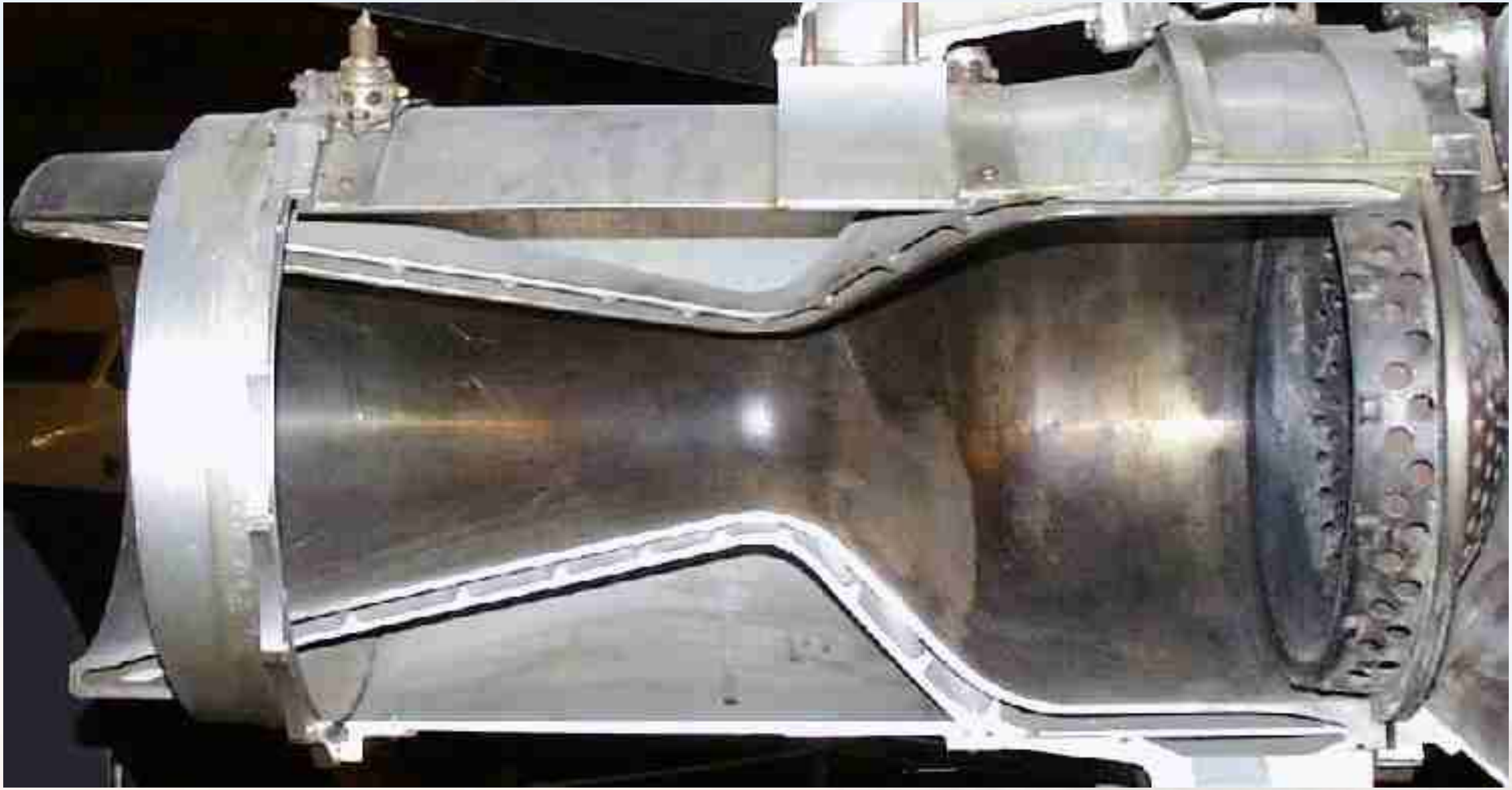
Propulsion and Power Systems Design

- Rocket engine basics
- Survey of the technologies
- Propellant feed systems
- Propulsion systems design
- Energy storage devices

Liquid Rocket Engine Cutaway



Thermal Rocket Exhaust Velocity

- Exhaust velocity is

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

where

$$\overline{M} \equiv average\ molecular\ weight\ of\ exhaust$$

$$\Re \equiv universal\ gas\ const. = 8314.3 \frac{Joules}{mole\,^\circ K}$$

$$\gamma \equiv ratio\ of\ specific\ heats \approx 1.2$$

Ideal Thermal Rocket Exhaust Velocity

- Ideal exhaust velocity is

$$V_e = \sqrt{\frac{2\gamma}{\gamma - 1} \frac{\Re T_0}{\overline{M}}}$$

- 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

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

- Effective exhaust velocity

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

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

- Expansion ratio

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

A Word About Specific Impulse

- Defined as "thrust/propellant used"
  - English units: lbs thrust/(lbs prop/sec)=sec
  - Metric units: N thrust/(kg prop/sec)=m/sec
- Two ways to regard discrepancy -
  - "lbs" is not mass in English units - should be slugs
  - Isp = "thrust/weight flow rate of propellant"
- If the real intent of specific impulse is

$$I_{sp} = \frac{T}{\dot{m}} \text{ and } T = \dot{m}V_e \text{ then } I_{sp} = V_e!!!$$

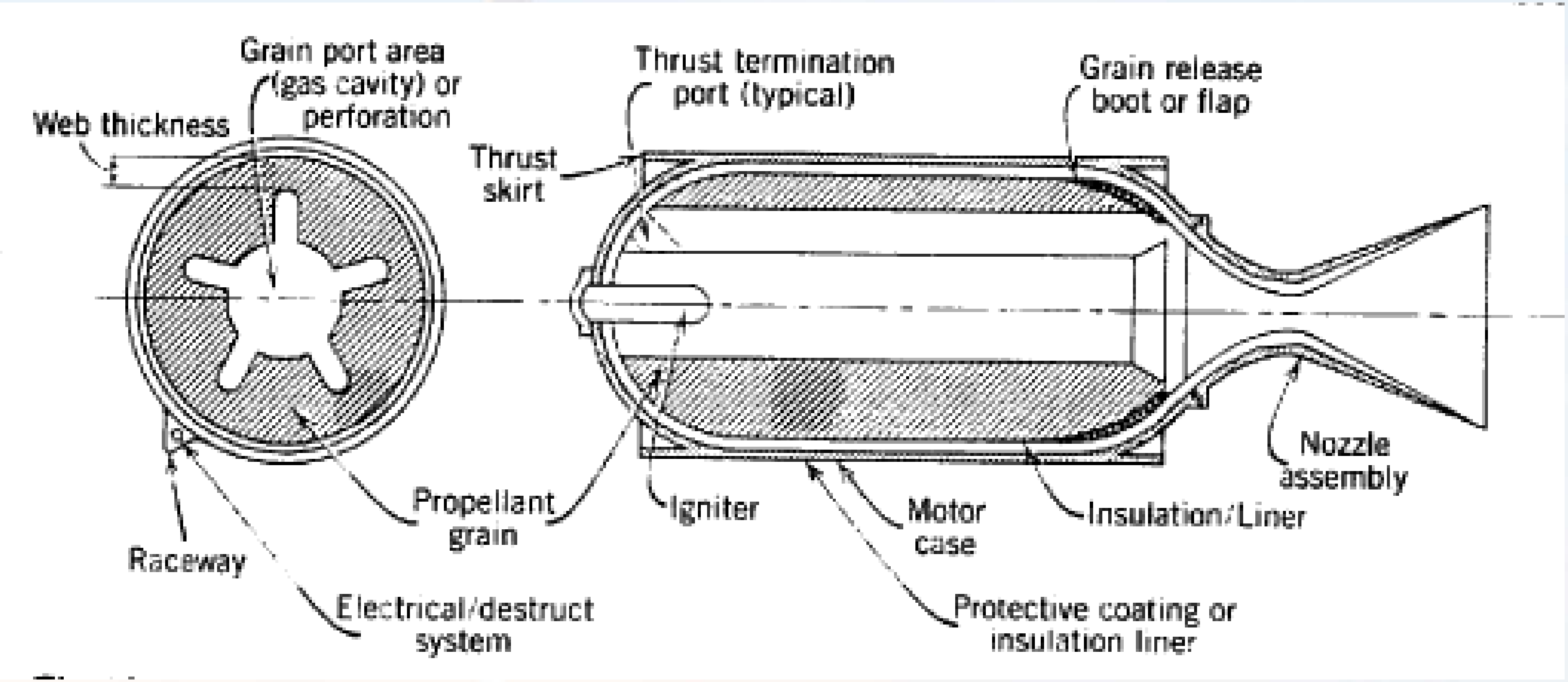
Nozzle Design

- 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

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

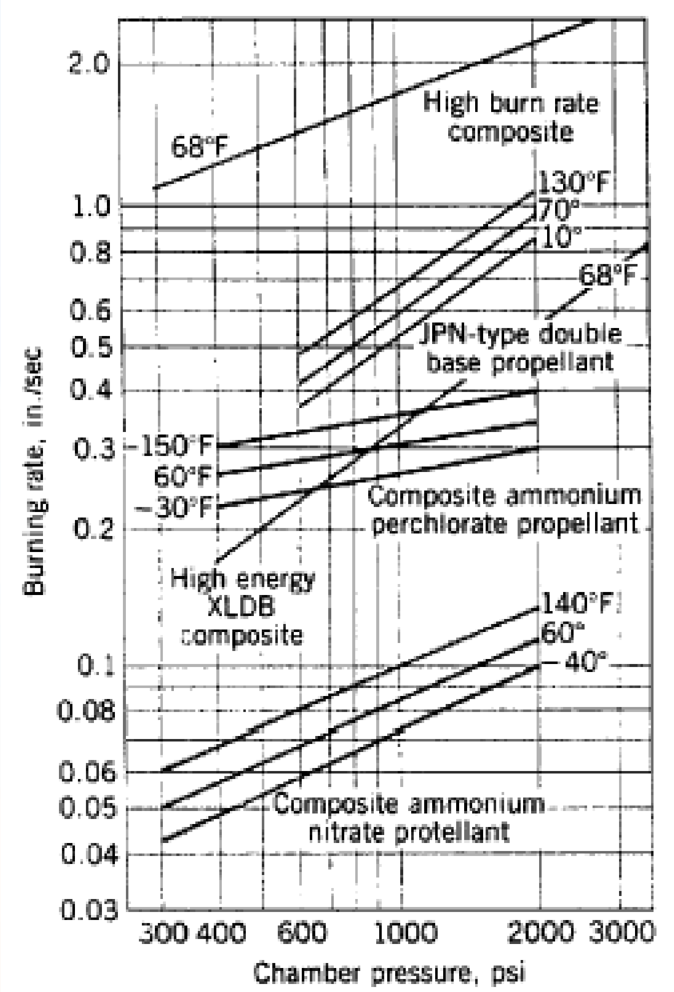
- $I_{sp,vacuum}$=455 sec --> $I_{sp,sl}$=333 sec

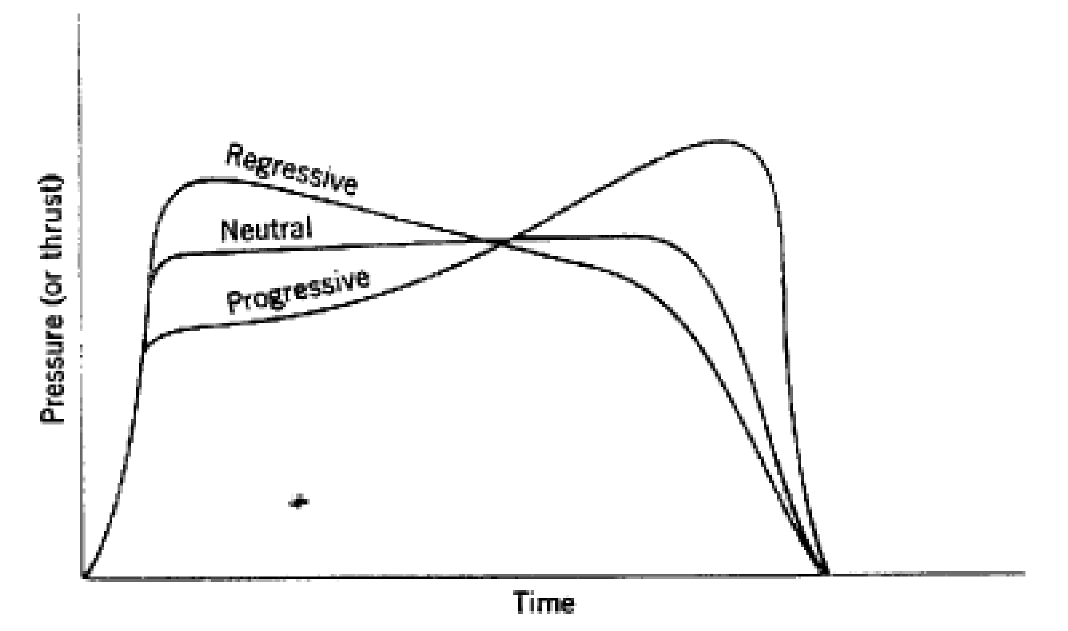
Solid Rocket Motor



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

Solid Propellant Combustion Characteristics





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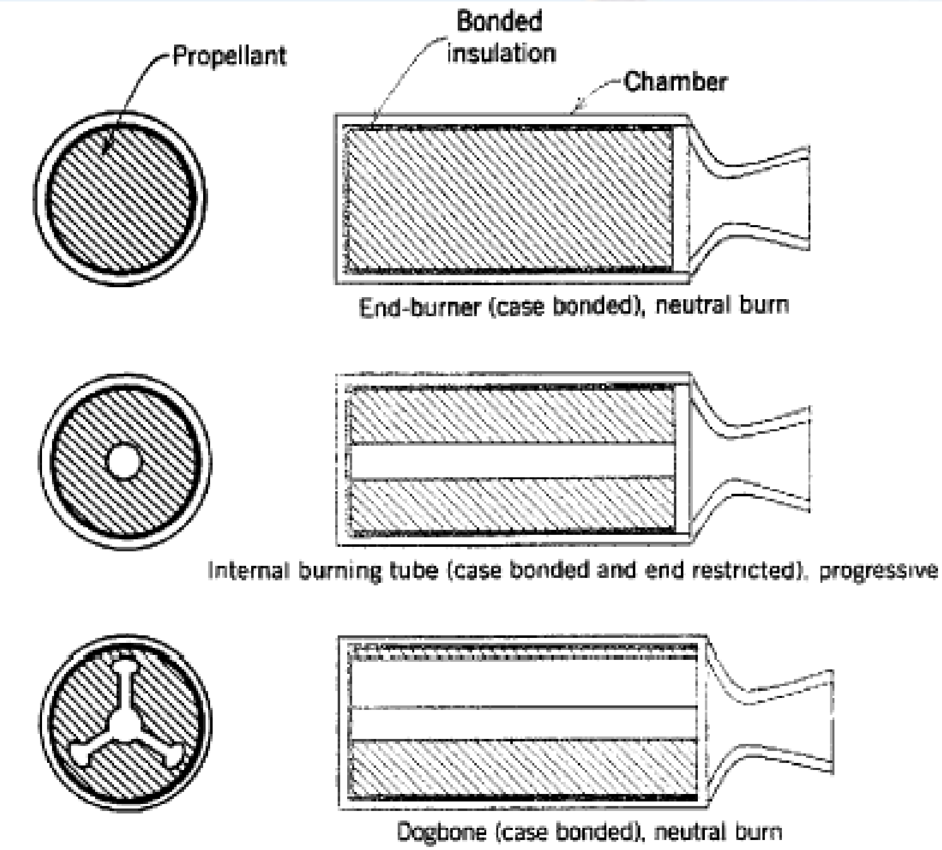
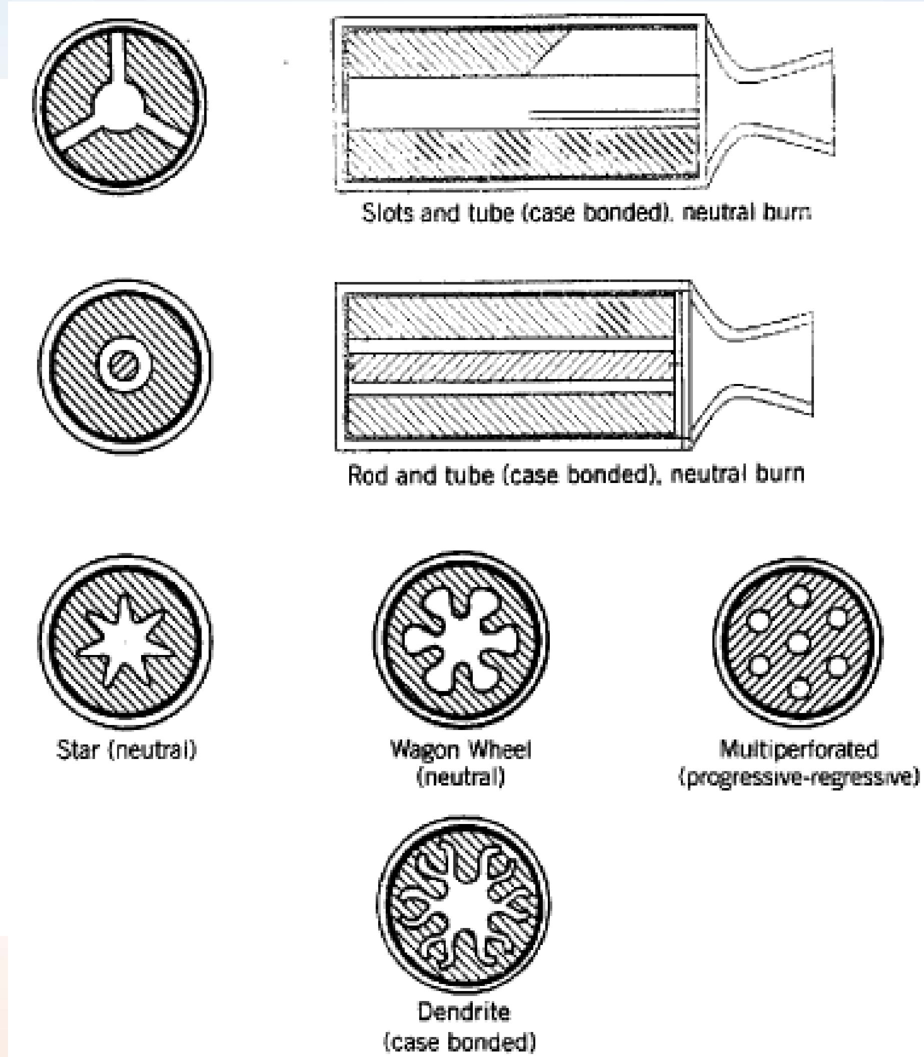
Solid Grain Configurations





