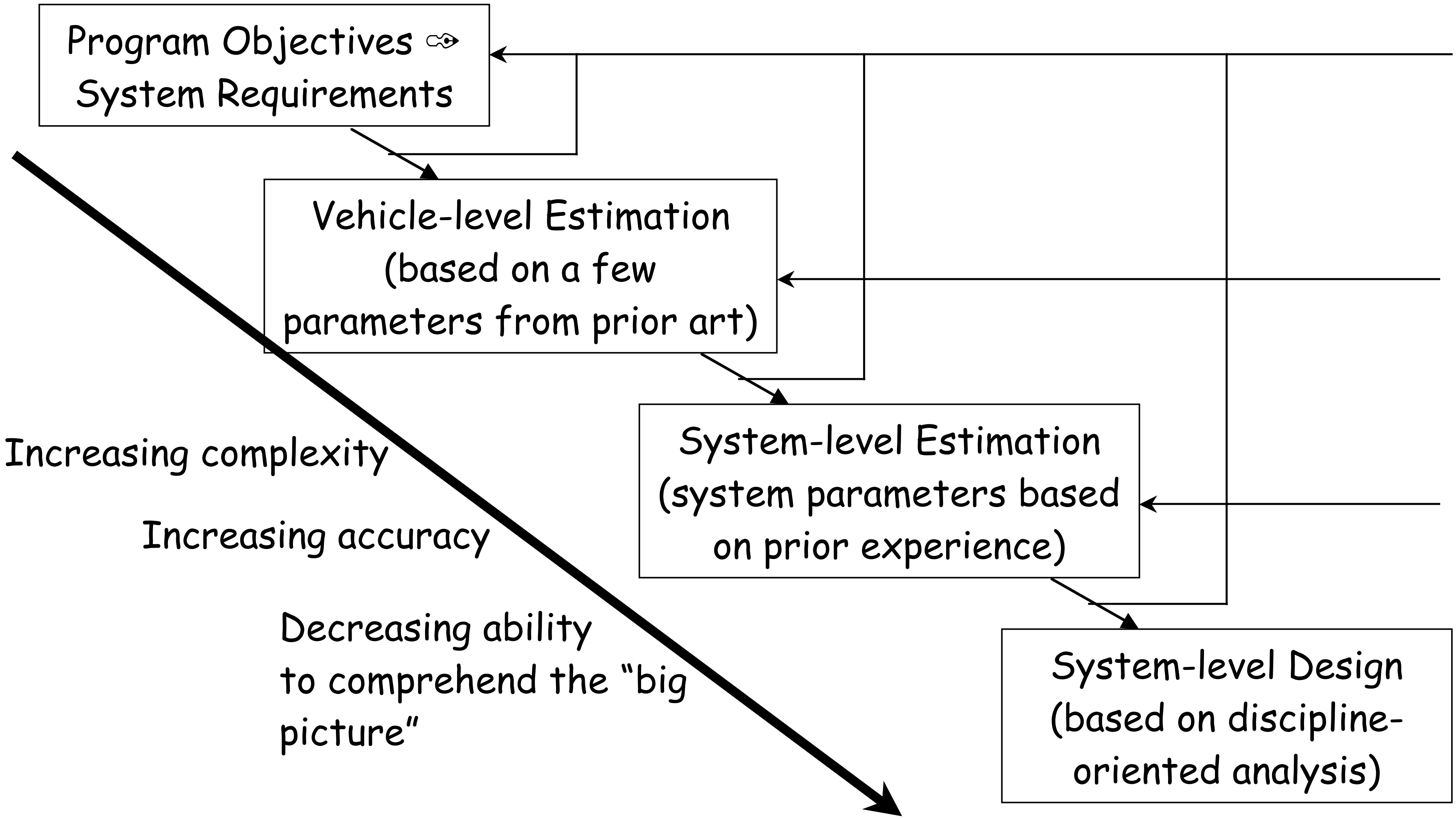
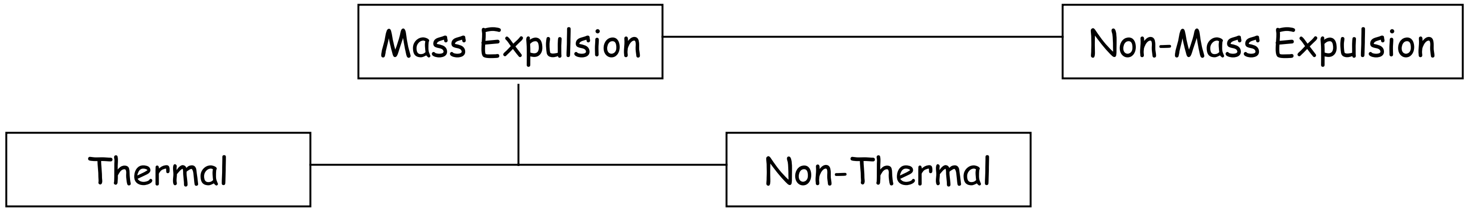
Propulsion Systems Design

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

Overview of the Design Process



Propulsion Taxonomy



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

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

$$\Re \equiv \text{universal gas const.} = 8314.3 \frac{Joules}{mole°K}$$

$$\gamma \equiv \text{ratio of specific heats} \approx 1.2$$

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

$$T = \dot{m}c \Rightarrow c = V_e + \left(p_e - p_{amb}\right)\frac{A_e}{\dot{m}} \qquad \left(I_{sp} = \frac{c}{g_0}\right)$$

