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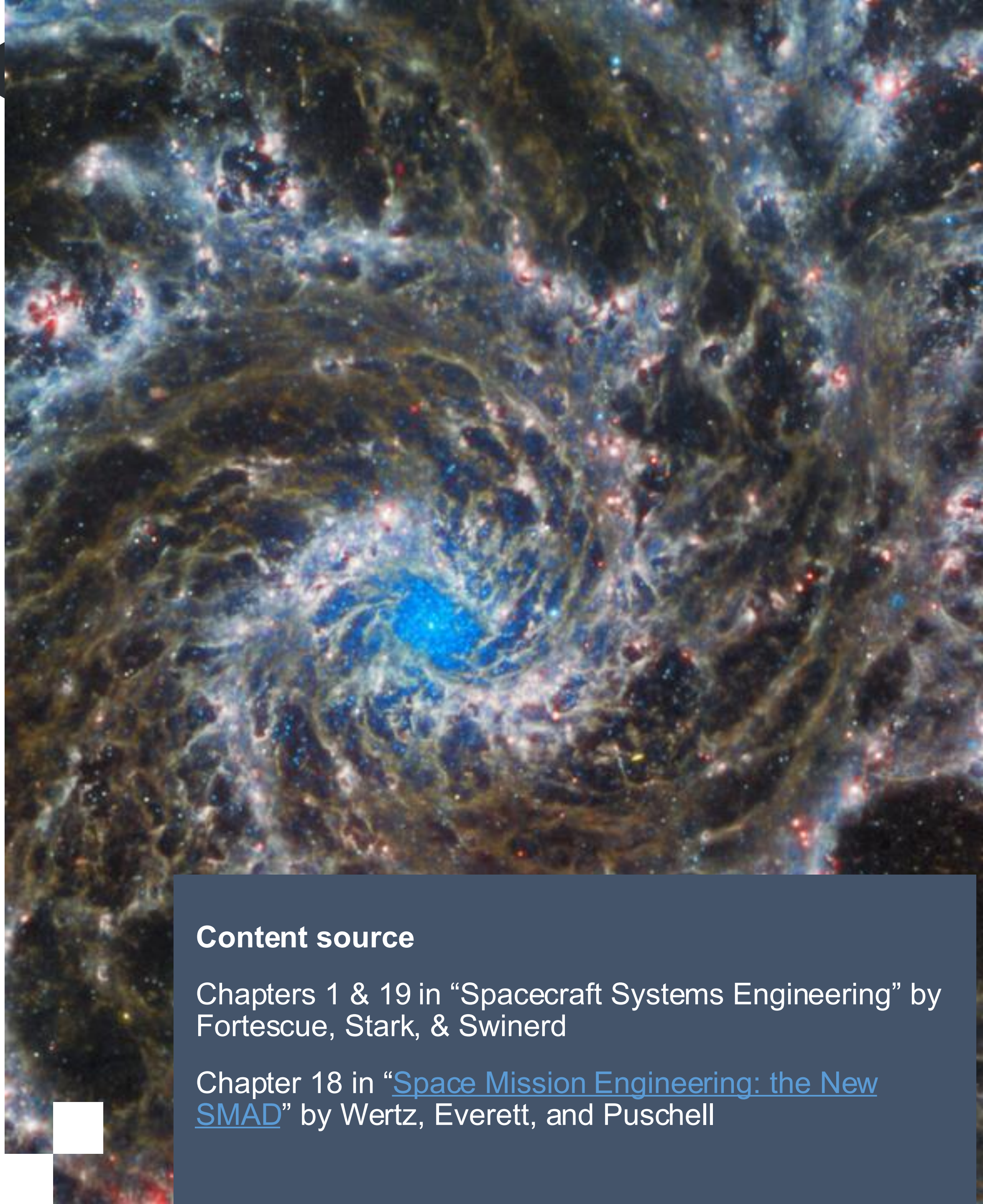
# CONTENTS

# Learning Outcomes

By the end of this lecture you should be familiar with…

- Different type of propulsion systems
- What are the impact on the spacecraft
- How to dimension the Propulsion system

The content is adapted from the slides from Muriel Richard teaching this class from 2010 to 2019



Source: NASA/JWST

**Content source**

Chapters 1 & 19 in “Spacecraft Systems Engineering” by Fortescue, Stark, & Swinerd

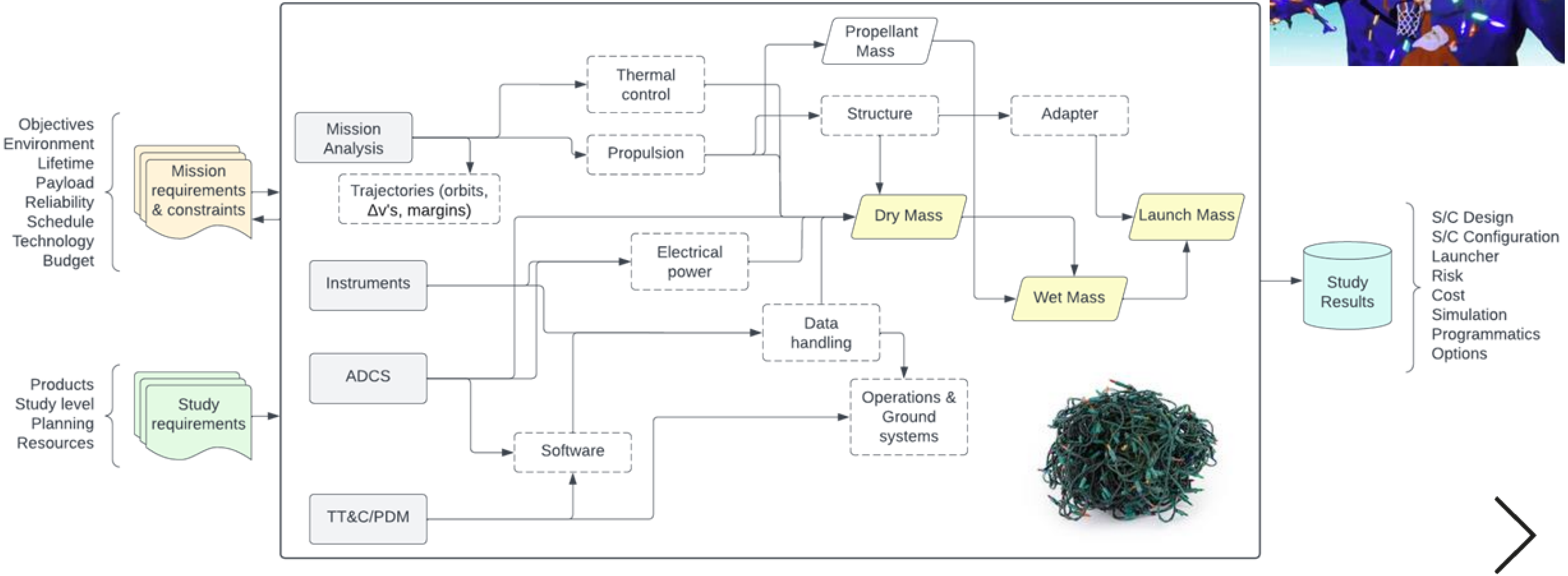
Chapter 18 in “Space Mission Engineering: the New SMAD” by Wertz, Everett, and Puschell

# Introduction

# How Does a Space Project Start?

## The Space Mission Engineering Process

CONCEPTUAL MODEL OF MISSION & SPACECRAFT DESIGN PROCESS

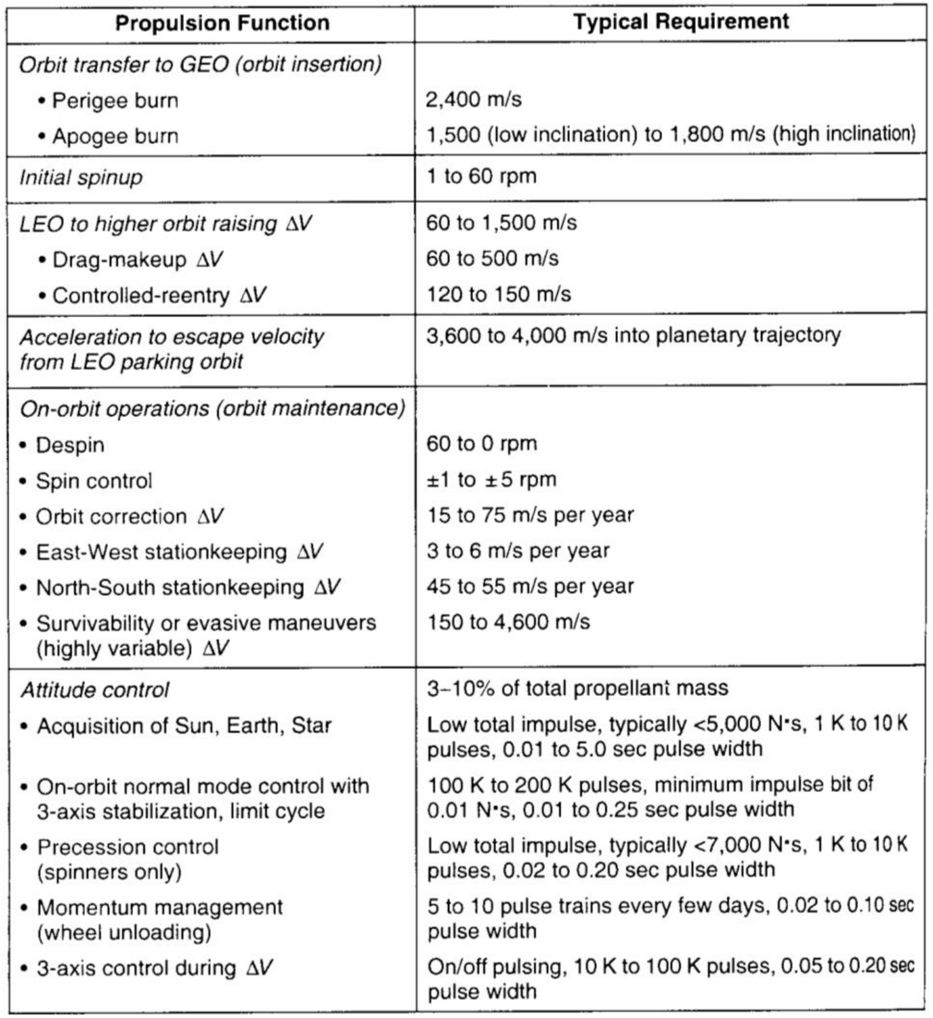


# Propulsion System Functions

Space propulsion subsystems' basic functions are:

- Lift a launch vehicle (launch vehicle propulsion)
- Transfer payloads from low-Earth orbits to higher orbits (primary propulsion) or into trajectories for planetary encounter
- Provide thrust for attitude control and orbit corrections (secondary propulsion)

This introduction will focus on space primary and secondary propulsion, not on launch vehicle propulsion



| **Propulsion Function** | **Typical Requirement** |
|---|---|
| *Orbit transfer to GEO (orbit insertion)* | |
| • Perigee burn | 2,400 m/s |
| • Apogee burn | 1,500 (low inclination) to 1,800 m/s (high inclination) |
| *Initial spinup* | 1 to 60 rpm |
| *LEO to higher orbit raising $\Delta V$* | 60 to 1,500 m/s |
| • Drag-makeup $\Delta V$ | 60 to 500 m/s |
| • Controlled-reentry $\Delta V$ | 120 to 150 m/s |
| *Acceleration to escape velocity from LEO parking orbit* | 3,600 to 4,000 m/s into planetary trajectory |
| *On-orbit operations (orbit maintenance)* | |
| • Despin | 60 to 0 rpm |
| • Spin control | ±1 to ±5 rpm |
| • Orbit correction $\Delta V$ | 15 to 75 m/s per year |
| • East-West stationkeeping $\Delta V$ | 3 to 6 m/s per year |
| • North-South stationkeeping $\Delta V$ | 45 to 55 m/s per year |
| • Survivability or evasive maneuvers (highly variable) $\Delta V$ | 150 to 4,600 m/s |
| *Attitude control* | 3–10% of total propellant mass |
| • Acquisition of Sun, Earth, Star | Low total impulse, typically <5,000 N·s, 1 K to 10 K pulses, 0.01 to 5.0 sec pulse width |
| • On-orbit normal mode control with 3-axis stabilization, limit cycle | 100 K to 200 K pulses, minimum impulse bit of 0.01 N·s, 0.01 to 0.25 sec pulse width |
| • Precession control (spinners only) | Low total impulse, typically <7,000 N·s, 1 K to 10 K pulses, 0.02 to 0.20 sec pulse width |
| • Momentum management (wheel unloading) | 5 to 10 pulse trains every few days, 0.02 to 0.10 sec pulse width |
| • 3-axis control during $\Delta V$ | On/off pulsing, 10 K to 100 K pulses, 0.05 to 0.20 sec pulse width |

# Design drivers

- Performance requirements:
  - Thrust
  - Total impulse
  - Duty cycle

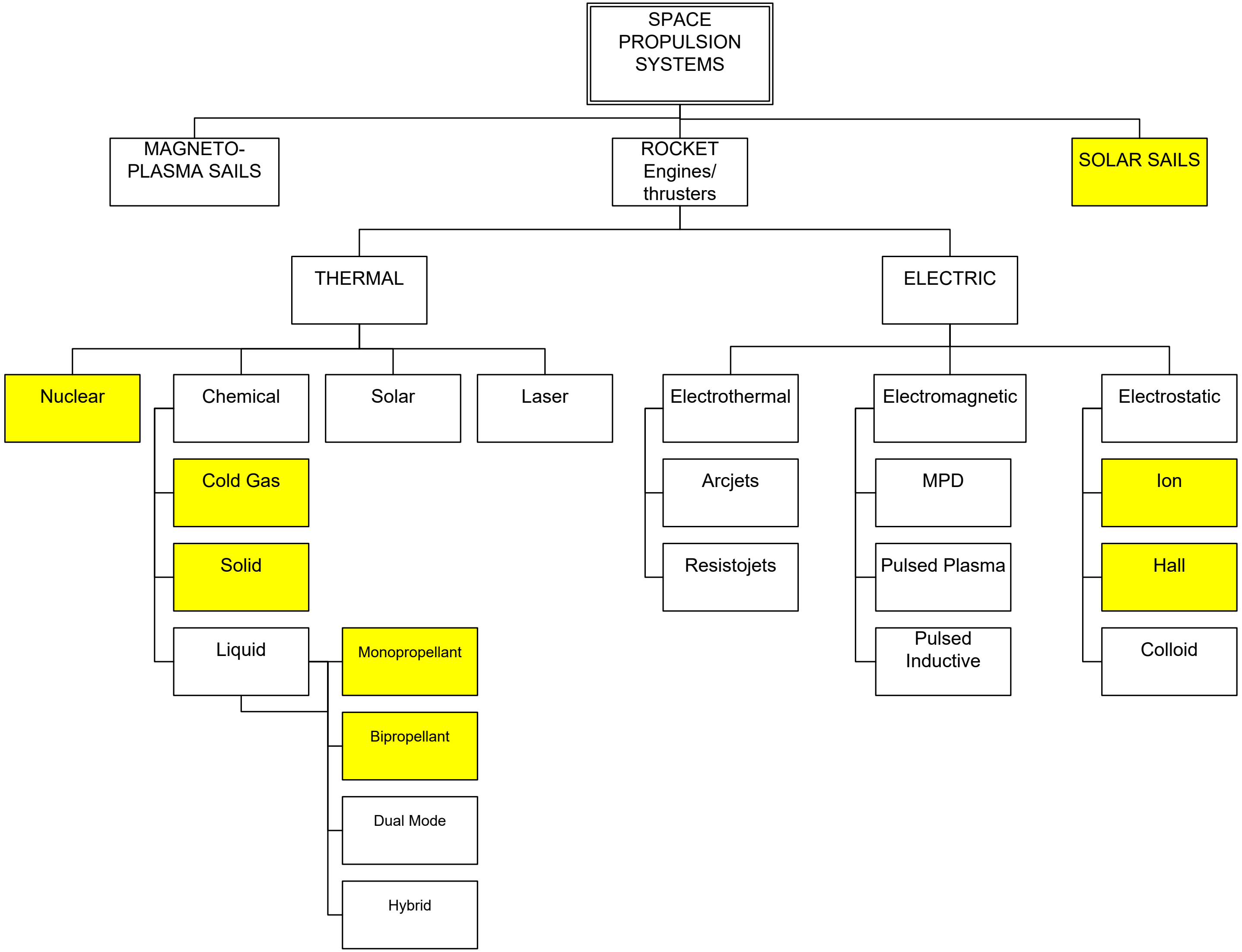
- Thruster design drivers:
  - Operating pressure
  - Internal and external leakage
  - Propellant type

- Configuration drivers:
  - Physical characteristics
  - Mass properties
  - Thruster location, alignment
  - Plume efflux

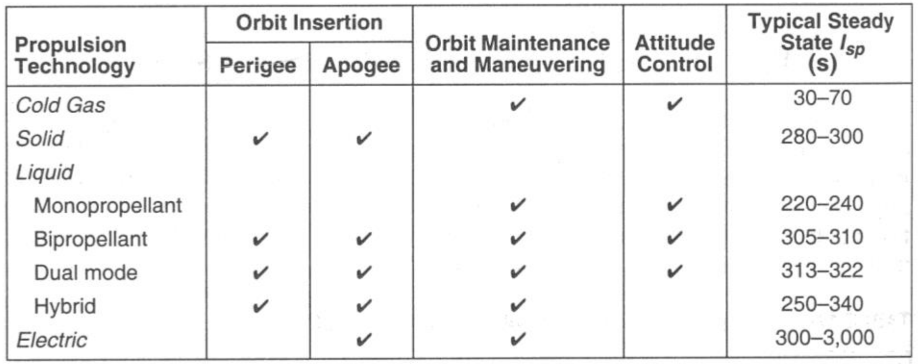
- Primary propulsion
  - For orbital transfers
  - Important design parameters
    - Total impulse, or maximum propellant load
    - Specific impulse
    - Propellant storage temperatures
    - Mass

- Secondary propulsion
  - For attitude control, and guidance/navigation
  - Important design parameters
    - Minimum impulse bit
    - Thruster mode
    - Mass
    - Power

# Propulsion Technologies



- SPACE PROPULSION SYSTEMS
  - MAGNETO-PLASMA SAILS
  - ROCKET Engines/ thrusters
    - THERMAL
      - Nuclear
      - Chemical
        - Cold Gas
        - Solid
        - Liquid
          - Monopropellant
          - Bipropellant
          - Dual Mode
          - Hybrid
      - Solar
      - Laser
    - ELECTRIC
      - Electrothermal
        - Arcjets
        - Resistojets
      - Electromagnetic
        - MPD
        - Pulsed Plasma
        - Pulsed Inductive
      - Electrostatic
        - Ion
        - Hall
        - Colloid
  - SOLAR SAILS