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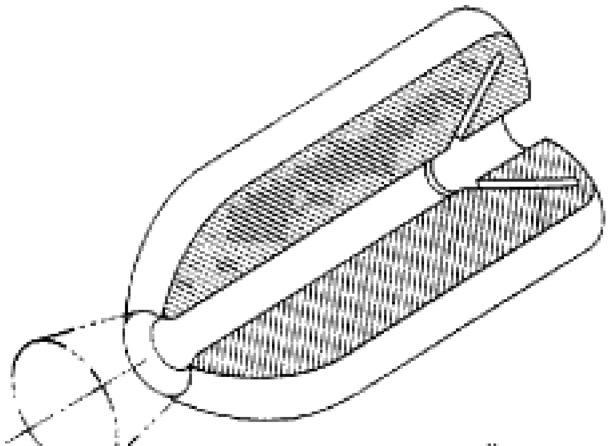
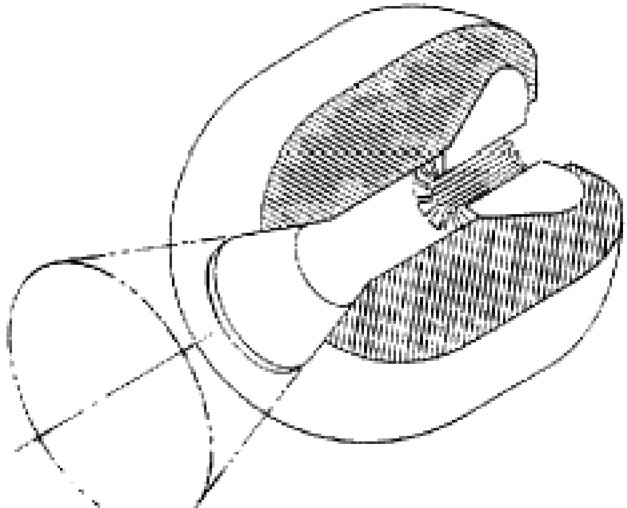
(5th ed.) John Wiley and Sons, 1986

Short-Grain Solid Configurations

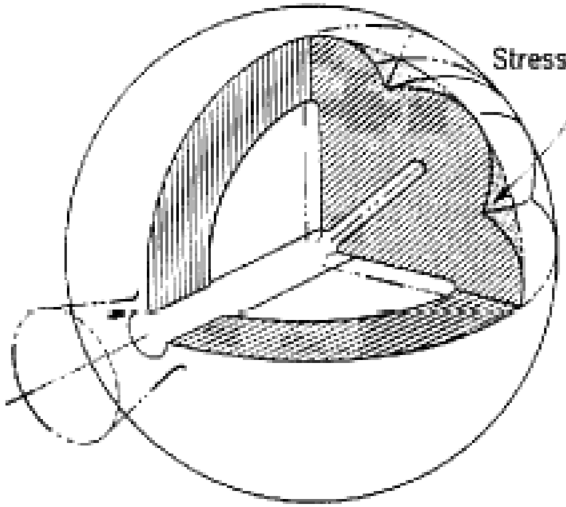


Conocyl (case-bonded)

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

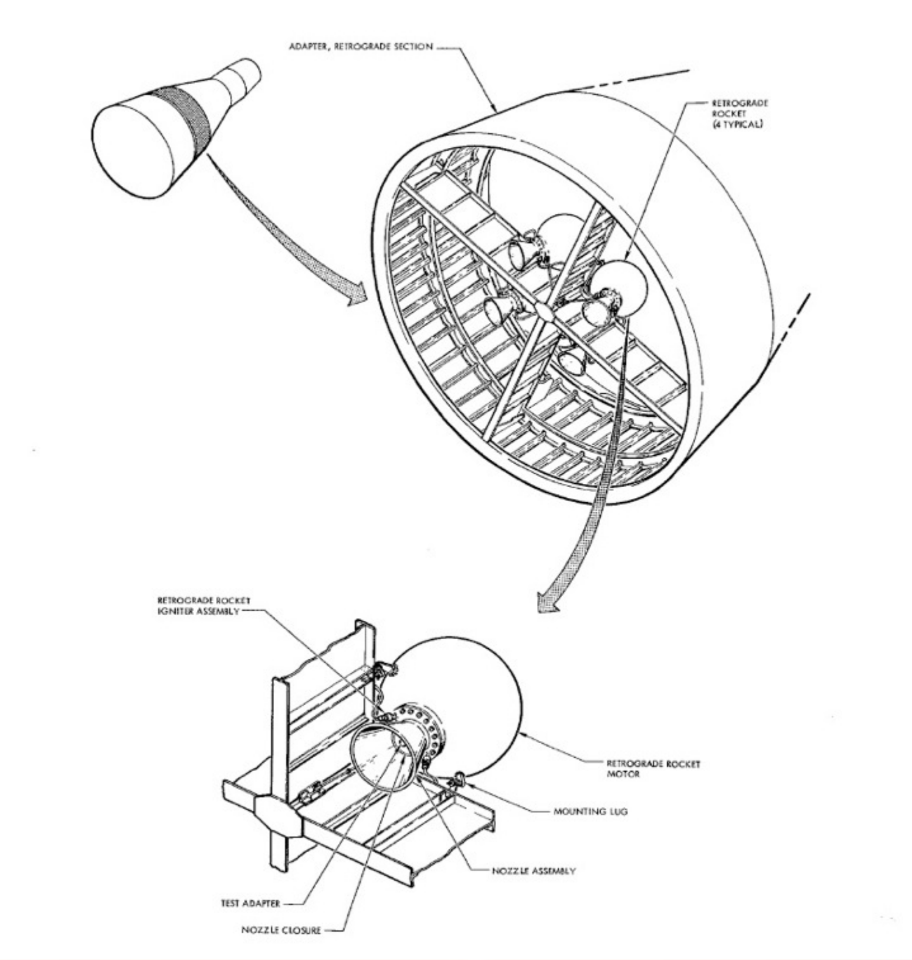


Finocyl (case-bonded)



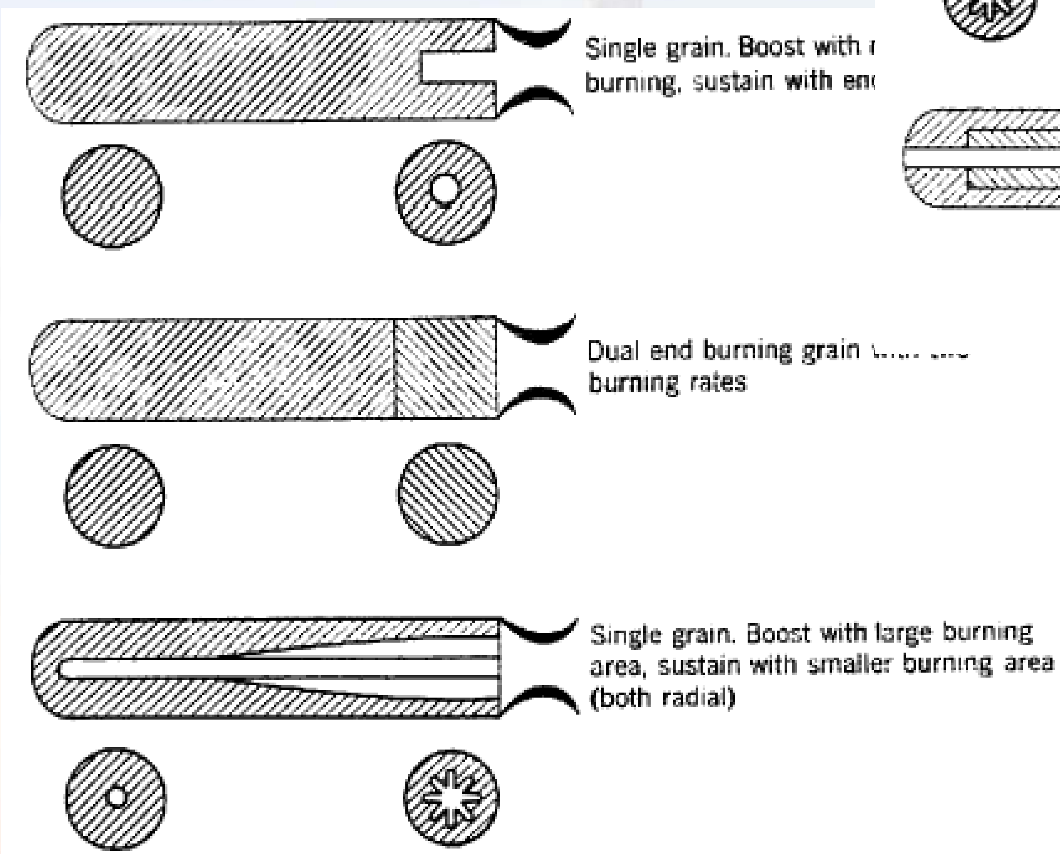
Spherical (case-bonded) with slots and cylinder

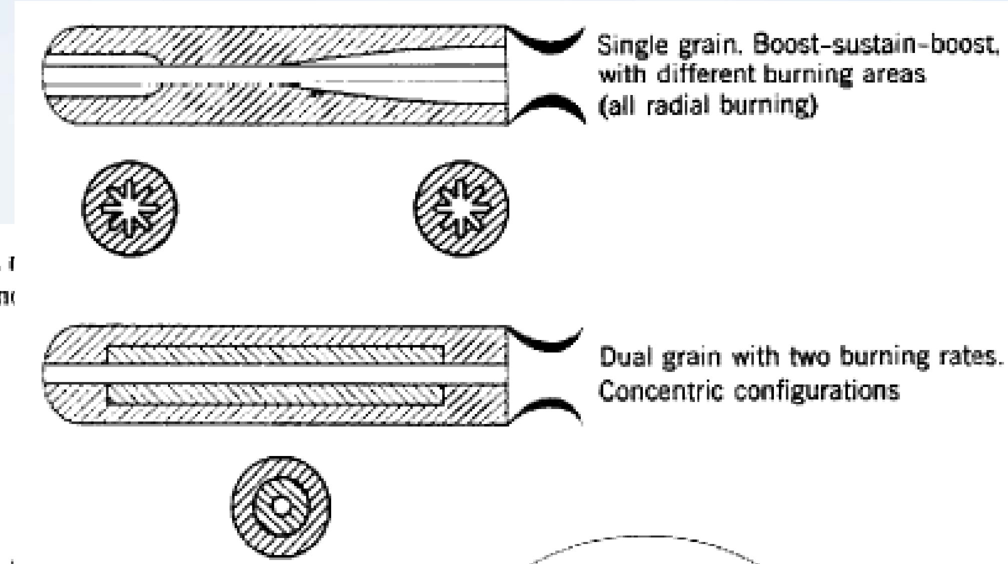
Gemini Retrograde Engine

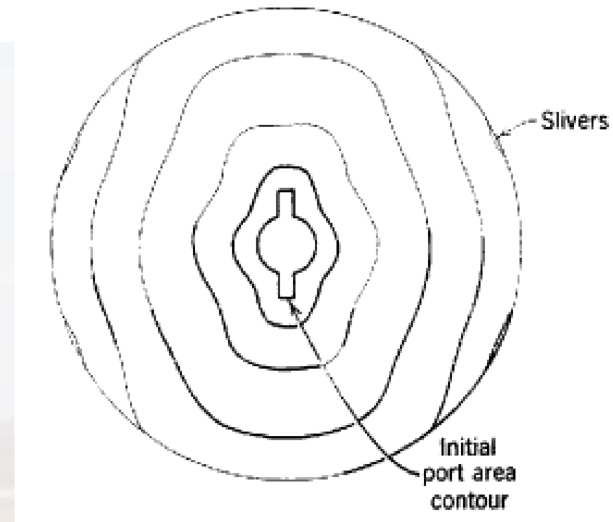


Advanced Grain Configurations

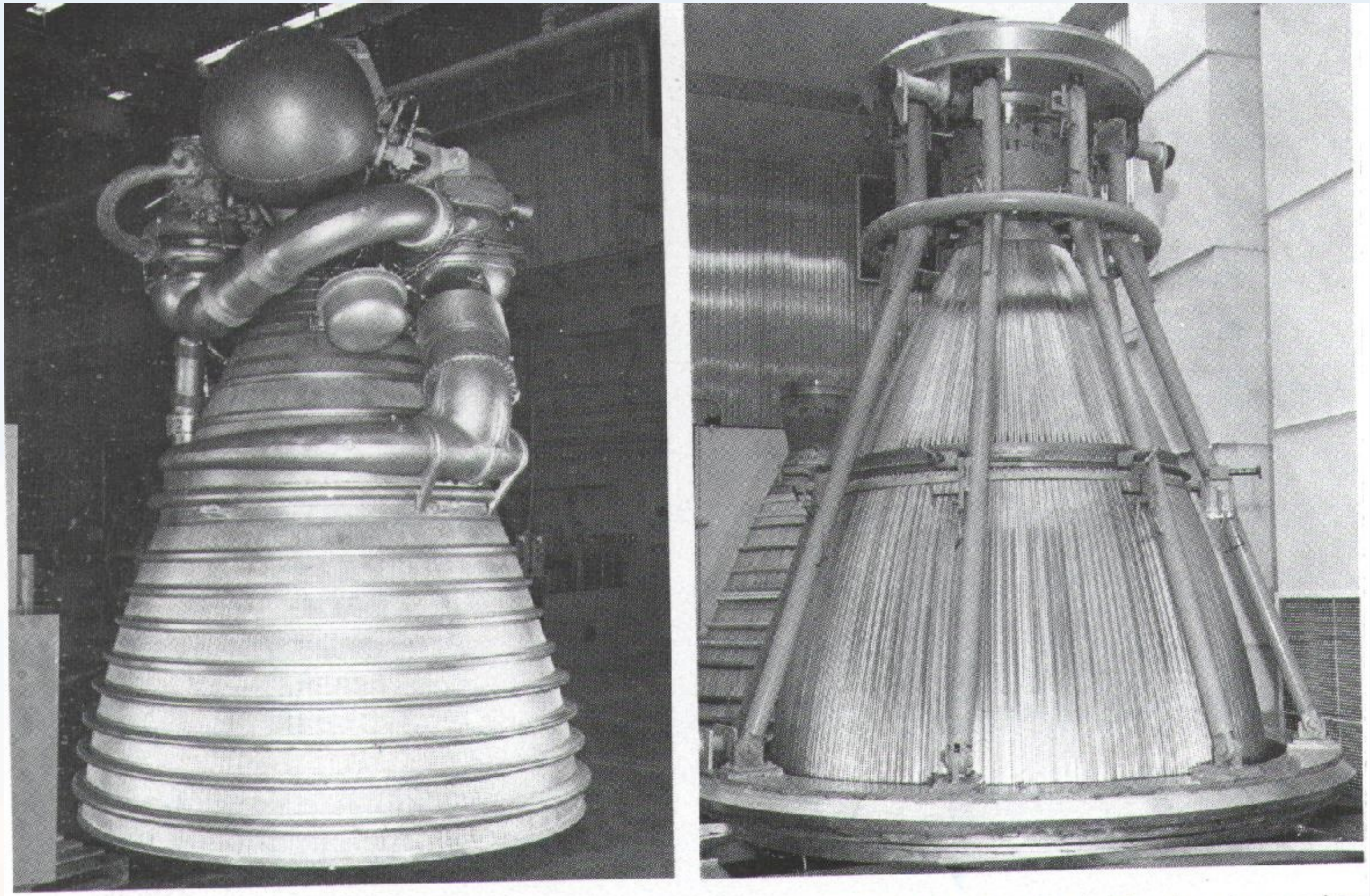
From G. P. Sutton, Rocket Propulsion Elements (5th ed.) John Wiley and Sons, 1986





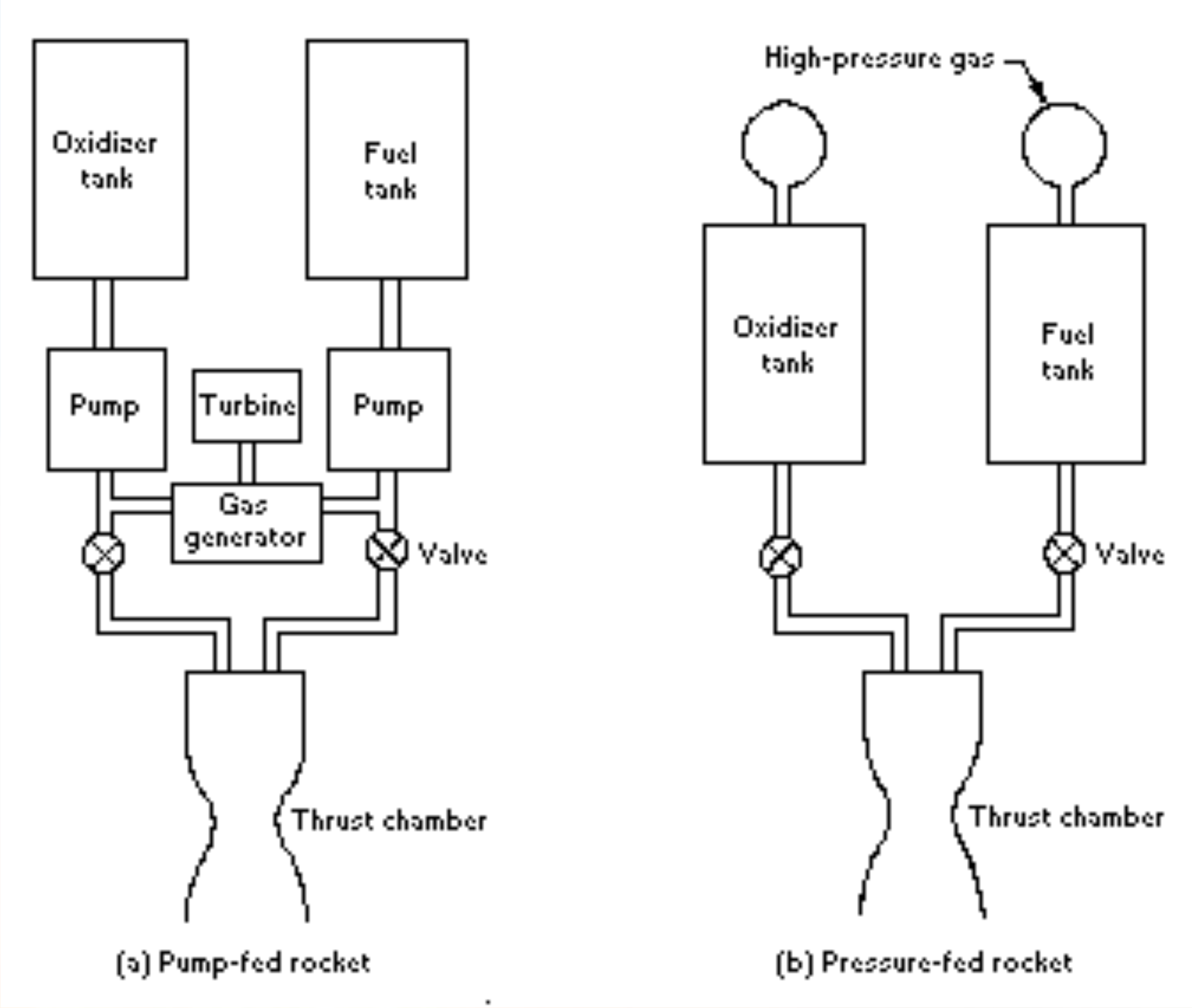


Liquid Rocket Engine

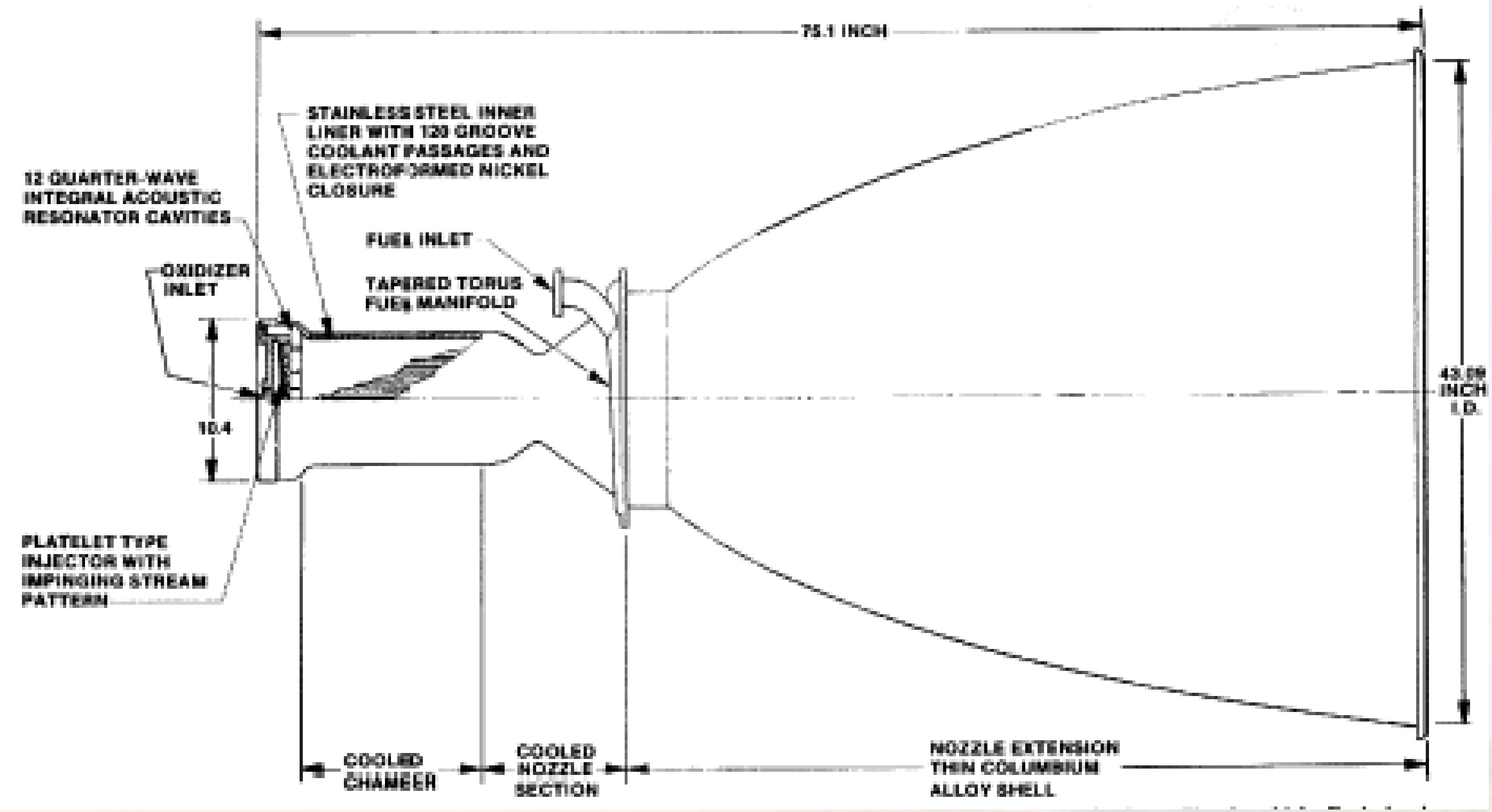


A completed J-2 rocket engine (left), with its pumps and lines installed. The basic engine structure is built up from a series of hollow tubes (right).