- Expansion ratio

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

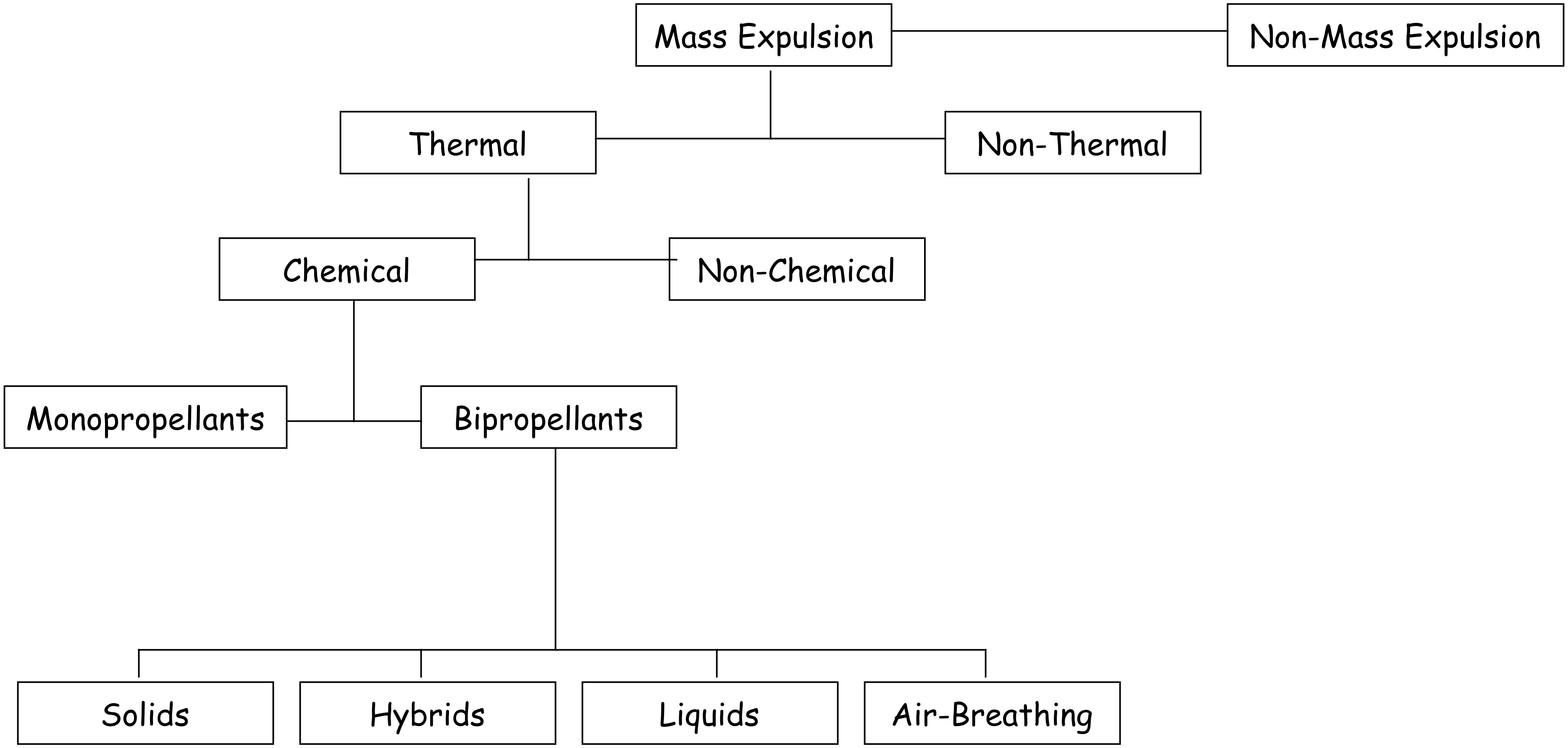
Nozzle Design

- 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

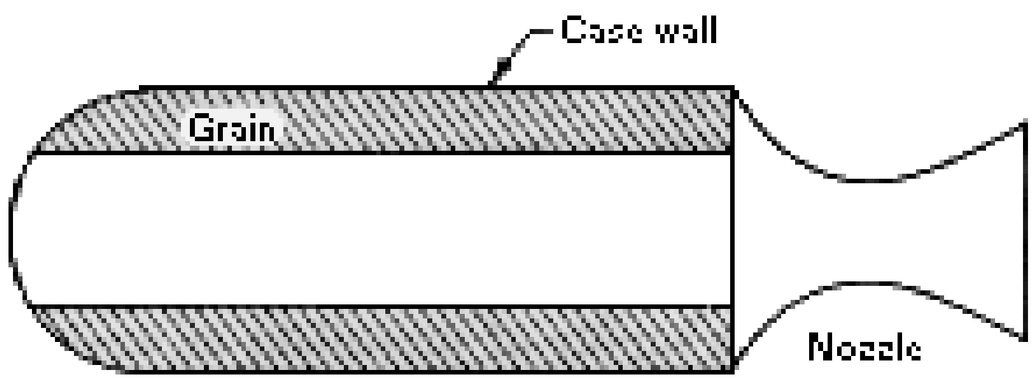
$$\frac{V_e}{V_{e,ideal}} = \sqrt{1-\left(\frac{p_e}{p_0}\right)^{\frac{\gamma-1}{\gamma}}}$$

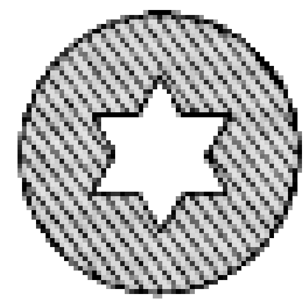
- $I_{sp,vacuum}$=455 sec --> $I_{sp,sl}$=333 sec

