


Liquid Propellant Feed Systems



Pressurization System Analysis

Adiabatic Expansion of Pressurizing Gas



$$P_{g,0} V_g^\gamma = P_{g,f} V_g^\gamma + P_L V_L^\gamma$$

Known quantities:

$P_{g,0}$ = Initial gas pressure

$P_{g,f}$ = Final gas pressure

P_L = Operating pressure of propellant tank(s)

V_L = Volume of propellant tank(s)

Solve for gas volume V_g



Boost Module Propellant Tanks

- Gross mass 23,000 kg
 - Inert mass 2300 kg
 - Propellant mass 20,700 kg
 - Mixture ratio $\text{N}_2\text{O}_4/\text{A50} = 1.8$ (by mass)
- N_2O_4 tank
 - Mass = 13,310 kg
 - Density = 1450 kg/m^3
 - Volume = $9.177 \text{ m}^3 \rightarrow r_{\text{sphere}} = 1.299 \text{ m}$
- Aerozine 50 tank
 - Mass = 7390 kg
 - Density = 900 kg/m^3
 - Volume = $8.214 \text{ m}^3 \rightarrow r_{\text{sphere}} = 1.252 \text{ m}$



Boost Module Main Propulsion

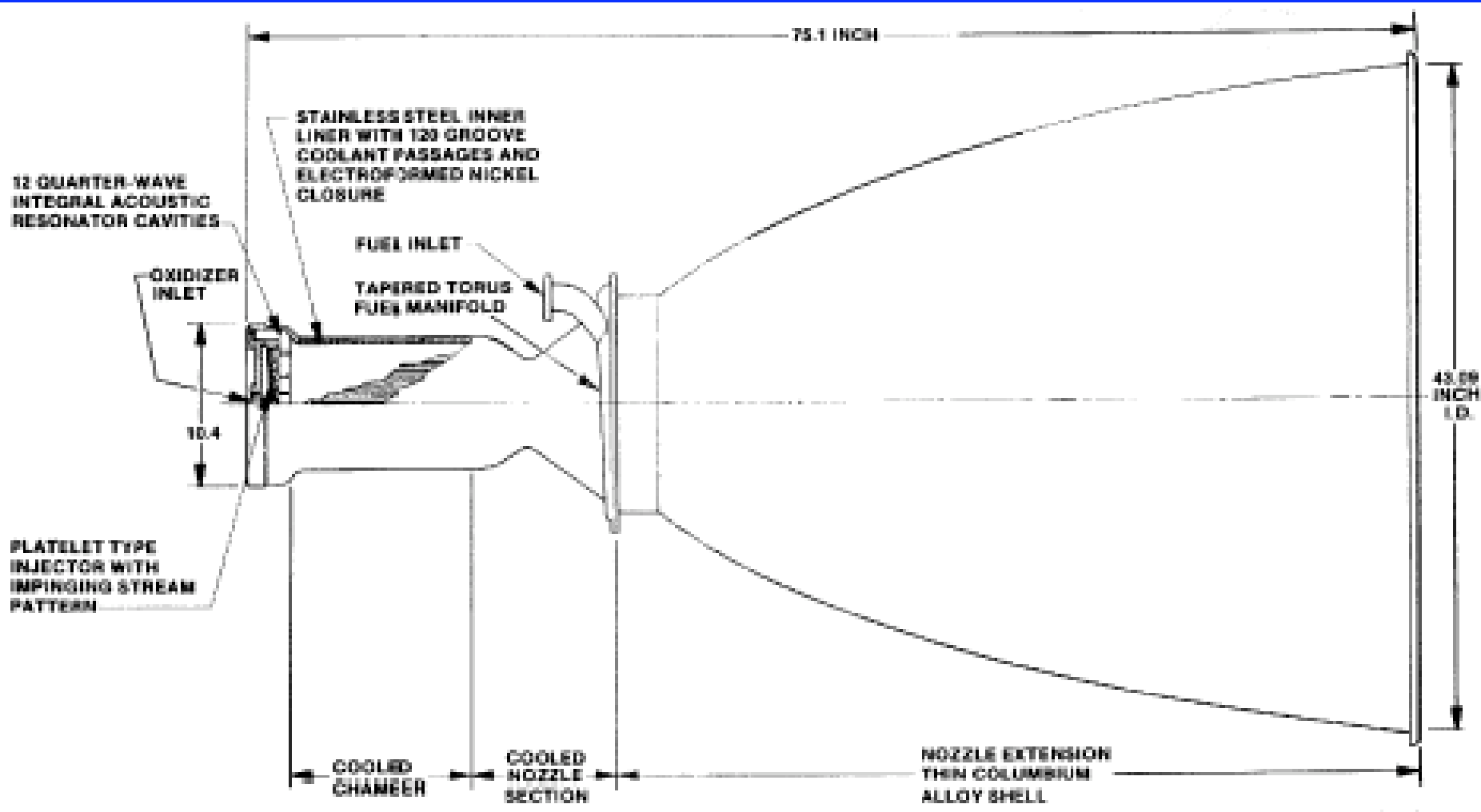
- Total propellant volume $V_L = 17.39 \text{ m}^3$
- Assume engine pressure $p_0 = 250 \text{ psi}$
- Tank pressure $p_L = 1.25 \cdot p_0 = 312 \text{ psi}$
- Final GHe pressure $p_{g,f} = 75 \text{ psi} + p_L = 388 \text{ psi}$
- Initial GHe pressure $p_{g,0} = 4500 \text{ psi}$
- Conversion factor $1 \text{ psi} = 6892 \text{ Pa}$
- Ratio of specific heats for He = 1.67

$$(4500 \text{ psi})V_g^{1.67} = (388 \text{ psi})V_g^{1.67} + (312 \text{ psi})(17.39 \text{ m}^3)^{1.67}$$

- $V_g = 3.713 \text{ m}^3$
- Ideal gas: $T=300^\circ\text{K} \rightarrow$
 $\rho=49.7 \text{ kg/m}^3$ (300 psi = 31.04 MPa) $M_{\text{He}}=185.1 \text{ kg}$