Liquid Propellant Feed Systems



Space Shuttle OMS Engine



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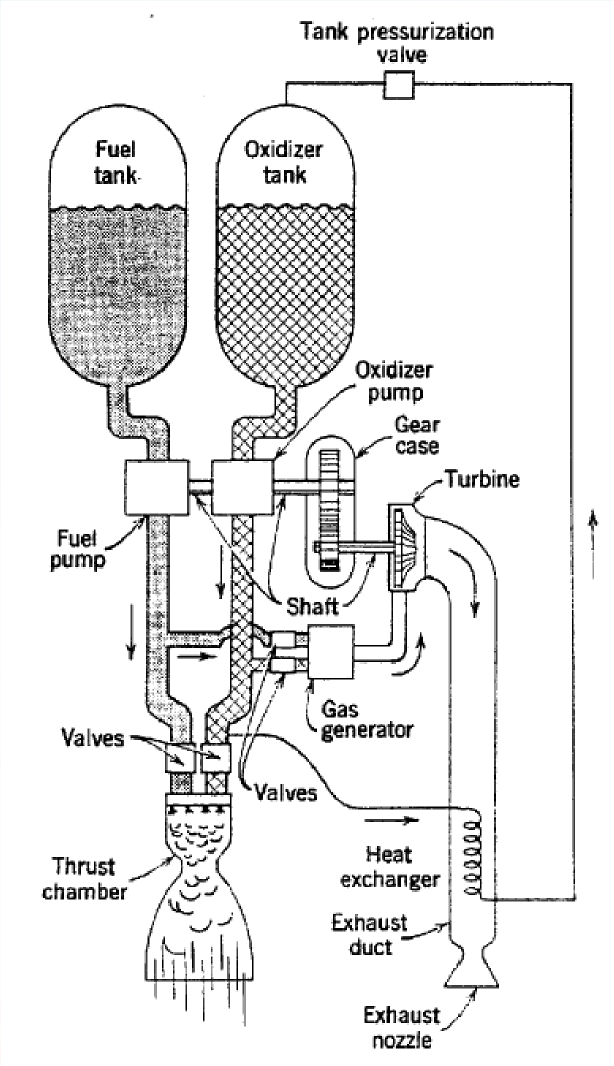
Turbopump Fed Liquid Rocket Engine



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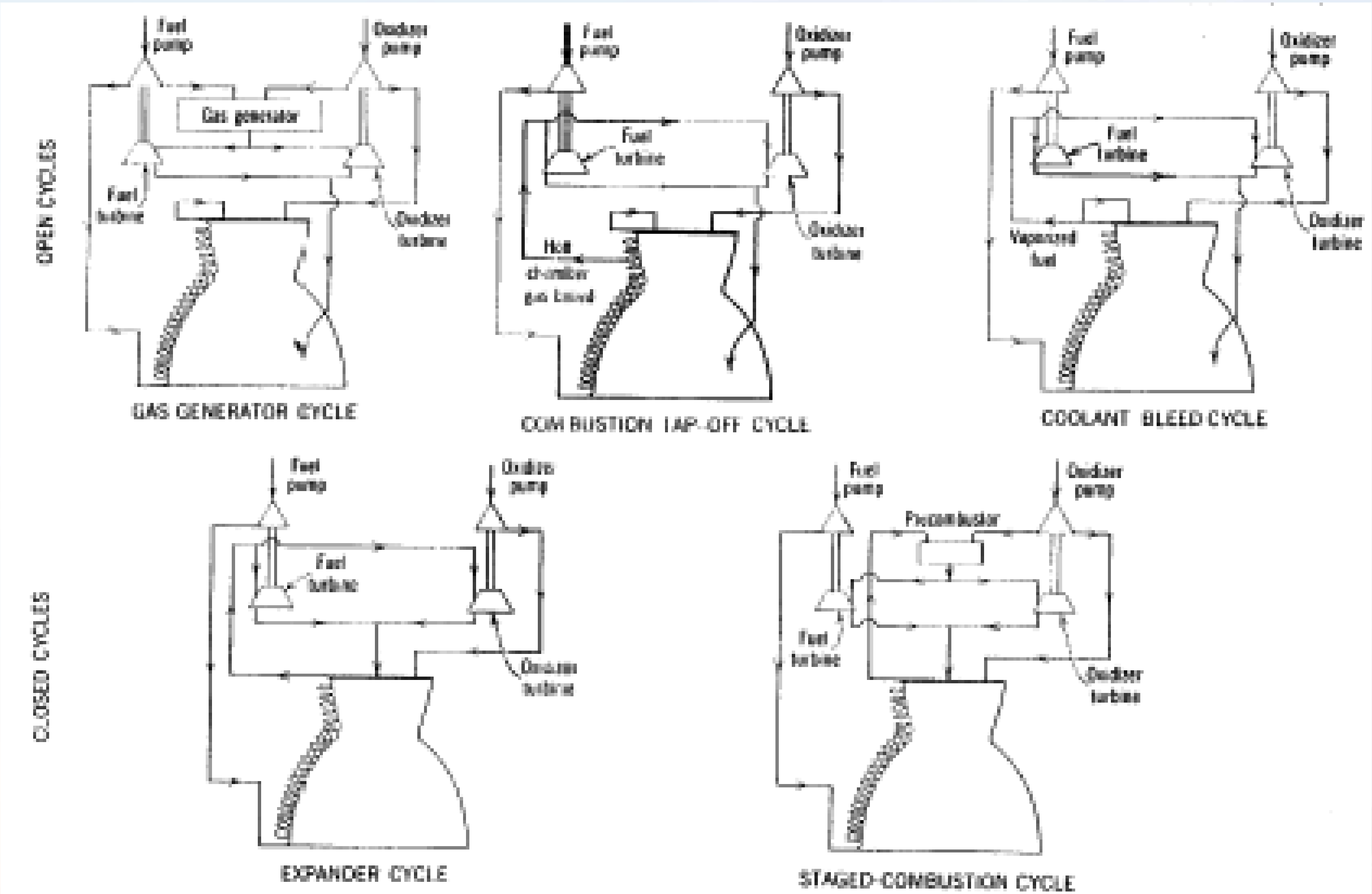
Sample Pump-fed Engine Cycles



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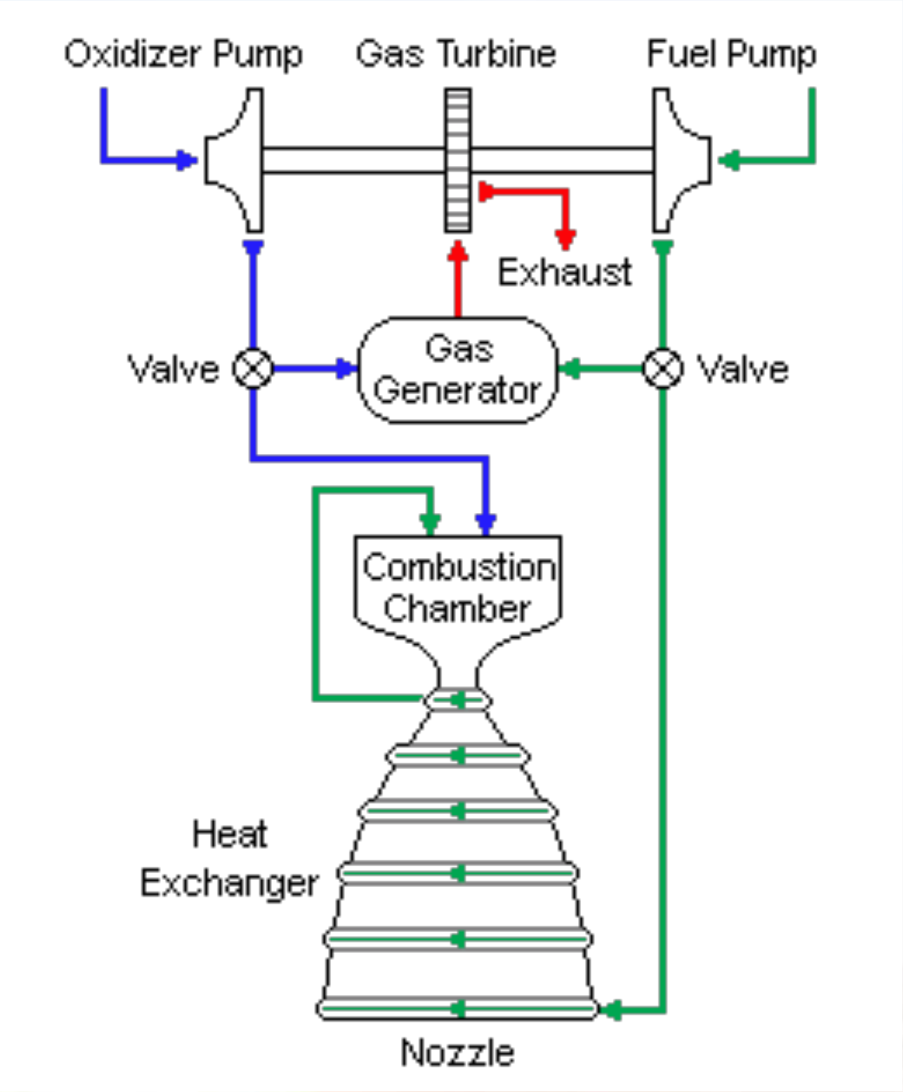
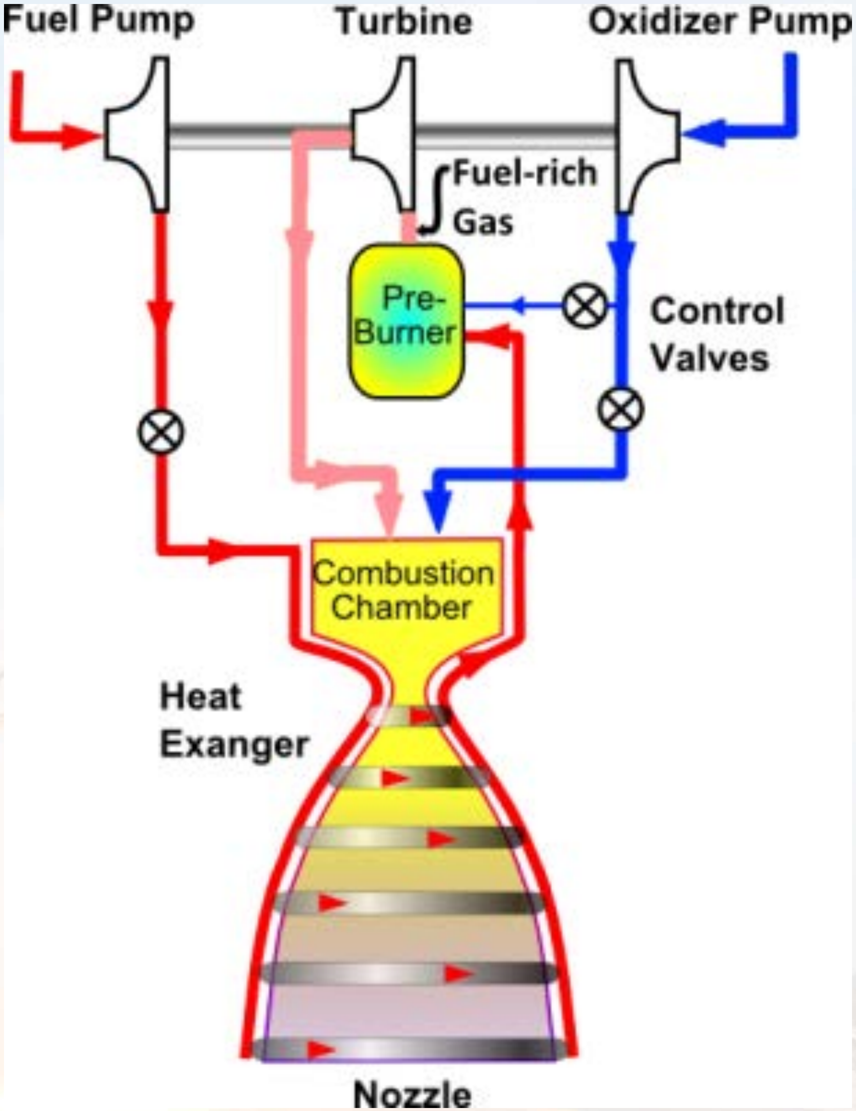
Gas Generator Engine Schematic