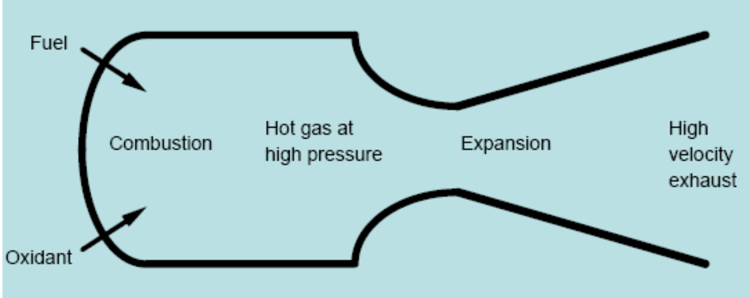


| Propulsion Technology | Orbit Insertion | | Orbit Maintenance and Maneuvering | Attitude Control | Typical Steady State $I_{sp}$ (s) |
|---|---|---|---|---|---|
| | Perigee | Apogee | | | |
| *Cold Gas* | | | ✔ | ✔ | 30–70 |
| *Solid* | ✔ | ✔ | | | 280–300 |
| *Liquid* | | | | | |
| Monopropellant | | | ✔ | ✔ | 220–240 |
| Bipropellant | ✔ | ✔ | ✔ | ✔ | 305–310 |
| Dual mode | ✔ | ✔ | ✔ | ✔ | 313–322 |
| Hybrid | ✔ | ✔ | ✔ | | 250–340 |
| *Electric* | | ✔ | ✔ | | 300–3,000 |

# Principles of Rocket Propulsion (1/3)

- Thrust provided by thruster can be written as:
    - $v_e$: exhaust gas velocity
    - : mass flow rate, consumed propellant per second
    - $P_e$: exhaust pressure
    - $P_{inf}$: pressure at infinity

$$F_{th} = v_e \dot{m} + A_e (P_e - P_\infty)$$



- Nozzle of the thruster designed to minimize ($P_e$ - $P_{inf}$)

$$F_{th} \approx v_e \dot{m}$$

- The total impulse $I_t$ is thrust $F_{th}(t)$ integrated over burn time:

$$I_t = \int_0^{t_{burn}} F_{th}(t).dt$$

- For constant thrust,

$$I_t = F_{th}.t_{burn}$$

# Principles of Rocket Propulsion (2/3)

- We define the *Specific Impulse* as:
  - (note that *Isp* has the units of time, and is expressed in seconds)

$$Isp = \frac{\int_0^{t_{burn}} F_{th}.dt}{g_o \int_0^{t_{burn}} \dot{m}.dt}$$

- The specific impulse provides an indication of the relative efficiency of a thruster
  - Isp is a measure of the energy content of the propellant and how efficiently it is converted into thrust
  - The higher the specific impulse the better (less propellant required for a given $\Delta$V)
- For constant thrust:

$$Isp = \frac{I_t}{g_o m_{prop}} = \frac{F_{th}}{g_o \dot{m}} = \frac{v_e}{g_o} \quad [s]$$

$g_o$: gravitational constant, 9.81 m/s$^2$

- Nozzle design theory tells that for a thermal rocket (solid or liquid propellant chemical, nuclear, solar thermal, electrothermal), the specific impulse can be directly related to chamber temperature and average molecular weight of exhaust gases:
  - *Isp* can be increased by using lighter gases or by increasing *Tc*

$$Isp = f(\frac{P_c}{P_a}, C_p).\sqrt{\frac{T_c}{M}}$$

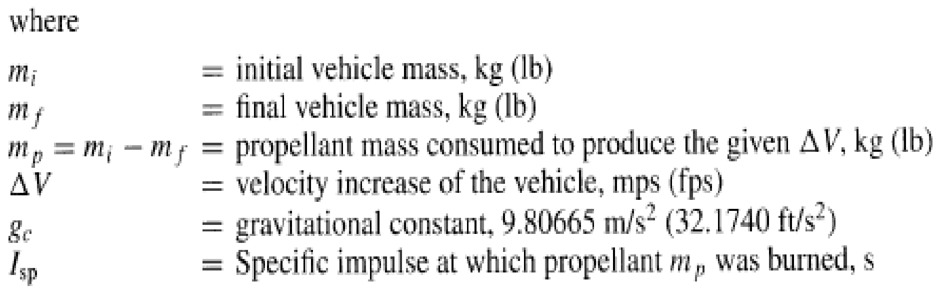
# Principles of Rocket Propulsion (3/3)

- The acceleration provided to the spacecraft is then: $$\frac{dv}{dt} = \frac{F_{th}}{m} \Rightarrow \frac{dv}{dt} = v_e \frac{\dot{m}}{m}$$
- Integrating over the duration of the burn: $$\Delta v = v_e \ln\left(\frac{m_i}{m_f}\right)$$
- Rocket Equation or Tsiolkowski Equation: $$\Delta v = g_o Isp \ln\left(\frac{m_i}{m_f}\right)$$
- Calculation of the propellant needed for a given transfer maneuver:

$$m_{prop} = m_i \left[ 1 - \exp\left(-\frac{\Delta v}{g_o Isp}\right) \right]$$

$$m_{prop} = m_f \left[ \exp\left(\frac{\Delta v}{g_o Isp}\right) - 1 \right]$$

$$m_{prop} = m_i - m_f$$



where

$m_i$ = initial vehicle mass, kg (lb)

$m_f$ = final vehicle mass, kg (lb)

$m_p = m_i - m_f$ = propellant mass consumed to produce the given $\Delta V$, kg (lb)

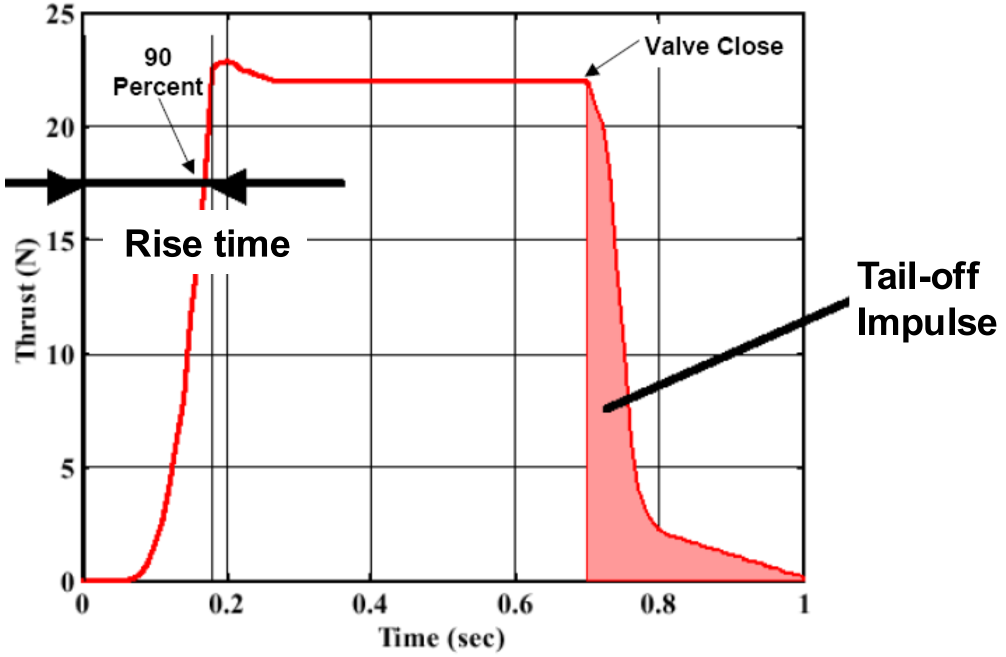
$\Delta V$ = velocity increase of the vehicle, mps (fps)

$g_c$ = gravitational constant, 9.80665 m/s$^2$ (32.1740 ft/s$^2$)

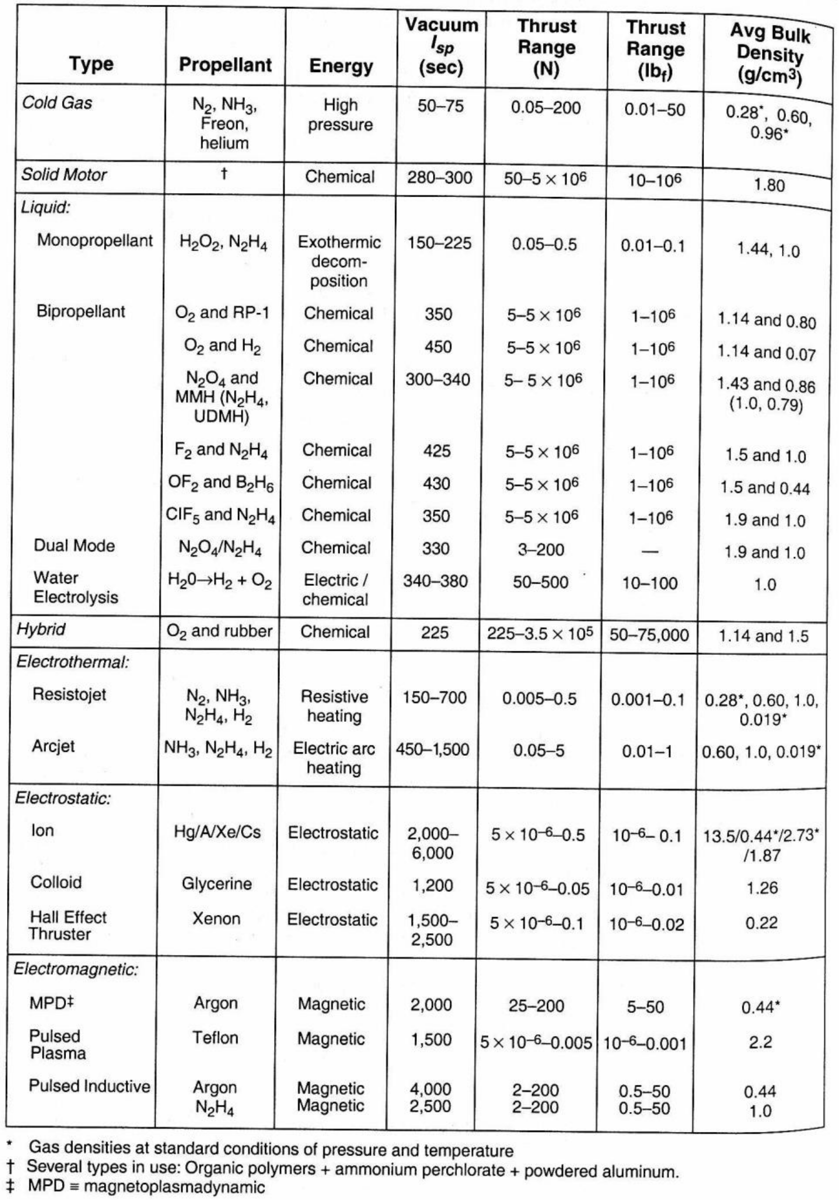
$I_{sp}$ = Specific impulse at which propellant $m_p$ was burned, s

# Minimum Impulse Bit

- Definition: smallest repeatable impulse that a device can provide. Defines the "fineness" of control that is possible.
- Symbol/Abbreviation: $I_{bit}$
  - SI Unit: Newton-seconds (N-sec)
  - Imperial Unit: pounds force-seconds (lbf-sec)
- Primarily dependent on
  - The type of engine used
  - How fast the engine's inlet valve can open and close ("response time")
  - The physical size and volume of components
  - The minimum unit of time that any command can be given by the spacecraft attitude control subsystem
- Has to be measured and cannot reliably be calculated
- Examples:
  - Very small cold gas thrusters ≈ $5 \times 10^{-7}$ N•s ($10^{-3}$ N•s more common)
  - Standard 0.9 N thruster ≈ $1 \times 10^{-3}$ N•s
  - Future Liquid Micro-thrusters ≈ $2 \times 10^{-5}$ N•s



# Performance Characteristics of Propulsion Systems



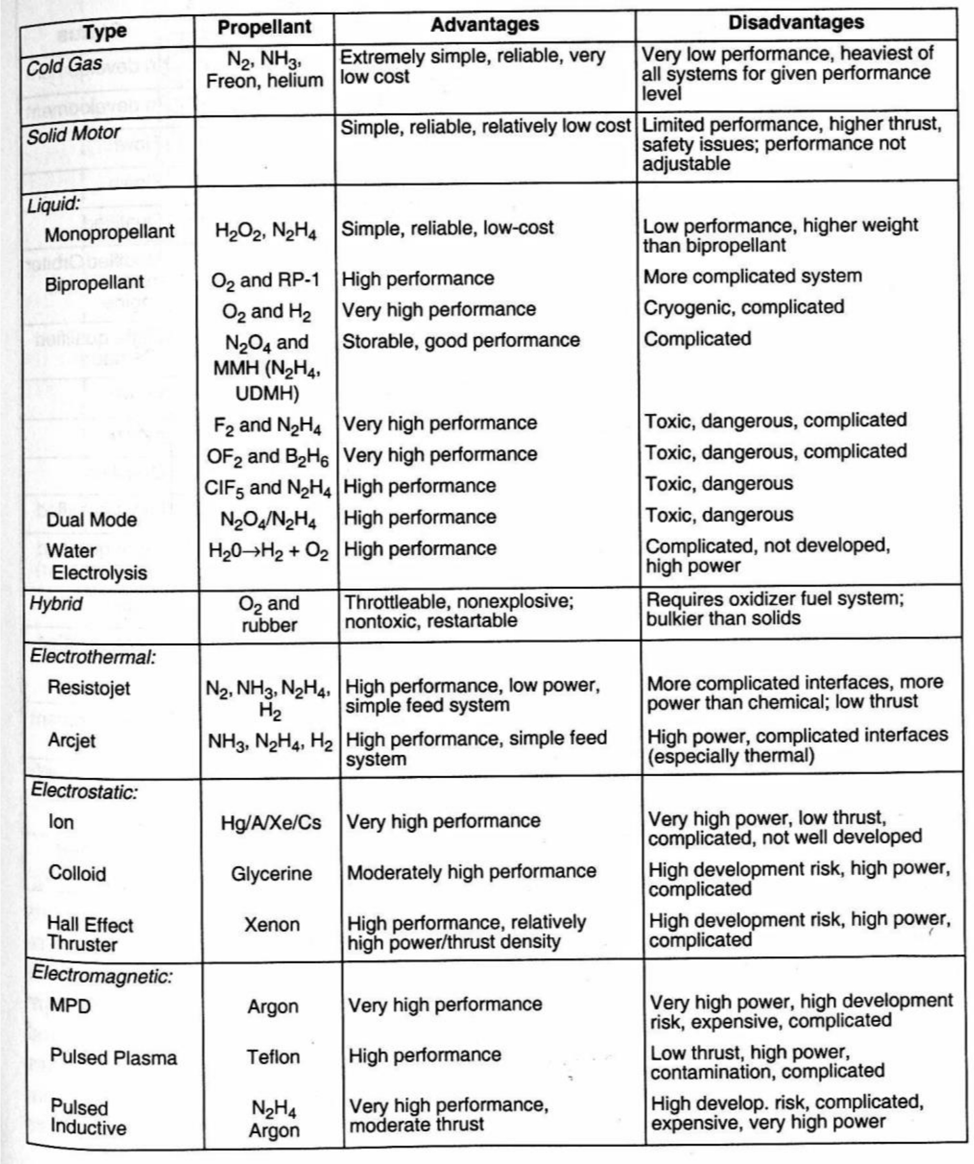
| Type | Propellant | Energy | Vacuum $I_{sp}$ (sec) | Thrust Range (N) | Thrust Range ($lb_f$) | Avg Bulk Density ($g/cm^3$) |
|---|---|---|---|---|---|---|
| *Cold Gas* | $N_2$, $NH_3$, Freon, helium | High pressure | 50–75 | 0.05–200 | 0.01–50 | 0.28*, 0.60, 0.96* |
| *Solid Motor* | † | Chemical | 280–300 | $50–5 \times 10^6$ | $10–10^6$ | 1.80 |
| *Liquid:* | | | | | | |
| Monopropellant | $H_2O_2$, $N_2H_4$ | Exothermic decom-position | 150–225 | 0.05–0.5 | 0.01–0.1 | 1.44, 1.0 |
| Bipropellant | $O_2$ and RP-1 | Chemical | 350 | $5–5 \times 10^6$ | $1–10^6$ | 1.14 and 0.80 |
| | $O_2$ and $H_2$ | Chemical | 450 | $5–5 \times 10^6$ | $1–10^6$ | 1.14 and 0.07 |
| | $N_2O_4$ and MMH ($N_2H_4$, UDMH) | Chemical | 300–340 | $5– 5 \times 10^6$ | $1–10^6$ | 1.43 and 0.86 (1.0, 0.79) |
| | $F_2$ and $N_2H_4$ | Chemical | 425 | $5–5 \times 10^6$ | $1–10^6$ | 1.5 and 1.0 |
| | $OF_2$ and $B_2H_6$ | Chemical | 430 | $5–5 \times 10^6$ | $1–10^6$ | 1.5 and 0.44 |
| | $ClF_5$ and $N_2H_4$ | Chemical | 350 | $5–5 \times 10^6$ | $1–10^6$ | 1.9 and 1.0 |
| Dual Mode | $N_2O_4/N_2H_4$ | Chemical | 330 | 3–200 | — | 1.9 and 1.0 |
| Water Electrolysis | $H_20 \rightarrow H_2 + O_2$ | Electric / chemical | 340–380 | 50–500 | 10–100 | 1.0 |
| *Hybrid* | $O_2$ and rubber | Chemical | 225 | $225–3.5 \times 10^5$ | 50–75,000 | 1.14 and 1.5 |
| *Electrothermal:* | | | | | | |
| Resistojet | $N_2$, $NH_3$, $N_2H_4$, $H_2$ | Resistive heating | 150–700 | 0.005–0.5 | 0.001–0.1 | 0.28*, 0.60, 1.0, 0.019* |
| Arcjet | $NH_3$, $N_2H_4$, $H_2$ | Electric arc heating | 450–1,500 | 0.05–5 | 0.01–1 | 0.60, 1.0, 0.019* |
| *Electrostatic:* | | | | | | |
| Ion | Hg/A/Xe/Cs | Electrostatic | 2,000–6,000 | $5 \times 10^{-6}–0.5$ | $10^{-6}– 0.1$ | 13.5/0.44*/2.73*/1.87 |
| Colloid | Glycerine | Electrostatic | 1,200 | $5 \times 10^{-6}–0.05$ | $10^{-6}–0.01$ | 1.26 |
| Hall Effect Thruster | Xenon | Electrostatic | 1,500–2,500 | $5 \times 10^{-6}–0.1$ | $10^{-6}–0.02$ | 0.22 |
| *Electromagnetic:* | | | | | | |
| MPD‡ | Argon | Magnetic | 2,000 | 25–200 | 5–50 | 0.44* |
| Pulsed Plasma | Teflon | Magnetic | 1,500 | $5 \times 10^{-6}–0.005$ | $10^{-6}–0.001$ | 2.2 |
| Pulsed Inductive | Argon | Magnetic | 4,000 | 2–200 | 0.5–50 | 0.44 |
| | $N_2H_4$ | Magnetic | 2,500 | 2–200 | 0.5–50 | 1.0 |

* Gas densities at standard conditions of pressure and temperature

† Several types in use: Organic polymers + ammonium perchlorate + powdered aluminum.