Propulsion Taxonomy

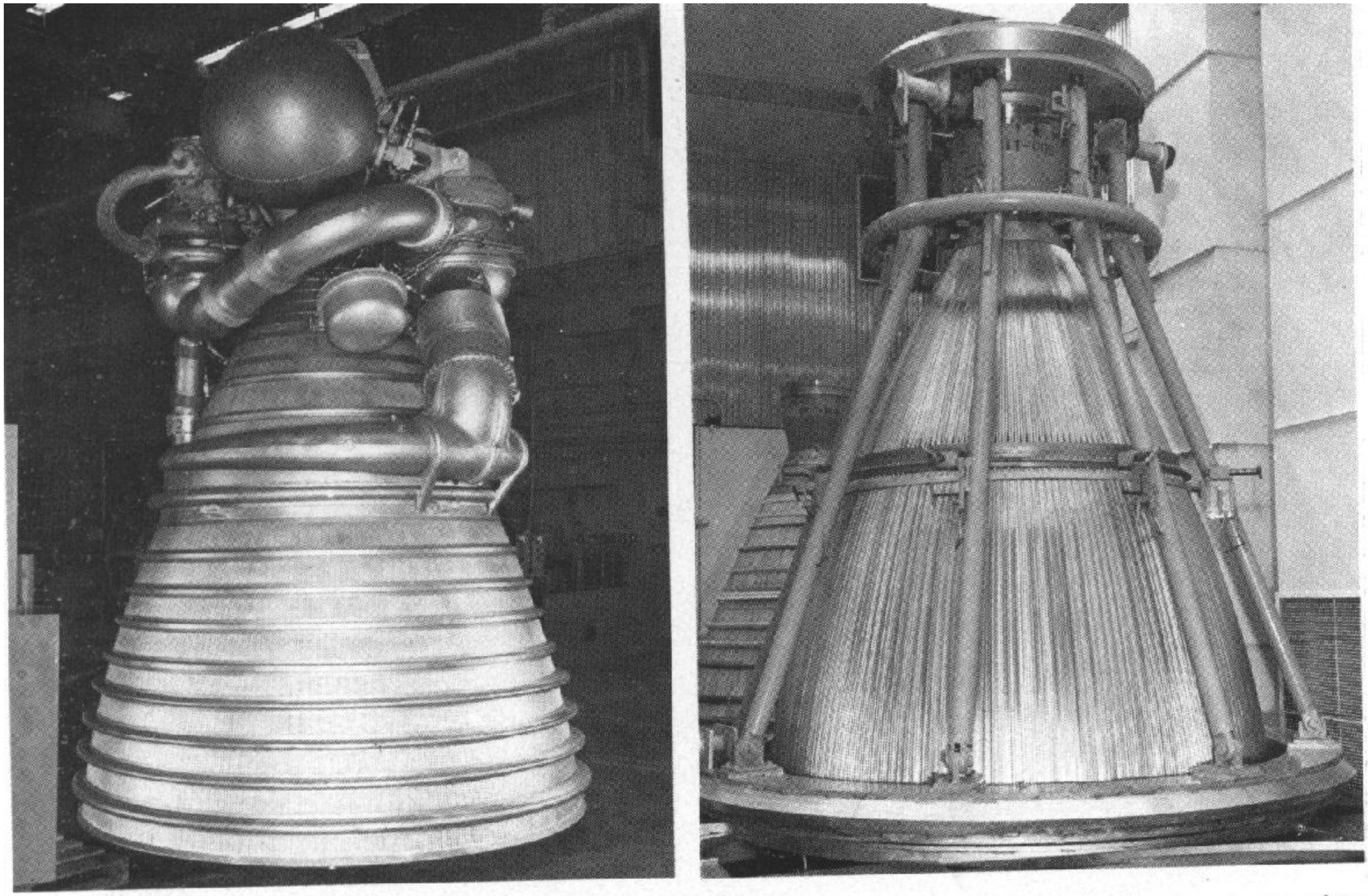


Solid Rocket Motor



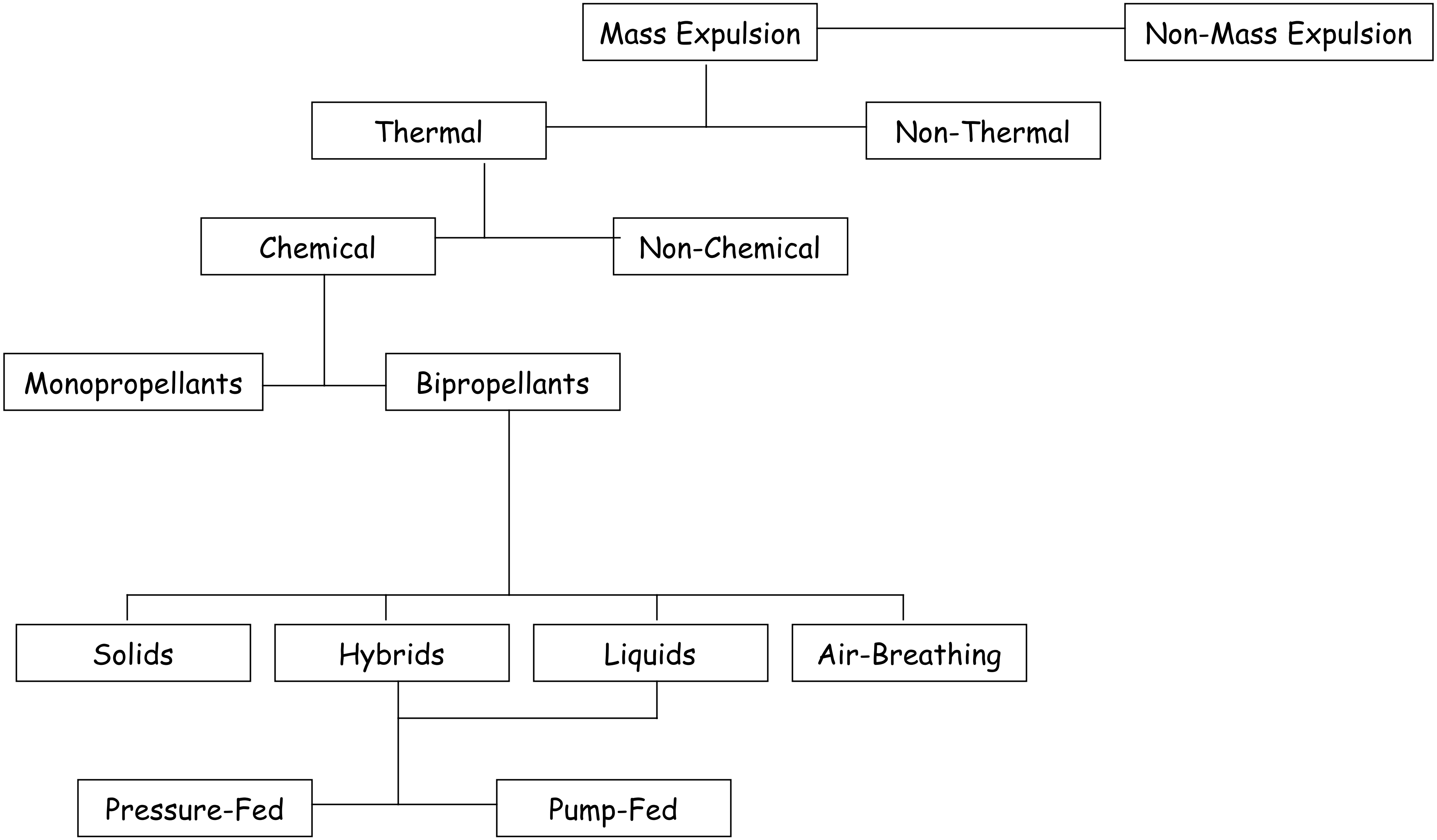


Liquid Rocket Engine

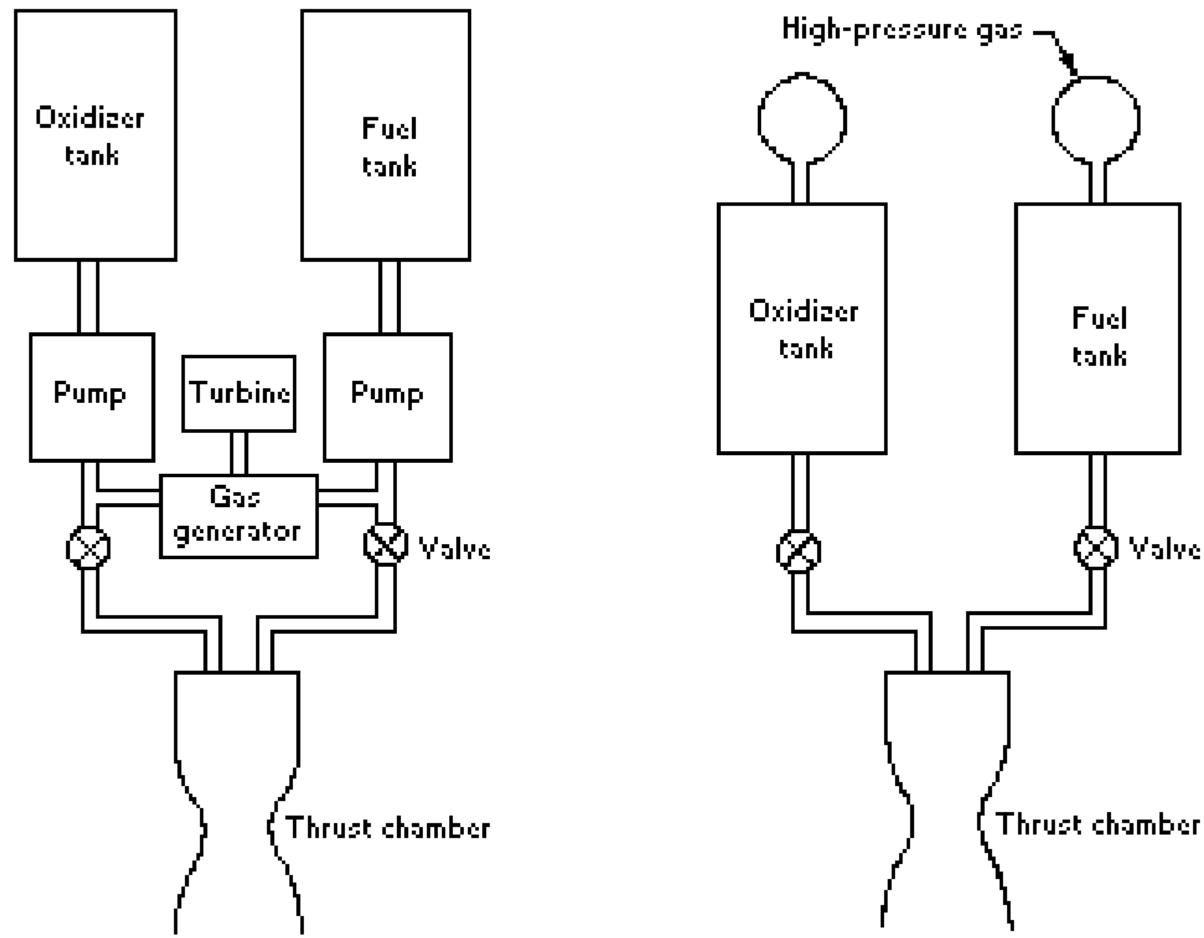


A completed J-2 rocket engine (left), with its pumps and lines installed. The basic engine structure is built up from a series of hollow tubes (right).