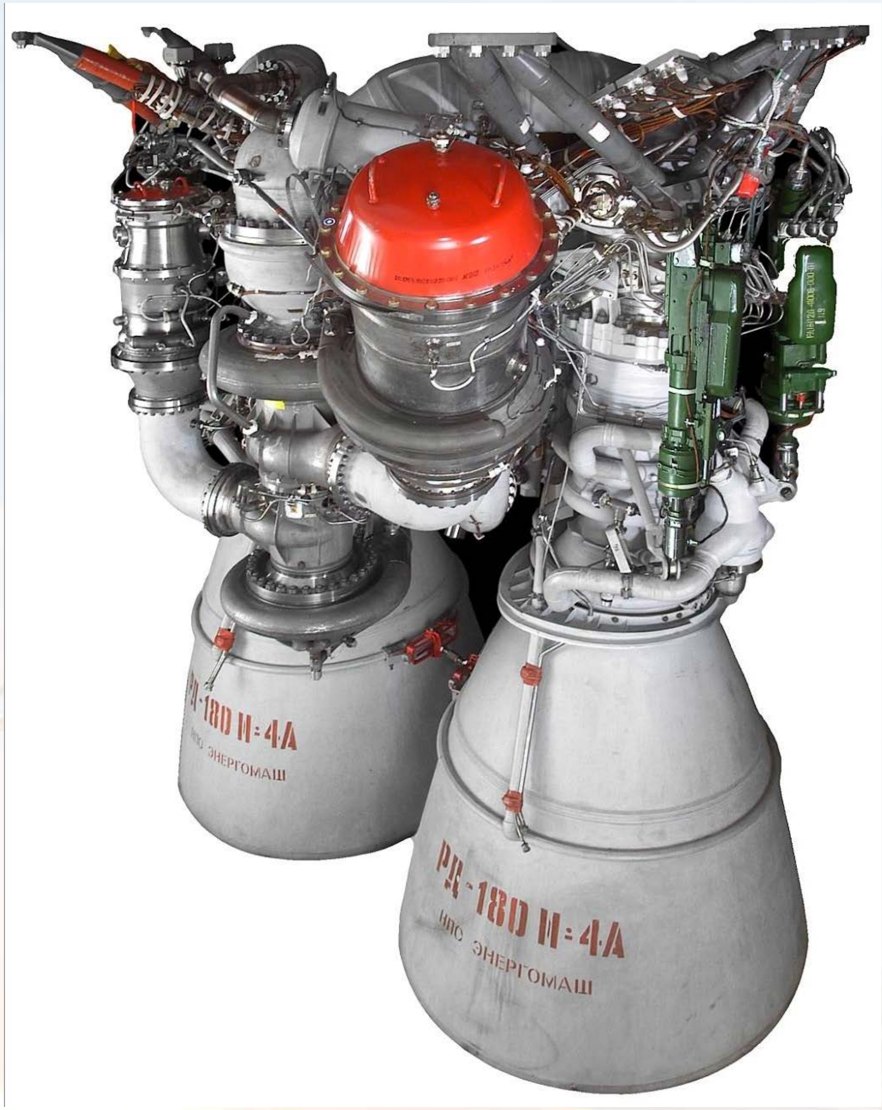
SpaceX Merlin 1d Engines

Falcon 9 Octoweb Engine Mount

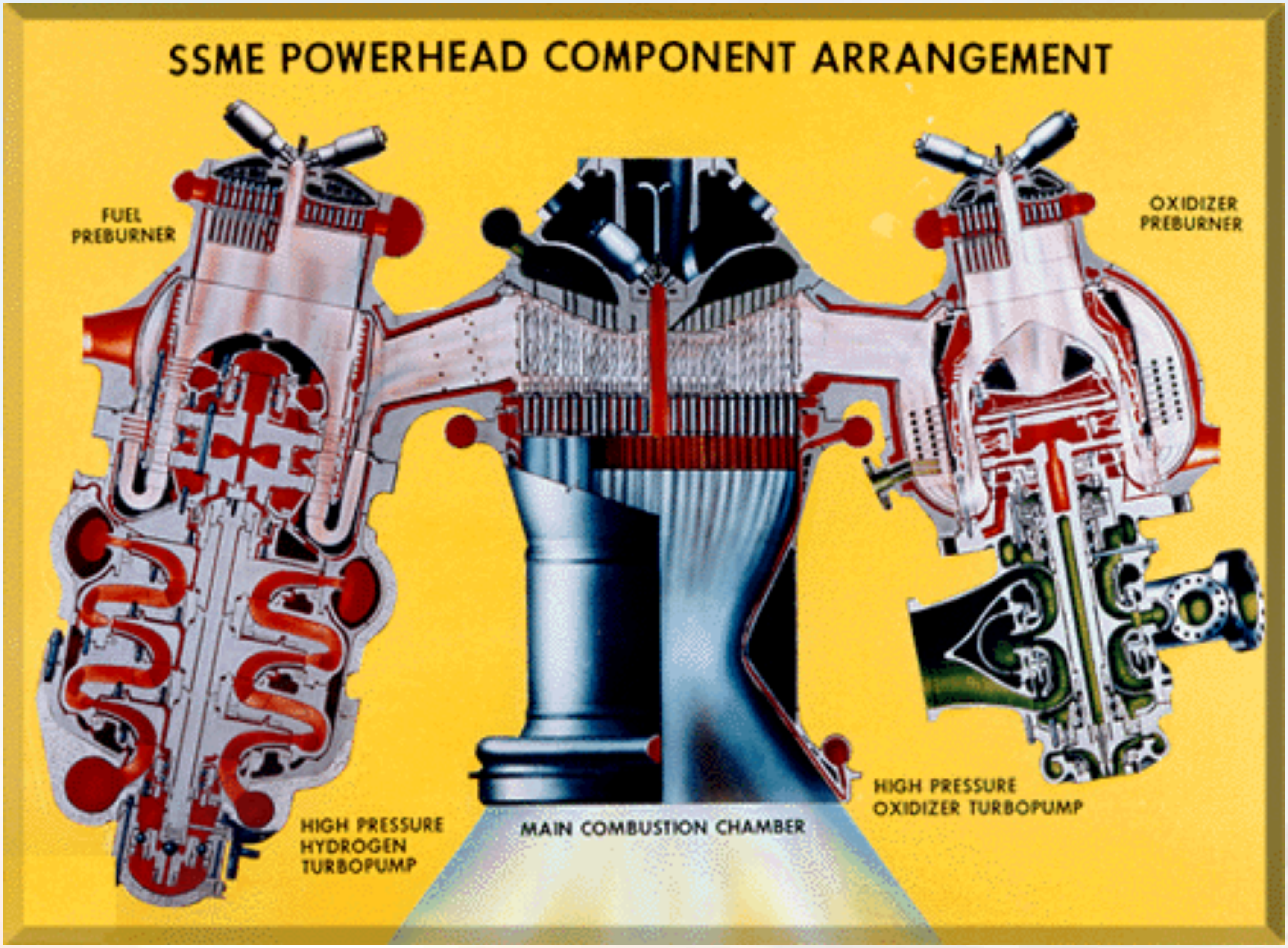
Staged-Combustion Engine Schematic



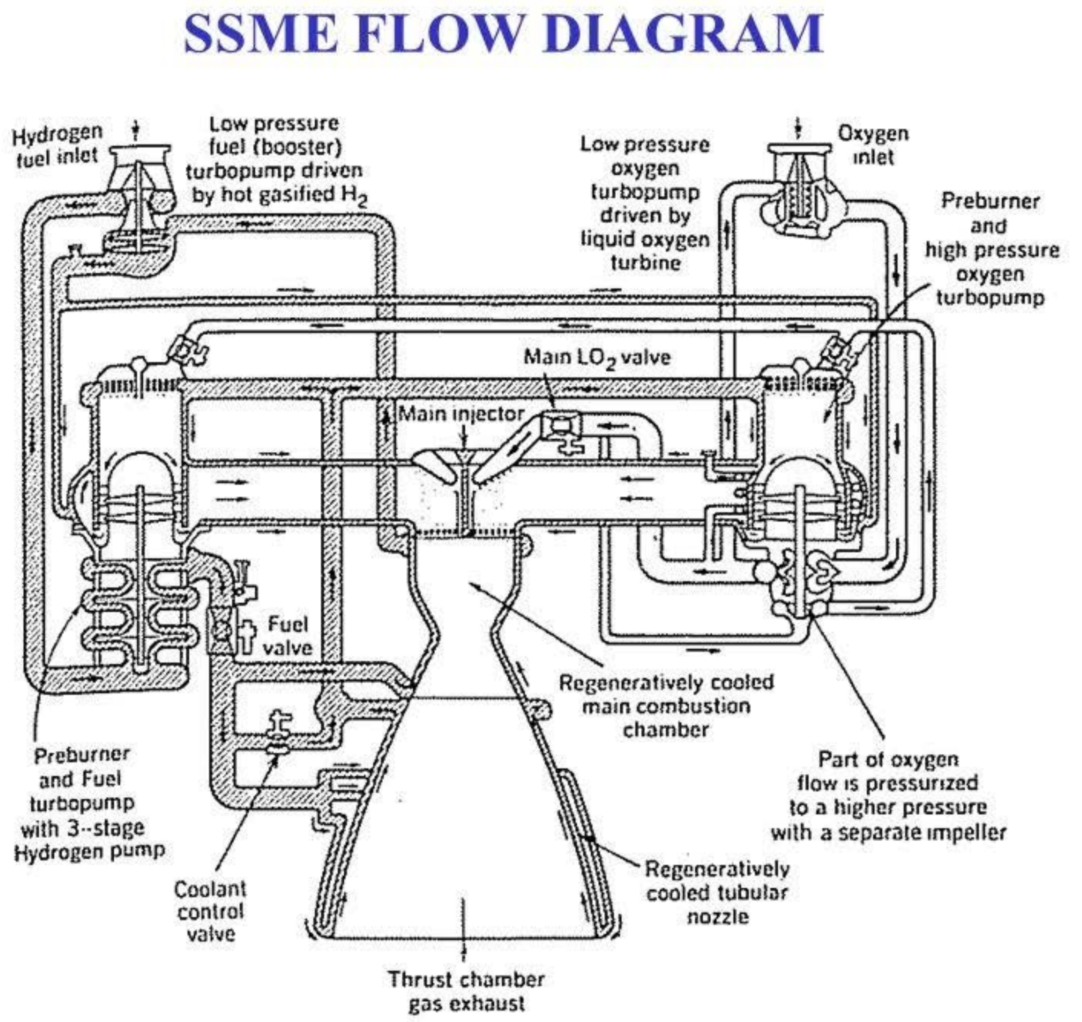
RD-180 Engine(s) (Atlas V)



SSME Powerhead Configuration



SSME Engine Cycle



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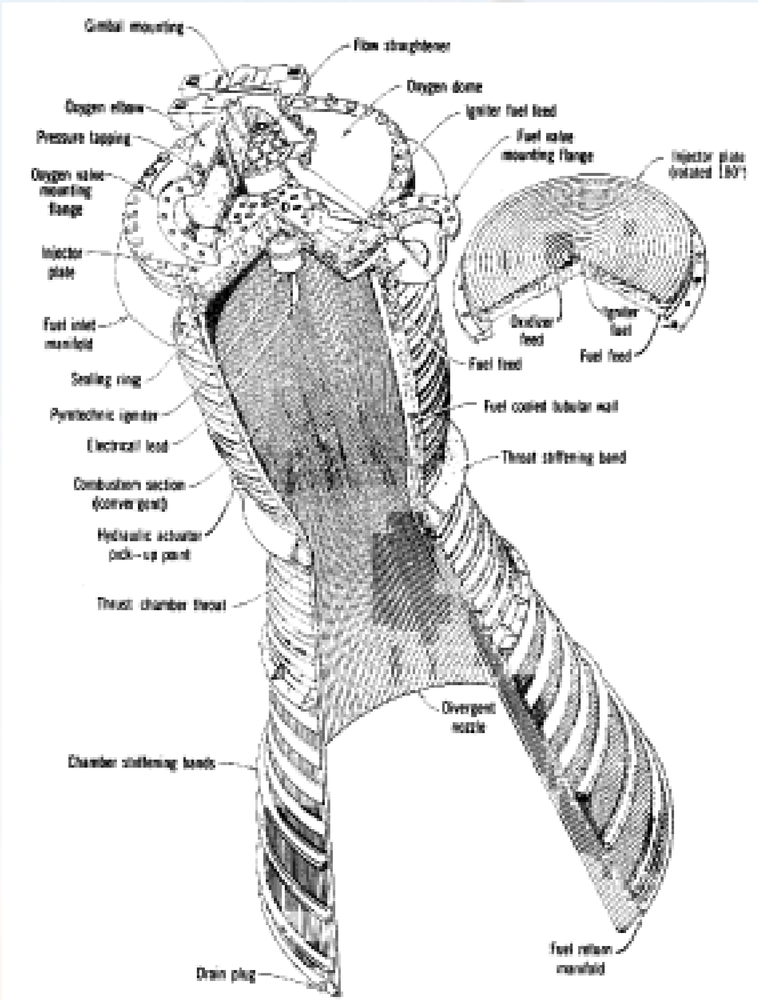
Liquid Rocket Engine Cutaway



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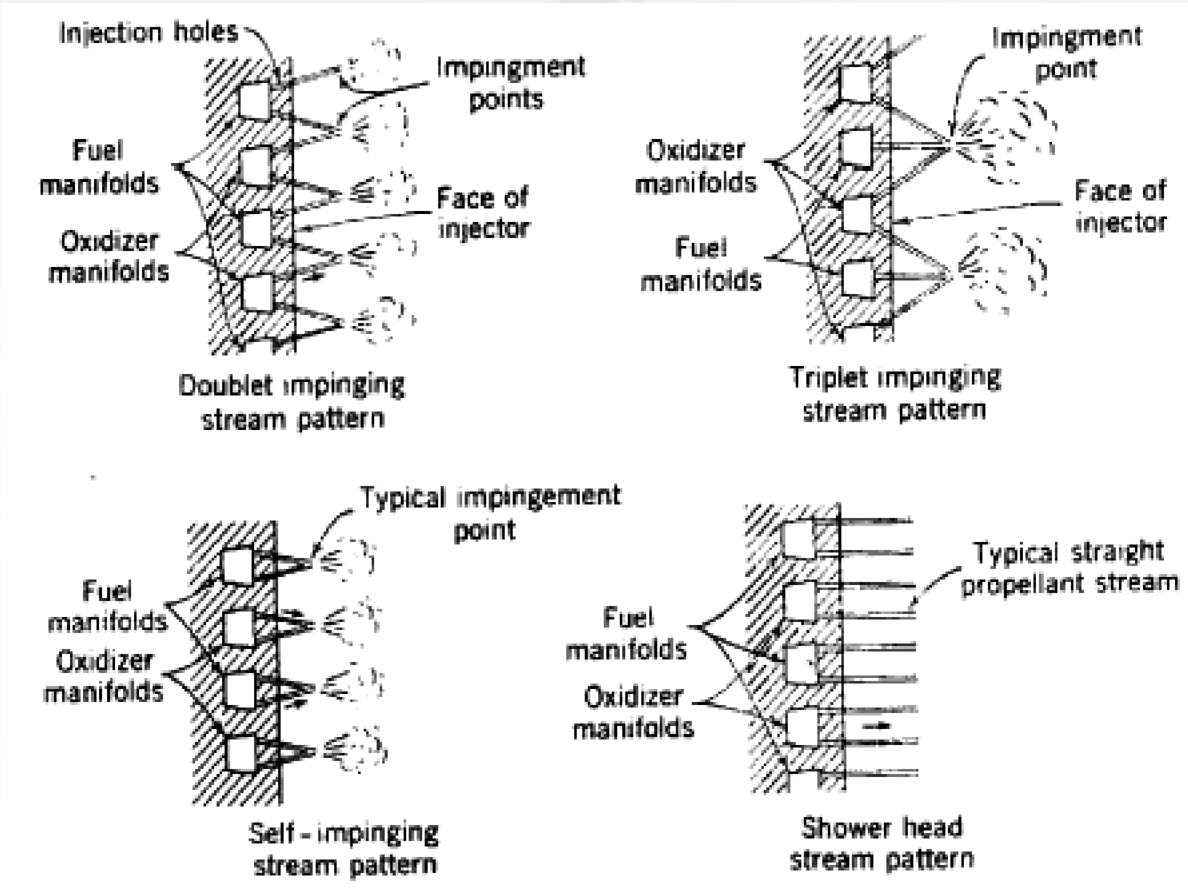
H-1 Engine Injector Plate

Injector Concepts

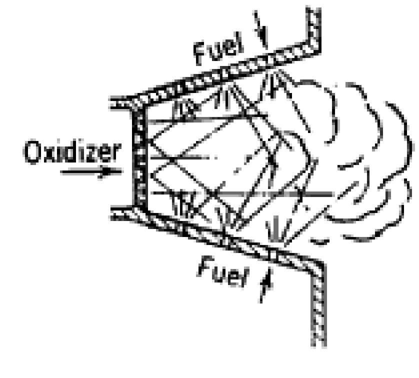


Doublet impinging stream pattern

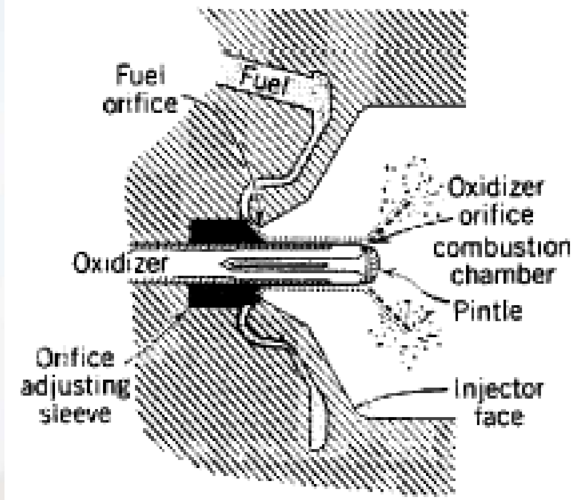
Triplet impinging stream pattern

Self-impinging stream pattern

Shower head stream pattern



Non-impinging stream pattern



Variable injection area concentric tube injector

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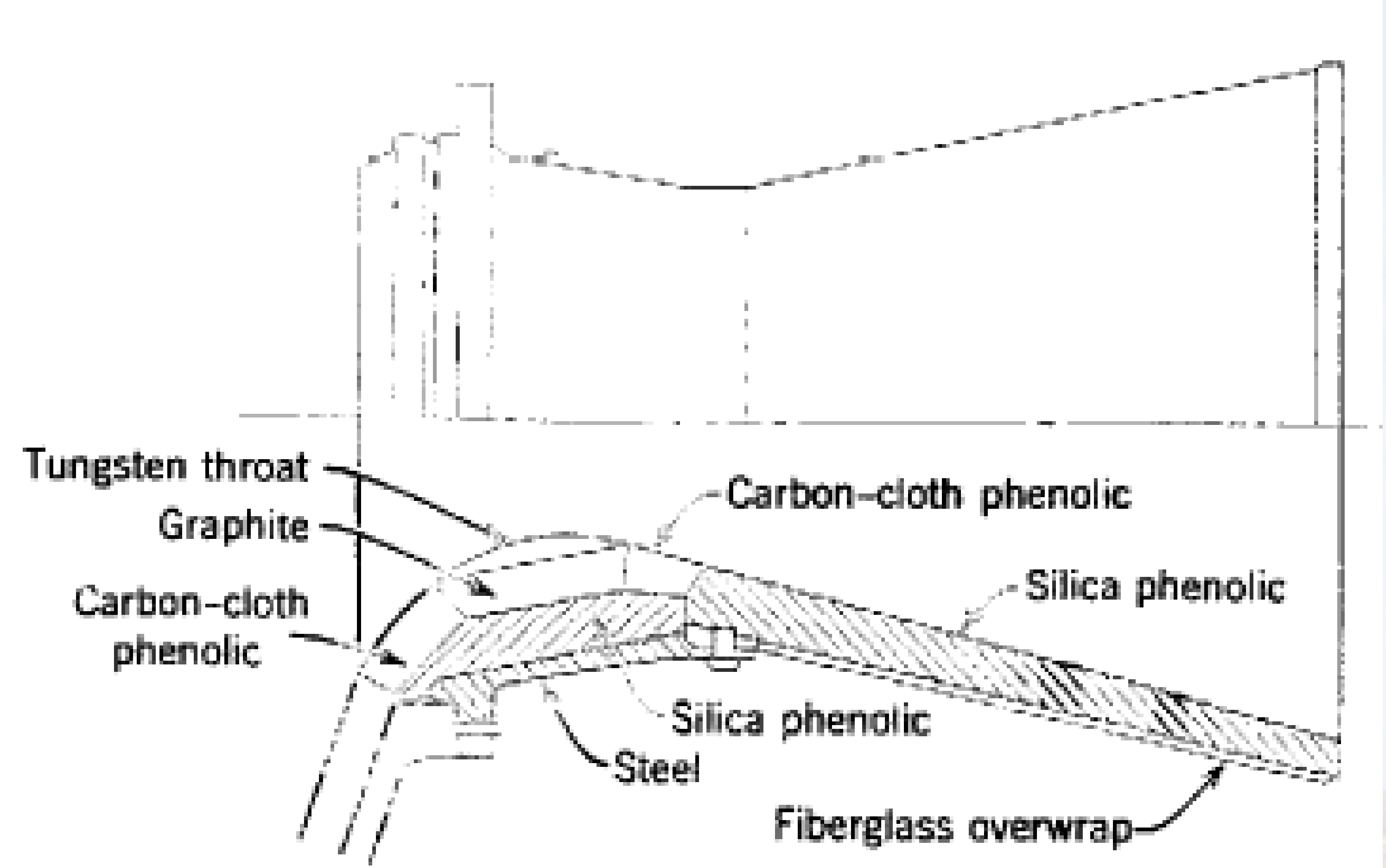
TR-201 Engine (LM Descent/Delta)

Solid Rocket Nozzle (Heat-Sink)



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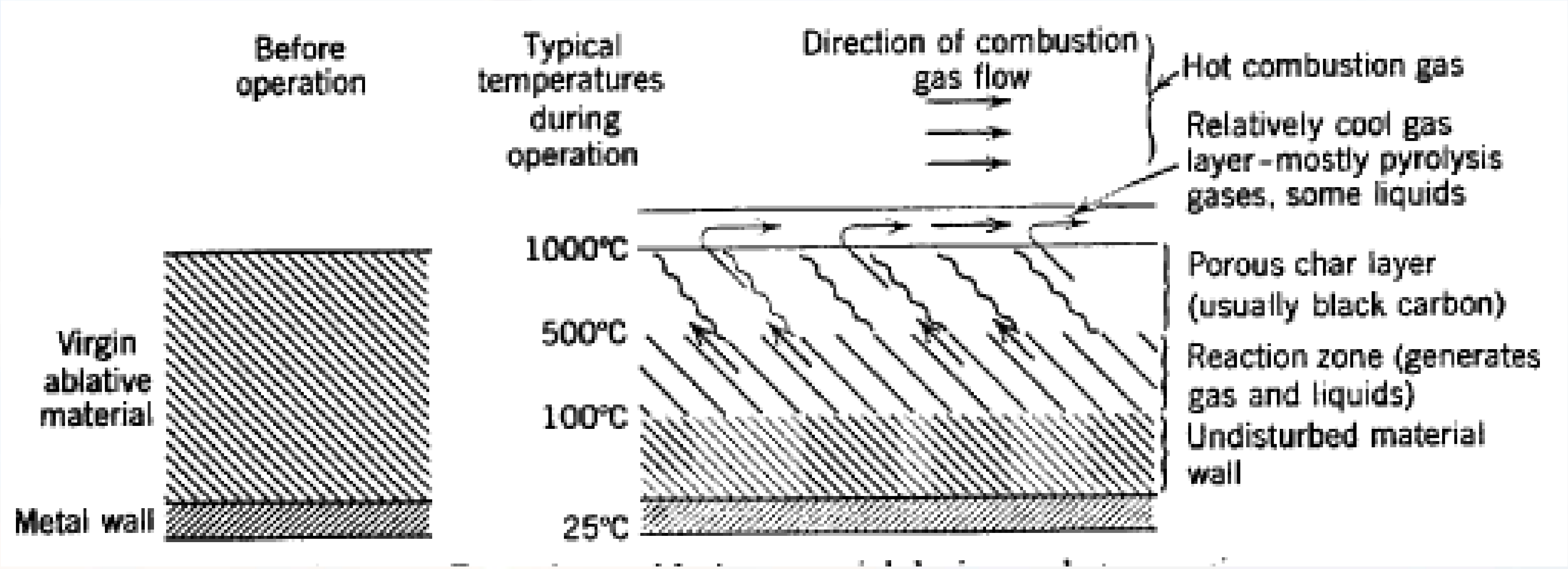
Ablative Nozzle Schematic