$$\rho_{\text{He}} = \frac{p_{g,0} \bar{M}}{\mathcal{R} T_0}$$

Space Shuttle OMS Engine



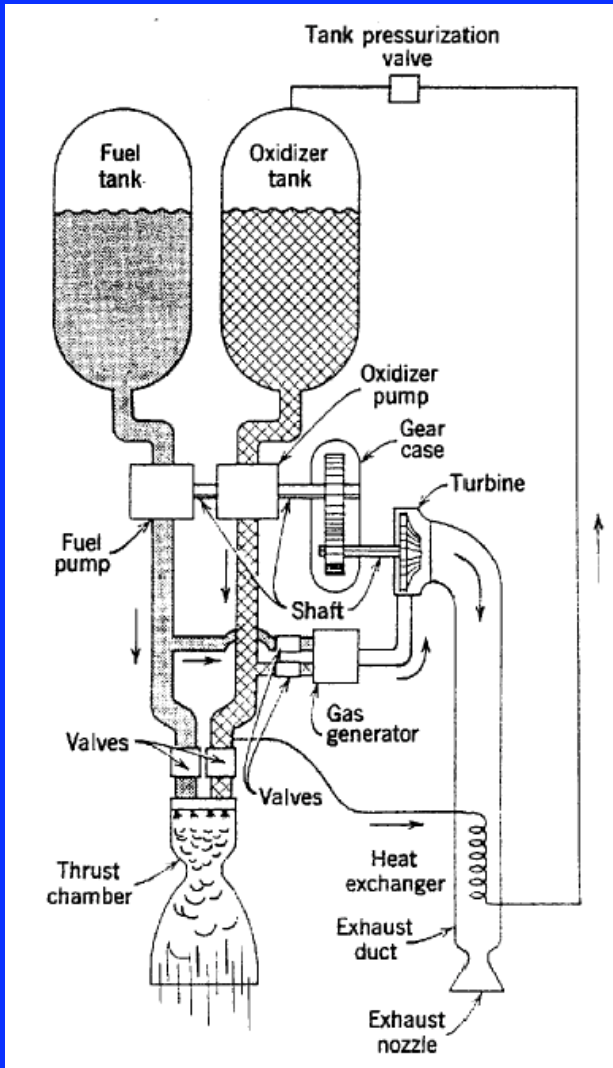
From G. P. Sutton, Rocket Propulsion Elements (5th ed.) John Wiley and Sons, 1986



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Rocket Propulsion
Launch and Entry Vehicle Design

Turbopump Fed Liquid Rocket Engine



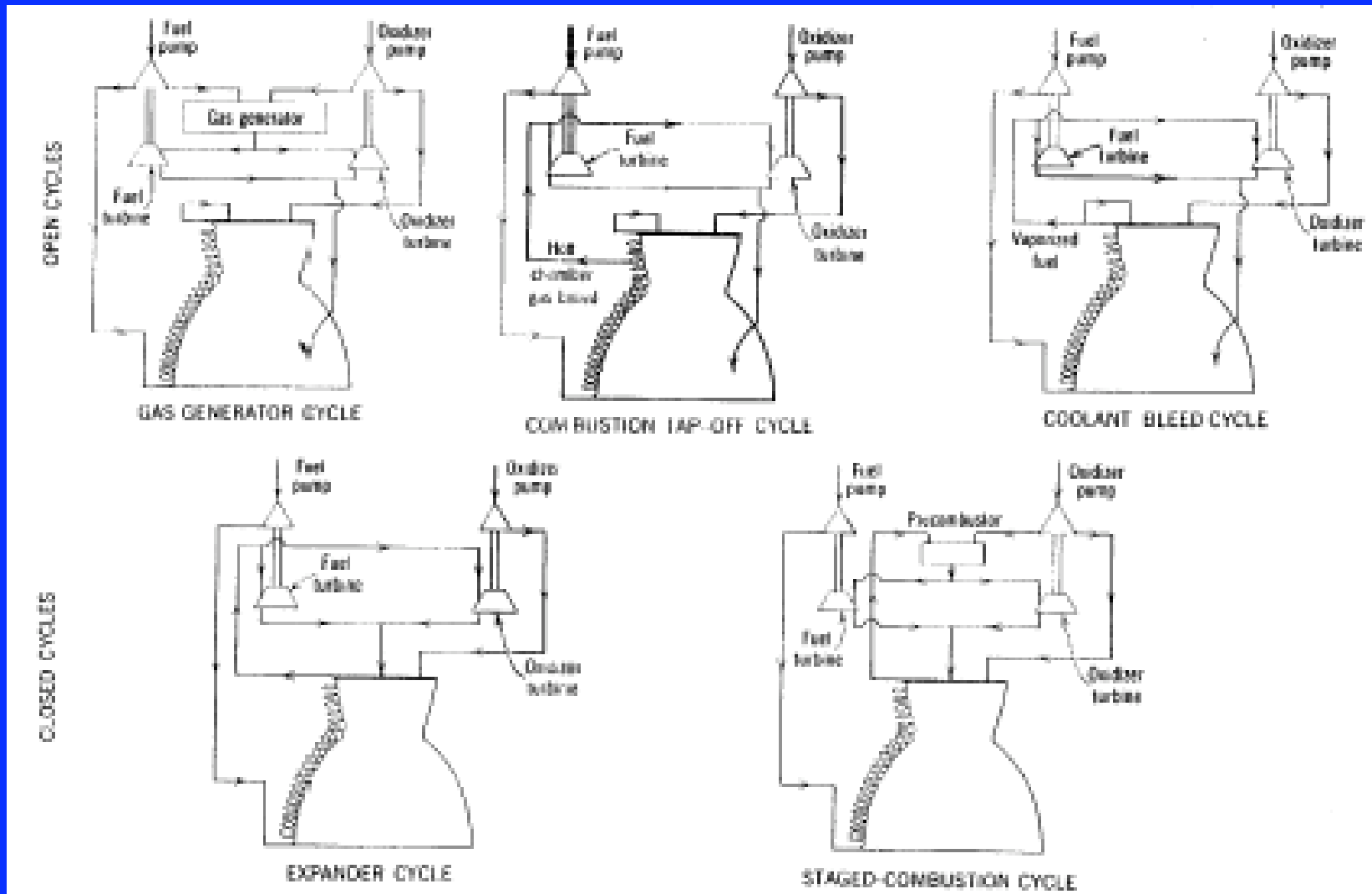
From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



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Sample Pump-fed Engine Cycles