Propulsion Taxonomy



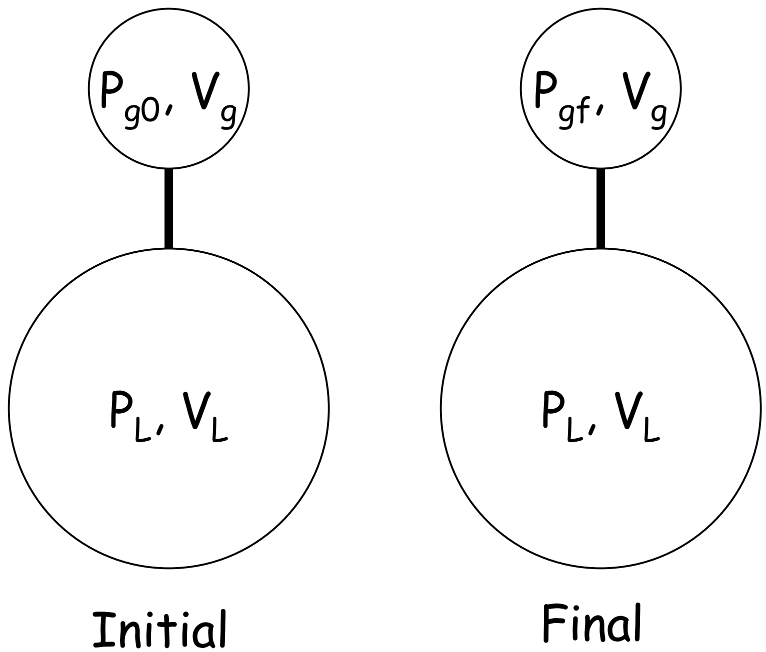
Liquid Propellant Feed Systems



(a) Pump-fed rocket (b) Pressure-fed rocket

Pressurization System Analysis

Adiabatic Expansion of Pressurizing Gas



$$p_{g,0}V_g^\gamma = p_{g,f}V_g^\gamma + p_\ell V_\ell^\gamma$$

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

PROJECT DIANA

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

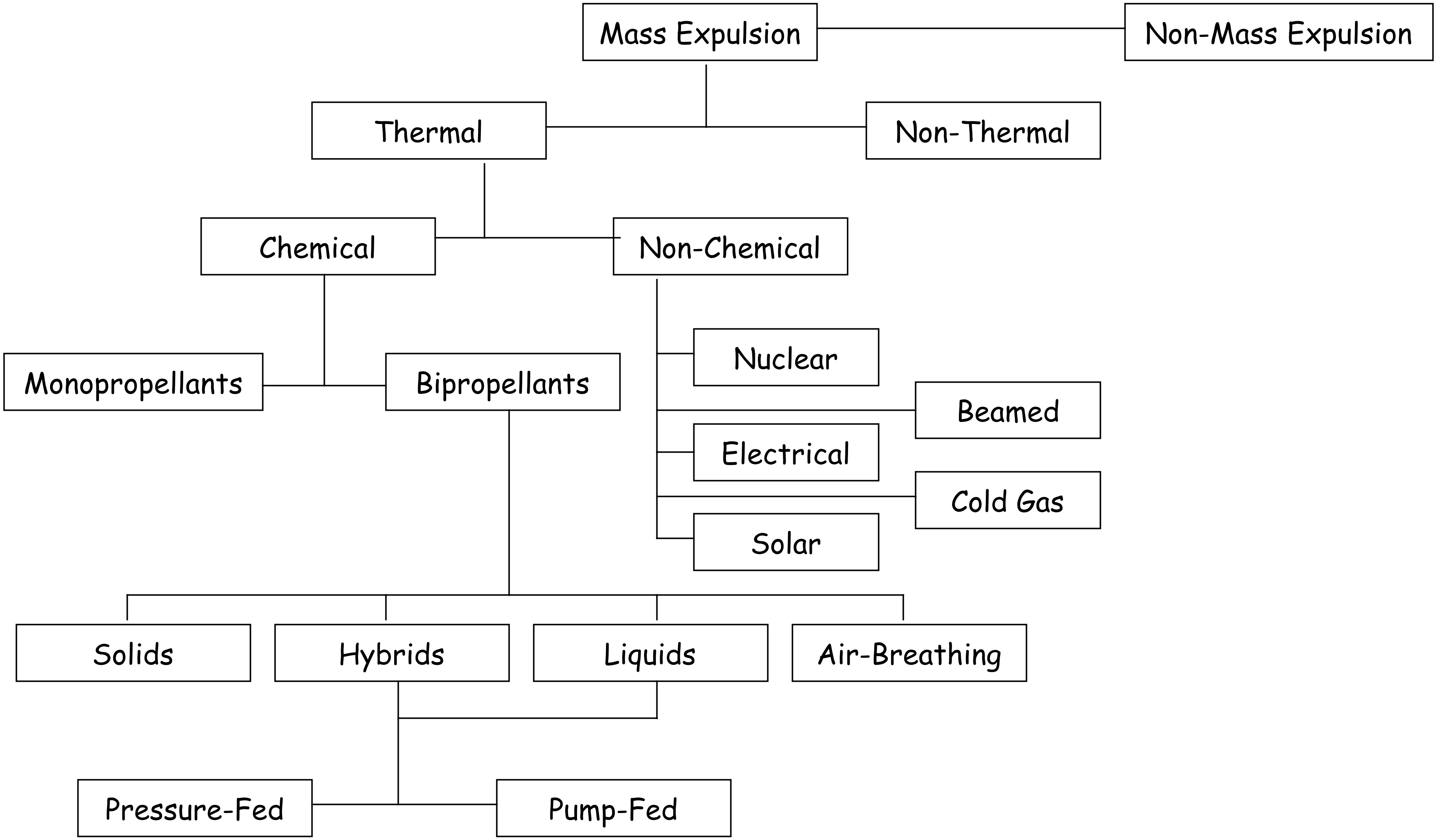
- Total propellant volume V_L = 17.39 m^3
- Assume engine pressure p_0 = 250 psi
- Tank pressure p_L = 1.25*p_0 = 312 psi
- Final GHe pressure $p_{g,f}$ = 75 psi + p_L = 388 psi
- Initial GHe pressure $p_{g,0}$ = 4500 psi
- Conversion factor 1 psi = 6892 Pa
- Ratio of specific heats for He = 1.67

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

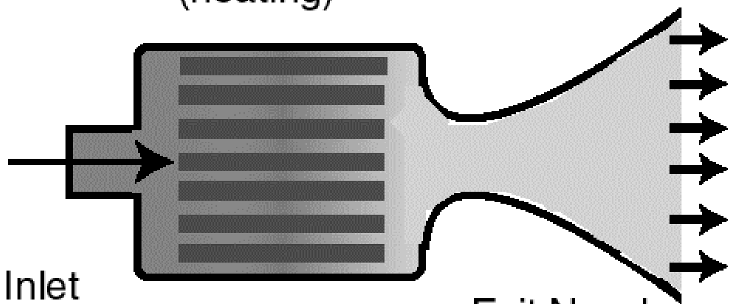
- V_g = 3.713 m^3
- Ideal gas: $\rho_{He} = \frac{p_{g,0}\overline{M}}{\Re T_0}$ T=300°K --> ρ=49.7 kg/m^3 (300 psi = 31.04 MPa) M_{He}=185.1 kg