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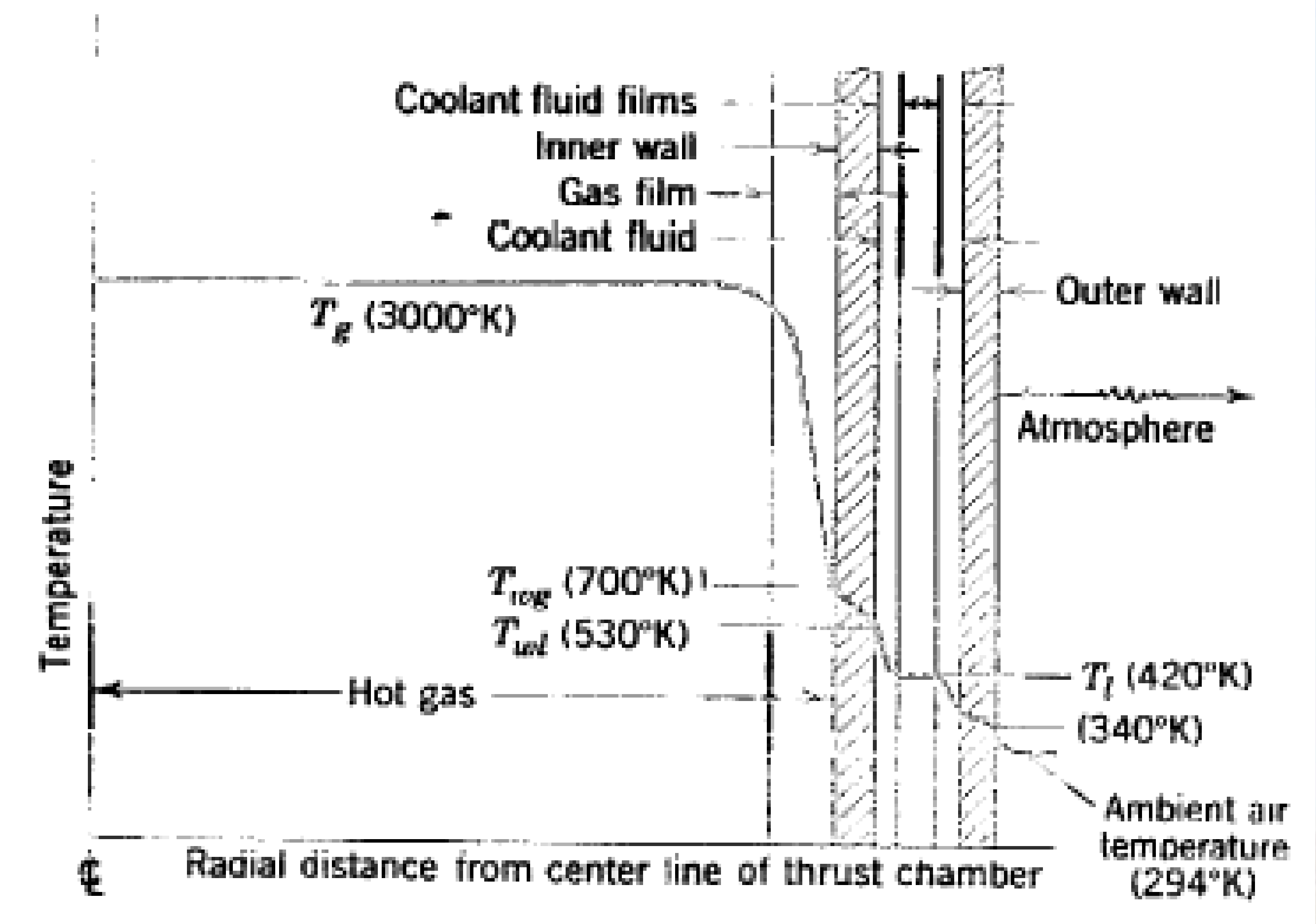
Active Chamber Cooling Schematic



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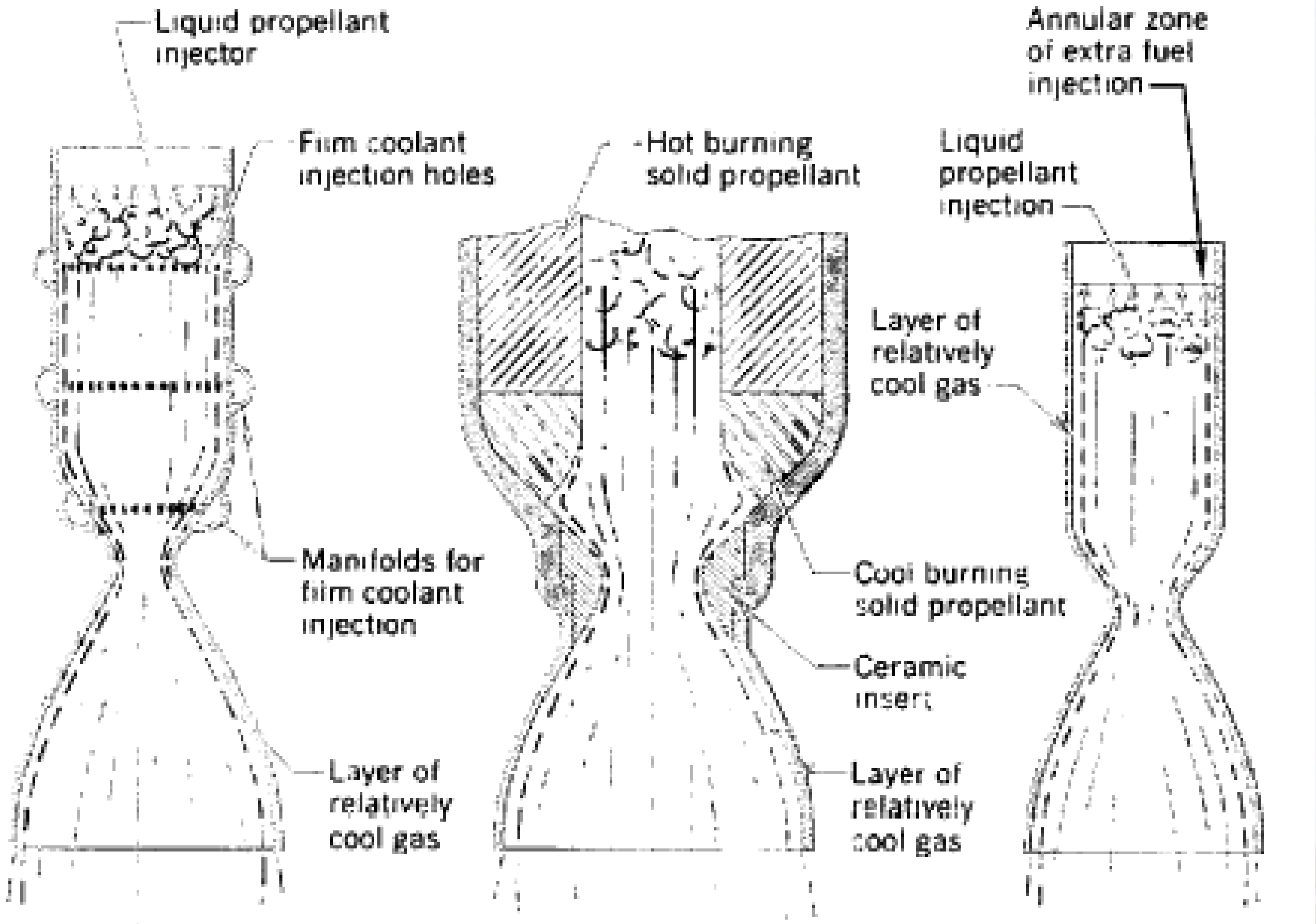
Boundary Layer Cooling Approaches



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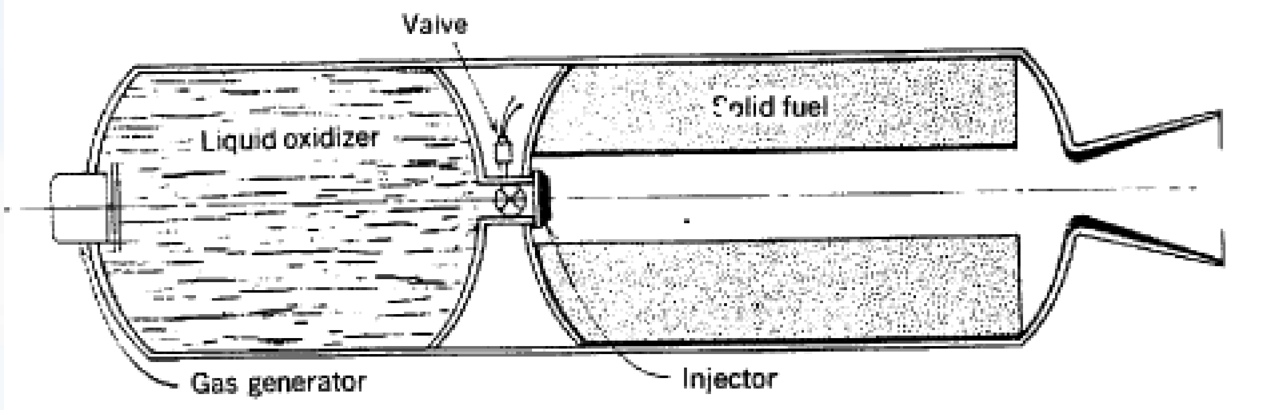
Hybrid Rocket Schematic



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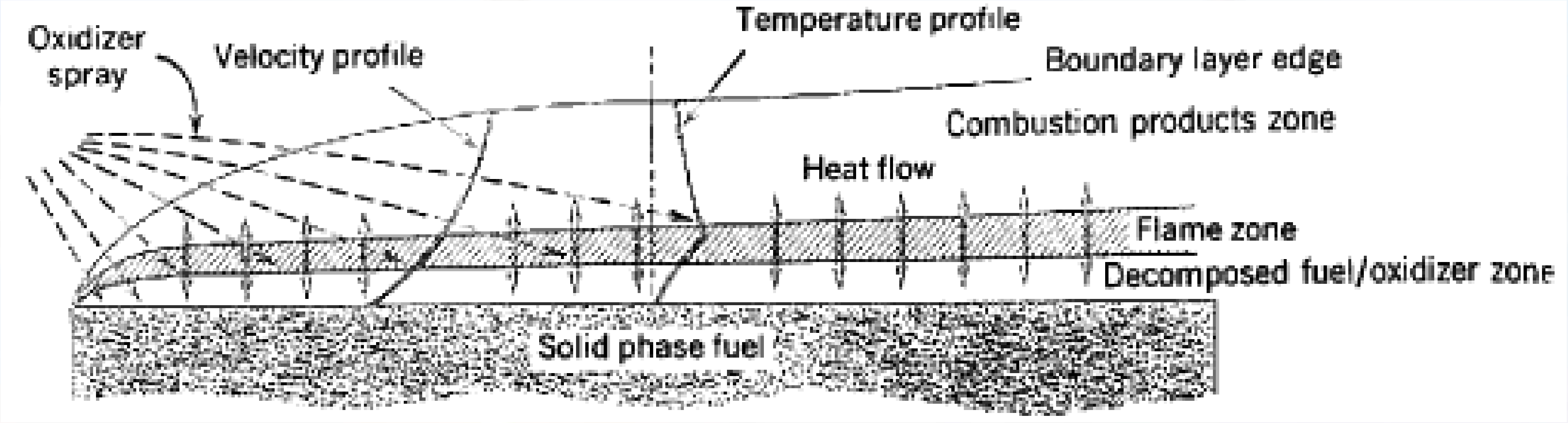
Hybrid Rocket Combustion



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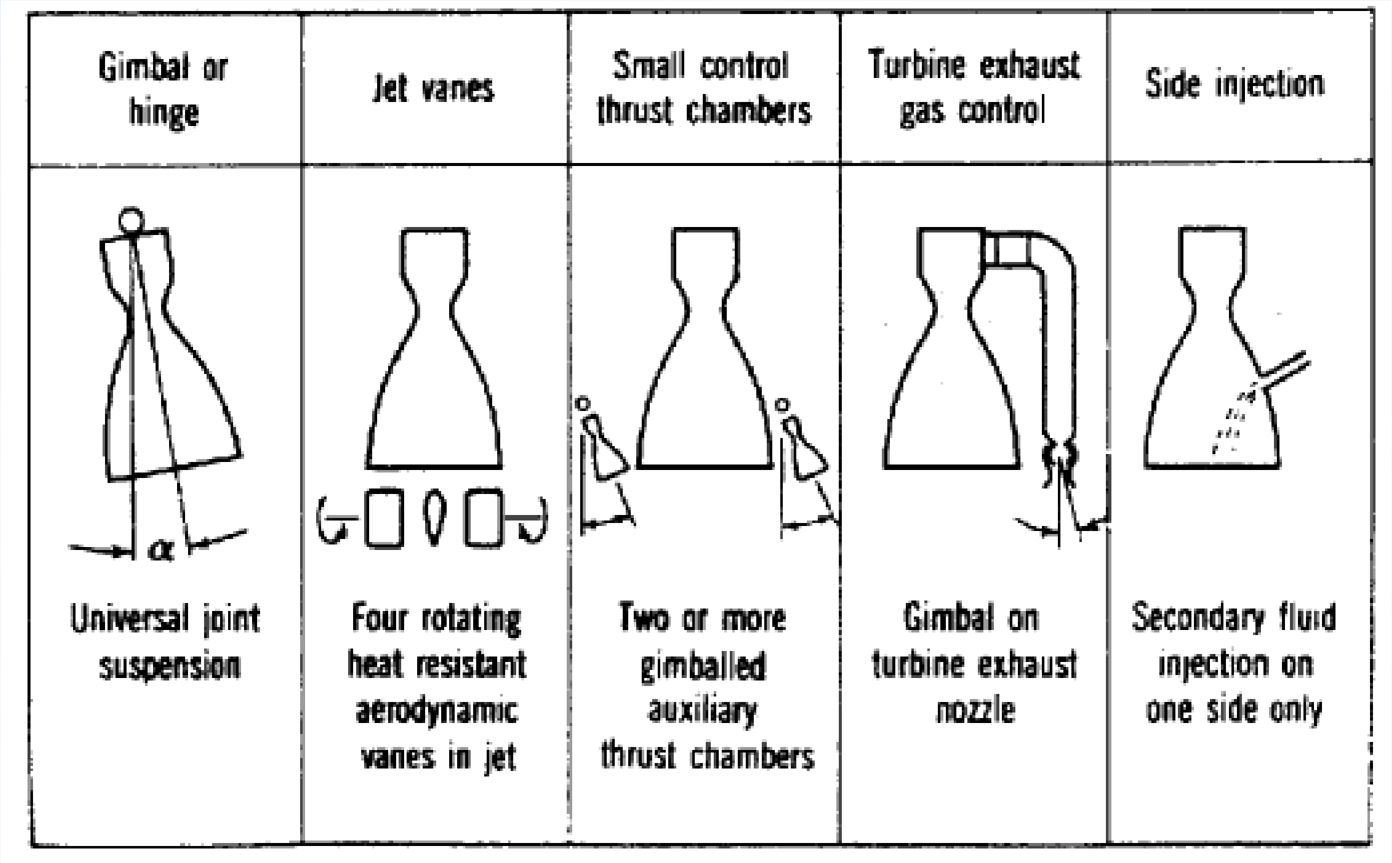
Thrust Vector Control Approaches



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Reaction Control Systems

- Thruster control of vehicle attitude and translation
- "Bang-bang" control algorithms
- Design goals:
  - Minimize coupling (pure forces for translation; pure moments for rotation)except for pure entry vehicles
  - Minimize duty cycle (use propellant as sparingly as possible)
  - Meet requirements for maximum rotational and linear accelerations

Single-Axis Equations of Motion

$$\tau = I\ddot{\theta}$$

$$\frac{\tau}{I}t = \dot{\theta} + C_1$$

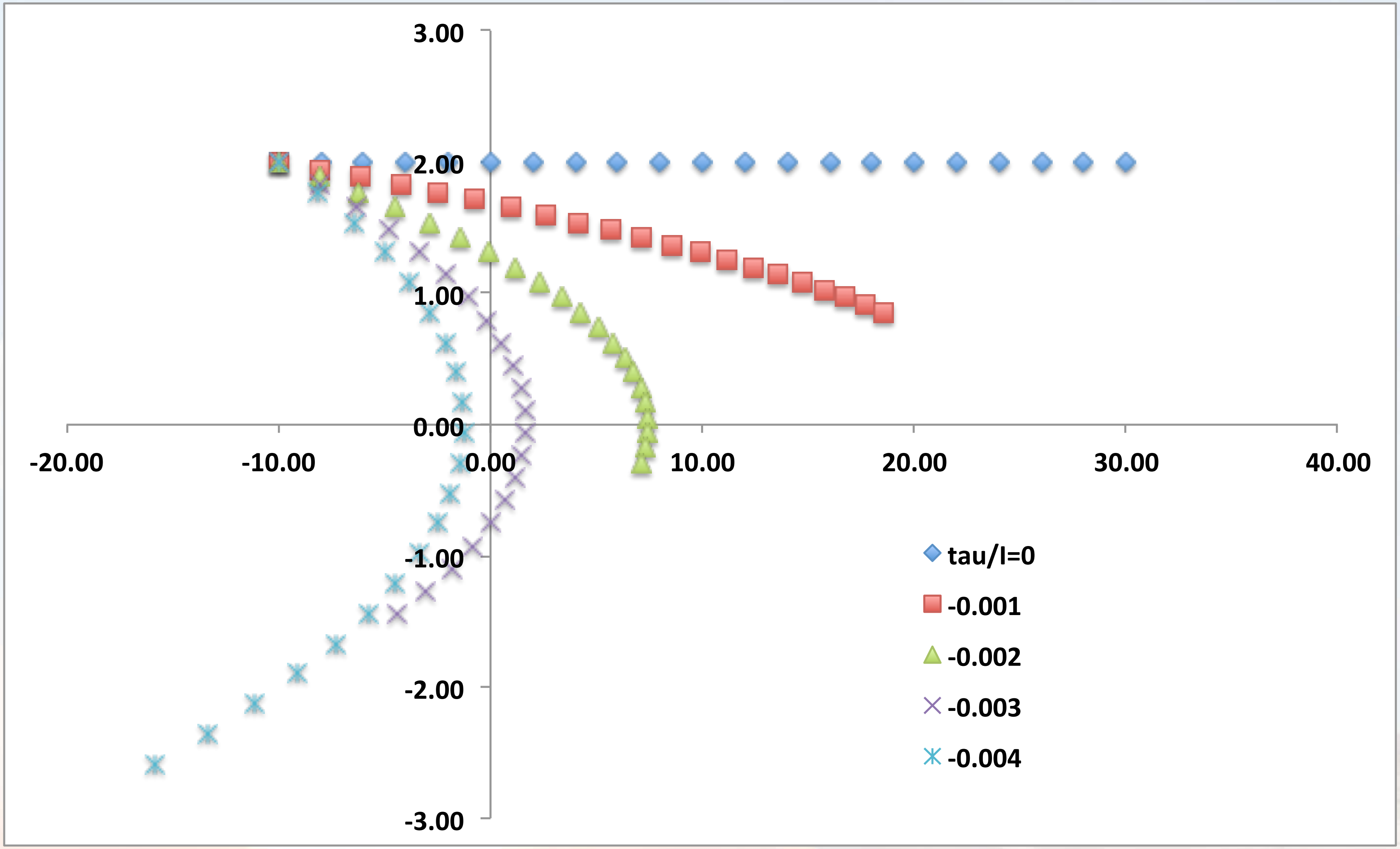
$$\text{at } t = 0,\ \dot{\theta} = \dot{\theta}_o \implies \frac{\tau}{I}t = \dot{\theta} - \dot{\theta}_o$$