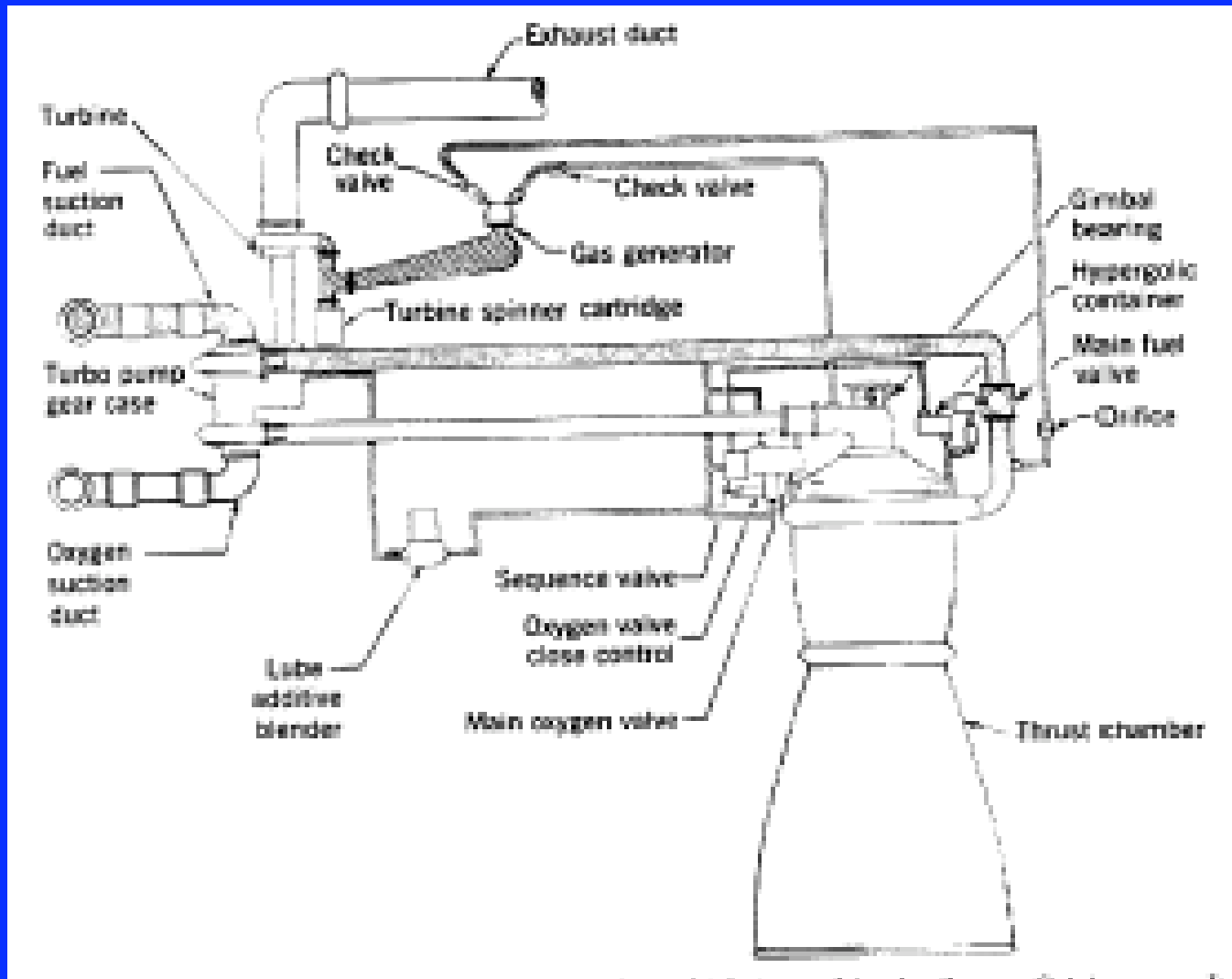
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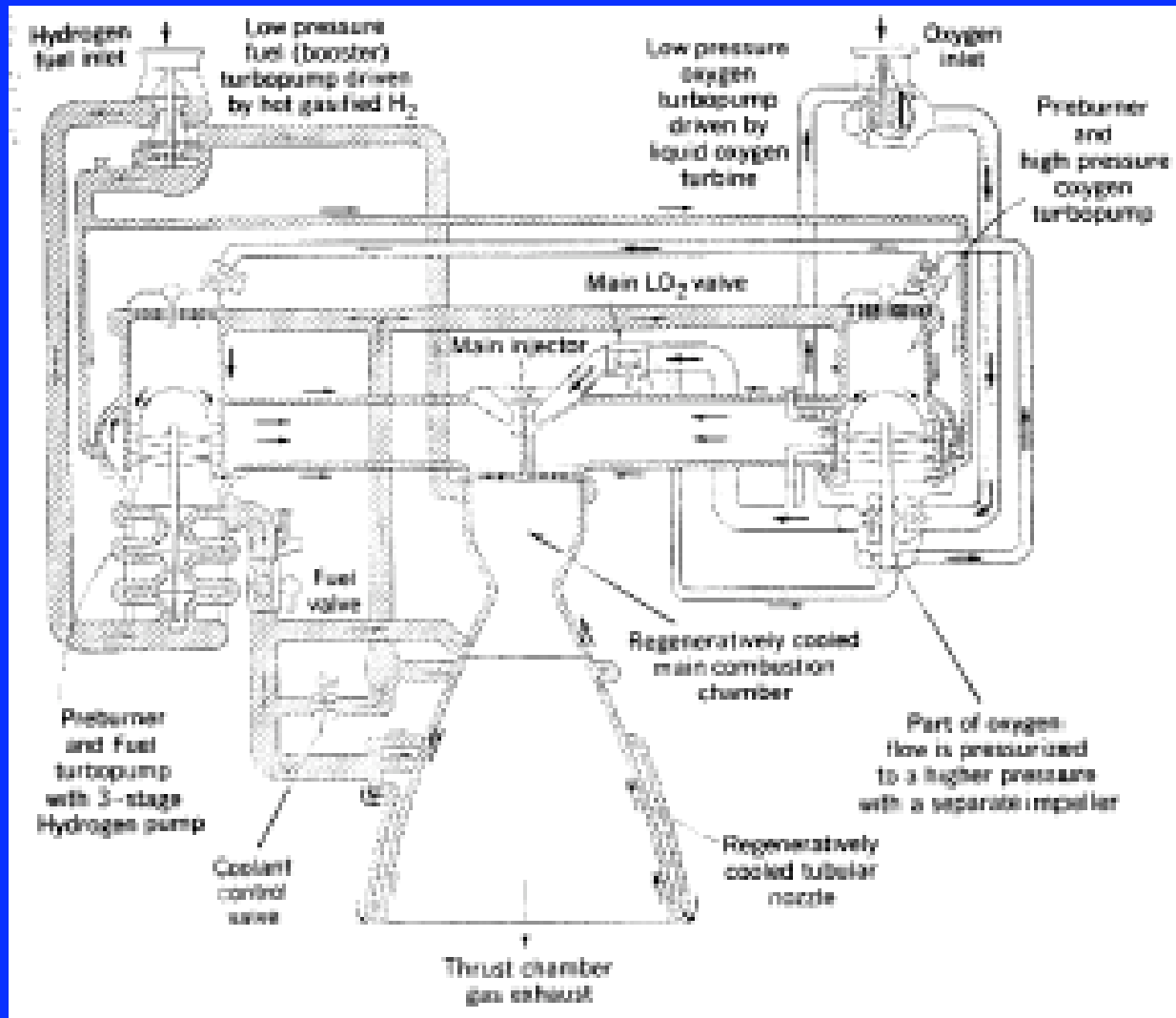
Gas Generator Cycle Engine