‡ MPD ≡ magnetoplasmadynamic

# Pros & Cons of Current Propulsion Systems

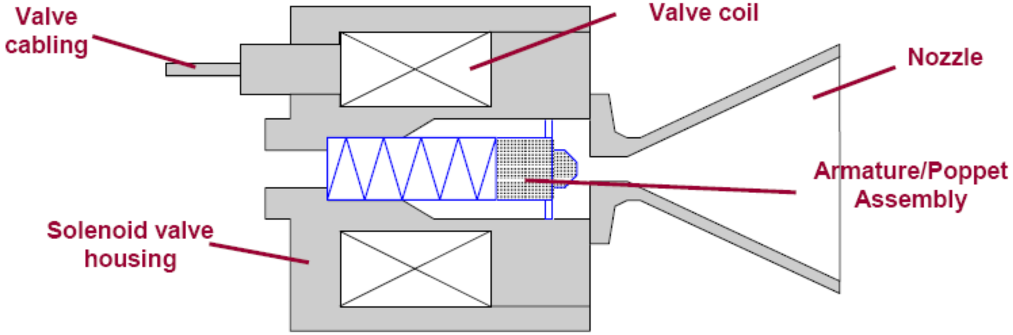


| Type | Propellant | Advantages | Disadvantages |
|---|---|---|---|
| *Cold Gas* | $N_2$, $NH_3$, Freon, helium | Extremely simple, reliable, very low cost | Very low performance, heaviest of all systems for given performance level |
| *Solid Motor* | | Simple, reliable, relatively low cost | Limited performance, higher thrust, safety issues; performance not adjustable |
| *Liquid:* | | | |
| Monopropellant | $H_2O_2$, $N_2H_4$ | Simple, reliable, low-cost | Low performance, higher weight than bipropellant |
| Bipropellant | $O_2$ and RP-1 | High performance | More complicated system |
| | $O_2$ and $H_2$ | Very high performance | Cryogenic, complicated |
| | $N_2O_4$ and MMH ($N_2H_4$, UDMH) | Storable, good performance | Complicated |
| | $F_2$ and $N_2H_4$ | Very high performance | Toxic, dangerous, complicated |
| | $OF_2$ and $B_2H_6$ | Very high performance | Toxic, dangerous, complicated |
| | $ClF_5$ and $N_2H_4$ | High performance | Toxic, dangerous |
| Dual Mode | $N_2O_4/N_2H_4$ | High performance | Toxic, dangerous |
| Water Electrolysis | $H_20 \rightarrow H_2 + O_2$ | High performance | Complicated, not developed, high power |
| *Hybrid* | $O_2$ and rubber | Throttleable, nonexplosive; nontoxic, restartable | Requires oxidizer fuel system; bulkier than solids |
| *Electrothermal:* | | | |
| Resistojet | $N_2$, $NH_3$, $N_2H_4$, $H_2$ | High performance, low power, simple feed system | More complicated interfaces, more power than chemical; low thrust |
| Arcjet | $NH_3$, $N_2H_4$, $H_2$ | High performance, simple feed system | High power, complicated interfaces (especially thermal) |
| *Electrostatic:* | | | |
| Ion | Hg/A/Xe/Cs | Very high performance | Very high power, low thrust, complicated, not well developed |
| Colloid | Glycerine | Moderately high performance | High development risk, high power, complicated |
| Hall Effect Thruster | Xenon | High performance, relatively high power/thrust density | High development risk, high power, complicated |
| *Electromagnetic:* | | | |
| MPD | Argon | Very high performance | Very high power, high development risk, expensive, complicated |
| Pulsed Plasma | Teflon | High performance | Low thrust, high power, contamination, complicated |
| Pulsed Inductive | $N_2H_4$<br>Argon | Very high performance, moderate thrust | High develop. risk, complicated, expensive, very high power |

# Chemical Propulsion

# Chemical Propulsion – Cold Gas Thrusters

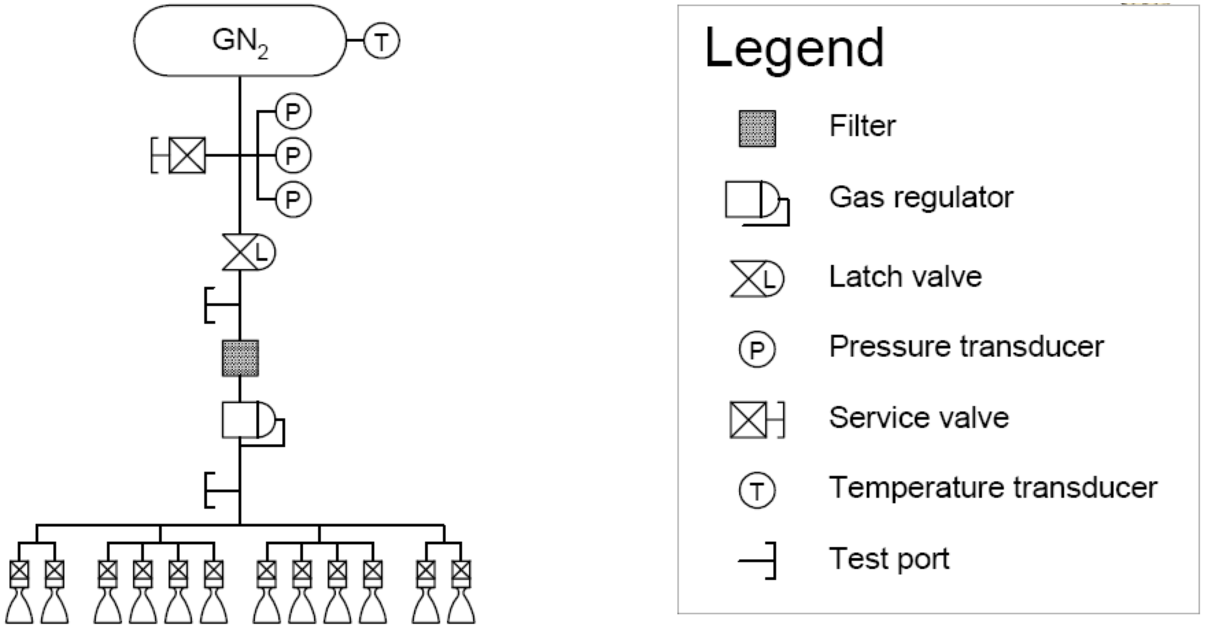
- Provides a force or reaction moment in a given direction by expelling a high-pressure gas
- Power energizes a coil which opens a valve allowing a gas to flow through the valve and out a nozzle
  - Typical Size: 2 cm diameter by 3 cm long
  - Typical Mass: as required (30 grams)
  - Typical Power: 30 W @ 28 VDC
- Simple nozzle attached to the outlet of a solenoid valve
  - Thrust level determines size and mass of cold-gas thruster
  - Leakage is a major issue for long life
    - can easily be contaminated by impurities in the flow and fail



*Normally closed solenoid valve where armature/poppet assembly (in blue) is held against the throat seat by a conical spiral spring*

- *–The valve coils are energized when an electrical signal is applied to the solenoid valve*
- *–When the electromagnetic force of the coil overcomes the spring pre-load, the armature/poppet assembly (in blue) lifts from the seat allowing gas flow*
- *–De-energizing the coil causes the magnetic field to decay and the spring preload force returns the armature/poppet assembly to its seat providing leak-tight gas shut off*

# Chemical Propulsion – Cold Gas Thrusters



| Cold Gas | Molecular formula | Molecular Mass (kg/kmol) | Density at 3.4 MPa (kg/m$^3$) | Density at 6.9 MPa (kg/m$^3$) | Density at 27.6 MPa (kg/m$^3$) | Hazards |
|---|---|---|---|---|---|---|
| Air |  | 28.97 | 41.43 | 83.26 | 308.49 |  |
| Carbon Dioxide | $CO_2$ | 44.01 | 79.65 | 350.66 | 662.62 | A |
| Helium | He | 4.00 | 5.56 | 10.93 | 39.88 | A |
| Hydrogen | $H_2$ | 2.02 | 2.80 | 5.48 | 19.04 | A, F |
| Methane | $CH_4$ | 16.04 | 24.16 | 51.38 | 219.18 | A, F |
| Nitrogen | $N_2$ | 28.02 | 39.89 | 79.75 | 286.31 | A |
| Oxygen | $O_2$ | 32.00 | 46.32 | 94.36 | 372.35 |  |

A= asphyxiative; B = burns skin; C = corrosive; D = decomposes; F = flammable; T = toxic

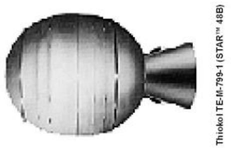
# Chemical Propulsion - Solid

- Propellant grain enclosed in a case ended by a nozzle.
  - The shape of the cross section of the grain selected to achieve thrust vs. time profile.

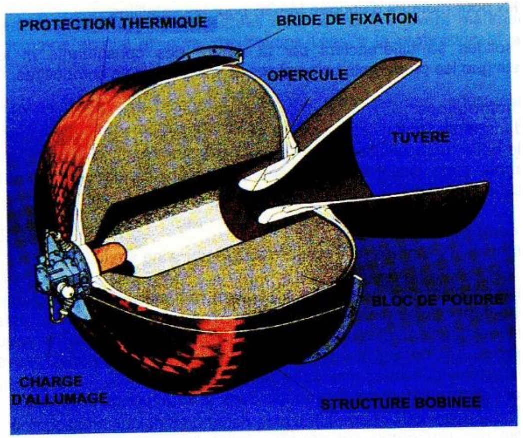
- Size:
  - 7 by 2 cm for a small spin-up solid rocket motor
  - 2.6 by 1.9 m for the STAR™ 75 perigee kick motor

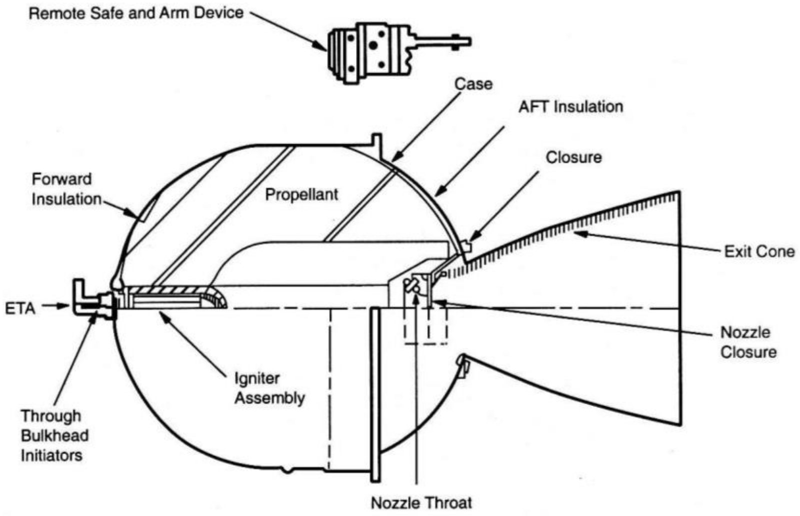
- Mass:
  - 40 grams for a small spin-up solid rocket motor
  - 8000 kg for the STAR™ 75 perigee kick motor

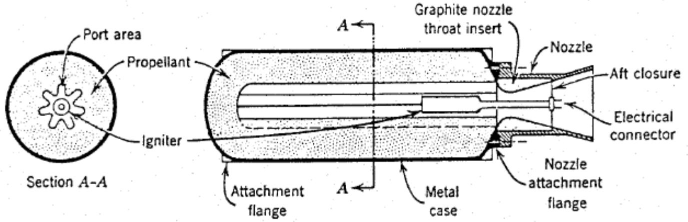
- Larger units are produced for launch vehicles



Thiokol TE-M-799-1 (STAR™ 48B)







*Section of simple solid propellant rocket motor. Here the propellant grain is bonded to the case. The grain has a seven-pointed star configuration and an igniter that is inserted through the nozzle.*

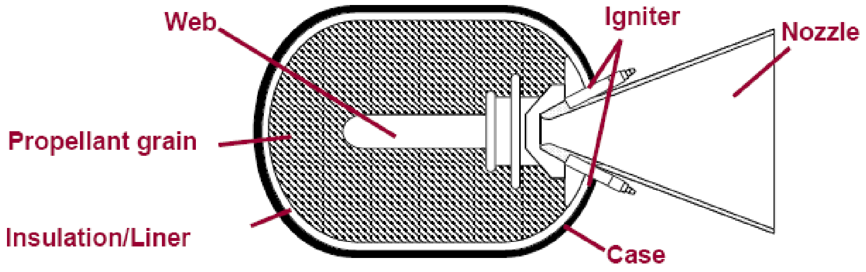
# Chemical Propulsion - Solid

- The case of a solid rocket motor serves both as a propellant tank and combustion chamber

- One or more igniters starts the propellant burning within the chamber while the (yet unburned) propellant and insulation shield the motor case from hot propellant gases

- The nozzle converts the thermal energy of the propellant gases to thrust

- The grain configuration, to a large extent, determines the thrust and burn rate of the solid rocket motor
  - –internal burning tube vs. end burner
  - –cylindrical vs. star vs. dog bone vs. slotted vs. wagon wheel vs. multiple perforations, etc.



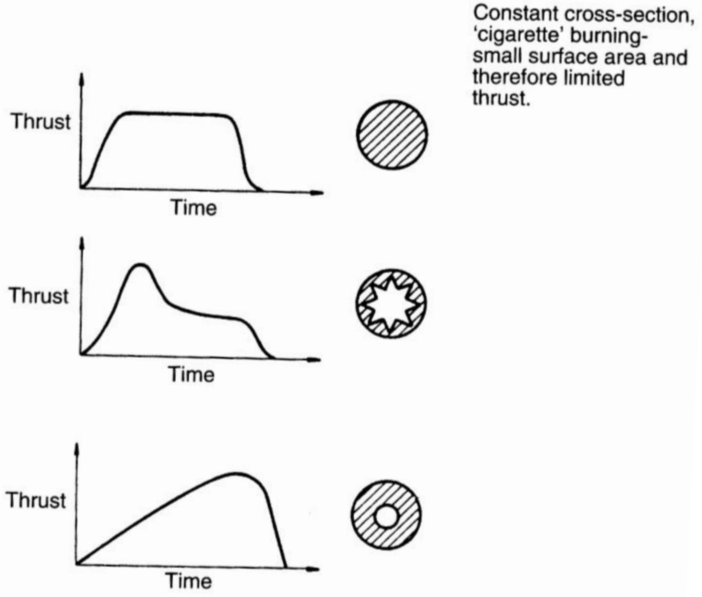
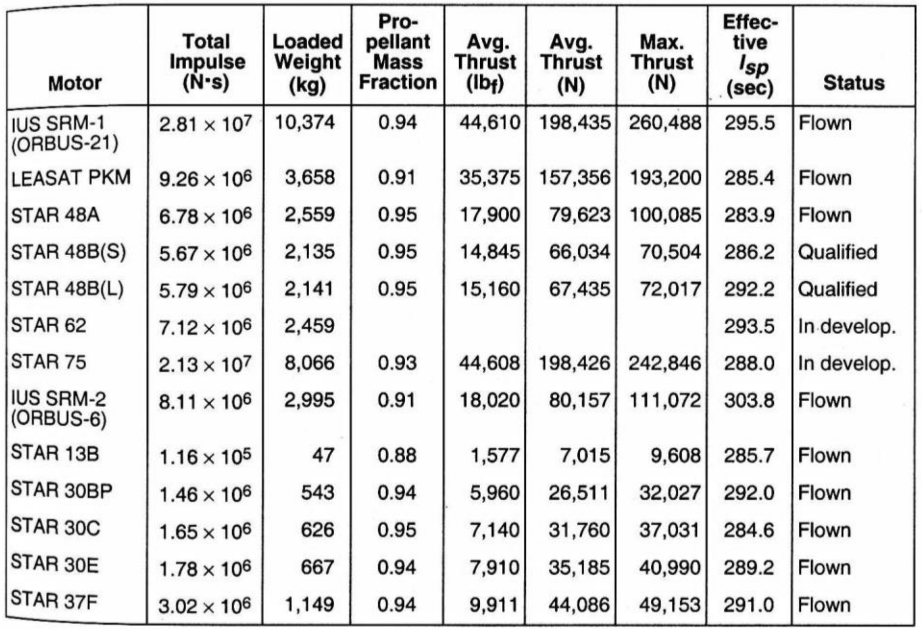


**Figure 6.12** Solid-propellant grain geometries

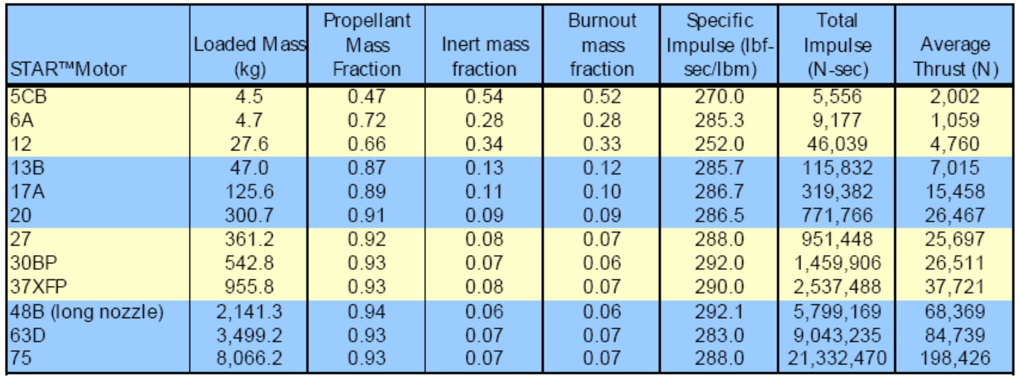
# Chemical Propulsion - Solid

**UPDATE**

**TABLE 17-7. Representative Solid Rocket Motors.** The firm United Technologies/Chemical Systems Division supplies the IUS SRM-1 and 2, as well as the current MinuteMan third-stage motor version of Leasat PKM. Thiokol Corp. supplies the STAR rocket motors as well as the LEASAT PKM.