$$\frac{1}{2}\frac{\tau}{I}t^2 + \dot{\theta}_o t = \theta + C_2$$

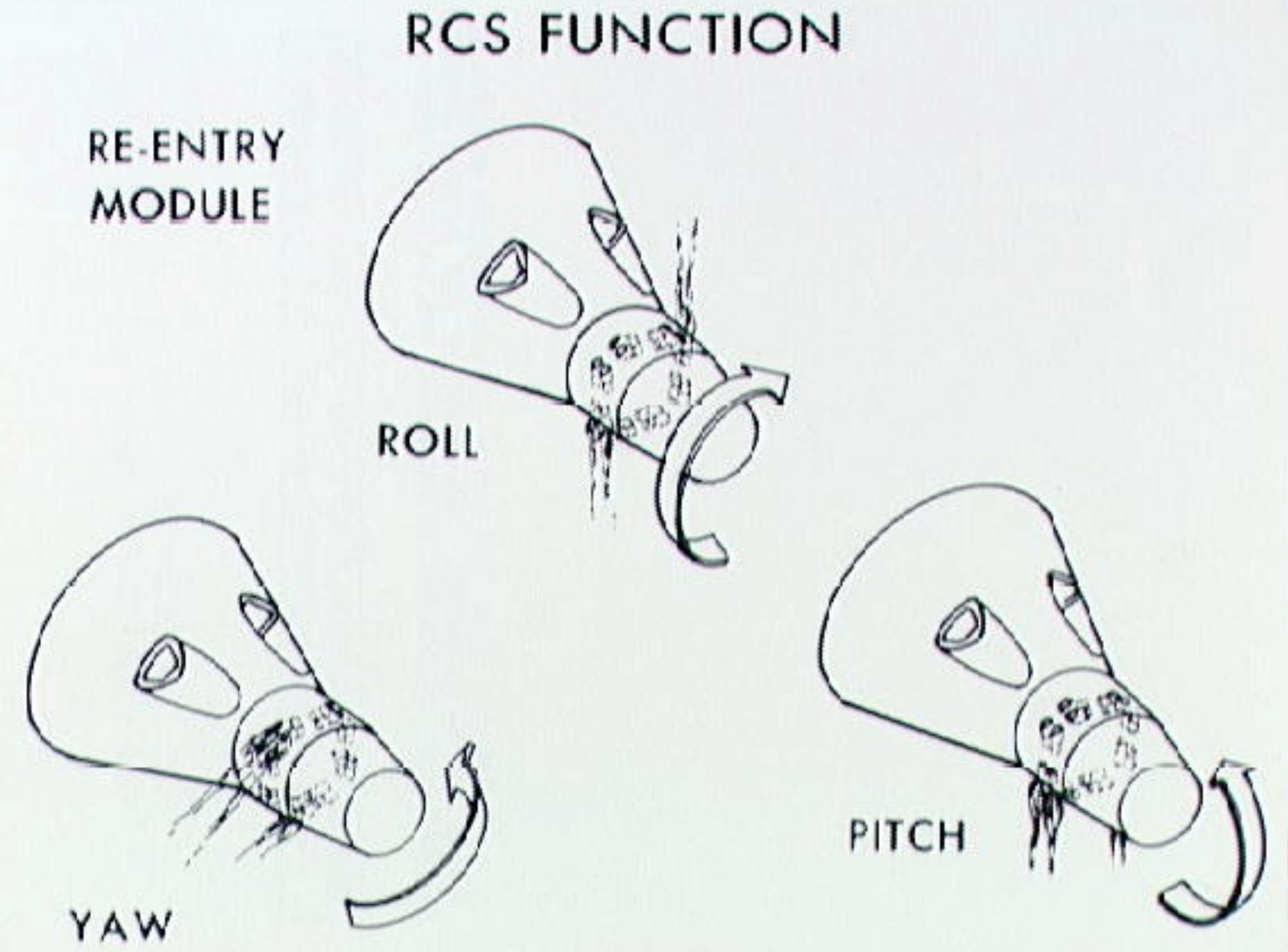
$$\text{at } t = 0,\ \theta = \theta_o \implies \frac{1}{2}\frac{\tau}{I}t^2 + \dot{\theta}_o t = \theta - \theta_o$$

$$\frac{1}{2}\left(\dot{\theta}^2 - \dot{\theta}_o{}^2\right) = \frac{\tau}{I}\left(\theta - \theta_o\right)$$