From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



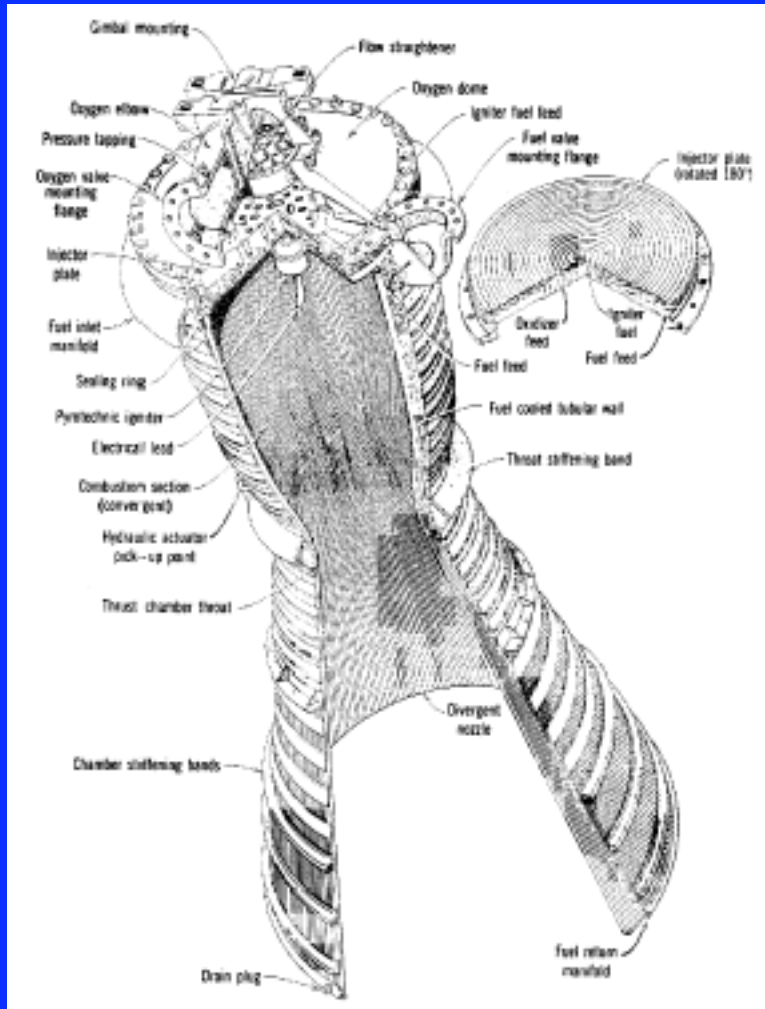
SSME Engine Cycle



From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



Liquid Rocket Engine Cutaway



From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



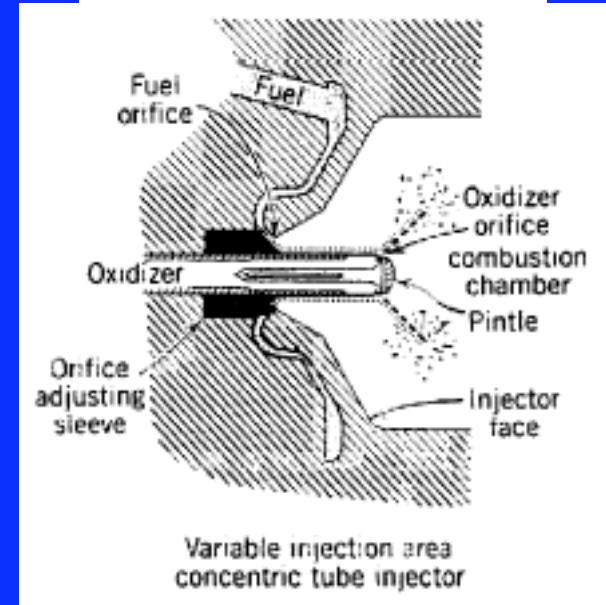
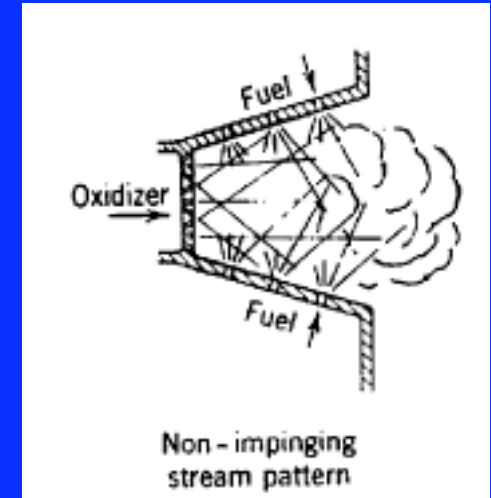
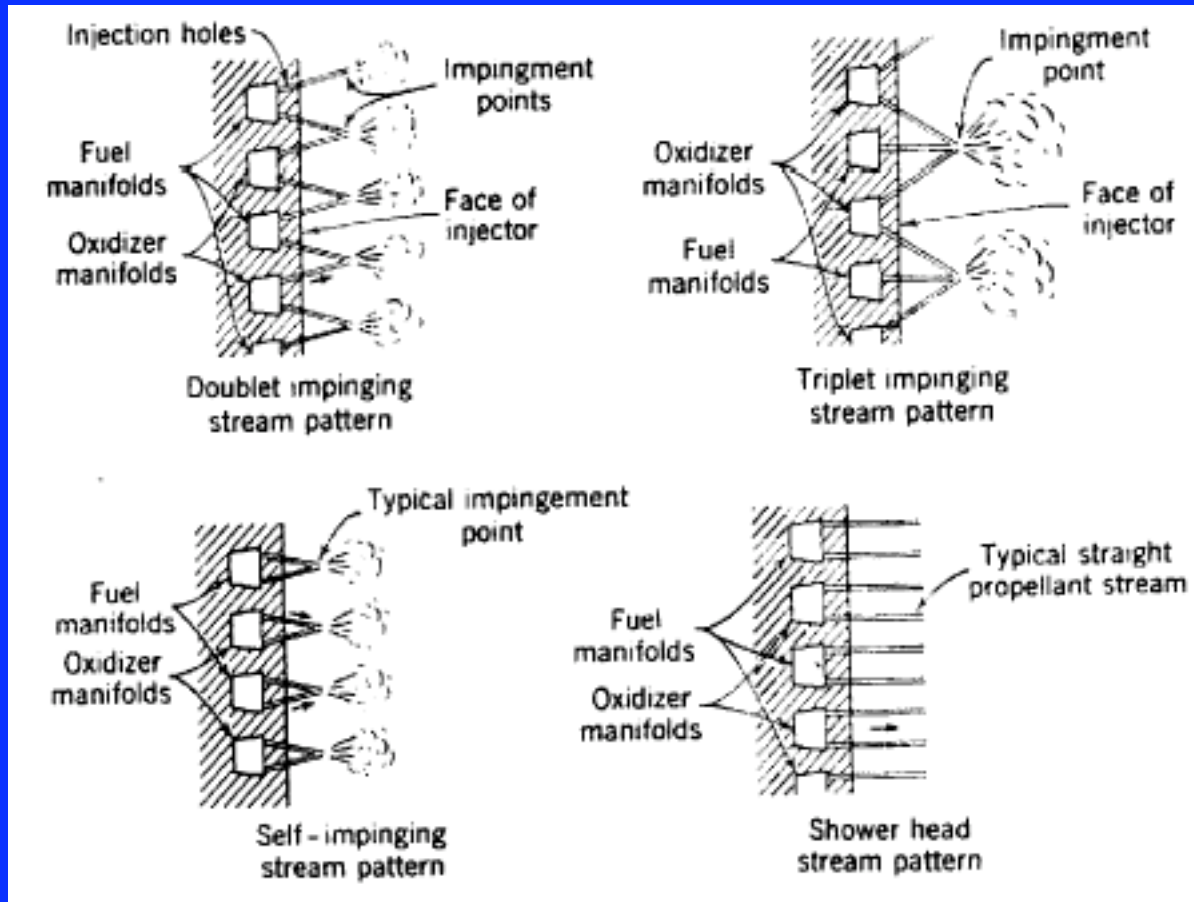
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H-1 Engine Injector Plate