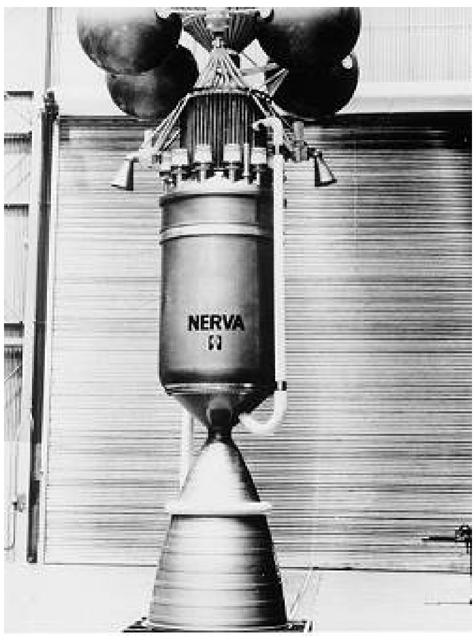
PROJECT DIANA

Propulsion Taxonomy



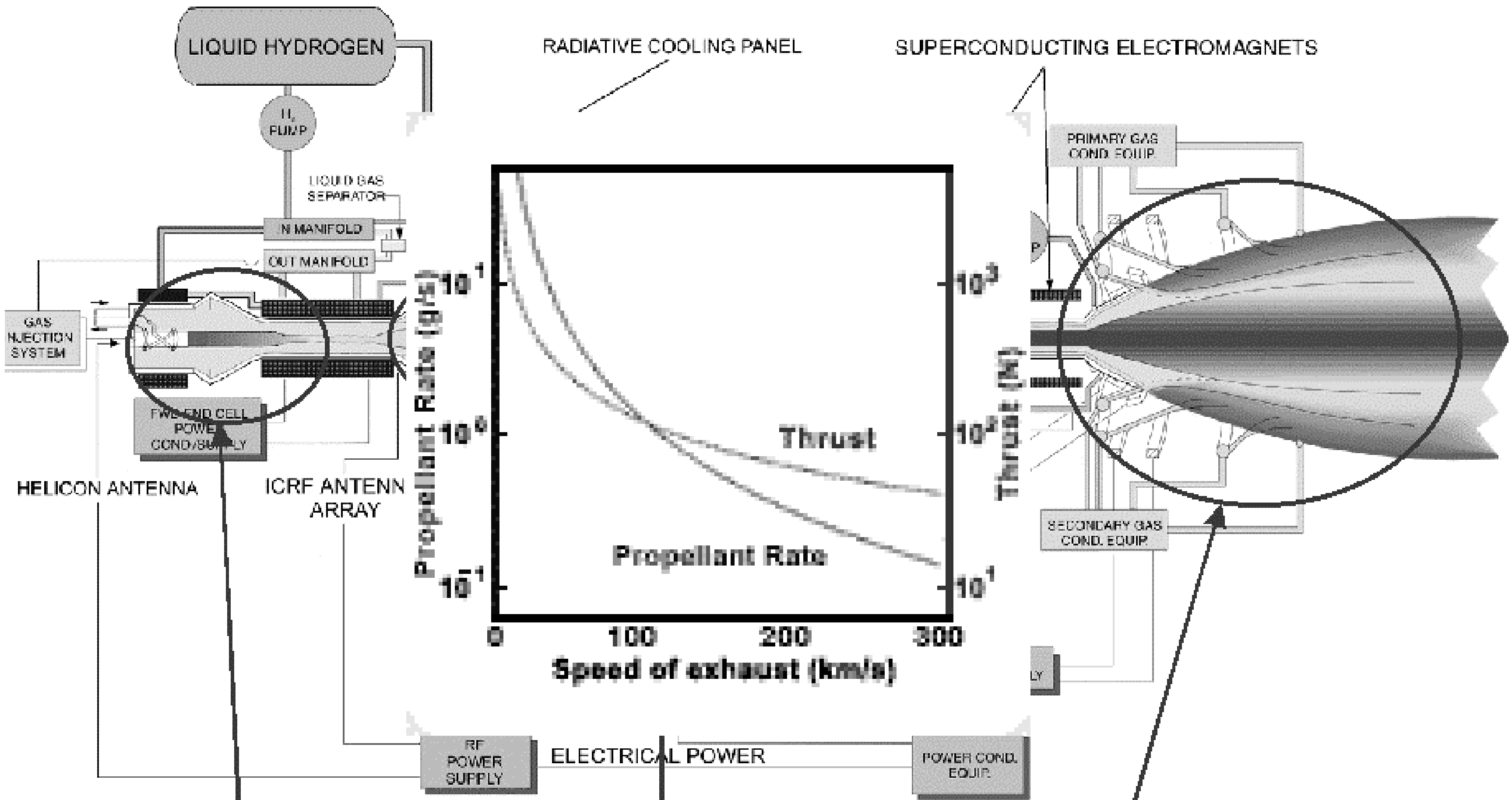
Nuclear Thermal Rockets





- 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