Attitude Trajectories in the Phase Plane



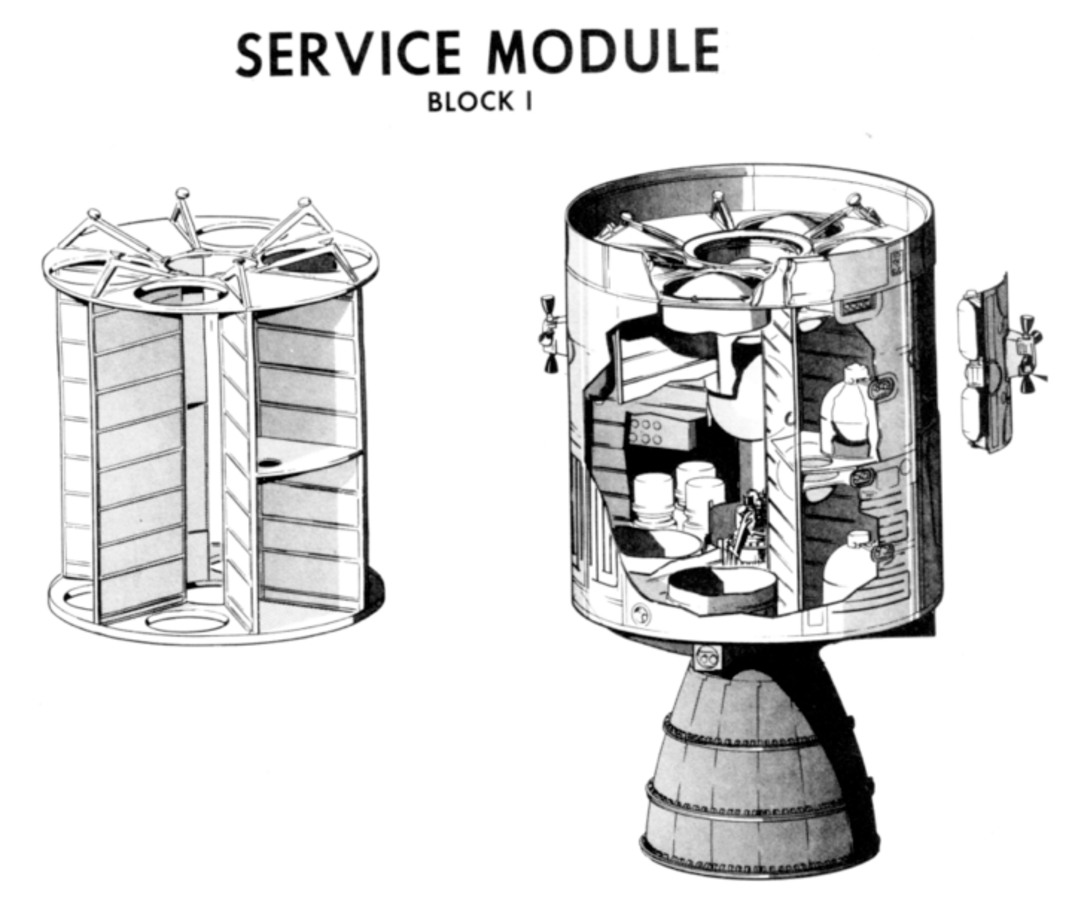
Gemini Entry Reaction Control System

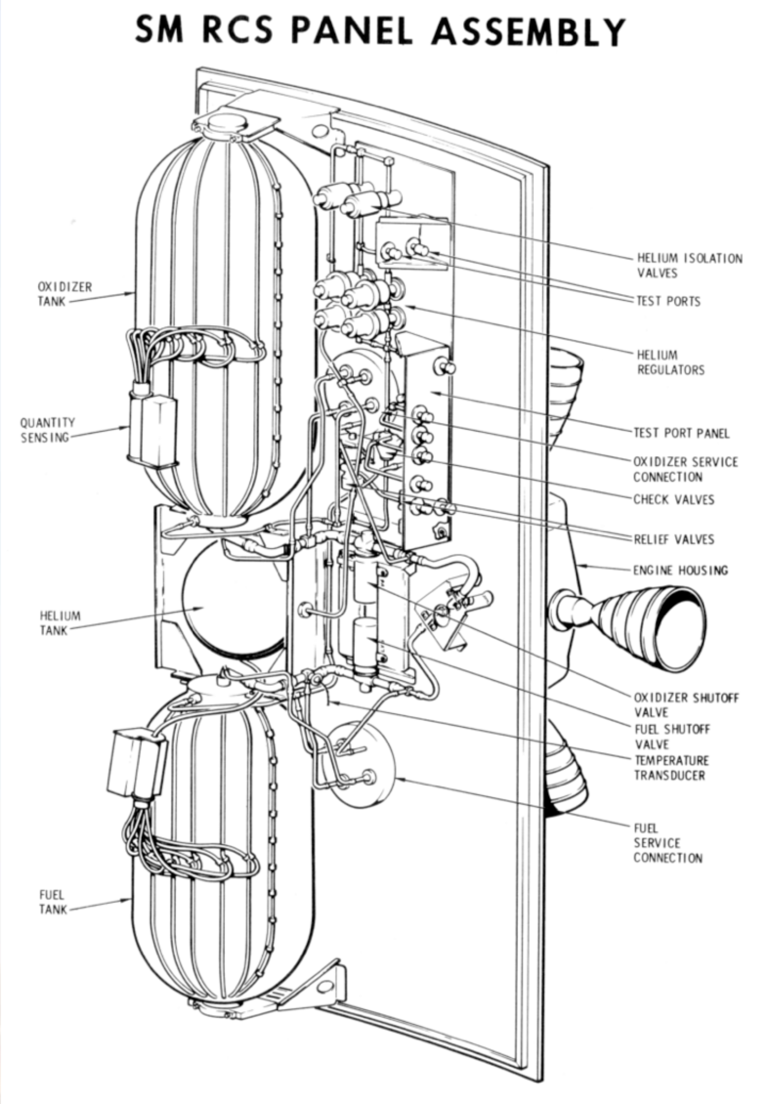


Apollo Reaction Control System Thrusters

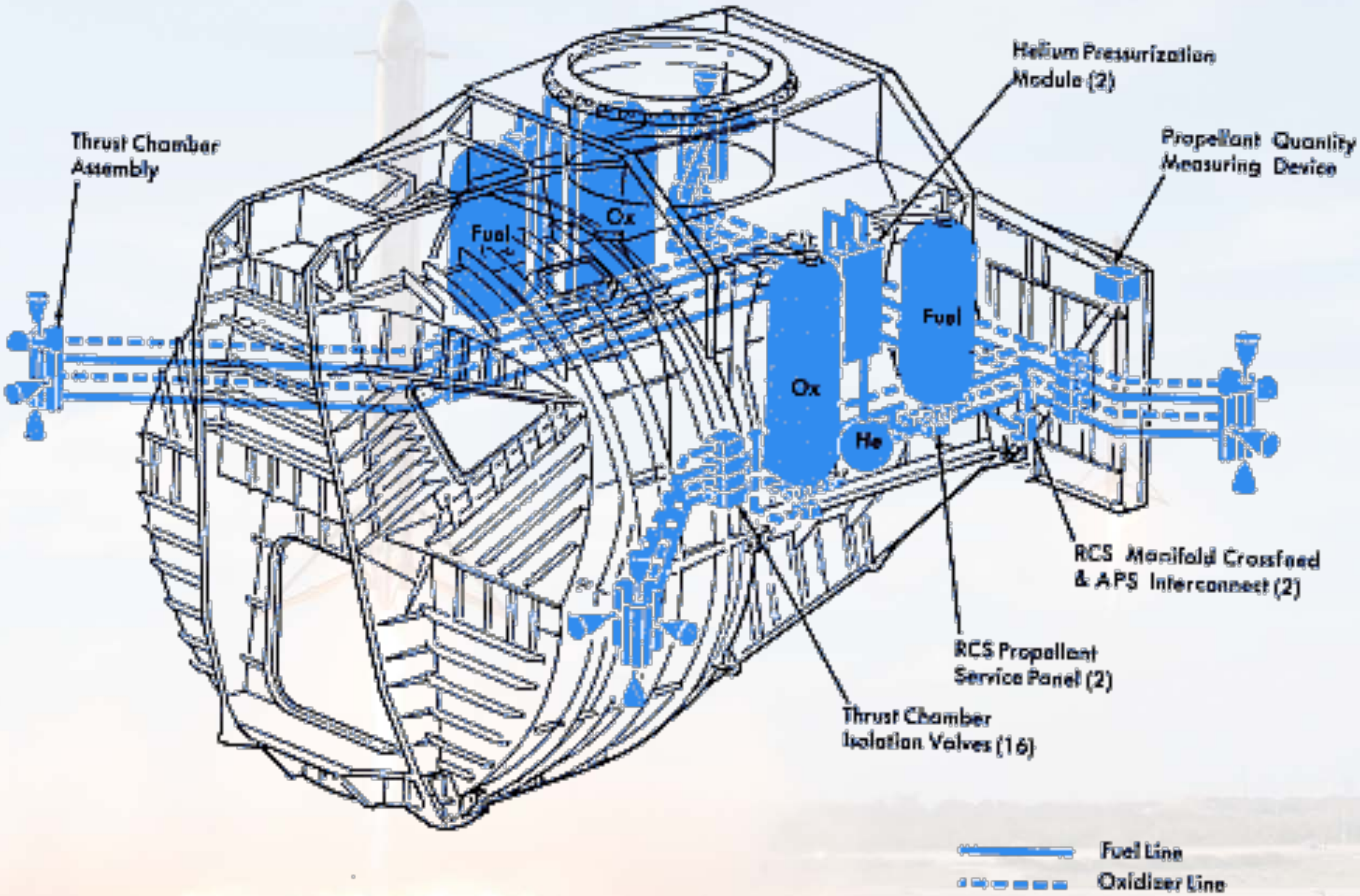
RCS Quad

Apollo CSM RCS Assembly

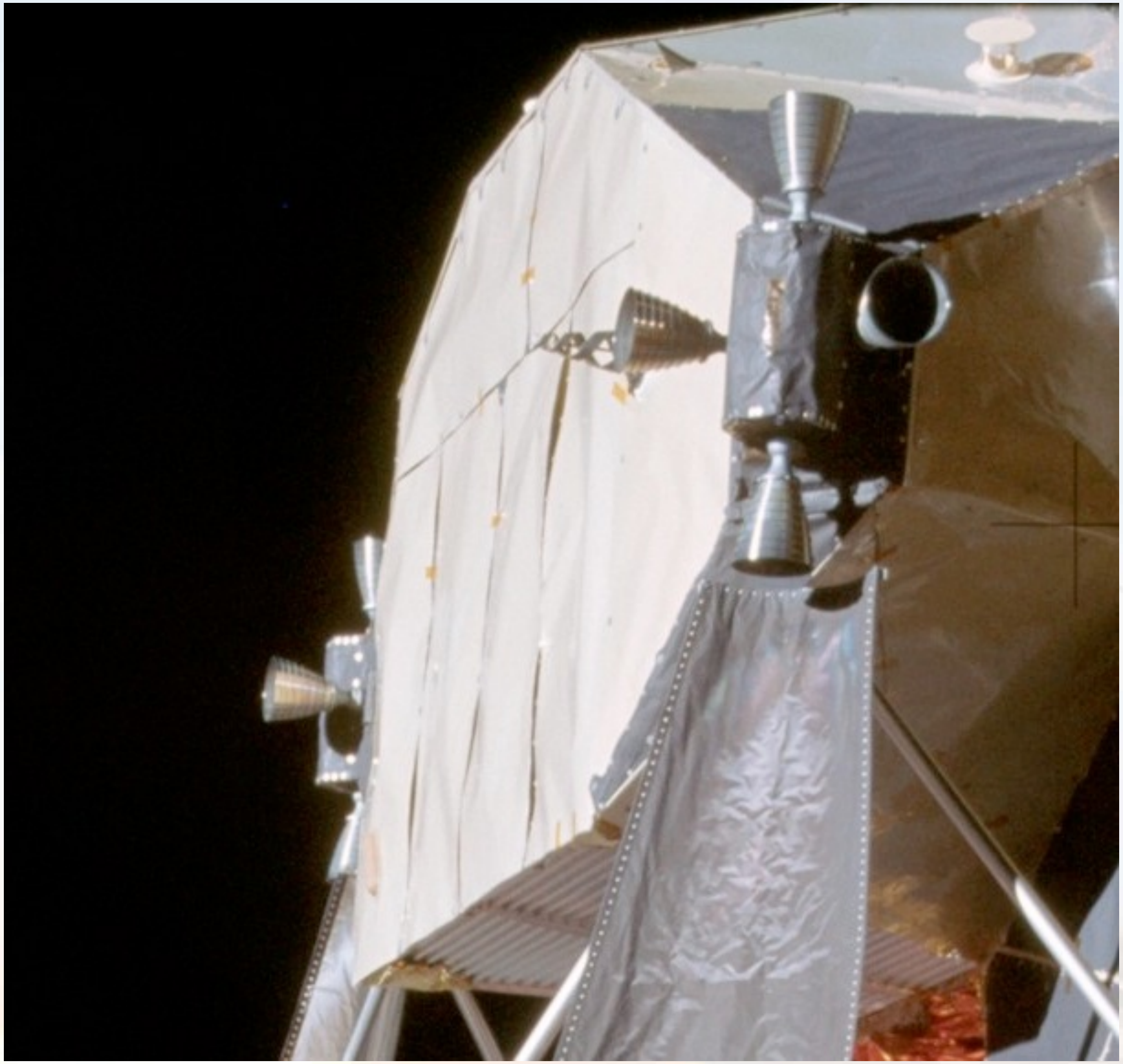




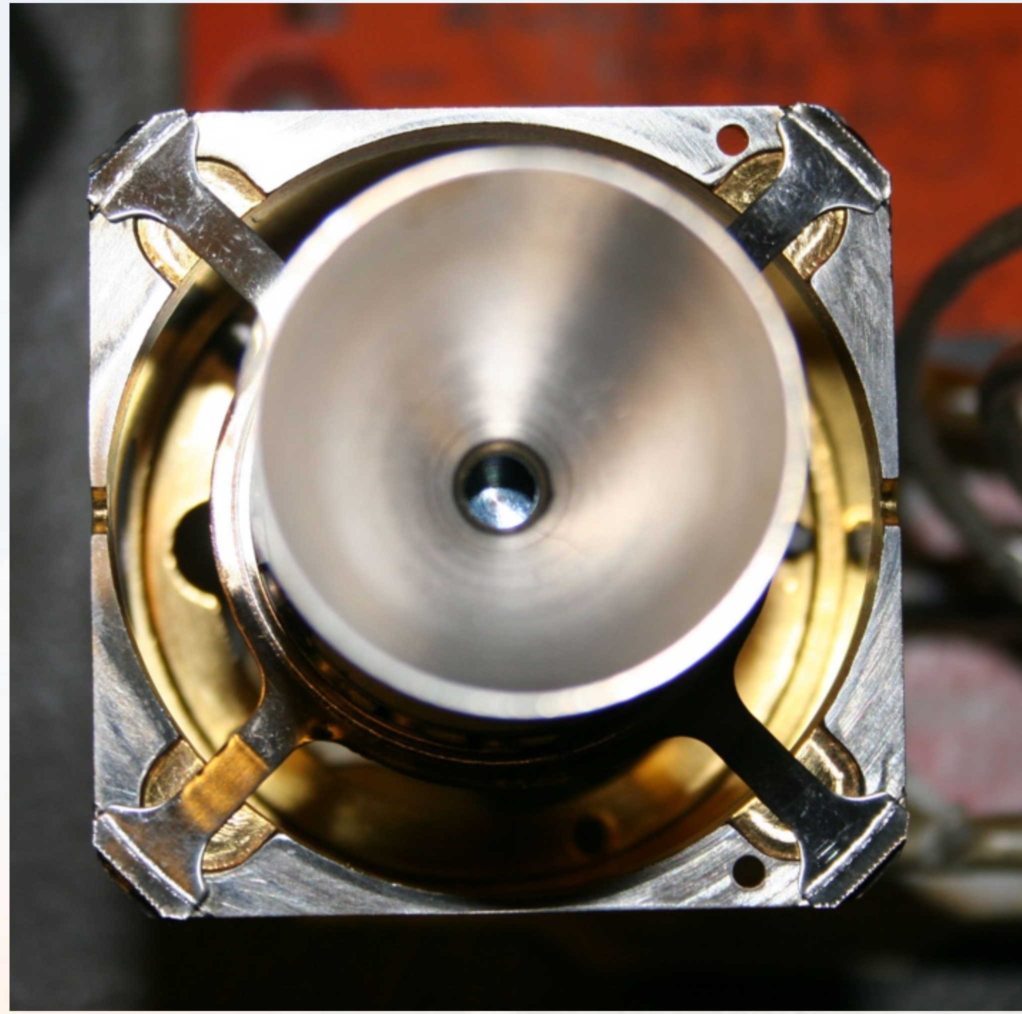
Lunar Module Reaction Control System



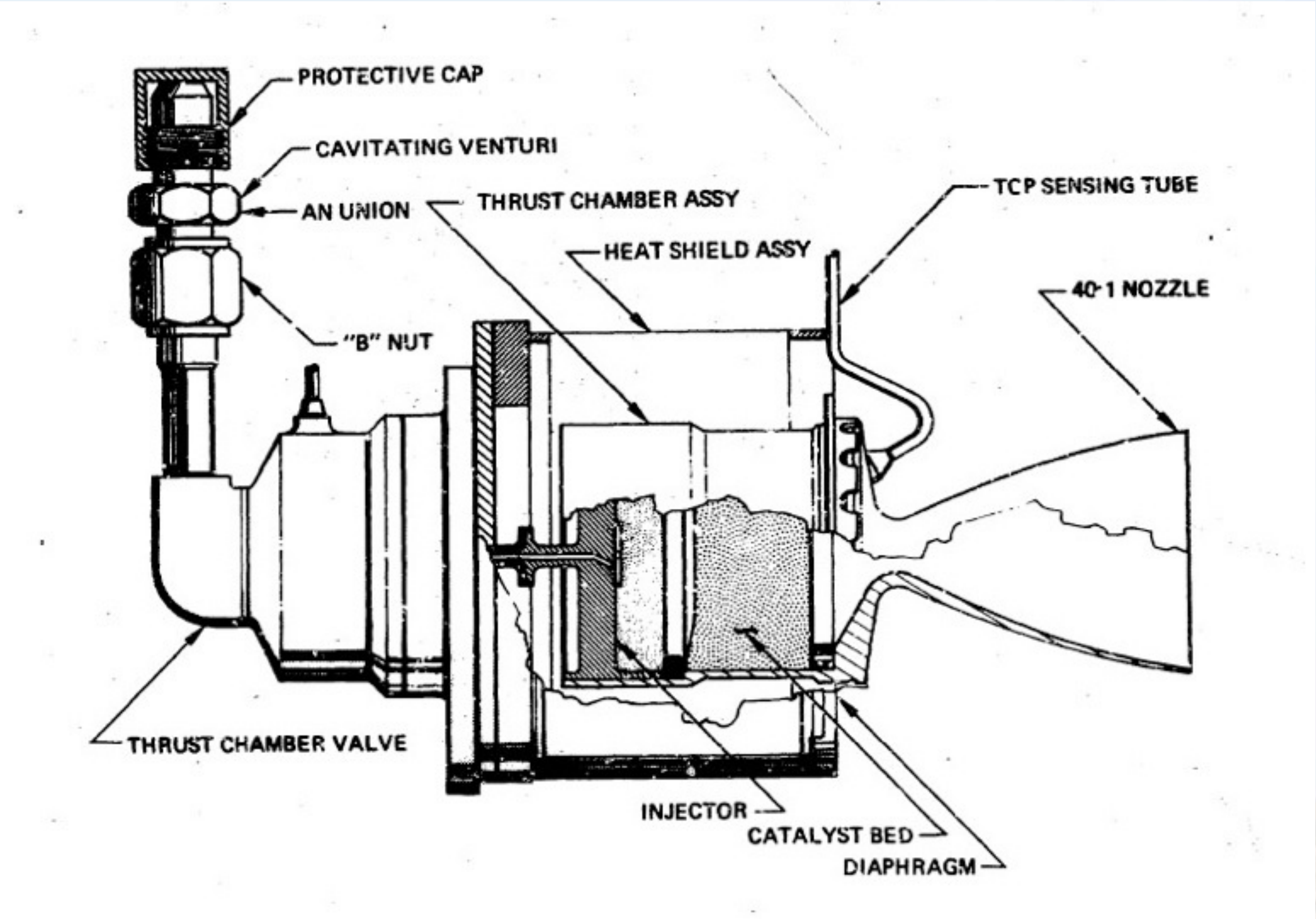
LM RCS Quad



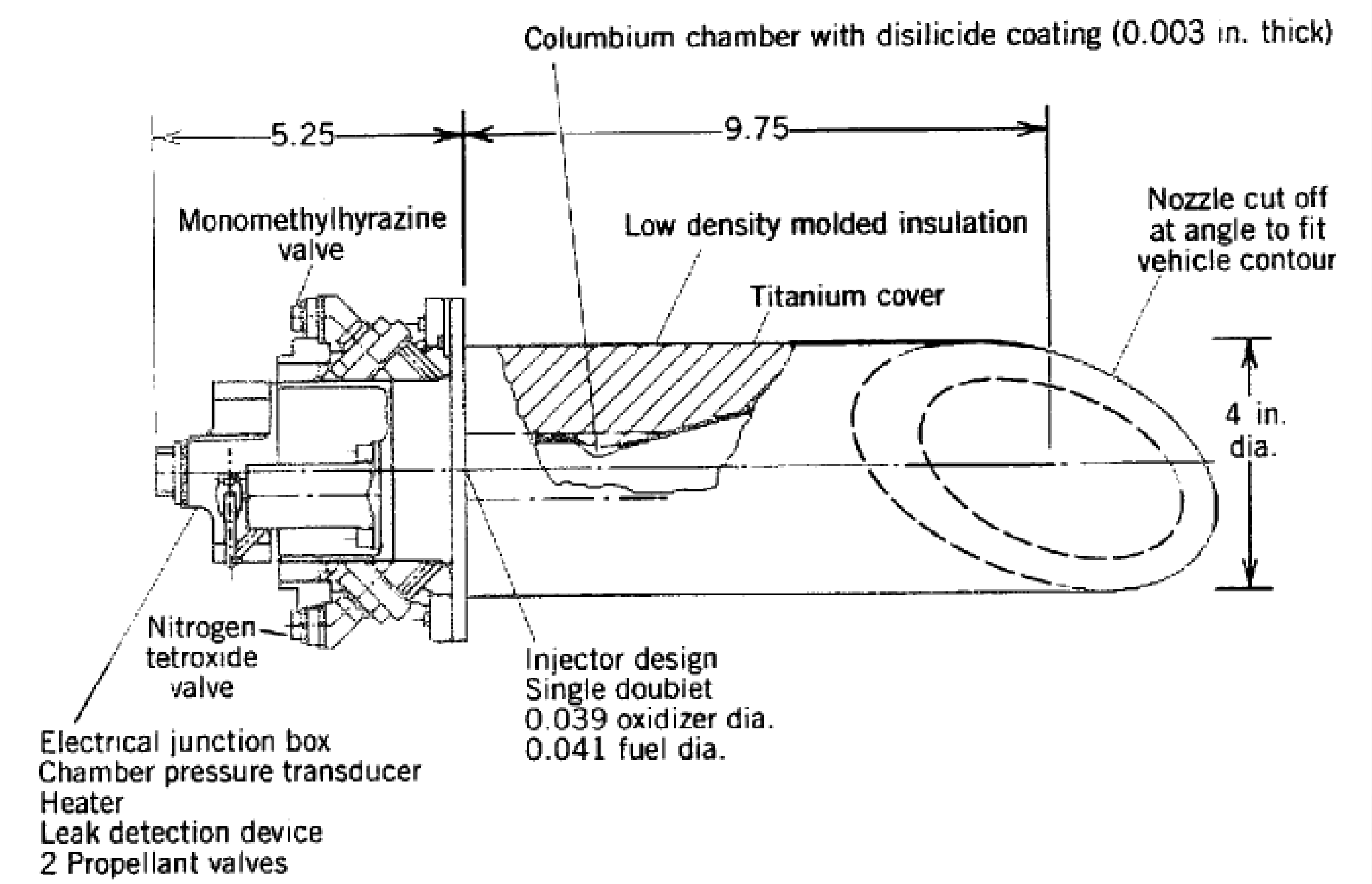
Viking Aeroshell RCS Thruster



Viking RCS Thruster Schematic



Space Shuttle Primary RCS Engine



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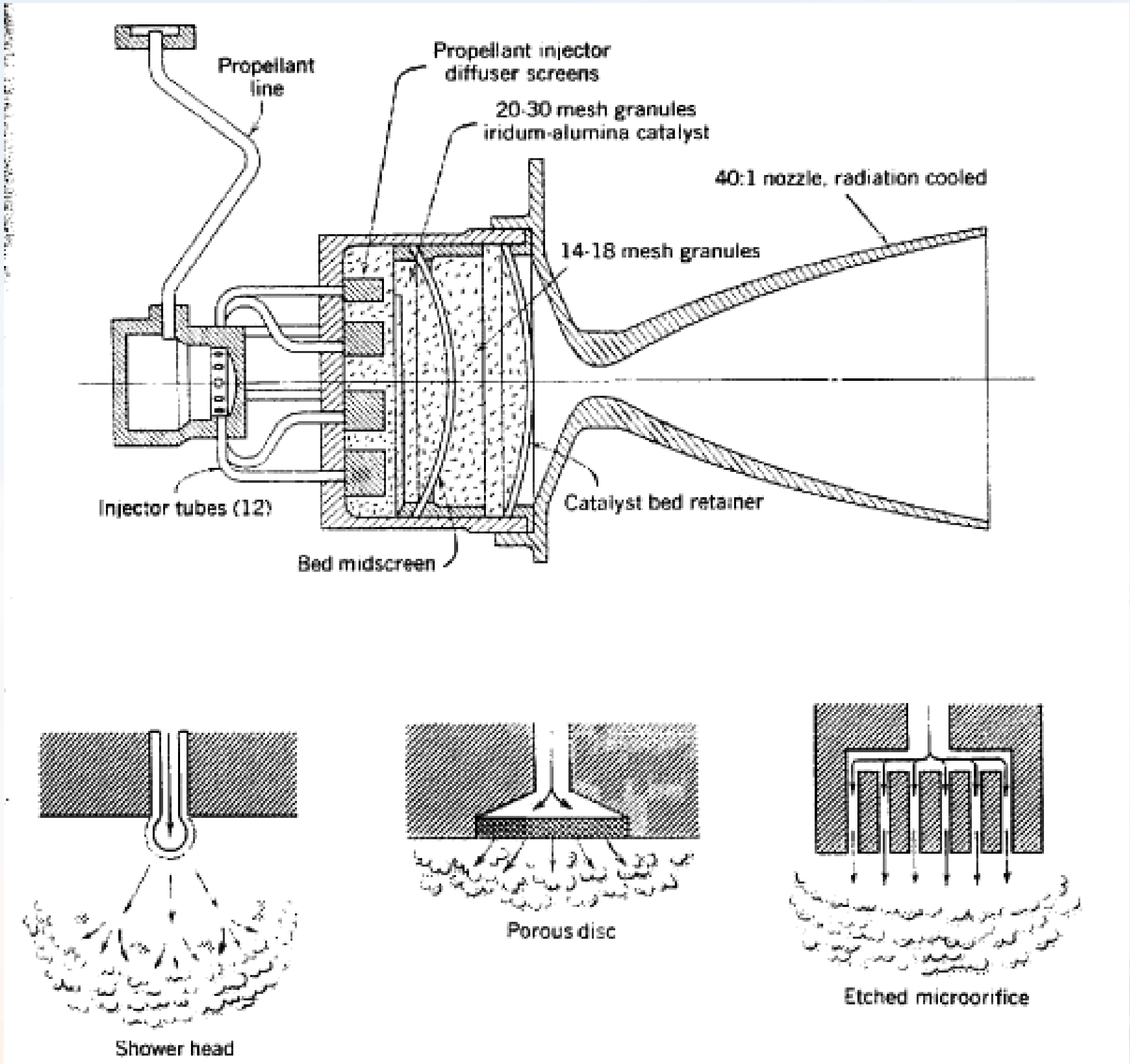
Monopropellant Engine Design



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

Cold Gas Thruster Exhaust Velocity

Assume nitrogen gas thrusters

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

$$\bar{M} = 28 \qquad p_0 = 300\ psi$$

$$T_0 = 300\ K \qquad p_e = 2\ psi$$

$$\Re = 8314.3 \qquad \gamma = 1.4$$

$$V_e = \sqrt{\frac{2(1.4)}{1.4 - 1} \frac{8314.3(300)}{28} \left[1 - \left(\frac{2}{300}\right)^{\frac{1.4-1}{1.4}}\right]} = 689\ \frac{m}{sec}$$

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

[a] At 3500 psia and 0°C.

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

Total Impulse

- Total impulse I_t is the total thrust-time product for the propulsion system, with units <N-sec>