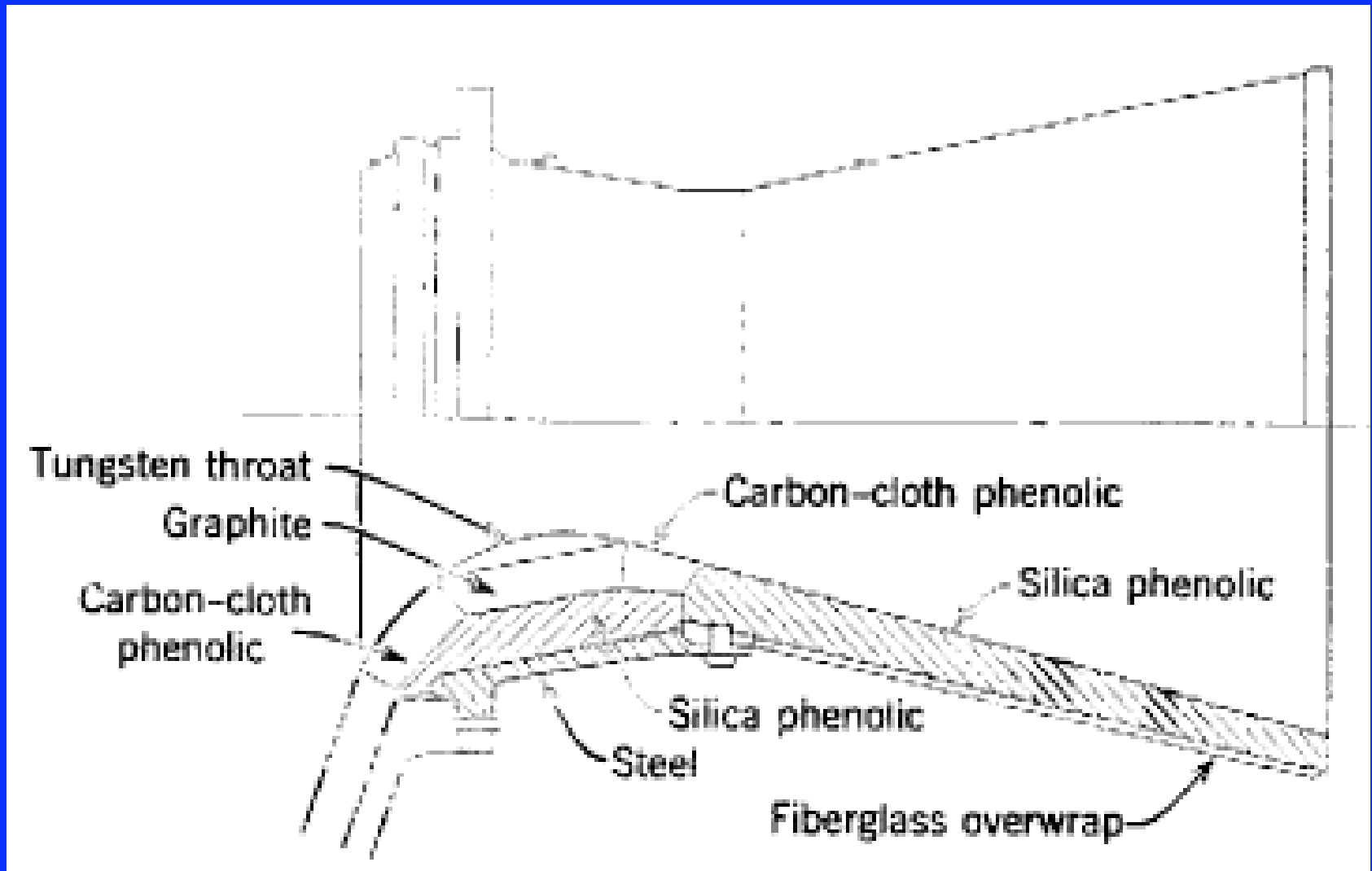
Injector Concepts



From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.)
John Wiley and Sons, 1986



Solid Rocket Nozzle (Heat-Sink)



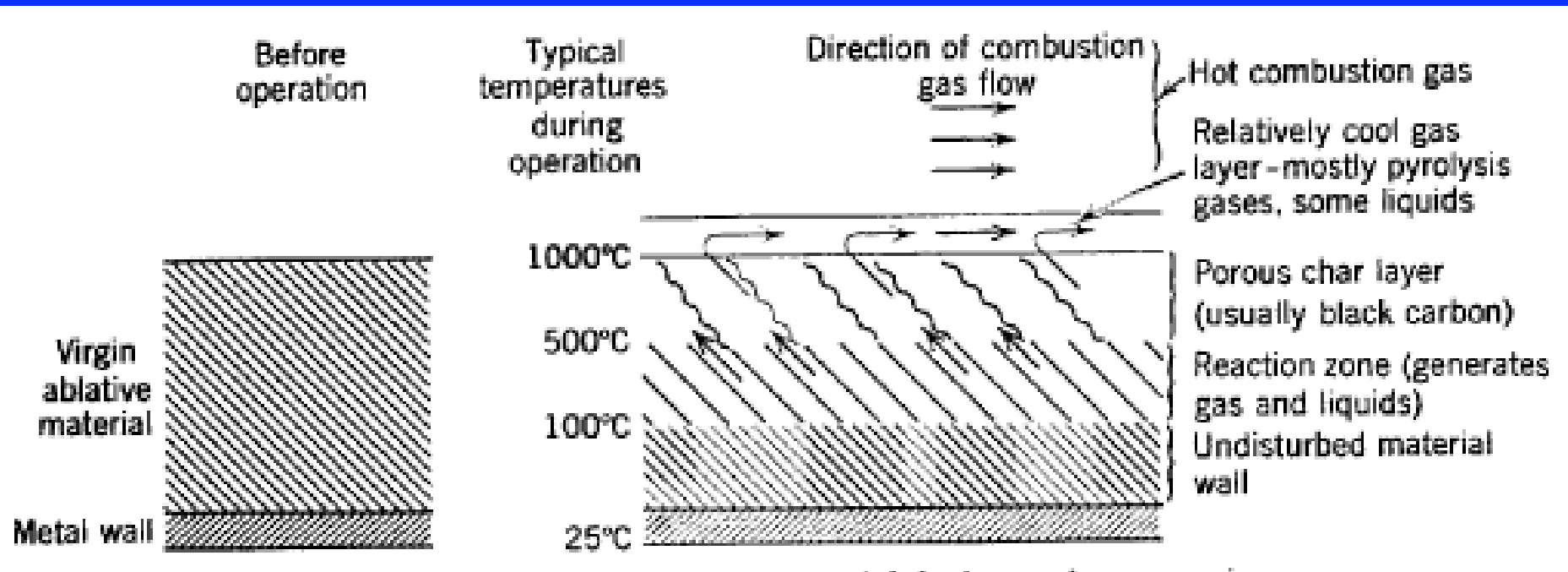
From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