| Motor | Total Impulse (N·s) | Loaded Weight (kg) | Propellant Mass Fraction | Avg. Thrust ($lb_f$) | Avg. Thrust (N) | Max. Thrust (N) | Effective $I_{sp}$ (sec) | Status |
|---|---|---|---|---|---|---|---|---|
| IUS SRM-1 (ORBUS-21) | $2.81 \times 10^7$ | 10,374 | 0.94 | 44,610 | 198,435 | 260,488 | 295.5 | Flown |
| LEASAT PKM | $9.26 \times 10^6$ | 3,658 | 0.91 | 35,375 | 157,356 | 193,200 | 285.4 | Flown |
| STAR 48A | $6.78 \times 10^6$ | 2,559 | 0.95 | 17,900 | 79,623 | 100,085 | 283.9 | Flown |
| STAR 48B(S) | $5.67 \times 10^6$ | 2,135 | 0.95 | 14,845 | 66,034 | 70,504 | 286.2 | Qualified |
| STAR 48B(L) | $5.79 \times 10^6$ | 2,141 | 0.95 | 15,160 | 67,435 | 72,017 | 292.2 | Qualified |
| STAR 62 | $7.12 \times 10^6$ | 2,459 | | | | | 293.5 | In develop. |
| STAR 75 | $2.13 \times 10^7$ | 8,066 | 0.93 | 44,608 | 198,426 | 242,846 | 288.0 | In develop. |
| IUS SRM-2 (ORBUS-6) | $8.11 \times 10^6$ | 2,995 | 0.91 | 18,020 | 80,157 | 111,072 | 303.8 | Flown |
| STAR 13B | $1.16 \times 10^5$ | 47 | 0.88 | 1,577 | 7,015 | 9,608 | 285.7 | Flown |
| STAR 30BP | $1.46 \times 10^6$ | 543 | 0.94 | 5,960 | 26,511 | 32,027 | 292.0 | Flown |
| STAR 30C | $1.65 \times 10^6$ | 626 | 0.95 | 7,140 | 31,760 | 37,031 | 284.6 | Flown |
| STAR 30E | $1.78 \times 10^6$ | 667 | 0.94 | 7,910 | 35,185 | 40,990 | 289.2 | Flown |
| STAR 37F | $3.02 \times 10^6$ | 1,149 | 0.94 | 9,911 | 44,086 | 49,153 | 291.0 | Flown |



| STAR™Motor | Loaded Mass (kg) | Propellant Mass Fraction | Inert mass fraction | Burnout mass fraction | Specific Impulse (lbf-sec/lbm) | Total Impulse (N-sec) | Average Thrust (N) |
|---|---|---|---|---|---|---|---|
| 5CB | 4.5 | 0.47 | 0.54 | 0.52 | 270.0 | 5,556 | 2,002 |
| 6A | 4.7 | 0.72 | 0.28 | 0.28 | 285.3 | 9,177 | 1,059 |
| 12 | 27.6 | 0.66 | 0.34 | 0.33 | 252.0 | 46,039 | 4,760 |
| 13B | 47.0 | 0.87 | 0.13 | 0.12 | 285.7 | 115,832 | 7,015 |
| 17A | 125.6 | 0.89 | 0.11 | 0.10 | 286.7 | 319,382 | 15,458 |
| 20 | 300.7 | 0.91 | 0.09 | 0.09 | 286.5 | 771,766 | 26,467 |
| 27 | 361.2 | 0.92 | 0.08 | 0.07 | 288.0 | 951,448 | 25,697 |
| 30BP | 542.8 | 0.93 | 0.07 | 0.06 | 292.0 | 1,459,906 | 26,511 |
| 37XFP | 955.8 | 0.93 | 0.08 | 0.07 | 290.0 | 2,537,488 | 37,721 |
| 48B (long nozzle) | 2,141.3 | 0.94 | 0.06 | 0.06 | 292.1 | 5,799,169 | 68,369 |
| 63D | 3,499.2 | 0.93 | 0.07 | 0.07 | 283.0 | 9,043,235 | 84,739 |
| 75 | 8,066.2 | 0.93 | 0.07 | 0.07 | 288.0 | 21,332,470 | 198,426 |

# Chemical Propulsion – Solid

- *Benefits*:
  - Simple
  - Storable
  - Self contained
  - Reliable
  - High energy density
- *Drawbacks/Issues*:
  - Can only be fired once
  - Can not have active control of thrust
  - Grain cracks lead to quick explosion of the motor
  - Requires manipulation of explosives during production
  - Generally toxic exhaust

- Thermal soak-back of the solid rocket motor to the spacecraft after it has burned out
- Thrust Vector Control (TVC) of the solid rocket motor
  - adding a liquid propulsion system (e.g. Magellan)
  - adding a gimbaling mechanism (e.g. STAR™ 48V)
    - roll control still needs to be provided
- Take into account sliver (unburned propellant remaining at the time of burnout)
- Account the difference between inert and burn-out mass
- System center of gravity shift during and after burn (particularly for end-burning SRMs)

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# Chemical Propulsion – Liquid Monopropellant

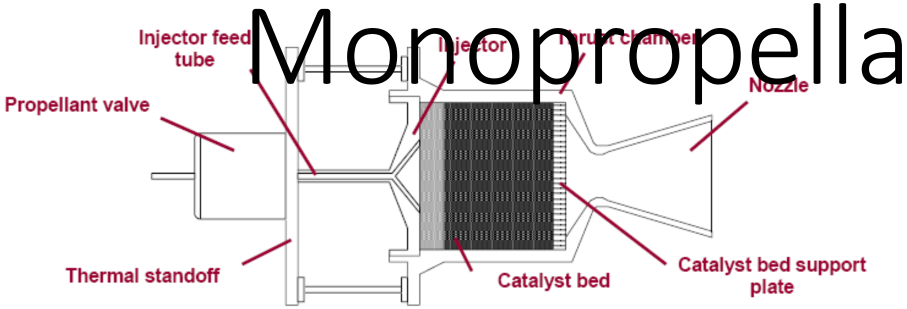
- Liquid hydrazine flows into a catalyst bed in a thruster where it decomposes to create a hot gas that is exhausted through a nozzle

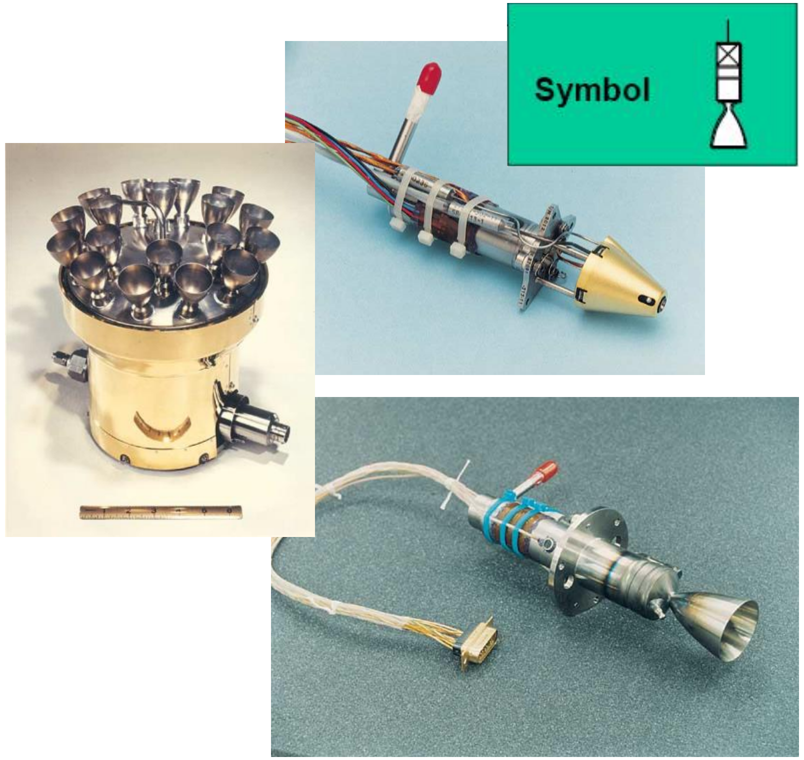
- Typical Dimensions:
  - 15 cm long by 3.5 cm diameter (for a 0.9 N thruster)
  - 46 cm long by 15 cm diameter (for a 445 N main engine)

- Typical Mass:
  - a few hundred grams (for a 0.9 N thruster)
  - several kilograms (for the 2700 N Viking main engine)

- Typical Power: 30 W (@ 28 VDC) for valve actuation

- Usually tolerate a wide operating range (inlet pressure)





***Aerojet MonoHydrazine Thrusters***

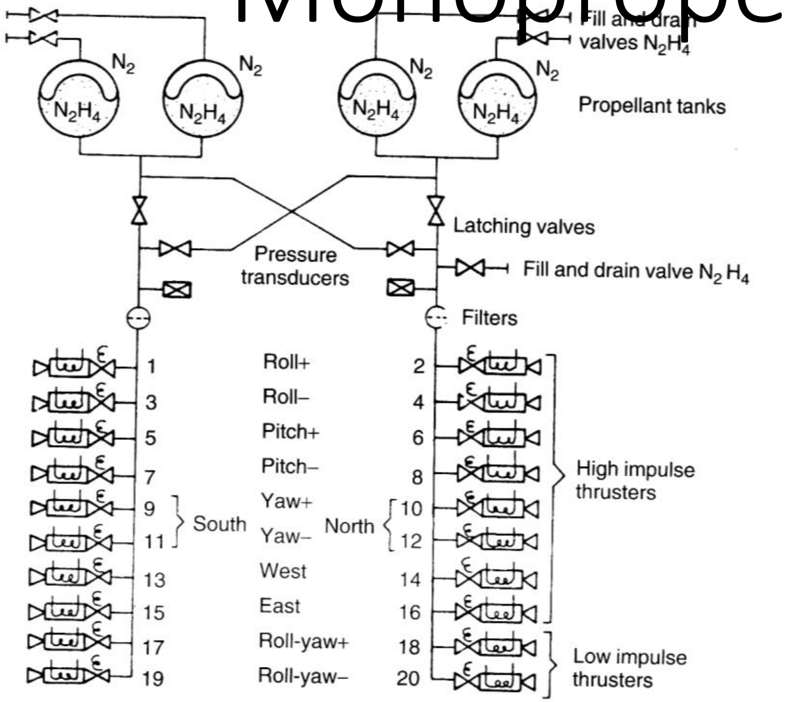
# Chemical Propulsion – Liquid Monopropellant

- *Benefits*:
  - low system complexity (no combustion and often a regulator is not even needed)
  - relatively inexpensive
  - requires only one set of tanks, components, and plumbing
  - good storability
- *Drawbacks/Issues*:
  - moderate to poor performance
  - moderately dangerous from a handling standpoint
  - contamination of a spacecraft's external surfaces from exhaust gases
- *Typically chosen as the propulsion system when*:
  - small thrust levels, minimum impulse bits, and/or ΔVs are required
  - operational lifetime of the system is long
    - the spacecraft temperature is tightly maintained
    - science dictates known and quantifiable contamination of ephemeral body

- Catalyst bed and valve heaters are usually required on all monopropellant thrusters
  - the duty cycle will dictate how long and often the cat. bed heaters are required
  - if the burns are close together (minutes), the catalyst bed should stay warm
  - how quickly the catalyst bed cools down is a function of the reactor design
  - If catalyst bed heaters are not wanted in the design, a warming pulse ("cold start") could be used before the maneuver(s) are conducted to warm the catalyst bed heaters up
- cold starts rapidly degrade the catalyst bed and are not recommended unless operational lifetime is short
- cold starts are not going to help if propellant lines or thruster valve is frozen
  - Warming up the catalyst beds on small hydrazine thrusters takes on the order of 2 hours at ~2 W
- A diaphragm propellant management device (PMD) is typically used
- Monopropellant systems will always have some hold-up/residual remaining in the propellant tanks at the end of the mission that must be accounted for

# Chemical Propulsion – Liquid Monopropellant

Example system for attitude control:



**UPDATE**

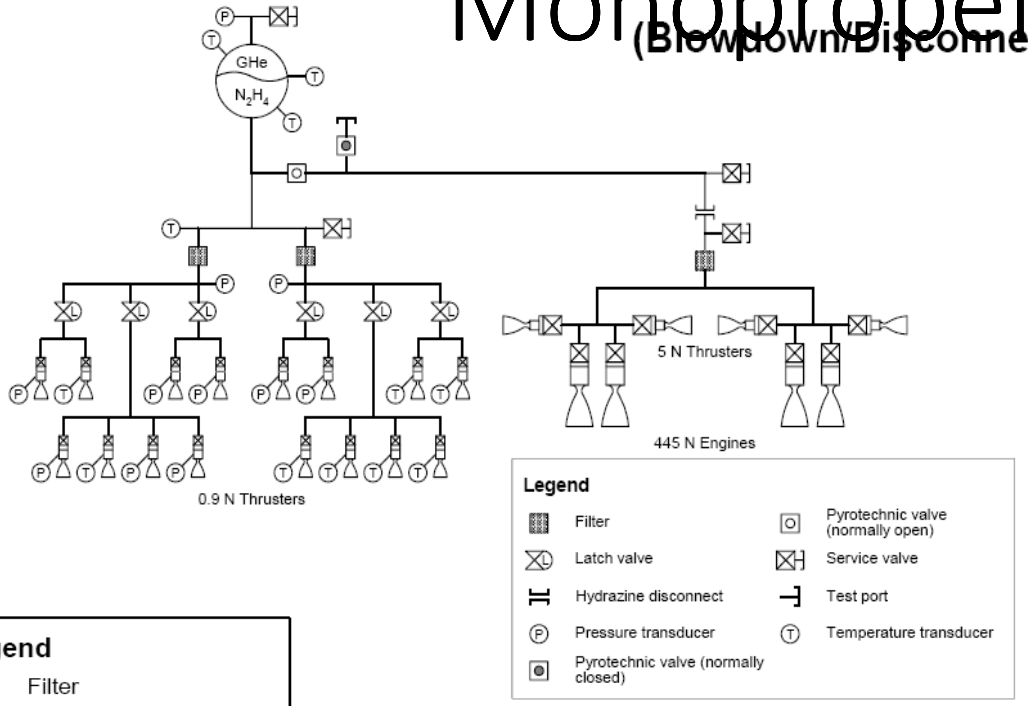
| Name | Symbol or Abbreviation | Exhaust Products | Molecular Mass of Exhaust (kg/kmol) | Delivered $I_{sp}$ (lbf-sec/lbm) | Density at 2.1 MPa and 20 °C (kg/m$^3$) | Melting Point at 1.0 MPa (° C) | Boiling Point at 1.0 MPa (° C) | Hazards |
|---|---|---|---|---|---|---|---|---|
| Hydrazine | $N_2H_4$ | $NH_3$, $N_2$, $H_2$ | 11 to 19 | 200 to 230 | 1008 | 2.0 | 114.2 | B, C, F, T |
| Hydrogen Peroxide | $H_2O_2$ | $H_2O$, $O_2$ | 22 | 150 | 1414 | -0.5 | 150.2 | B, C, D, F |
| HAN/Glycine | $H_2NCH_2COOH$ | $H_2O$, $N_2$, $CO_2$ | 22 | 190 | 1400 | -30.0 | 100.0 | B, D, F |

A= asphyxiative; B = burns skin; C = corrosive; D = decomposes; F = flammable; T = toxic

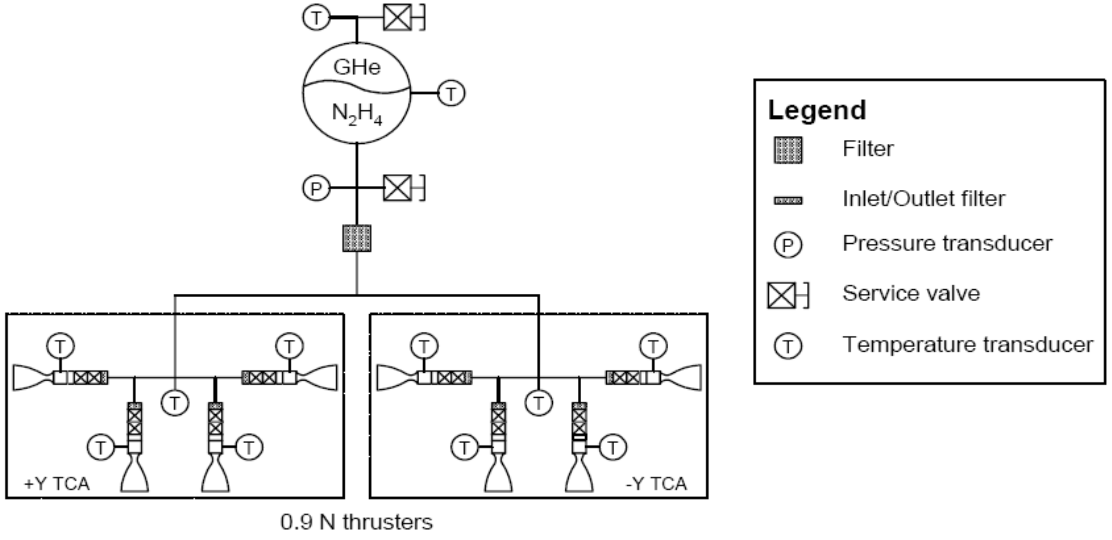
# Chemical Propulsion – Liquid Monopropellant

Example systems:

**(Blowdown/Disconnect)**



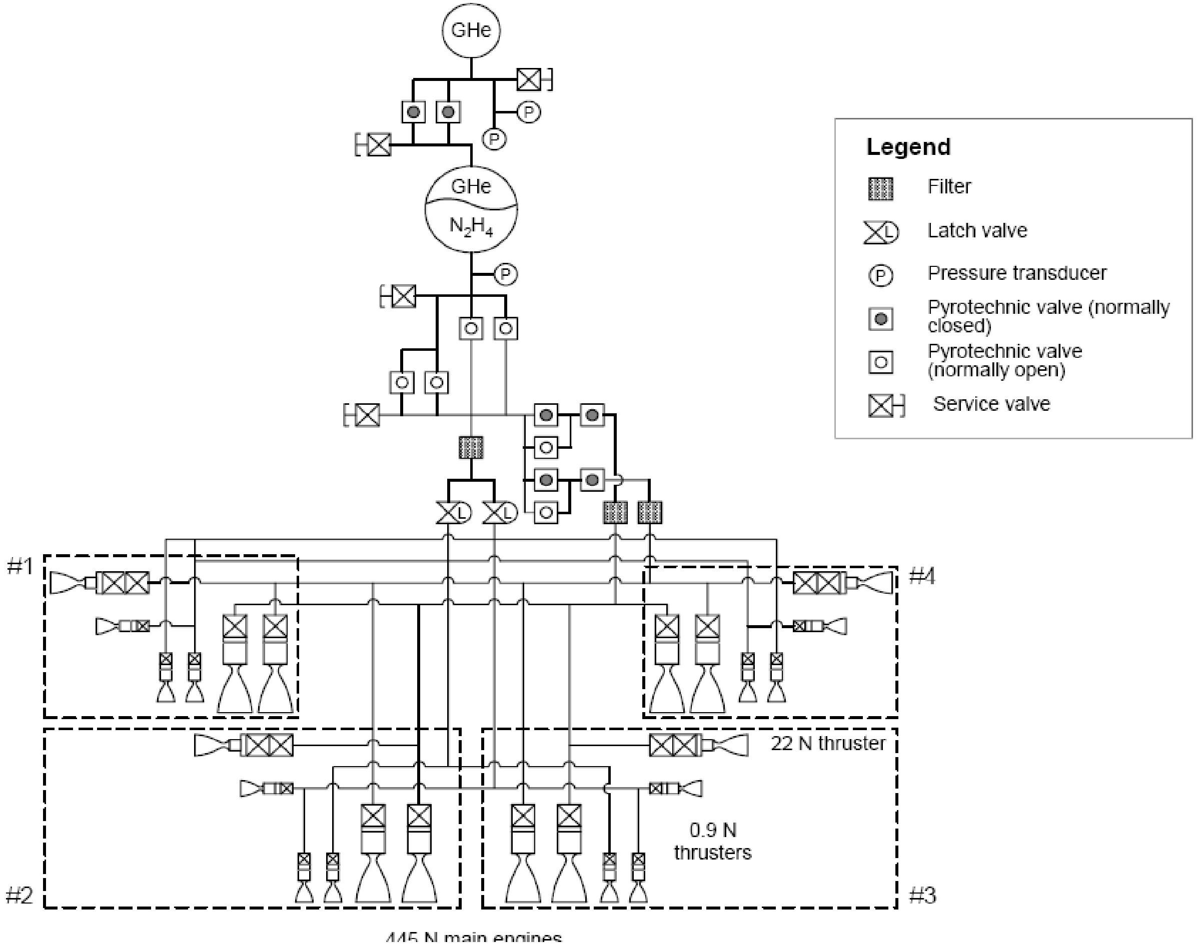
**Voyager Propulsion System**



**Deep Space 1 Reaction Control System**

# Chemical Propulsion – Liquid Monopropellant

Example system :