$$I_t = Tt = \dot{m} v_e t$$

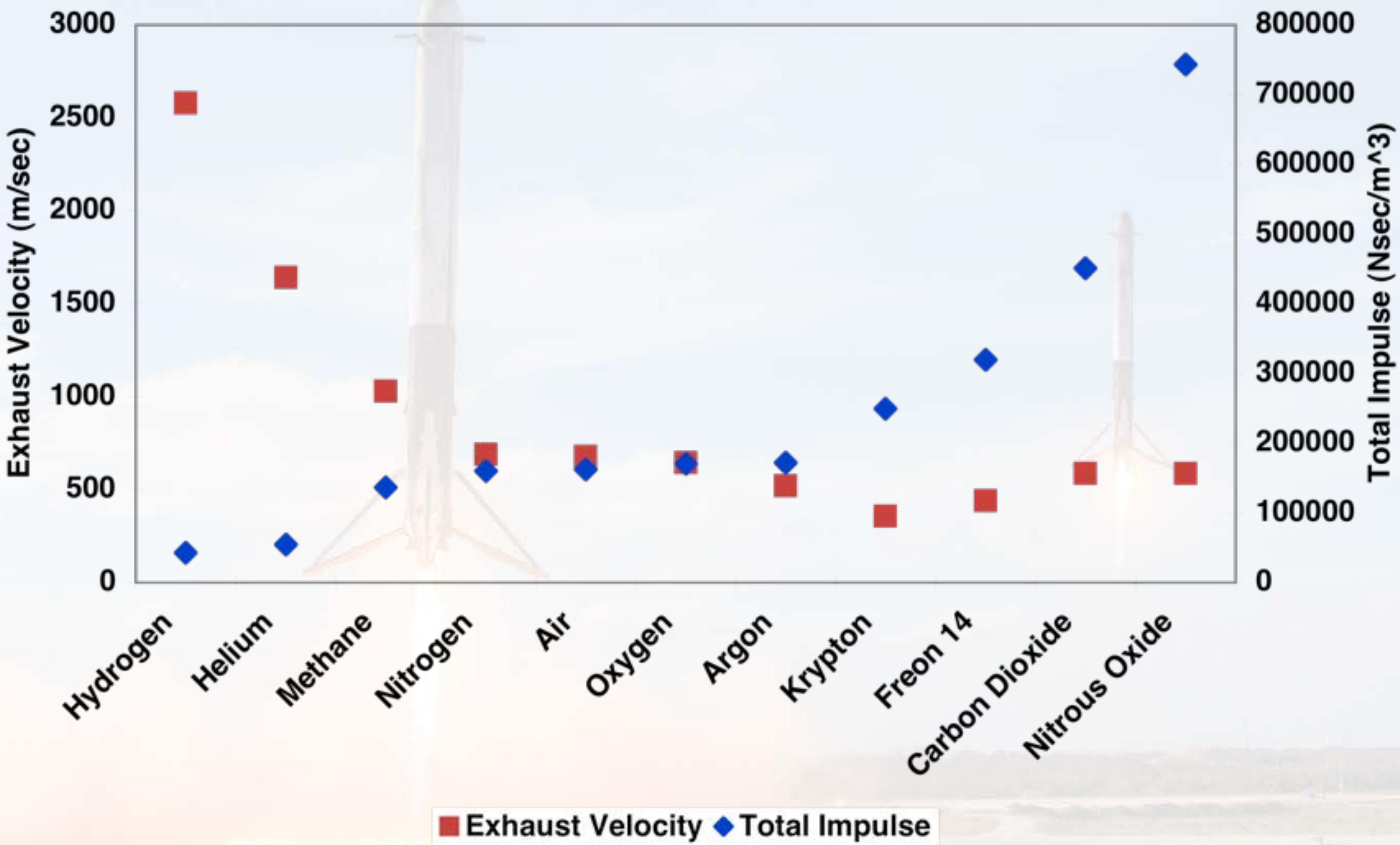
$$t = \frac{\rho V}{\dot{m}}$$

$$I_t = \rho V v_e$$

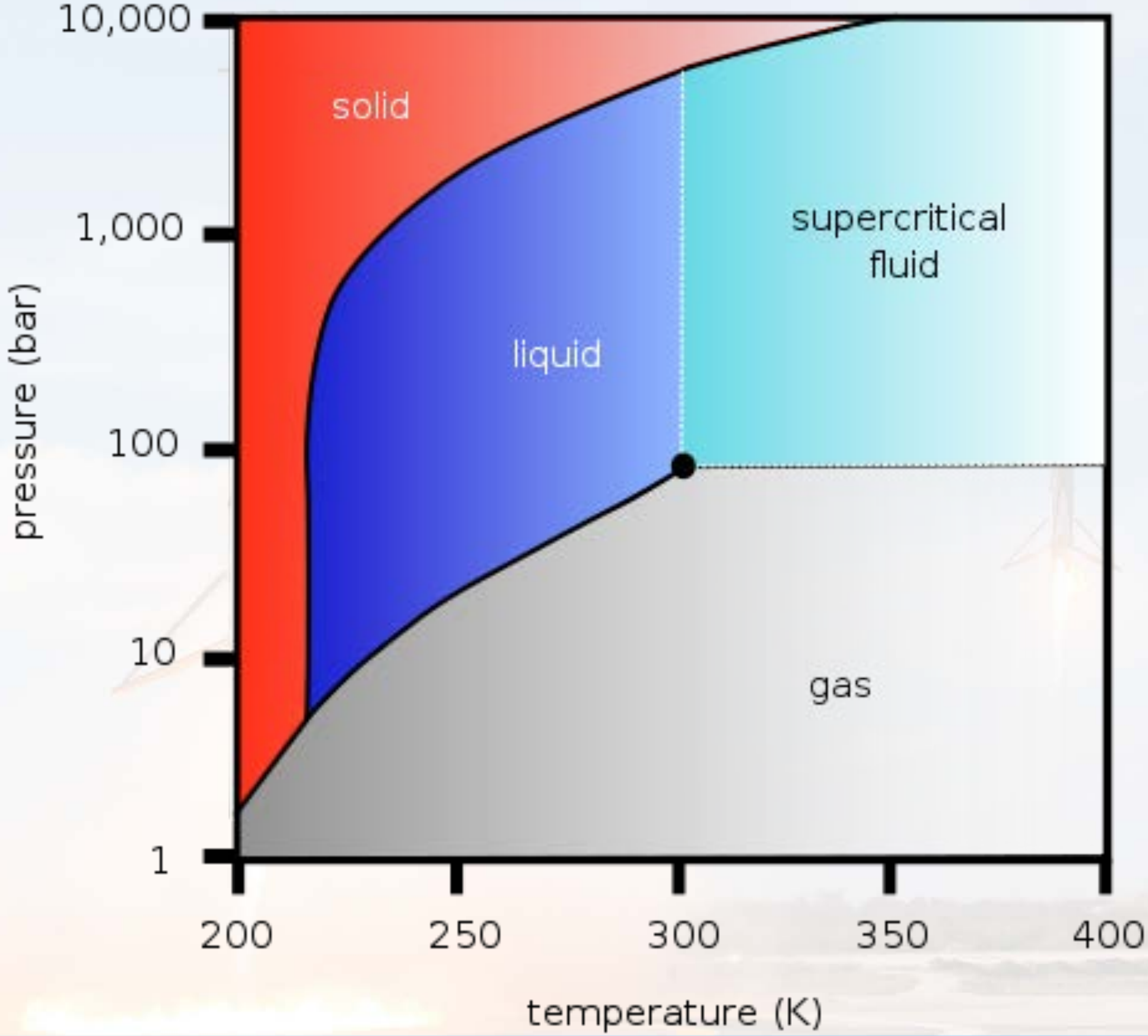
- To assess cold-gas systems, we can examine total impulse per unit volume of propellant storage

$$\frac{I_t}{V} = \rho v_e$$

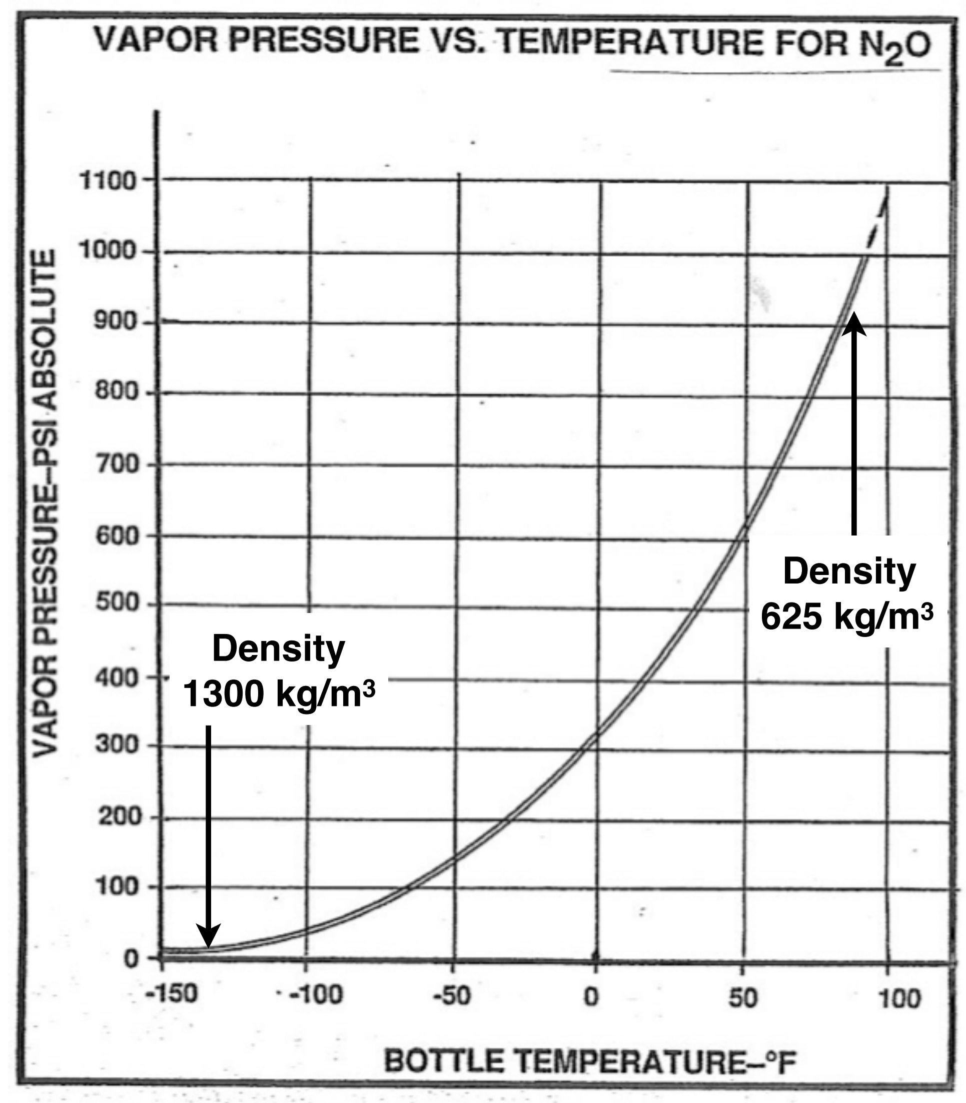
Performance of Cold-Gas Systems



Self-Pressurizing Propellants (CO_2)



Self-Pressurizing Propellants (N_2O)

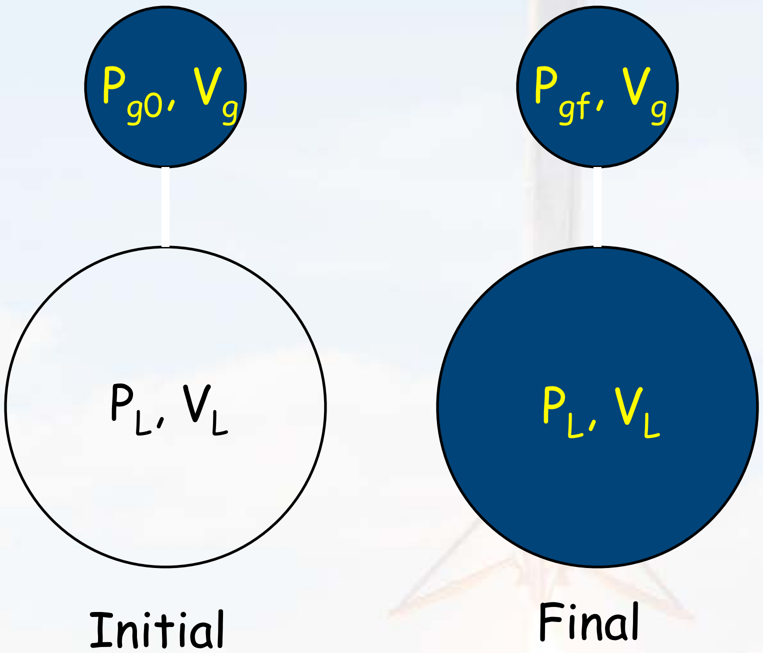


N_2O Performance Augmentation

- Nominal cold-gas exhaust velocity ~600 m/sec
- N_2O dissociates in the presence of a heated catalyst
  $$2N_2O \longrightarrow 2N_2 + O_2$$
  engine temperature ~1300°C
  exhaust velocity ~1800 m/sec
- NOFB (Nitrous Oxide Fuel Blend) - store premixed N_2O/hydrocarbon mixture
  exhaust velocity >3000 m/sec

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 N_2O_4/A50 = 1.8 (by mass)
- N_2O_4 tank
  - Mass = 13,310 kg
  - Density = 1450 kg/m^3
  - Volume = 9.177 m^3 --> r_{sphere}=1.299 m
- Aerozine 50 tank
  - Mass = 7390 kg
  - Density = 900 kg/m^3
  - Volume = 8.214 m^3 --> r_{sphere}=1.252 m

Boost Module Main Propulsion

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

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

- $V_g = 3.713\ m^3$
- Ideal gas: T=300°K --> $\rho_{He} = \dfrac{p_{g,0}\overline{M}}{\Re T_0}$

$\rho = 49.7\ kg/m^3$ (4500 psi = 31.04 MPa) $M_{He} = 185.1$ kg

Autogenous Pressurization

- Use gaseous propellants to pressurize tanks with liquid propellants
- Heat exchanger to gasify and warm propellants, then route back into ullage volume
- Eliminates need for pressurized gases for ullage and high-pressure storage bottles (e.g., Falcon 9 failures)
- Issue: start-up transient

Energy and Power - *Not the Same!!!*

- Energy - the capacity of a physical system to do work (J, N-m, kWhr)
- Power - time rate of change of energy (W, N-m/sec, J/sec)
- We are interested in generating *power*; we store and use *energy* at a given *power* level.

Batteries

- Energy storage via chemical reactions
- Primary batteries - use once and discard
- Secondary batteries - rechargable
- Critical parameters
  - Energy density
  - Discharge rate
  - Allowable depth of discharge
  - Cycle life
  - Temperature limits

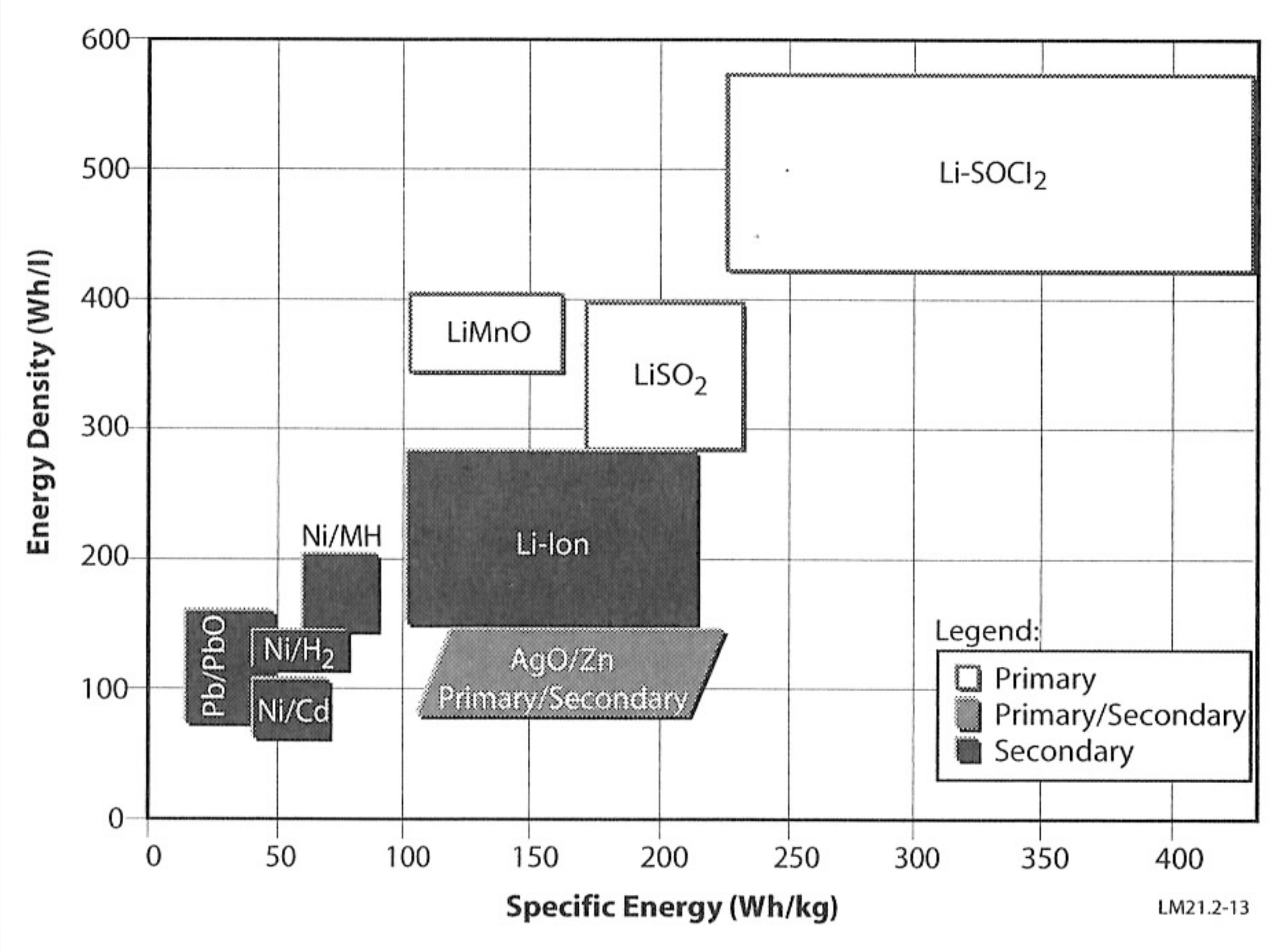
Primary Batteries

	Silver zinc	Lithium sulfur dioxide	Lithium carbon monofluoride	Lithium thionyl chloride
Energy density (W h/kg)	130	220	210	275
Energy density (W h/dm^3)	360	300	320	340
Operating temp. range (°C)	0–40	−50–75	?–82	−40–70
Storage temp. range (°C)	0–30	0–50	0–10	0–30
Storage life	30–90 d (wet) 5 yr (dry)	10 yr	2 yr[a]	5 yr[a]
Open circuit voltage (V/cell)	1.6	3.0	3.0	3.6
Discharge voltage (V/cell)	1.5	2.7	2.5	3.2
Manufacturer(s)	Eagle-Picher, Yardney Technical Products	Honeywell, Power Conversion	Eagle-Picher	Duracell, Electrochem, Altus, ITT

[a]These cells are still in the development stage, and their storage life may be longer than that indicated.

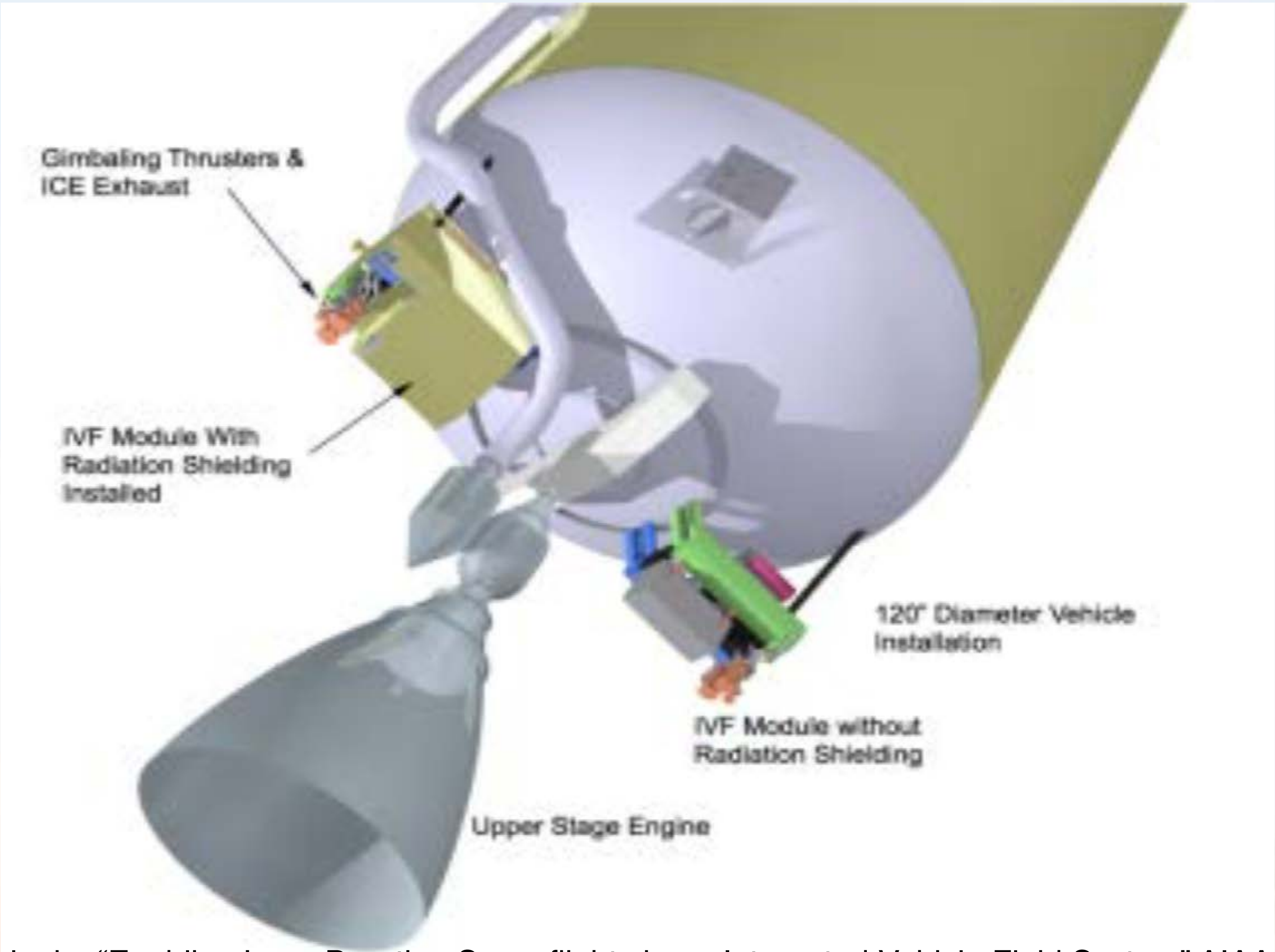
From Pisacane and Moore, *Fundamentals of Space Systems* Oxford University Press, 1994

Battery Application Domains



From Wertz, Everett, and Puschell, *Space Mission Engineering: The New SMAD* Microcosm Press, 2011

Integrated Vehicle Fluids (IVF) System



From M. Holguin, “Enabling Long Duration Spaceflight via an Integrated Vehicle Fluid System” AIAA 2016-5495

ULA IVF Concept

- 750cc internal combustion (piston) engine powered by LOX/LH2 boil-off
- Engine powers generator to supply electrical power (30V and 300V) to vehicle (also serves as a starter)
- Compressor/heat exchanger increases pressure of boil-off gases from propellant tank, and cools ICE
- Pressurized O2/H2 provides reaction control system through thruster/gimbal assembly
- Growth option: on-orbit refueling