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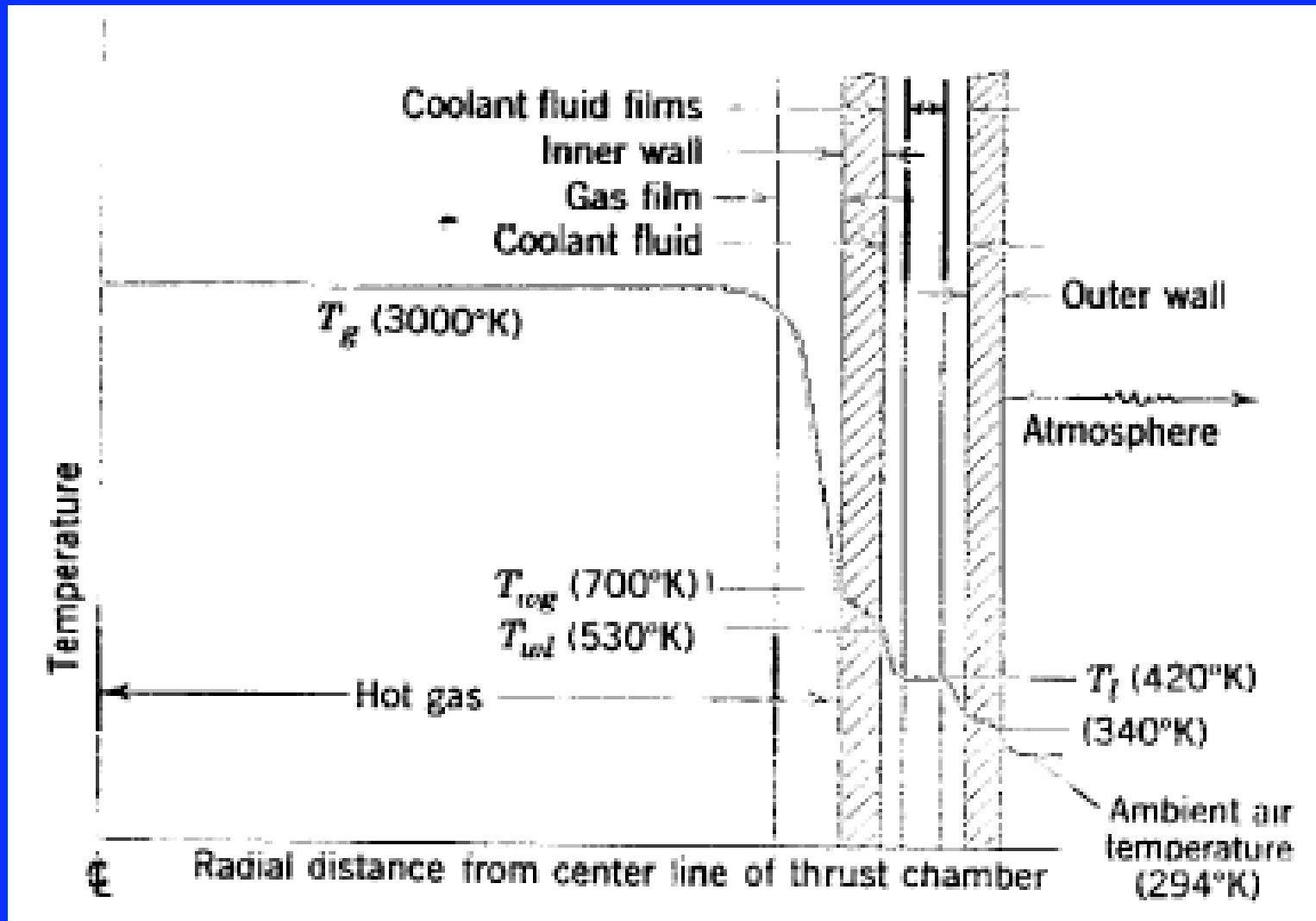
Ablative Nozzle Schematic



From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



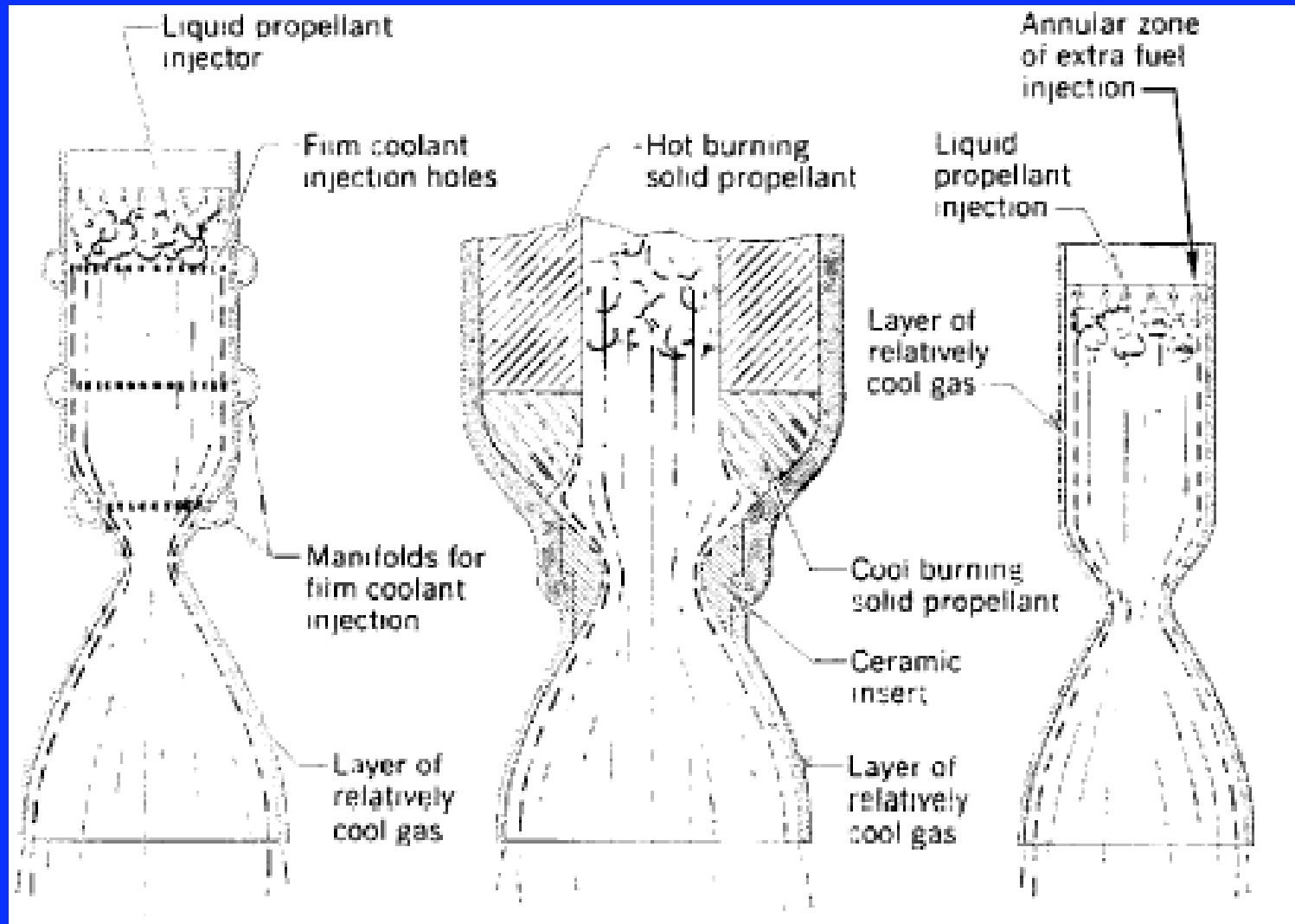
Active Chamber Cooling Schematic



From G. P. Sutton, Rocket Propulsion Elements (5th ed.) John Wiley and Sons, 1986