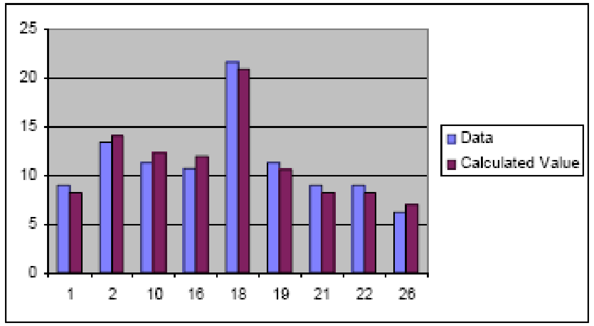
**Magellan Propulsion System**

# Chemical Propulsion – Liquid Monopropellant

Typical propulsion system dry mass:

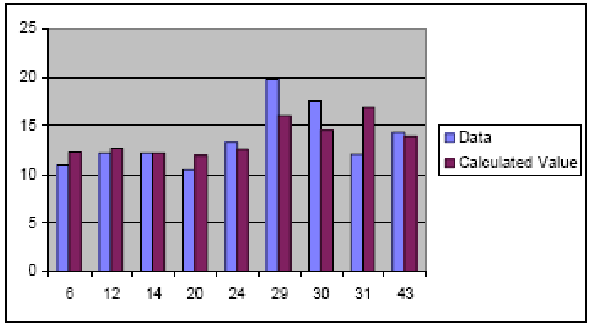
**UPDATE**

## Secondary Propulsion



M(kg) = 6.36 + .19 (Propellant Mass)

## Primary Propulsion



M(kg) = 9.43 + .09 (Propellant Mass)

±25 percent

# Chemical Propulsion – Liquid Bipropellant

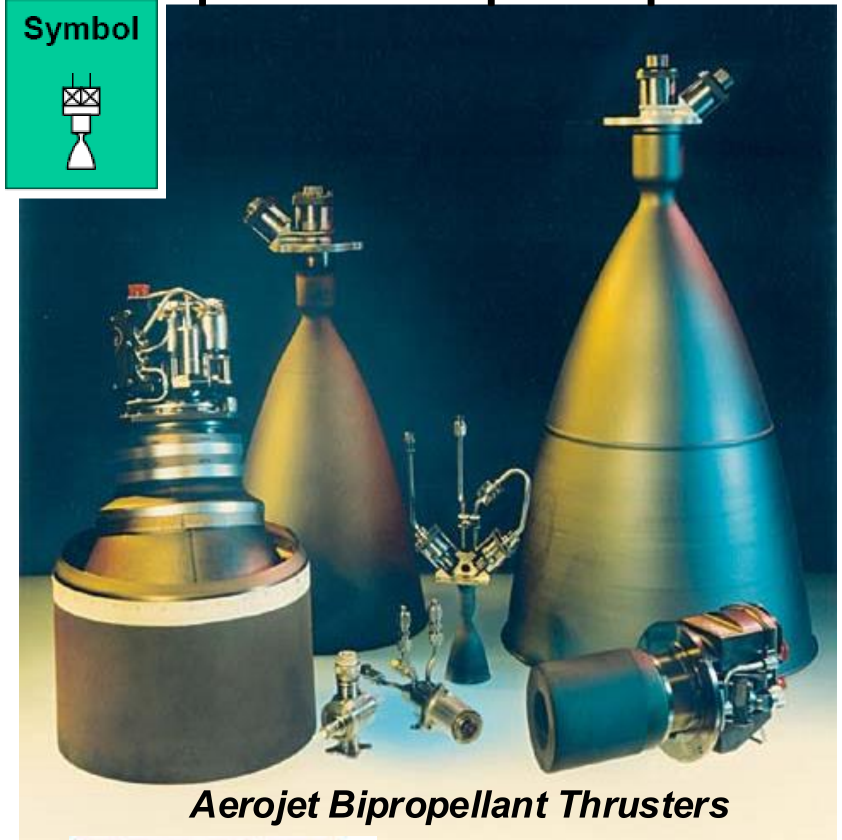
- Provides a force or reaction moment in a given direction by mixing two propellant together and exhausting the resulting products
    - Liquid oxidizer and fuel feed into a thrust chamber where they mix and react chemically. Combustion gases accelerate and exhaust through a converging-diverging nozzle

- Size:
    - 5 cm diameter by 17 cm long (for a 10 N)
    - 30 cm diameter by 60 cm long (1335 N Viking orbiter main engine)

- Mass:
    - 400 grams (for a 10 N thruster)
    - 8.1 kg (for the 1335 N Viking orbiter main engine)

- Power:
    - 14 W @ 28 VDC (10 N) to 88 W @ 28 VDC (460 N)

**Symbol**

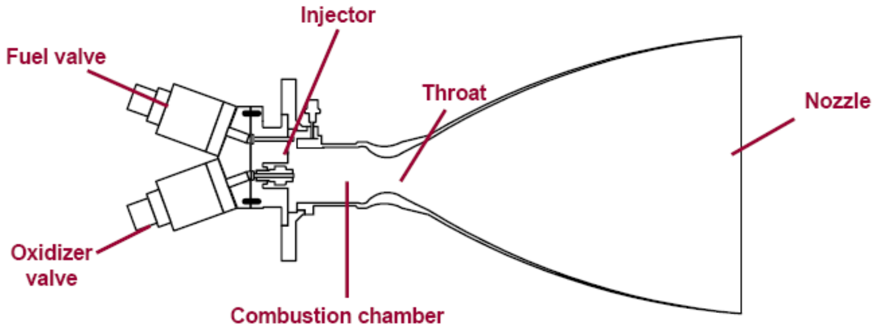


***Aerojet Bipropellant Thrusters***

***Snecma Bipropellant Thruster***

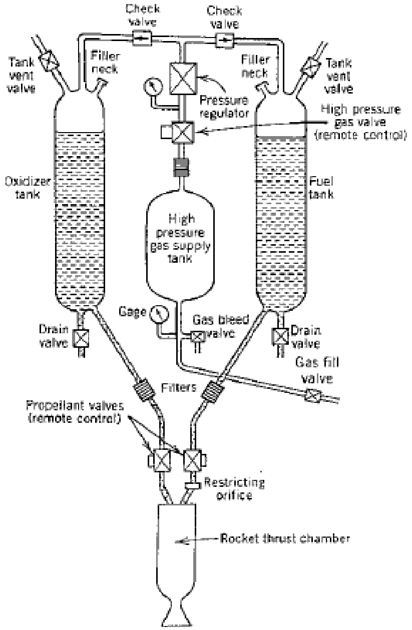
# Chemical Propulsion – Liquid Bipropellant

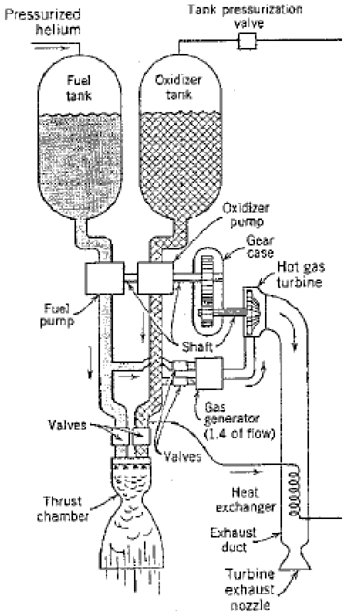
- A liquid propellant motor consists of:
  - Combustion chamber
  - Propellant tanks
  - Fuel and oxidizer injectors
  - Propellant feed system



- *Hypergolic* propellants combust together spontaneously
- *Nonhypergolic* propellants require some kind of ignition system

- There are two typical configurations for the feed system:
  - Pressure fed
  - Turbopump-fed engine





# Chemical Propulsion – Liquid Bipropellant

- *Advantages*
  - Can control thrust
  - Multiple firings
  - Can be easily shut-off
  - Can be used for long firings
  - Non-toxic exhaust (with some propellant/oxidizer combinations)

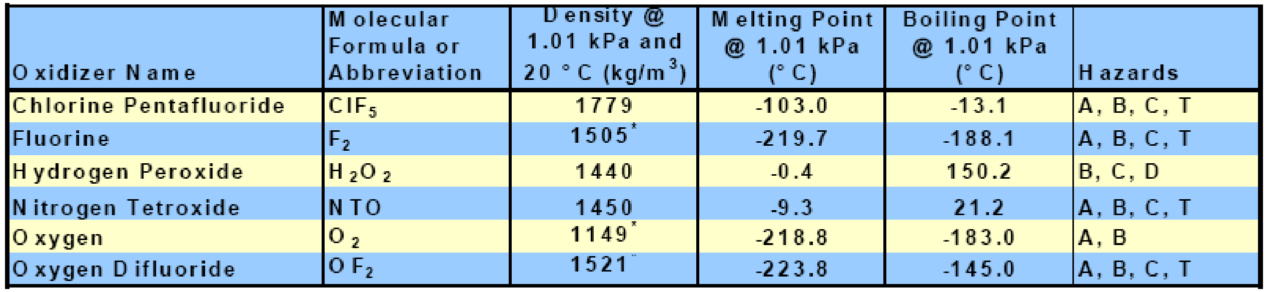
- *Disadvantages*
  - Complexity
  - Cost
  - High *Is* propellants are generally non-storable
  - Lower reliability (compared to solid motors)

- Turbo-pump feed system
  - The most complex system of the engine, especially for high thrust engines using cryogenic propellants.

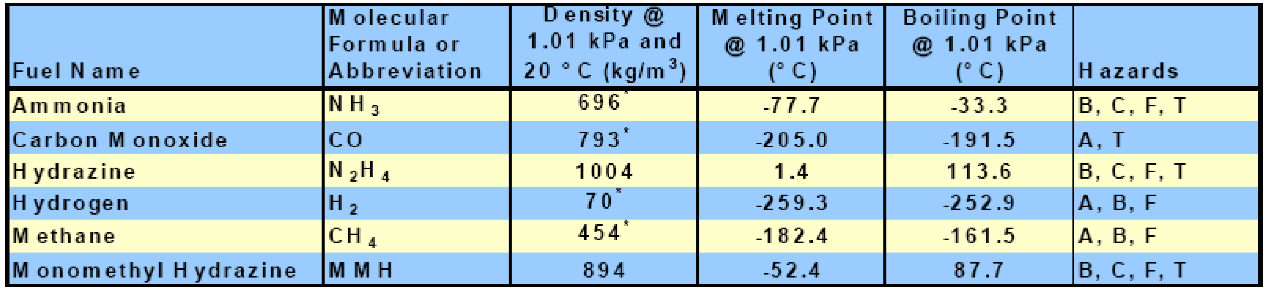
- Other engine types
  - Hybrid (solid fuel, liquid oxidizer)
  - Solar Thermal Rockets
  - Nuclear
  - – ...

# Chemical Propulsion – Liquid Bipropellant

UPDATE



| Oxidizer Name | Molecular Formula or Abbreviation | Density @ 1.01 kPa and 20 °C (kg/m$^3$) | Melting Point @ 1.01 kPa (°C) | Boiling Point @ 1.01 kPa (°C) | Hazards |
|---|---|---|---|---|---|
| Chlorine Pentafluoride | $ClF_5$ | 1779 | -103.0 | -13.1 | A, B, C, T |
| Fluorine | $F_2$ | 1505* | -219.7 | -188.1 | A, B, C, T |
| Hydrogen Peroxide | $H_2O_2$ | 1440 | -0.4 | 150.2 | B, C, D |
| Nitrogen Tetroxide | NTO | 1450 | -9.3 | 21.2 | A, B, C, T |
| Oxygen | $O_2$ | 1149* | -218.8 | -183.0 | A, B |
| Oxygen Difluoride | $OF_2$ | 1521* | -223.8 | -145.0 | A, B, C, T |

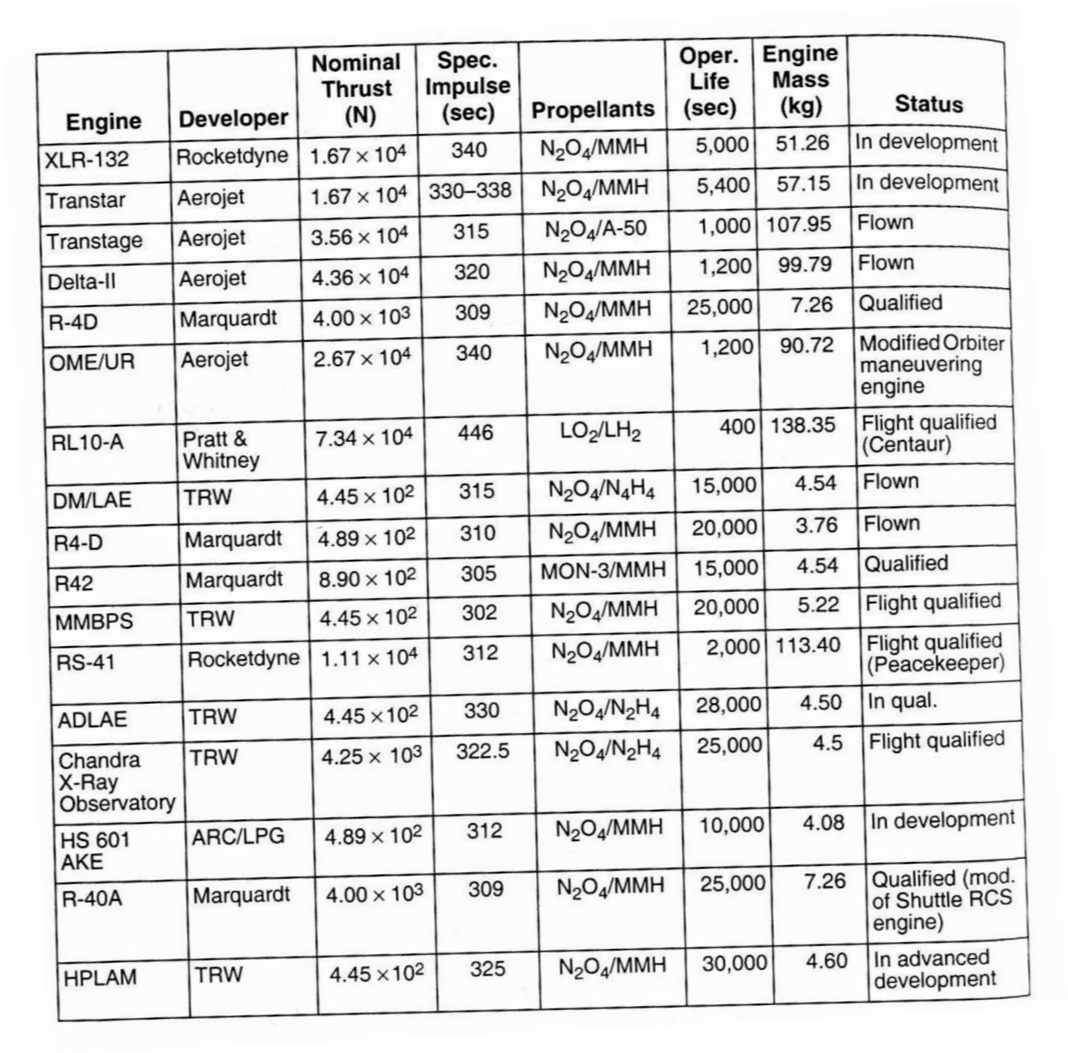


| Fuel Name | Molecular Formula or Abbreviation | Density @ 1.01 kPa and 20 °C (kg/m$^3$) | Melting Point @ 1.01 kPa (°C) | Boiling Point @ 1.01 kPa (°C) | Hazards |
|---|---|---|---|---|---|
| Ammonia | $NH_3$ | 696* | -77.7 | -33.3 | B, C, F, T |
| Carbon Monoxide | CO | 793* | -205.0 | -191.5 | A, T |
| Hydrazine | $N_2H_4$ | 1004 | 1.4 | 113.6 | B, C, F, T |
| Hydrogen | $H_2$ | 70* | -259.3 | -252.9 | A, B, F |
| Methane | $CH_4$ | 454* | -182.4 | -161.5 | A, B, F |
| Monomethyl Hydrazine | MMH | 894 | -52.4 | 87.7 | B, C, F, T |

A= asphyxiative; B = burns skin; C = corrosive; D = decomposes; F = flammable; T = toxic