VASIMR Engine Concept

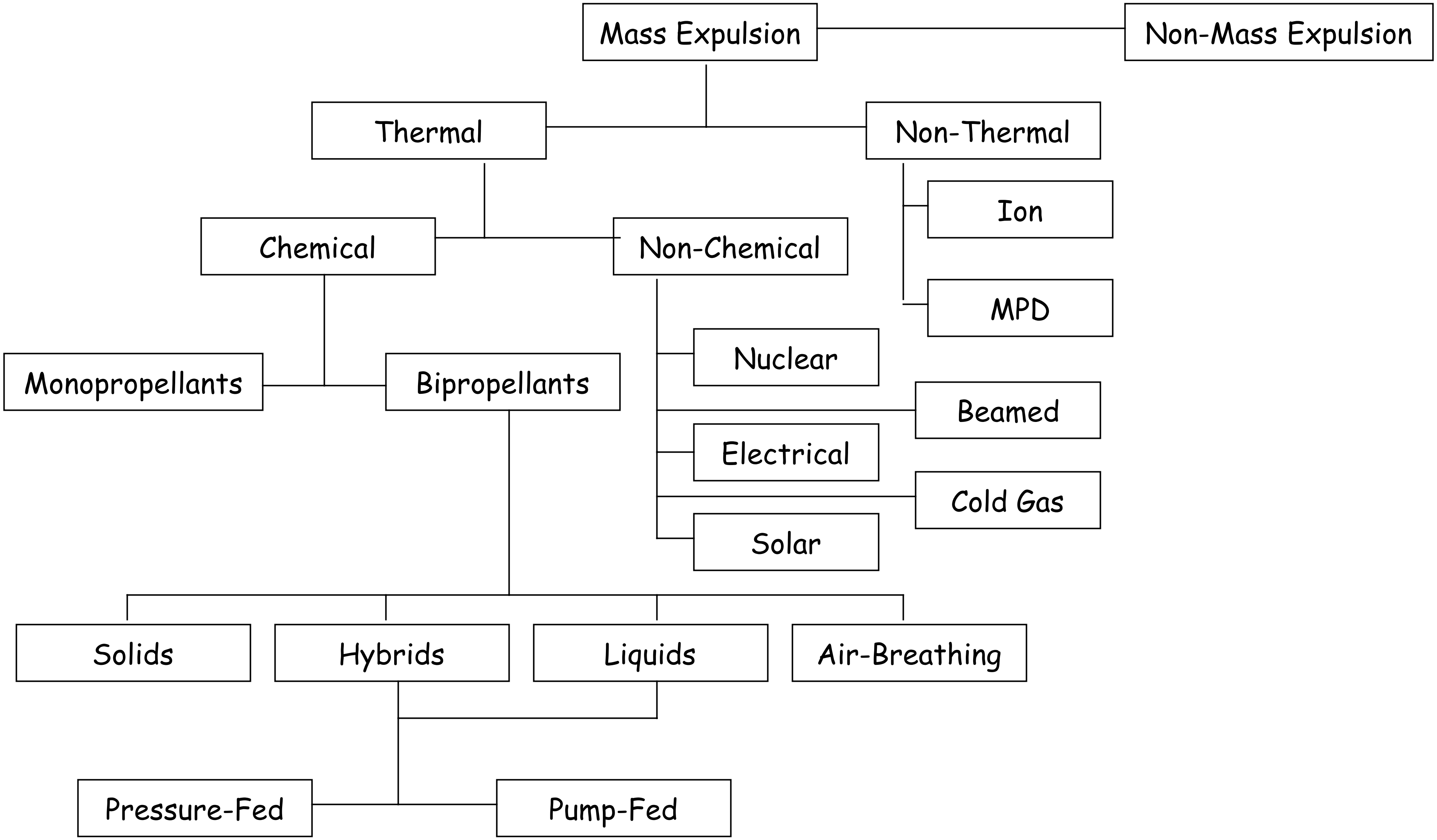


1st stage: helicon plasma generator

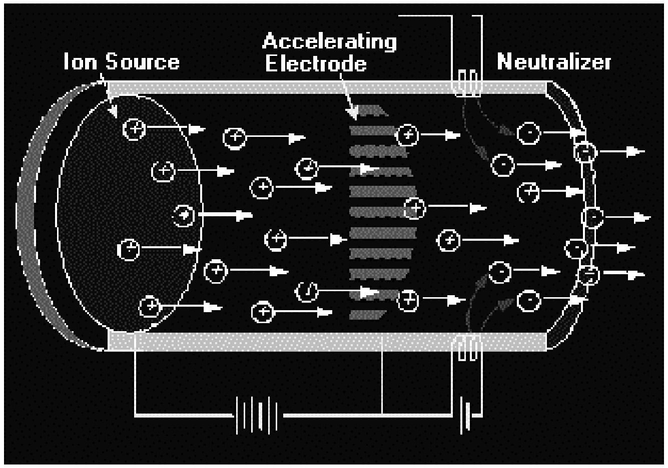
2nd stage: ion cyclotron resonance power amplifier