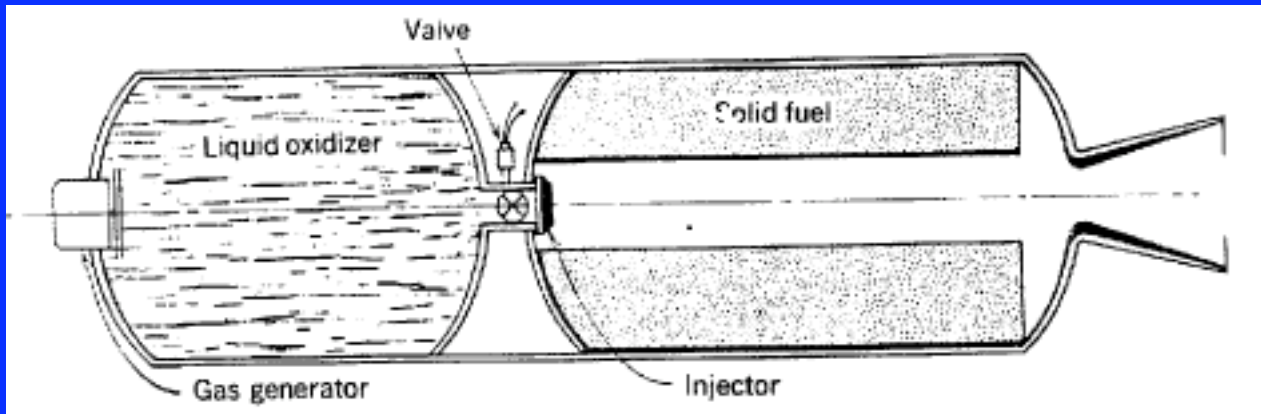
Boundary Layer Cooling Approaches



From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



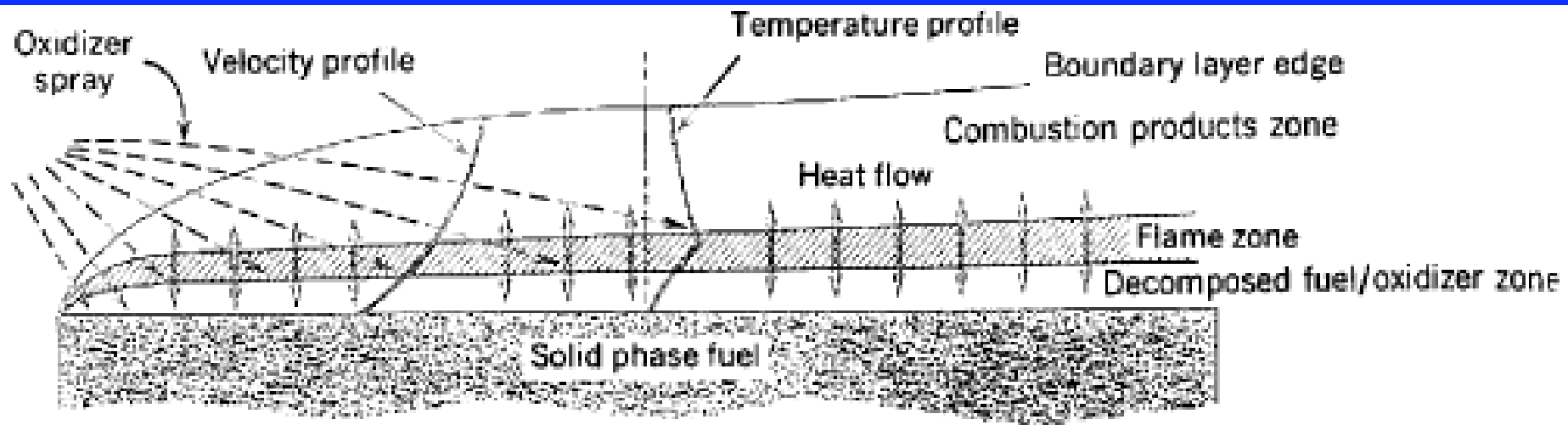
Hybrid Rocket Schematic



From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



Hybrid Rocket Combustion




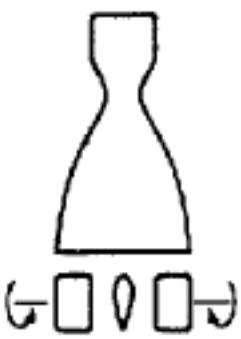

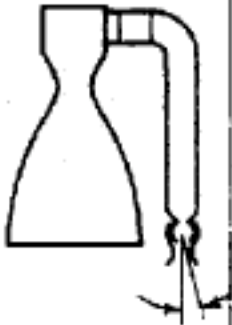

From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



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Rocket Propulsion
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Thrust Vector Control Approaches

Gimbal or hinge	Jet vanes	Small control thrust chambers	Turbine exhaust gas control	Side injection
				
Universal joint suspension	Four rotating heat resistant aerodynamic vanes in jet	Two or more gimbaled auxiliary thrust chambers	Gimbal on turbine exhaust nozzle	Secondary fluid injection on one side only

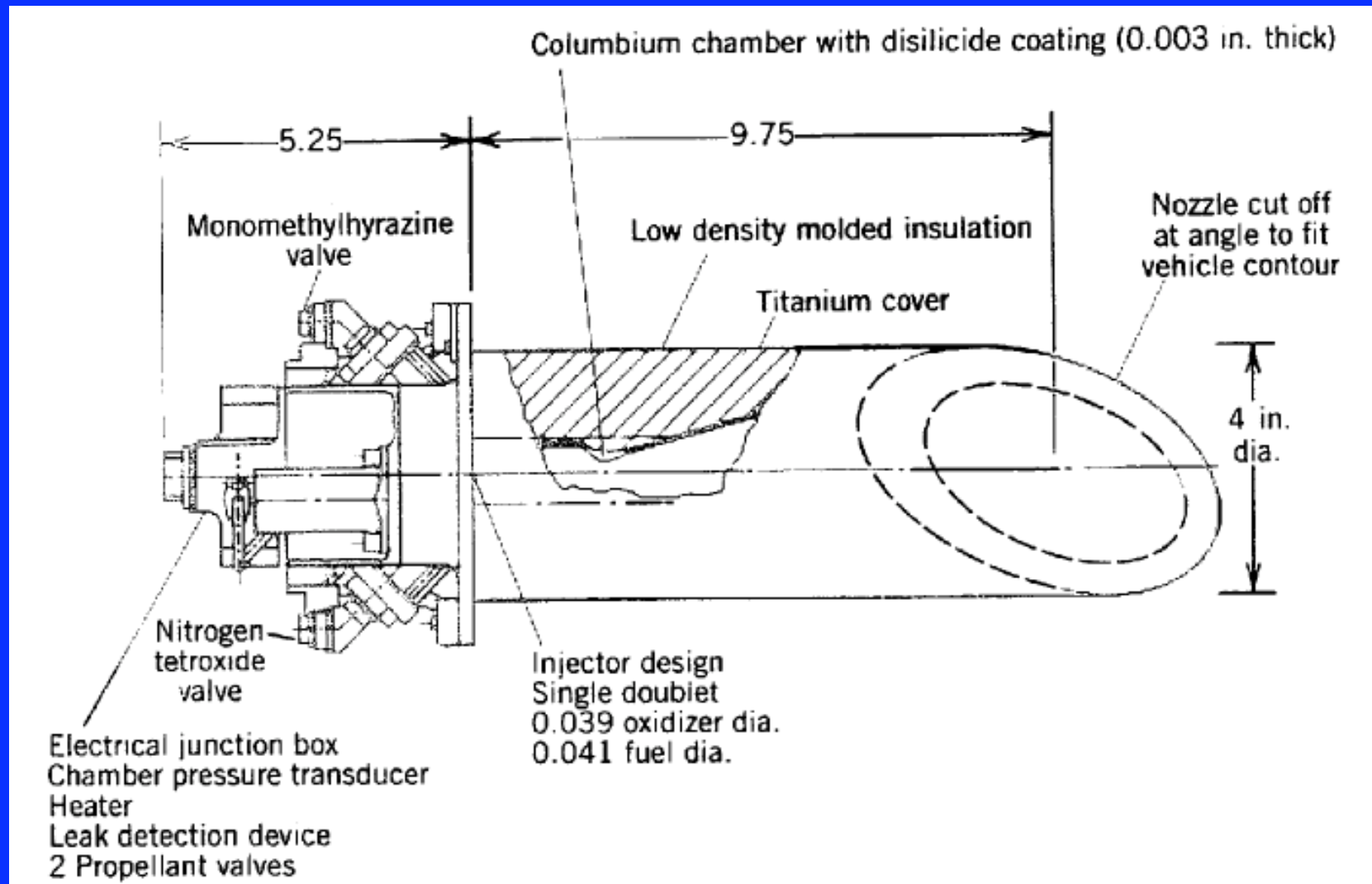
From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