# Chemical Propulsion – Liquid Bipropellant

**UPDATE**



| Engine | Developer | Nominal Thrust (N) | Spec. Impulse (sec) | Propellants | Oper. Life (sec) | Engine Mass (kg) | Status |
|---|---|---|---|---|---|---|---|
| XLR-132 | Rocketdyne | $1.67 \times 10^4$ | 340 | $N_2O_4$/MMH | 5,000 | 51.26 | In development |
| Transtar | Aerojet | $1.67 \times 10^4$ | 330–338 | $N_2O_4$/MMH | 5,400 | 57.15 | In development |
| Transtage | Aerojet | $3.56 \times 10^4$ | 315 | $N_2O_4$/A-50 | 1,000 | 107.95 | Flown |
| Delta-II | Aerojet | $4.36 \times 10^4$ | 320 | $N_2O_4$/MMH | 1,200 | 99.79 | Flown |
| R-4D | Marquardt | $4.00 \times 10^3$ | 309 | $N_2O_4$/MMH | 25,000 | 7.26 | Qualified |
| OME/UR | Aerojet | $2.67 \times 10^4$ | 340 | $N_2O_4$/MMH | 1,200 | 90.72 | Modified Orbiter maneuvering engine |
| RL10-A | Pratt & Whitney | $7.34 \times 10^4$ | 446 | $LO_2/LH_2$ | 400 | 138.35 | Flight qualified (Centaur) |
| DM/LAE | TRW | $4.45 \times 10^2$ | 315 | $N_2O_4/N_4H_4$ | 15,000 | 4.54 | Flown |
| R4-D | Marquardt | $4.89 \times 10^2$ | 310 | $N_2O_4$/MMH | 20,000 | 3.76 | Flown |
| R42 | Marquardt | $8.90 \times 10^2$ | 305 | MON-3/MMH | 15,000 | 4.54 | Qualified |
| MMBPS | TRW | $4.45 \times 10^2$ | 302 | $N_2O_4$/MMH | 20,000 | 5.22 | Flight qualified |
| RS-41 | Rocketdyne | $1.11 \times 10^4$ | 312 | $N_2O_4$/MMH | 2,000 | 113.40 | Flight qualified (Peacekeeper) |
| ADLAE | TRW | $4.45 \times 10^2$ | 330 | $N_2O_4/N_2H_4$ | 28,000 | 4.50 | In qual. |
| Chandra X-Ray Observatory | TRW | $4.25 \times 10^3$ | 322.5 | $N_2O_4/N_2H_4$ | 25,000 | 4.5 | Flight qualified |
| HS 601 AKE | ARC/LPG | $4.89 \times 10^2$ | 312 | $N_2O_4$/MMH | 10,000 | 4.08 | In development |
| R-40A | Marquardt | $4.00 \times 10^3$ | 309 | $N_2O_4$/MMH | 25,000 | 7.26 | Qualified (mod. of Shuttle RCS engine) |
| HPLAM | TRW | $4.45 \times 10^2$ | 325 | $N_2O_4$/MMH | 30,000 | 4.60 | In advanced development |

# Chemical Propulsion – Liquid Bipropellant

Example systems:

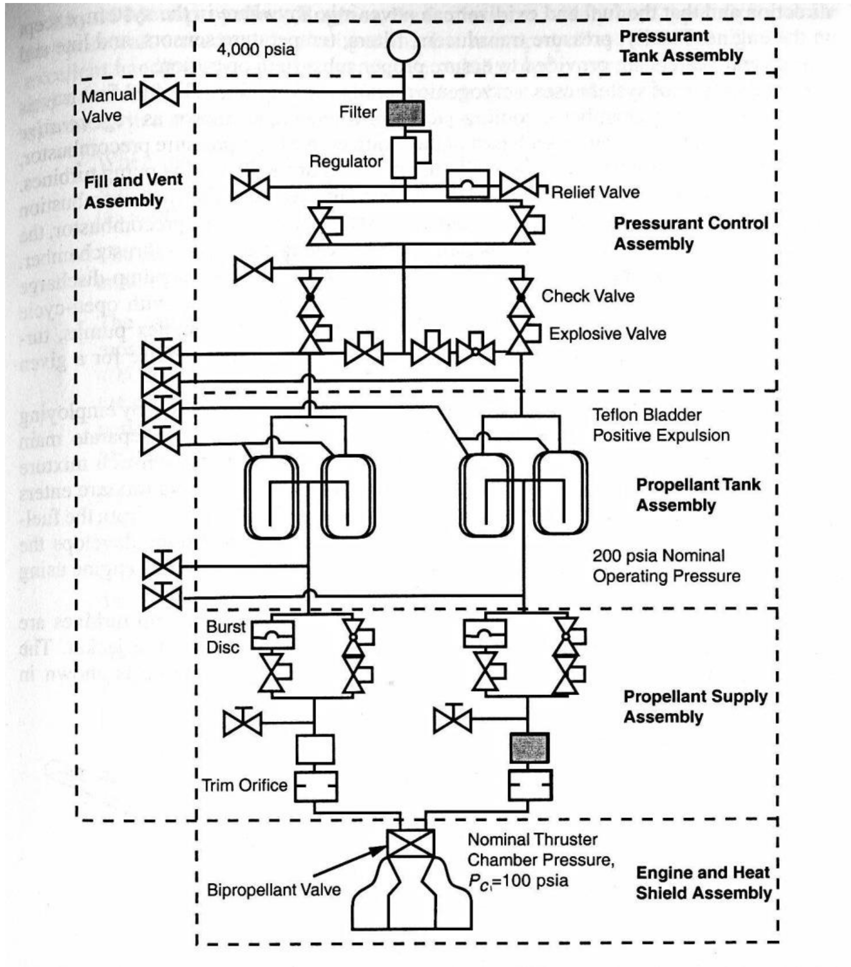
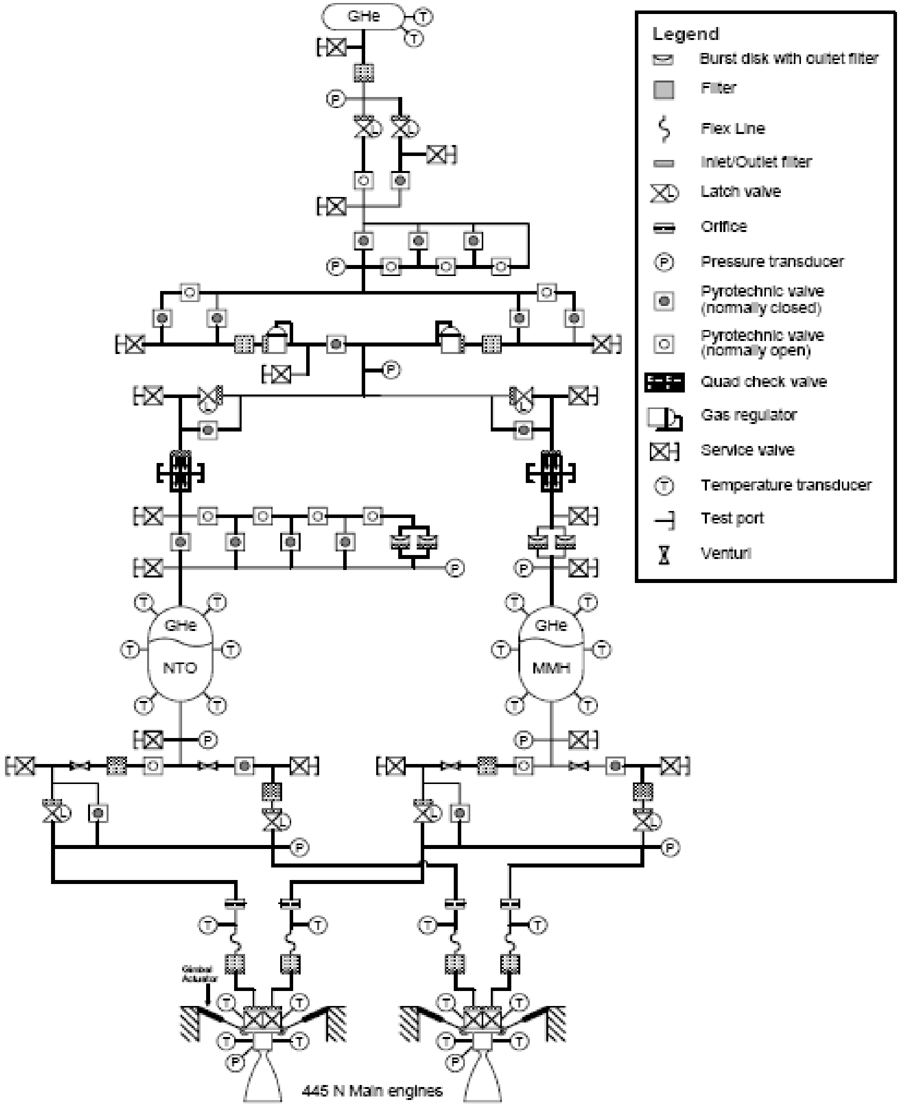


**Fig. 17-3. Pressure-Fed Propulsion System Using Earth-Storable Bipropellant ($N_2O_4$/MMH).** Propulsion system designers trade-off reliability and safety with complexity and mass.



**Cass**

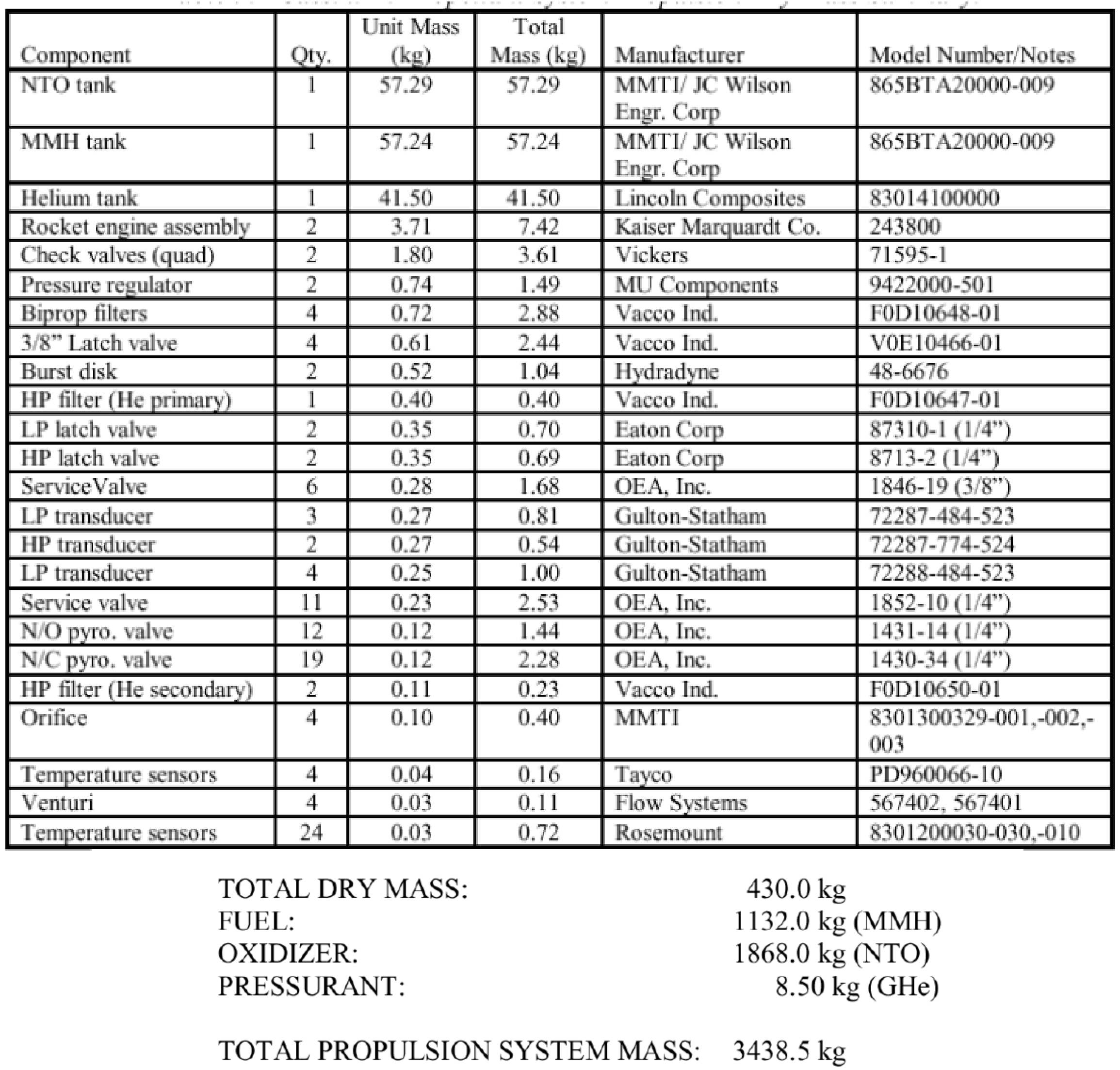
# Chemical Propulsion – Liquid Bipropellant

**UPDATE**

## Example systems:

Note: The Cassini system was a complete module dropped into the spacecraft. This mass includes primary and secondary structure not normally book kept as propulsion.

Cassini Propulsion System Components



| Component | Qty. | Unit Mass (kg) | Total Mass (kg) | Manufacturer | Model Number/Notes |
|---|---|---|---|---|---|
| NTO tank | 1 | 57.29 | 57.29 | MMTI/ JC Wilson Engr. Corp | 865BTA20000-009 |
| MMH tank | 1 | 57.24 | 57.24 | MMTI/ JC Wilson Engr. Corp | 865BTA20000-009 |
| Helium tank | 1 | 41.50 | 41.50 | Lincoln Composites | 83014100000 |
| Rocket engine assembly | 2 | 3.71 | 7.42 | Kaiser Marquardt Co. | 243800 |
| Check valves (quad) | 2 | 1.80 | 3.61 | Vickers | 71595-1 |
| Pressure regulator | 2 | 0.74 | 1.49 | MU Components | 9422000-501 |
| Biprop filters | 4 | 0.72 | 2.88 | Vacco Ind. | F0D10648-01 |
| 3/8" Latch valve | 4 | 0.61 | 2.44 | Vacco Ind. | V0E10466-01 |
| Burst disk | 2 | 0.52 | 1.04 | Hydradyne | 48-6676 |
| HP filter (He primary) | 1 | 0.40 | 0.40 | Vacco Ind. | F0D10647-01 |
| LP latch valve | 2 | 0.35 | 0.70 | Eaton Corp | 87310-1 (1/4") |
| HP latch valve | 2 | 0.35 | 0.69 | Eaton Corp | 8713-2 (1/4") |
| ServiceValve | 6 | 0.28 | 1.68 | OEA, Inc. | 1846-19 (3/8") |
| LP transducer | 3 | 0.27 | 0.81 | Gulton-Statham | 72287-484-523 |
| HP transducer | 2 | 0.27 | 0.54 | Gulton-Statham | 72287-774-524 |
| LP transducer | 4 | 0.25 | 1.00 | Gulton-Statham | 72288-484-523 |
| Service valve | 11 | 0.23 | 2.53 | OEA, Inc. | 1852-10 (1/4") |
| N/O pyro. valve | 12 | 0.12 | 1.44 | OEA, Inc. | 1431-14 (1/4") |
| N/C pyro. valve | 19 | 0.12 | 2.28 | OEA, Inc. | 1430-34 (1/4") |
| HP filter (He secondary) | 2 | 0.11 | 0.23 | Vacco Ind. | F0D10650-01 |
| Orifice | 4 | 0.10 | 0.40 | MMTI | 8301300329-001,-002,-003 |
| Temperature sensors | 4 | 0.04 | 0.16 | Tayco | PD960066-10 |
| Venturi | 4 | 0.03 | 0.11 | Flow Systems | 567402, 567401 |
| Temperature sensors | 24 | 0.03 | 0.72 | Rosemount | 8301200030-030,-010 |

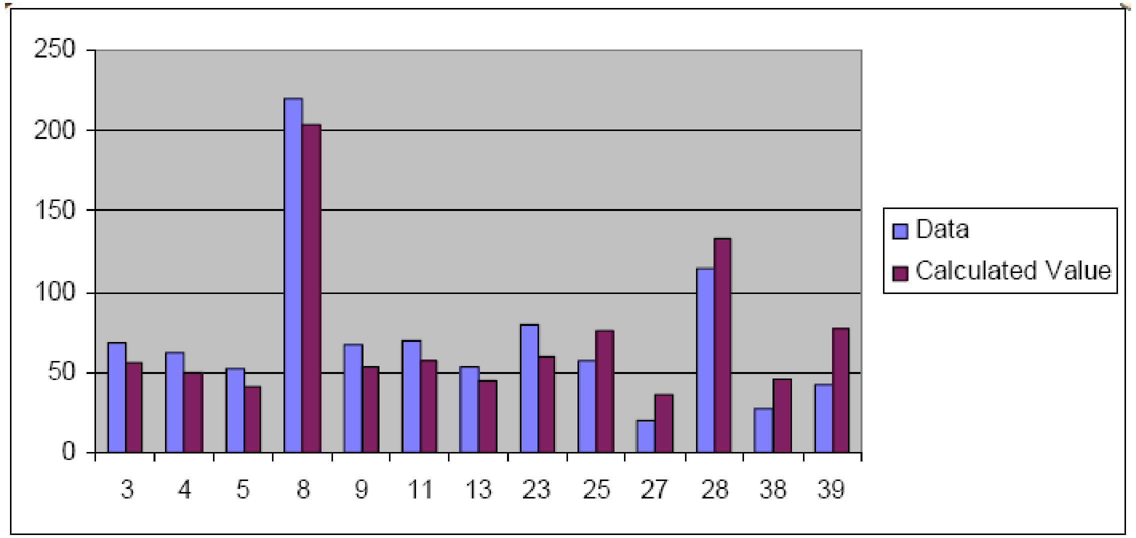
| | |
|---|---|
| TOTAL DRY MASS: | 430.0 kg |
| FUEL: | 1132.0 kg (MMH) |
| OXIDIZER: | 1868.0 kg (NTO) |
| PRESSURANT: | 8.50 kg (GHe) |
| TOTAL PROPULSION SYSTEM MASS: | 3438.5 kg |

Space Center

# Chemical Propulsion – Liquid Bipropellant

**UPDATE**

Typical propulsion system dry mass:



- M(kg) = 26.4 + .077 (Propellant Mass)
- ±25 percent

# Propulsion Hardware (in addition to the thrusters)

- Tanks

- Feed Systems

  - Accumulators: Attenuates feed system oscillations or used to store limited quantities of fluid

  - Burst Disks: Provides a positive, hermetic, zero-leakage seal of a fluid from other fluids or from o initiate flow at a predetermined pressure

  - Filters: Removes impurities in the fluid thereby protecting downstream components from contar
  - Orifices: A passive device that limits transient or steady-state flow of propellant due to a reduce age through a small hole

  - Pressure transducers: provide measurements of system pressures

  - Regulators: mechanically passive devices that maintains a constant pressure at the regula stream pr essure