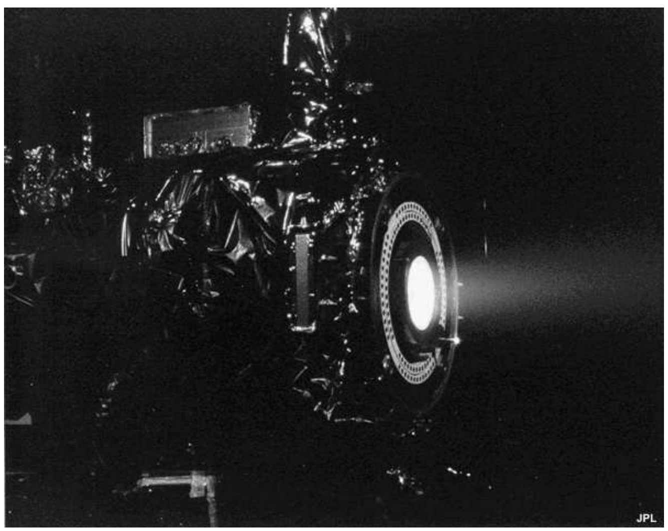
3rd stage: magnetic nozzle

Propulsion Taxonomy



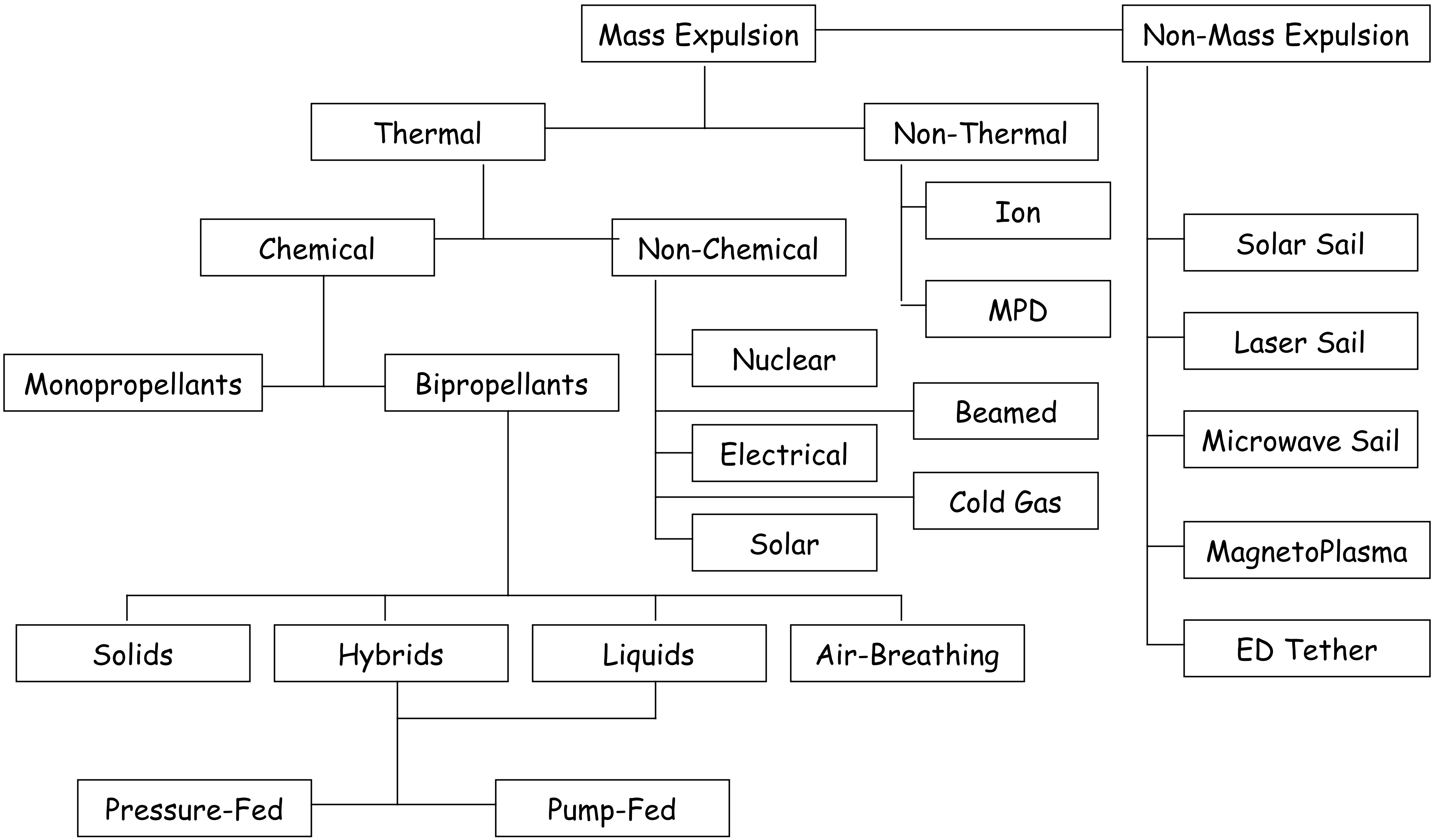
Ion Propulsion



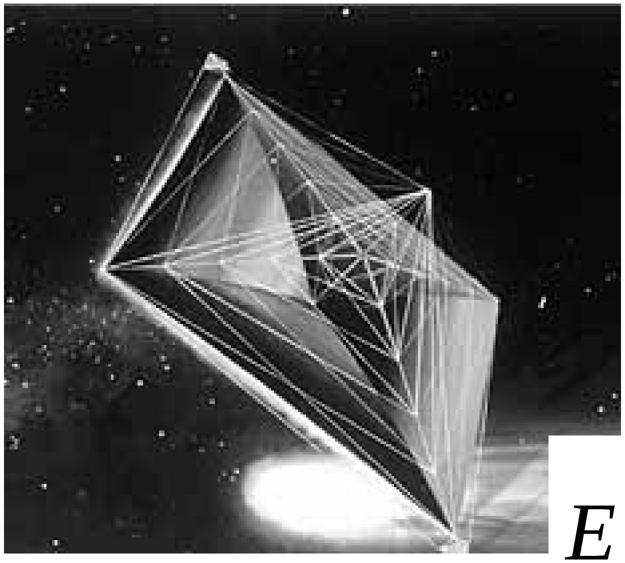


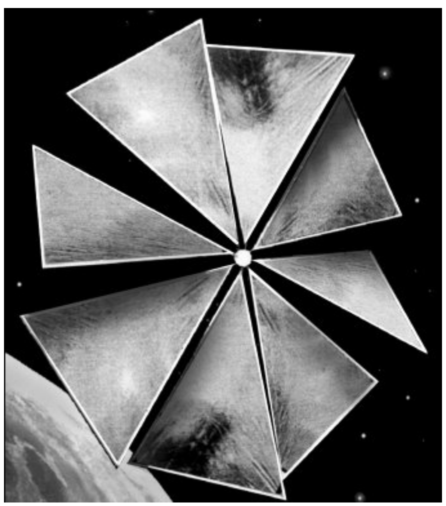
- Uses electrostatic forces to accelerate ions
- Injects electrons to keep beam neutral
- High Isp (~3000 sec) at low thrust (~10 N)
- Substantial mass penalty for electrical power generation

Propulsion Taxonomy



Solar Sails





- Sunlight reflecting off sail produces momentum transfer

$$T = 2\dot{m}V = 2\dot{m}c$$

$$E = mc^2 \Rightarrow m = \frac{E}{c^2} \Rightarrow \dot{m} = \frac{E}{t}\frac{1}{c^2} = \frac{P}{c^2}$$

- At 1 AU, P=1394 W/m^2
- c=3×10^8 m/sec
- T=9×10^{-6} N/m^2

Propulsion Taxonomy