Apollo Reaction Control System Thrusters



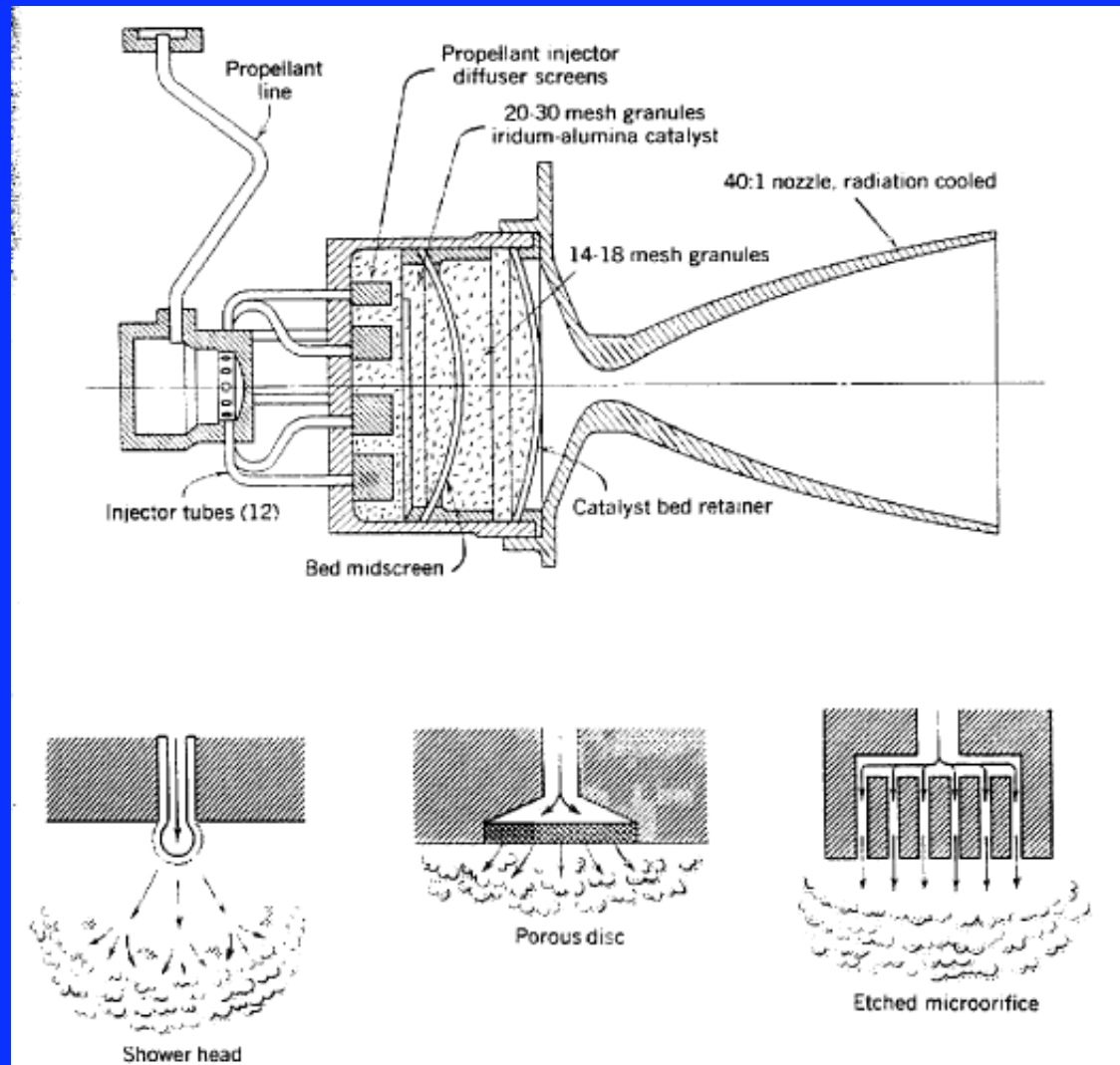
Space Shuttle Primary RCS Engine



From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



Monopropellant Engine Design



From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



Cold-gas Propellant Performance

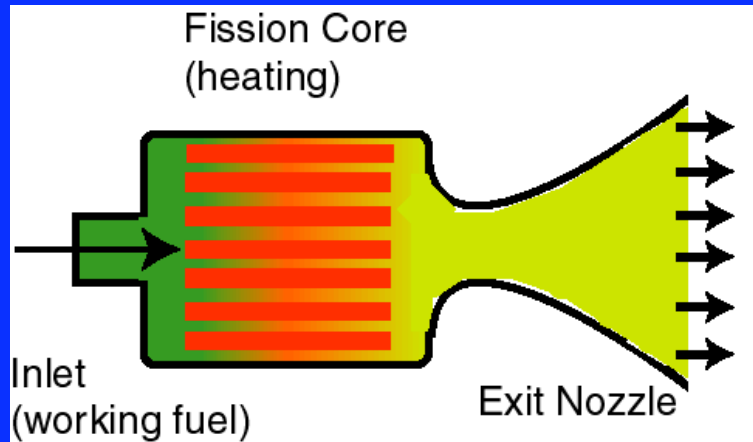
Propellant	Molecular Mass	Density ^a (lb/ft ³)	Theoretical Specific Impulse (sec)
Hydrogen	2.0	1.21	296
Helium	4.0	2.37	179
Methane	16.0	12.10	114
Nitrogen	28.0	17.37	80
Air	28.9	19.3	74
Argon	39.9	27.60	57
Krypton	83.8	67.20	39
Freon 14	88.0	60.01	55
Carbon dioxide	44.0	Liquid	67

^aAt 3500 psia and 0°C.

From G. P. Sutton, *Rocket Propulsion Elements* (5th ed.) John Wiley and Sons, 1986



Nuclear Thermal Rockets



- Heat propellants by passing through nuclear reactor
- Isp limited by temperature limits on reactor elements (~900 sec for H₂ propellant)
- Mass impacts of reactor, shielding
- High thrust system