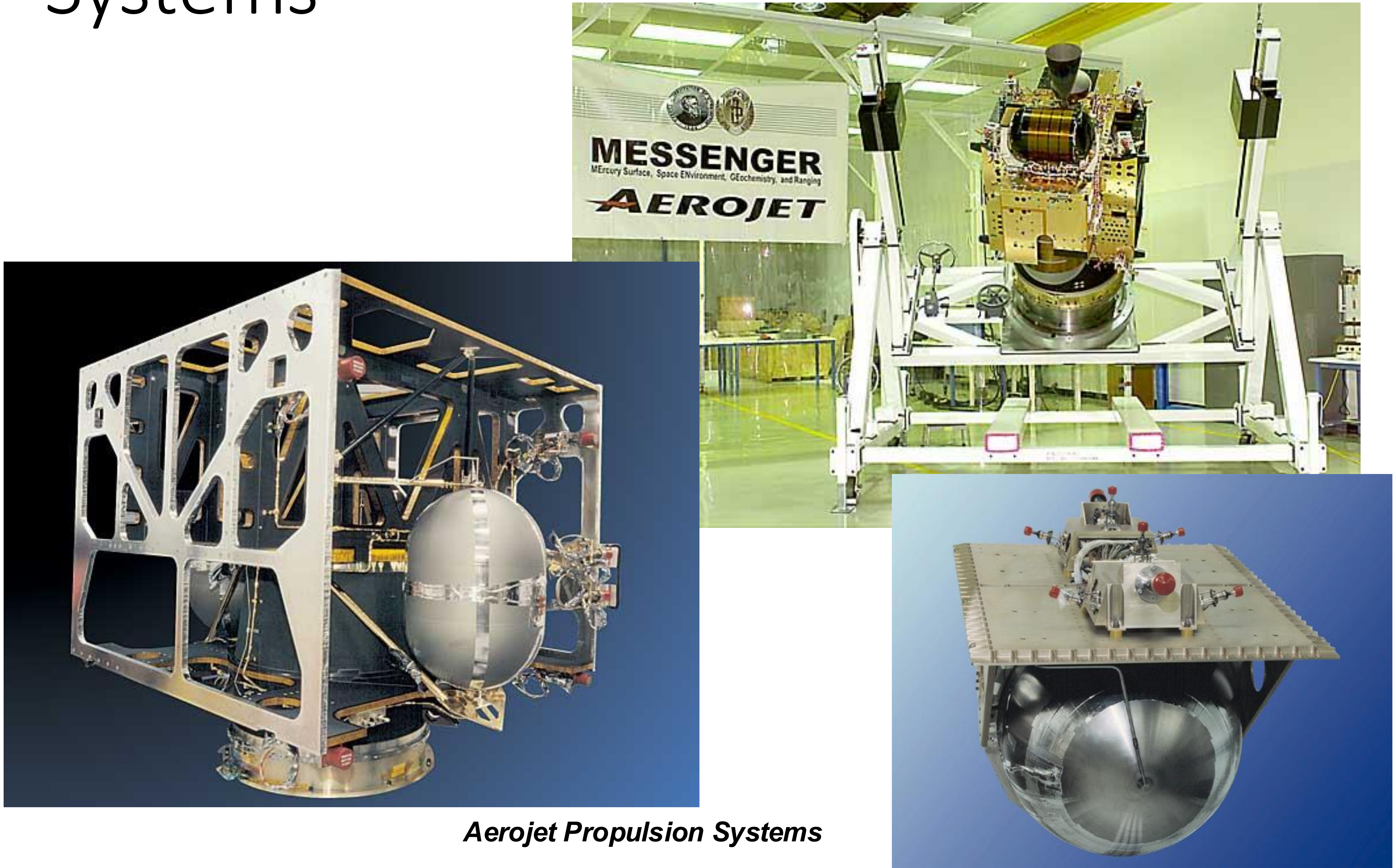
# Propulsion Hardware (in addition to the thrusters)

- Feed Systems (continued)
  - Various Types of Valves

| Type of Valve | Purpose | Method of Actuation |
|---|---|---|
| **Check** | Allow flow of a fluid in one direction only. | Spring holds poppet closed against back flow while allowing flow in forward direction. |
| **Latch** | Positive, controlled isolation of components. | Two solenoids, one for opening, and one for closing, can latch a valve into open or closed position. |
| **Pyrotechnic** | One time only actuation of a zero leakage valve. | Current initiates explosive charge actuating a ram that either knocks out a parent-metal plug or interposes a plug. |
| **Relief** | Protection from overpressure. | Spring-loaded poppet opens and fluid is expelled until the pressure falls below reseat pressure. |
| **Service** | Fluid service, test, loading, and/or unloading | Rotary actuator axially translates poppet to open or close valve |
| **Solenoid** | Provide fluid flow to downstream components on demand | Current energizes coil that generates a magnetic force that overcomes pre-loaded spring force and pressure force to open the valve |

# Chemical Propulsion – Systems

**UPDATE**



*Aerojet Propulsion Systems*

# Electrical Propulsion

# Electric Propulsion – Basic Principle

$$F_{th} \approx v_e \dot{m}$$

- Basic principle: acceleration of gaseous molecules at very high velocities (increased Ve but reduces mdot)

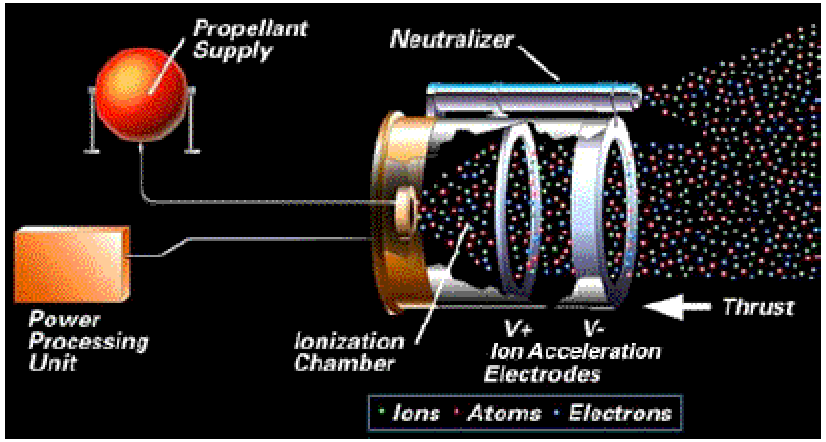
$$F_{th} = \frac{2.P_{Beam}}{g_0 Isp} \qquad \dot{m} = \frac{F_{th}}{g_0 Isp}$$

- Acceleration of the particles is provided by electric or magnetic field. Thrust created is proportional to power in the field:

$$P_{Beam} = \eta_t . P_{input} \qquad \eta_t : \text{thruster efficiency}$$

$$\eta_t = \frac{\textit{Jet Power}}{\textit{Input Power}} = \frac{\eta_u \gamma^2}{1 + \frac{\varepsilon + V_{NC}}{V_B}}$$

- Ion thrust
  - $\eta_t$ : *Ion Thruster Efficiency*
  - $\eta_u$ : *Propellant Utilization*
  - $\gamma$ : *Double Ion Production Factor*
  - $\varepsilon$ : *Ion Production Cost* $\left[{}^{eV}\!/_{\text{beam ion}}\right]$
  - $V_{NC}$ : *Neutral Coupling Voltage*
  - $V_B$ : *Beam Voltage* $(a.k.a.\ \Phi_0)$

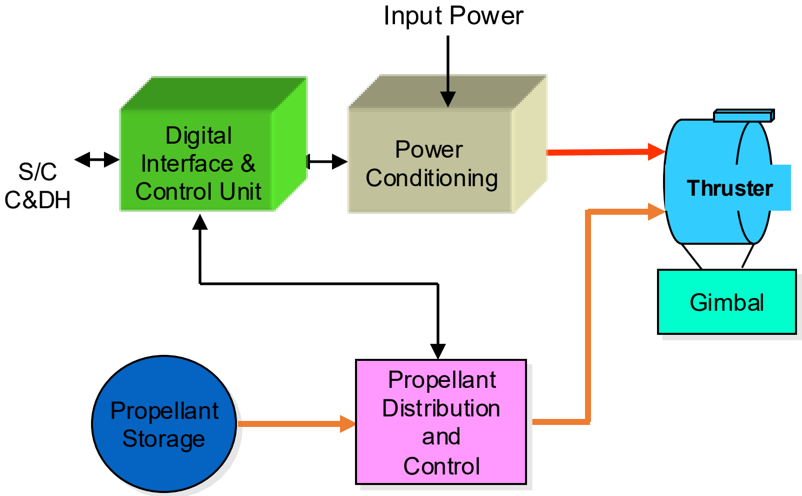


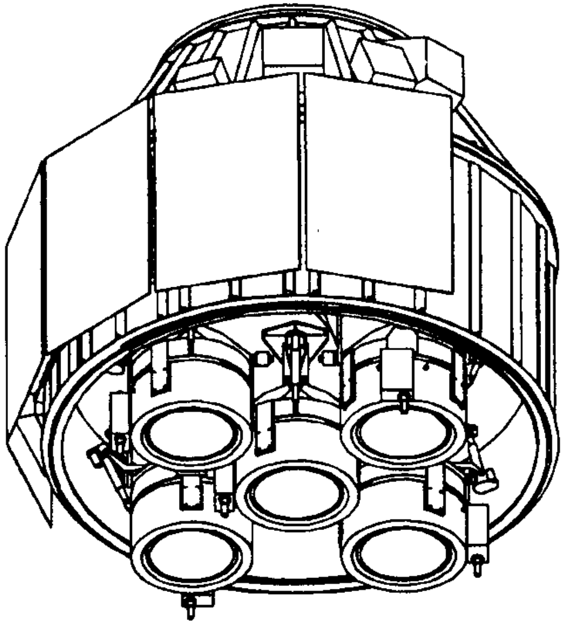
# Electric Propulsion – Overall System

- EP systems typically have greater dry masses compared to chemical thrusters but much lower propellant masses (due to the higher Isp)

- EP systems are more complex, they include:
  - Power Processing Unit: to transform low voltage to the required thruster high voltage
  - Digital control unit: to control the power units and feed system

- Propellant throughput varies per engine and depending on the DV requirements, several engines might be needed





# Electric Propulsion – Types of Thrusters

- Electrothermal
  - Electrical heating of propellant
  - Thermodynamic expansion through nozzle
  - Resistojets, arcjets

- Electrostatic
  - Charged particles are accelerated by electrostatic fields
  - Sources of ions:
    - Mercury, rubidium, xenon (high atomic weight)
    - Release of free electrons through thermionic effect
  - Ion Engines, Hall thrusters, Field Emission Electric thrusters, Pulse inductive thrusters

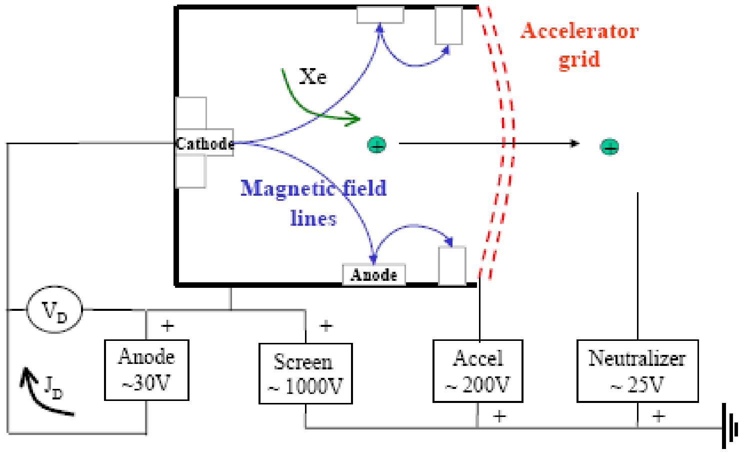
- Electromagnetic
  - Plasma is accelerated by time-dependent or crossed electric and magnetic fields
  - Magnetoplasmadynamic thrusters…

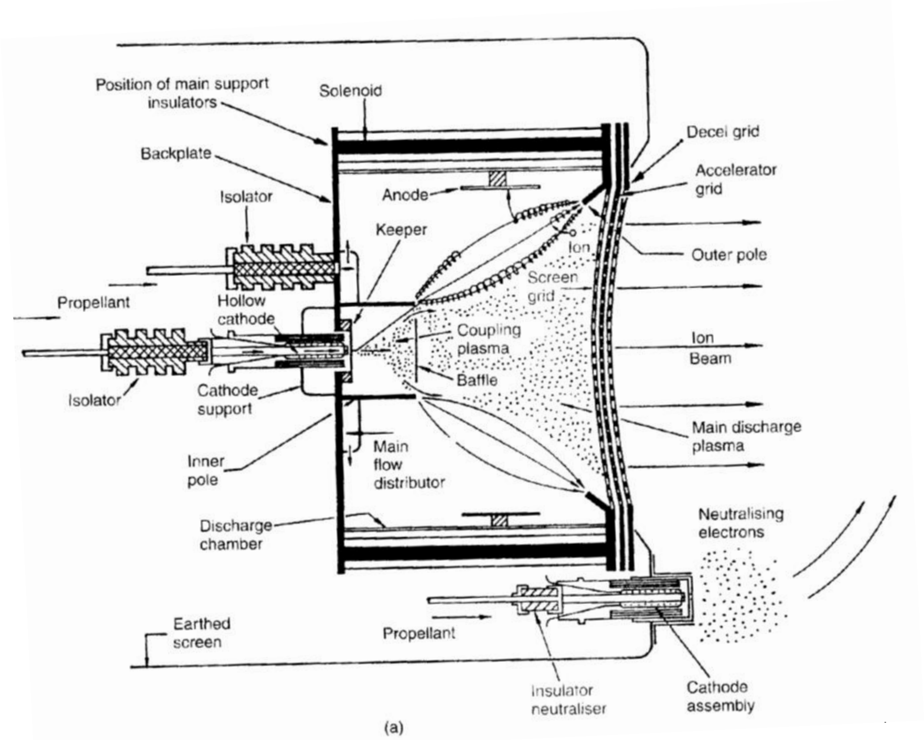
# Electric Propulsion – Ion Thrusters

- The gas xenon (which is like helium or neon, but heavier) flows into the ion engine, where it is given an electrical charge. As soon as the xenon atoms become xenon ions, they can be pushed out by an electrical voltage. A pair of grids in the ion engine, electrified to several 1000 volts, accelerates the ions to very high speed and shoots them out of the engine.

- The xenon ions travel at about 35 kilometers/second (77,000 miles/hour). This is about 10 times faster than the exhaust from conventional rocket engines, so the xenon gives about 10 times as much of a push to the spacecraft as chemical propellants do. That means that it takes only one tenth as much propellant for an ion engine to work as it does for a chemical propulsion system.

- Now the ion engines use only a very small amount of xenon at a time. That means that the thrust is very very low. If you rest a piece of paper on your hand, the paper pushes on your hand about as hard as the ion engine pushes on the spacecraft! It may take 4 days or more just to use up 1 kilogram of xenon. Unlike chemical engines, which can be operated for minutes, or in extreme cases, for an hour or so, ion engines can be operated for years. The effect of the gentle thrust slowly builds up, eventually attaining speeds far beyond the reach of conventional propellants.

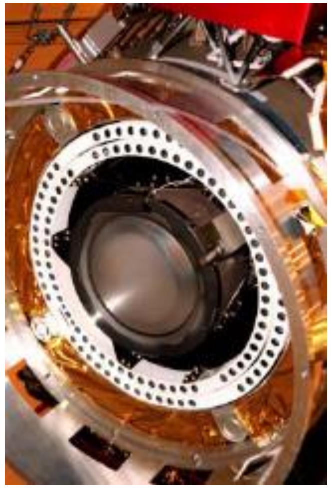


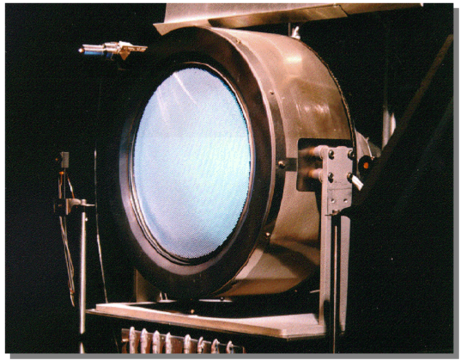


# Electric Propulsion – NSTAR Engine

- Deep Space 1, using less than 74 kg of xenon, accelerated by about 4.3 kilometers/second. This is greater than any spacecraft has ever been able to change its speed. It thrusted for 678 days, far far longer than any propulsion system had ever been operated.

- DS-1 NSTAR Engine Input Power Range
  - 0.52 to 2.30 kW
- Thrust
  - 22 to 92 mN
- Specific Impulse
  - 2200 to 3370s
- Flow Rates
  - Main flow: 0.59 to 2.20 mg/s
  - Cathode flow: 0.21 to 0.30 mg/s
  - Neutralizer Flow: 0.21 to 0.30 mg/s
- Physical Size
  - 28.5 cm Dia. Ion Beam
  - 40 cm Outer Diameter x 40 cm Long
  - 7 kg Mass
- Design Life
  - 83 kg of Xeon (8000 hrs at full power)

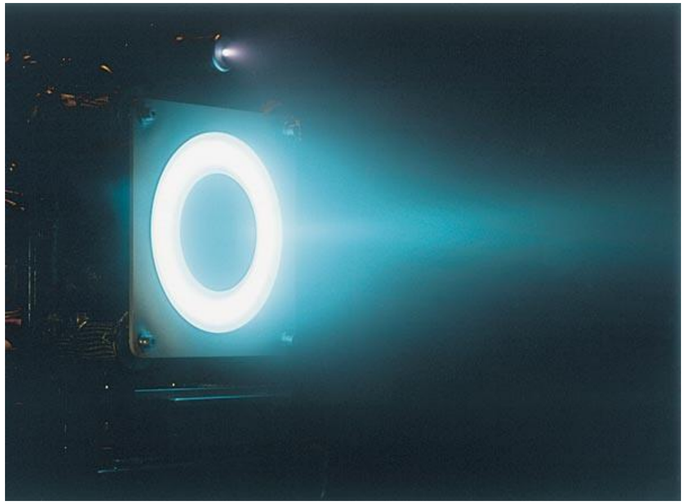




# Electric Propulsion – Hall Effect Thrusters

- A Hall effect thruster (HET) or Hall thruster is a type of ion thruster in which the propellant is accelerated by an electric field in a plasma discharge with a radial magnetic field
    - Use the Hall effect to trap electrons (magnetic confinement) and then use the electrons to ionize propellant, efficiently accelerate the ions to produce thrust, and neutralize the ions in the plume
    - Plasma is neutral, no charge accumulation
    - Widely used for station keeping in low altitude satellites by former USSR

