Propulsion Systems Design

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

- Exhaust velocity is

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

where

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

\( \mathcal{R} \equiv \text{universal gas const.} = 8314.3 \, \text{Joules mole}^{-1} \text{K}^{-1} \)

\( \gamma \equiv \text{ratio of specific heats} \approx 1.2 \)
**Ideal Thermal Rocket Exhaust Velocity**

- Ideal exhaust velocity is

  \[ V_e = \sqrt{\frac{2\gamma}{\gamma - 1} \frac{\mathcal{R} T_0}{M}} \]

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

- 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 $V_e$

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

- $I_{\text{sp, vacuum}}=455$ sec $\rightarrow I_{\text{sp, sl}}=333$ sec
Solid Rocket Motor

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

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

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

Rocket Propulsion
Principles of Space Systems 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
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

(a) Pump-fed rocket

(b) Pressure-fed rocket

Oxidizer tank
Fuel tank
Pump
Turbine
Gas generator
Valve
Thrust chamber

High-pressure gas
Oxidizer tank
Fuel tank
Valve
Thrust chamber
Space Shuttle OMS Engine

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

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

Rocket Propulsion
Principles of Space Systems Design

UNIVERSITY OF MARYLAND
Sample Pump-fed Engine Cycles

From G. P. Sutton, Rocket Propulsion Elements (5th ed.) John Wiley and Sons, 1986
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
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
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
## Thrust Vector Control Approaches

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

Apollo Reaction Control System
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

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

$^a$ At 3500 psia and 0°C.

From G. P. Sutton, Rocket Propulsion Elements (5th ed.) John Wiley and Sons, 1986
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 $\text{N}_2\text{O}_4$/A50 = 1.8 (by mass)

- $\text{N}_2\text{O}_4$ tank
  - Mass = 13,310 kg
  - Density = 1450 kg/m$^3$
  - Volume = 9.177 m$^3$ --> $r_{\text{sphere}}$ = 1.299 m

- Aerozine 50 tank
  - Mass = 7390 kg
  - Density = 900 kg/m$^3$
  - Volume = 8.214 m$^3$ --> $r_{\text{sphere}}$ = 1.252 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 $p_L = 1.25 \times p_0 = 312 \text{ psi}$
- 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 psi = 6892 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: $\rho = 49.7 \text{ kg/m}^3$ (300 psi = 31.04 MPa) $M_{\text{He}} = 185.1 \text{ kg}$
- $T = 300^\circ \text{K} \implies \rho_{\text{He}} = \frac{p_{g,0} \overline{M}}{\gamma T_0}$

Low-Cost Return to the Moon
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
VASIMR Engine Concept

1st stage: helicon plasma generator
2nd stage: ion cyclotron resonance power amplifier
3rd stage: magnetic nozzle
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
Solar Sails

- Sunlight reflecting off sail produces momentum transfer.
  \[ T = 2\dot{m}V = 2mc \]

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

\[
E = mc^2 \quad \Rightarrow \quad m = \frac{E}{c^2} \quad \Rightarrow \quad \dot{m} = \frac{E}{t} \frac{1}{c^2} = \frac{P}{c^2}
\]
Propulsion Taxonomy

Mass Expulsion
- Thermal
- Chemical
  - Monopropellants
  - Bipropellants
    - Solids
    - Hybrids
    - Liquids
    - Air-Breathing
      - Pressure-Fed
      - Pump-Fed

Non-Mass Expulsion
- Non-Thermal
  - Ion
  - MPD
  - Nuclear
  - Beamed
    - Solar Sail
    - Laser Sail
    - Microwave Sail
    - MagnetoPlasma
  - Electrical
  - Cold Gas
  - Solar
  - ED Tether