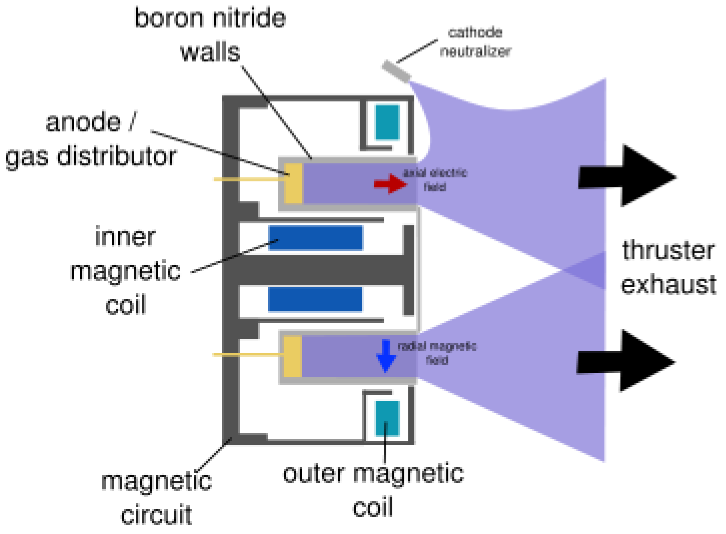
**SNECMA PPS 1350 (W)**



**Aerojet 4.5 kW Hall Thruster**

**Fakel ISTI SPT-100**

# Electric Propulsion – Hall Effect Thrusters

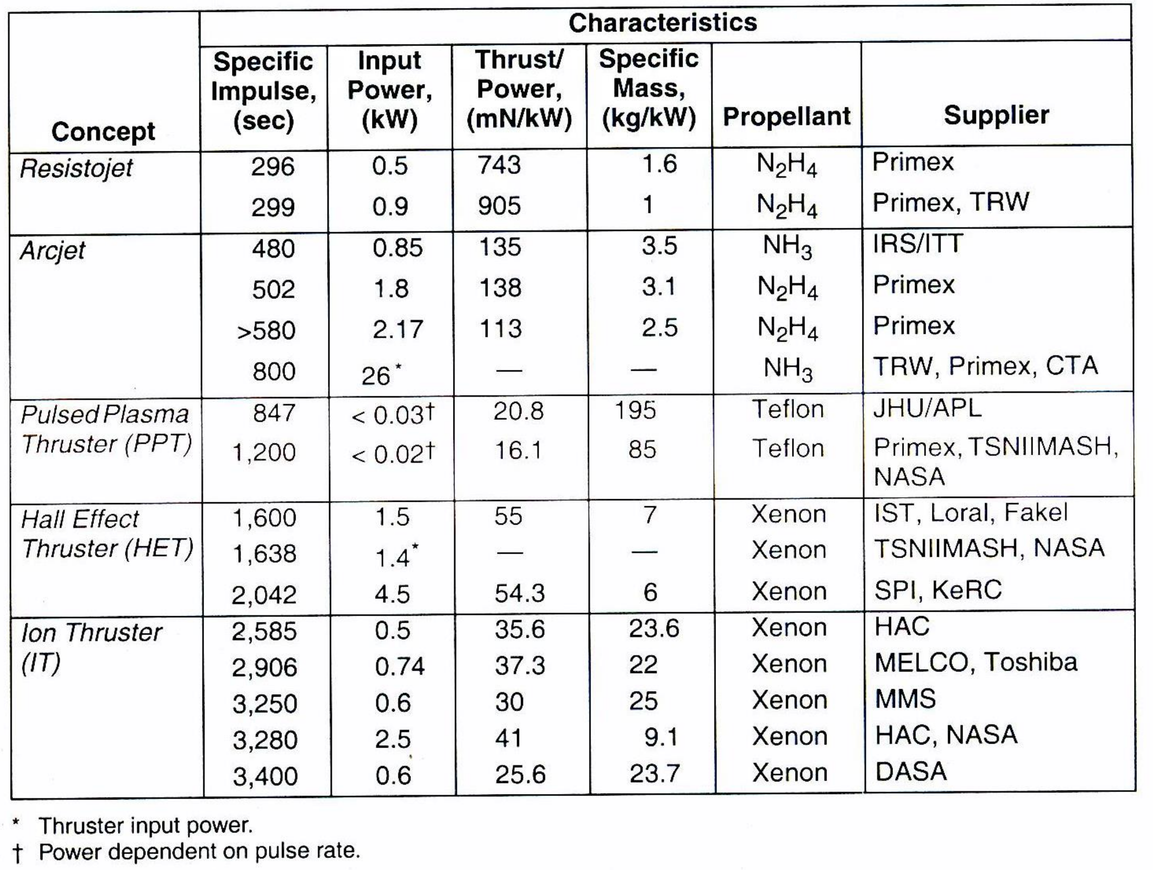


The Hall thruster discharge is a DC plasma discharge. An electric potential on the order of 300 volts is applied between the anode and cathode. Xenon gas, which is the propellant, is fed through the anode, which has numerous small holes in it to act as a gas distributor. Xenon propellant is used because of its high molecular weight and low ionization potential. As the neutral xenon atoms diffuse into the channel of the thruster, they are ionized by collisions with high energy electrons (10–20 eV or 100,000 to 250,000 °C). The xenon ions typically have a charge of +1 though a small fraction (~10%) are +2. The xenon ions are then accelerated by the electric field between the anode and the cathode. The electric field accelerates the ions to around 15,000 m/s (or a specific impulse of 1,500 seconds (15 kN·s/kg)).

The magnetic field in the thruster traps electrons, creating a ring-shaped electron cloud at the exit of the anode channel. The ions are accelerated toward this cloud and out of the thruster. Upon exiting, the ions pull an equal number of electrons with them, creating a plume with no net charge. In a hall thruster, a magnetic field is used to ensure that the discharge power goes into accelerating the xenon propellant and not the electrons, thus the thruster is efficient. The magnetic field is strong enough to substantially deflect the low-mass electrons, but not the high-mass ions. The majority of electrons are thus stuck orbiting in the region of high radial magnetic field near the thruster exit plane, while the ions are accelerated and produce thrust. The electrons are trapped in E×B (axial electric field and radial magnetic field) and rotate azimuthally. This azimuthal rotation of the electrons is a Hall current and it is from this that the Hall thruster gets its name. Collisions and instabilities allow some of the electrons to be freed from the magnetic field and they move towards the anode. About 30% of the discharge current is electron current and doesn't produce thrust, which limits the efficiency of the thruster; only 70% of current is ions. Because the majority of electrons are trapped in the Hall current, they have a long residence time inside the thruster and are able to ionize almost all (~90%) of the xenon propellant. The ionization efficiency of the thruster is thus around 90%, while the discharge current efficiency is around 70% for a combined thruster efficiency of around 60% (= 90% × 70%). Actual thruster test show total efficiencies around 50% for Hall thrusters.

# Electric Propulsion – Performances

**UPDATE**



| Concept | Characteristics | | | | | |
|---|---|---|---|---|---|---|
| | Specific Impulse, (sec) | Input Power, (kW) | Thrust/ Power, (mN/kW) | Specific Mass, (kg/kW) | Propellant | Supplier |
| *Resistojet* | 296 | 0.5 | 743 | 1.6 | $N_2H_4$ | Primex |
| | 299 | 0.9 | 905 | 1 | $N_2H_4$ | Primex, TRW |
| *Arcjet* | 480 | 0.85 | 135 | 3.5 | $NH_3$ | IRS/ITT |
| | 502 | 1.8 | 138 | 3.1 | $N_2H_4$ | Primex |
| | >580 | 2.17 | 113 | 2.5 | $N_2H_4$ | Primex |
| | 800 | 26* | — | — | $NH_3$ | TRW, Primex, CTA |
| *Pulsed Plasma Thruster (PPT)* | 847 | < 0.03† | 20.8 | 195 | Teflon | JHU/APL |
| | 1,200 | < 0.02† | 16.1 | 85 | Teflon | Primex, TSNIIMASH, NASA |
| *Hall Effect Thruster (HET)* | 1,600 | 1.5 | 55 | 7 | Xenon | IST, Loral, Fakel |
| | 1,638 | 1.4* | — | — | Xenon | TSNIIMASH, NASA |
| | 2,042 | 4.5 | 54.3 | 6 | Xenon | SPI, KeRC |
| *Ion Thruster (IT)* | 2,585 | 0.5 | 35.6 | 23.6 | Xenon | HAC |
| | 2,906 | 0.74 | 37.3 | 22 | Xenon | MELCO, Toshiba |
| | 3,250 | 0.6 | 30 | 25 | Xenon | MMS |
| | 3,280 | 2.5 | 41 | 9.1 | Xenon | HAC, NASA |
| | 3,400 | 0.6 | 25.6 | 23.7 | Xenon | DASA |

* Thruster input power.

† Power dependent on pulse rate.

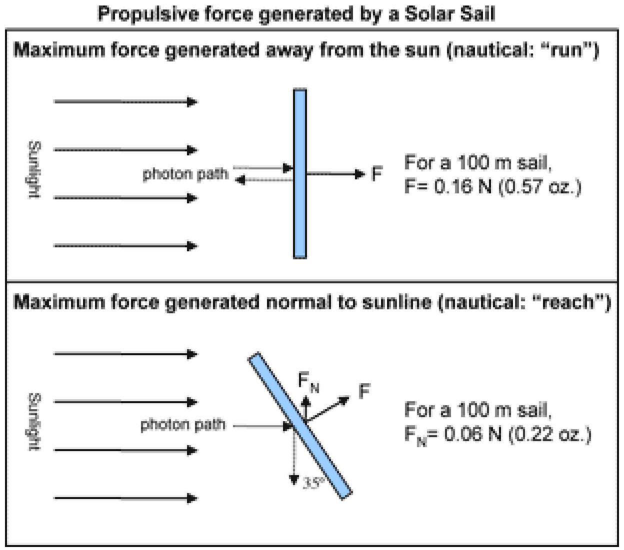
# Other types

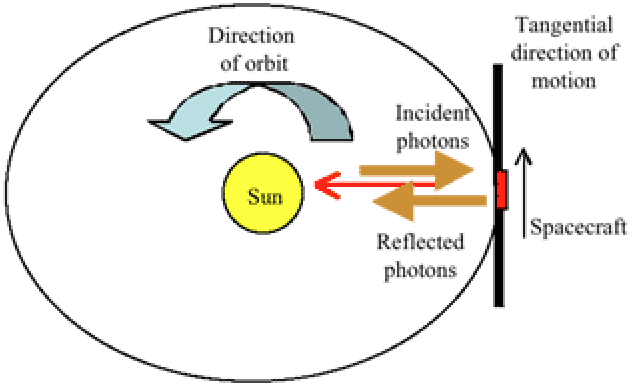
Solar sails

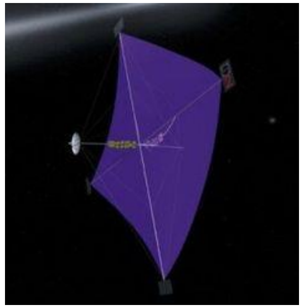
Nuclear propulsion

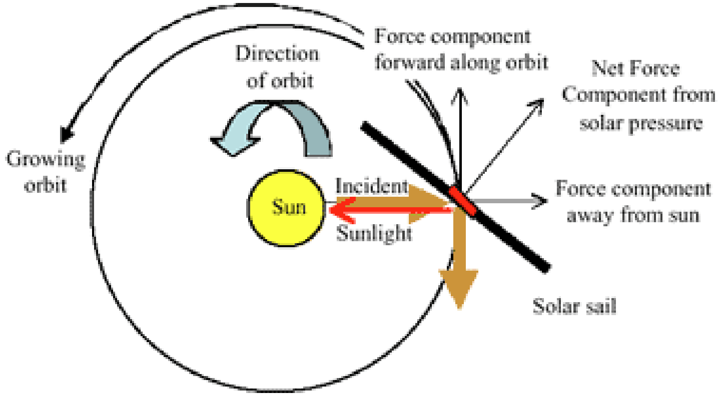
# Solar Sails – How they work

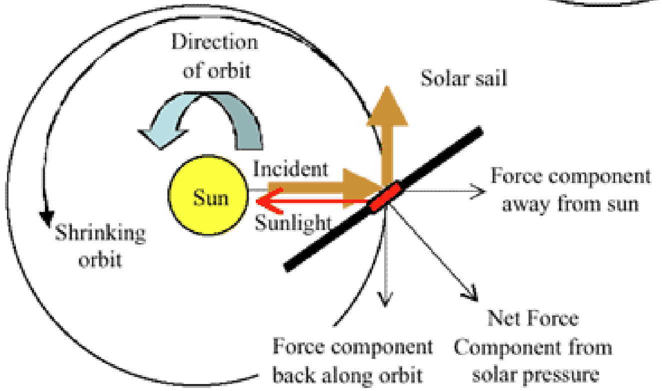
- Form of spacecraft propulsion using large membrane mirrors.
- The radiation pressure on the mirror provides a minuscule amount of thrust by reflecting photons.
- Tilting the reflective sail at an angle from the Sun produces thrust at an angle that bisects the angle between the Sun and the spacecraft.
- Radiation pressure is small and decreases by the square of the distance from the sun, but unlike rockets, solar sails require no fuel. Although the thrust is small, it continues





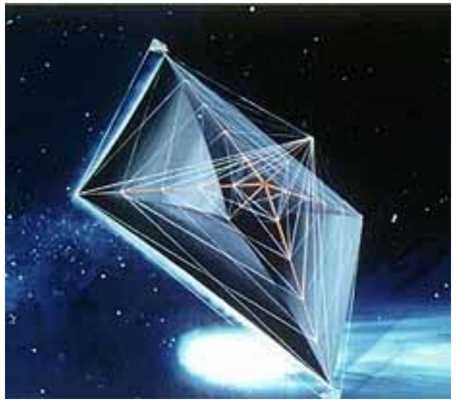


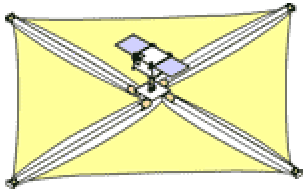




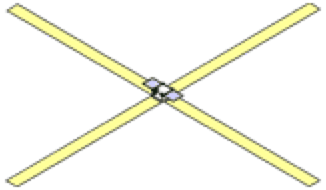
# Solar Sails – Types of Sails

- There are three major designs used for light sail construction:
  - Three axis stabilized sails which require booms to support the sail material.
  - Heliogyro sails, which are bladed like a helicopter and must be rotated for stability
  - Disc sails which must be controlled by moving the center of mass relative to the center of pressure.

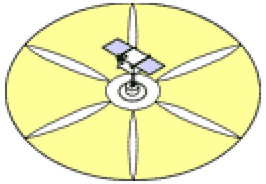




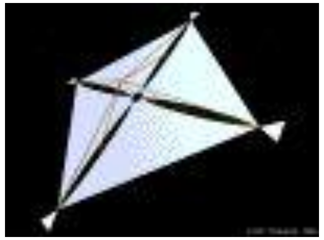
Square Sail (not to scale)

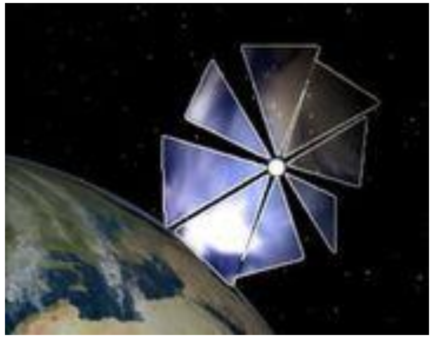


Heliogyro (not to scale)



Spinning Disk Sail
(not to scale)





- In most designs, steering is done with auxiliary vanes, acting as small solar sails to change the attitude of the large solar sail. The vanes would be adjusted by electric motors.

# Solar Sails – Challenges

- A practical sail places great demands on our physical construction capabilities. The sail must be **as large as possible** so that it can **collect enough light to gain a useful thrust**. At the same time it must be **as light weight as possible**.
  - This implies a very, very thin sail film with minimal mass.
  - Conventional light sail film has comprised 5 micron thick aluminized mylar or kapton with a thin film aluminum layer (approximately 100 nm thick) deposited on one side to form a mirror surface with 90% reflectivity.

- It must be durable enough to **withstand a wide range of temperature changes, charged particles, and micrometeoroid hazards.**

- Light sailing works well for inner planet missions and for activities extending out to the Mars orbit. However, the solar flux falls off as the inverse square of the distance from the sun. Thus for missions beyond the Jupiter orbit, an alternative to solar propulsion is to use directed light from a high power laser.

- One of the more important sail film figures of merit is the areal density (equation next slide). From the areal density, one can calculate acceleration due to the solar light pressure at Earth orbit (1 AU).

Star Wars Geonosian Sail

# Solar Sails – Equations

$$\sigma_t = (total\ sail\ loading) = \left(\frac{total\ mass}{sail\ area}\right) = \frac{m_t}{A} = \frac{m_p + m_{sail}}{A};\left[\frac{g}{m^2}\right]$$

$$a_c = (characteristic\ acceleration\ at\ 1AU) = \frac{9.1263\eta}{\sigma_t};\left[\frac{mm}{s^2}\right]$$

$$9.1263 \Rightarrow perfectly\ reflective\ sail$$

$$\eta = sail\ efficiency(\approx 0.85)$$

$$\sigma_s = (sail\ areal\ density) = \sigma_t - \frac{m_p}{A} = \frac{9.1263\eta}{a_c} - \frac{m_p}{A};\left[\frac{g}{m^2}\right]$$

$$m_{sail} = \sigma_s A = m_{sail\ material} + m_{sail\ structures} + m_{sail\ control\ mechs};[g]$$

$$m_p = m_{s/c} + m_{sci} + \Delta m_{dep\ mechs-stay} + \Delta m_{cannister-stay};[g]$$

$$m_{INJ} = m_{sail} + m_p + \Delta m_{dep\ mechs-jett} + \Delta m_{cannister-jett};[g]$$

# Chemical Propulsion – Nuclear Thermal

- Concept is to maximize Isp by reducing molecular weight of propellant
  - Chemical reaction energy is replaced by external energy source
  - Isp limited to about 1200 s due to material constraints
- 4GWth nuclear rocket motor tested in NERVA program in 1960s
  - Program terminated with piloted Mars missions
- Air Force Research Lab Program:
  - Tested small solar thermal rocket in 80s, currently investigating mission applications

# Conclusion and next steps

- Quizz what did we learn today?
- How you can apply what you have learned into your projects?

# For your projects

**Size the propulsion system for your satellite**

During the mission design session, you have started calculating the total ΔV needed for your mission, and the associated propellant mass. It is time to define the propulsion system that with provide that ΔV.

## Primary Propulsion

Assuming your ΔV and an additional margin of 10% to account for uncertainties, tank residuals and other:

a. Determine the thrust you need if the maximum acceleration you allow the spacecraft to see is 0.1 g (for solar arrays and other ADCS);
b. Choose a propulsion system based on the thrust you need and your system complexity, infer the Isp; define the number of engines needed for lifetime, and dimensions; define preliminary architecture (make a hardware block diagram);
c. Given the total ΔV computed in mission design and the total mass injected by the launch vehicle, calculate the amount of propellant you need to perform the transfers and the “dry” mass of your satellite; iterate if necessary;
d. Estimate mass of primary propulsion system dry mass (either with approximate formulas given or external sources);
e. Estimate power needed to heat up the system (see datasheet of particular engine);
f. If the data you have on your selected thruster allows, calculate the burn time for your maneuvers. If this burn time is higher than 20 min, then investigate possibility of making several burns instead of 1.

# References

- *Space Mission Analysis and Design*, W.J. Larson, J.R. Wertz
- *Fundamentals of Space Systems*, V.L. Pisacane, R.C. Moore
- *Spacecraft Systems Engineering*, P. Fortescue, J. Stark, G. Swinerd
- *Space System Engineering,* Caltech ME Class 2005, J. Sercel

# Learn more and dig deeper into Space Propulsion

- **ENG 510 -** **Space Propulsion** (Spring Semester) by Markus Jäger

- Recordings of the **Seminar Series** on Space Propulsion by Prof. Hiroyuki Koizumi at EPFL Space Center public webinars (2022).

- Get hands on at **EPFL Rocket Team** (ERT) → https://epflrocketteam.ch/

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