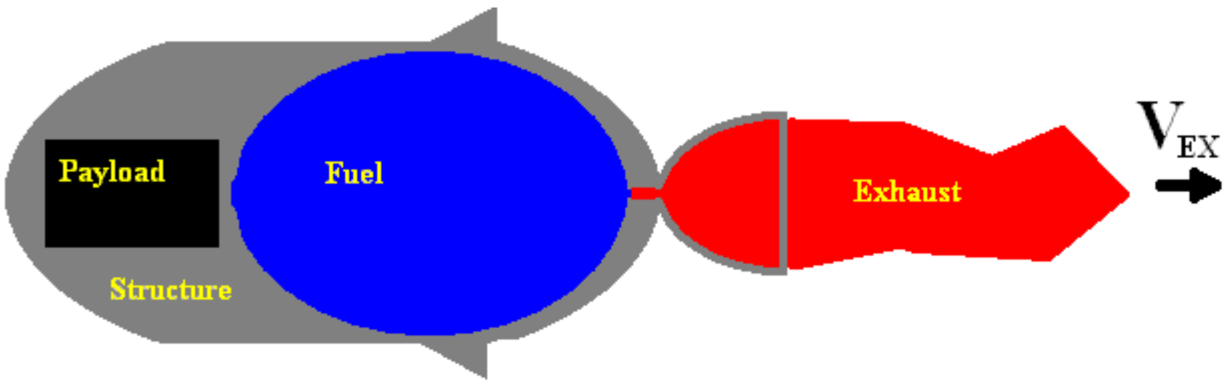
Chemical and Plasma Rocket Propulsion

Conservation of Momentum

initial momentum = final momentum

(rocket is at rest) $$0 = m_{craft} v_{craft} + m_{fuel}\left(-v_{fuel}\right)$$



$$m_{craft} v_{craft} = m_{fuel} v_{fuel}$$

$$v_{craft} = \frac{m_{fuel} v_{fuel}}{m_{craft}}$$

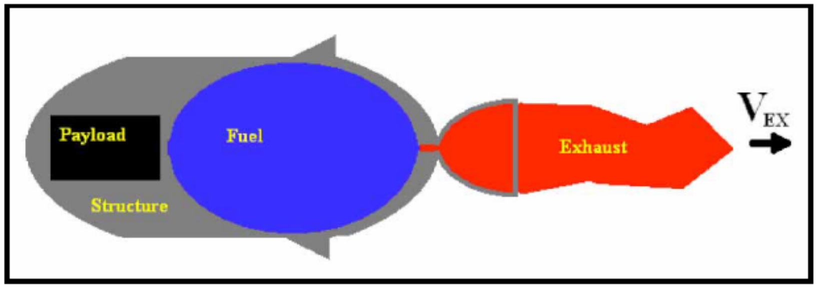
So this shows the basic tradeoff for rockets.

To go faster you must:

1. Maximize fuel speed
2. Maximize fuel mass
3. Minimize craft mass

Conservation of Momentum (Rocket Style):

Actually it's worse than it appears.



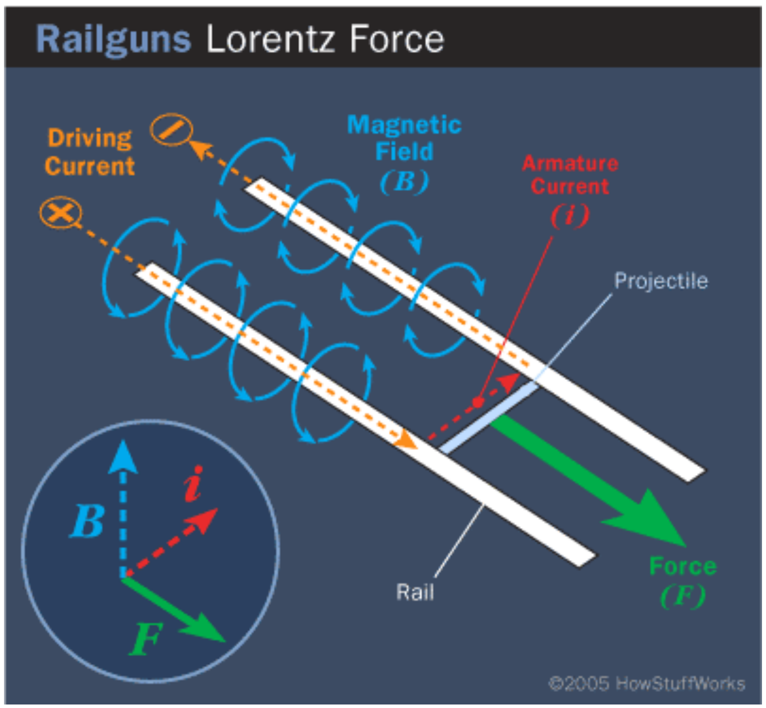
$$v_{craft} = \frac{m_{fuel} v_{fuel}}{m_{craft}}$$

Rockets don't work by throwing all of their fuel off at once. To get into orbit would kill an astronaut!

So, each part of the fuel ejected is pushing against the payload *and* the remaining fuel!!!!

An Example of a High G launcher is a Railgun

- A railgun uses electromagnetic forces to accelerate a payload
- You have already seen an example of one – ring launcher
- One example: 1.6 km barrel launches projectiles at 7.5 km/s (that's almost 2000 g's).



Rocket Equation

To correctly compute the change in speed, we need to use calculus.

Here's the answer written in two ways:

$$\Delta v = c_e \ln\left(1 + \frac{m_{fuel}}{m_{rocket}}\right) \qquad \frac{m_{fuel}}{m_{rocket}} = e^{\left(\frac{\Delta v}{c_e}\right)} - 1$$

m_{fuel} = fuel mass
m_{rocket} = payload + structure mass
c_e = exhaust speed
Δv = change in spacecraft's speed

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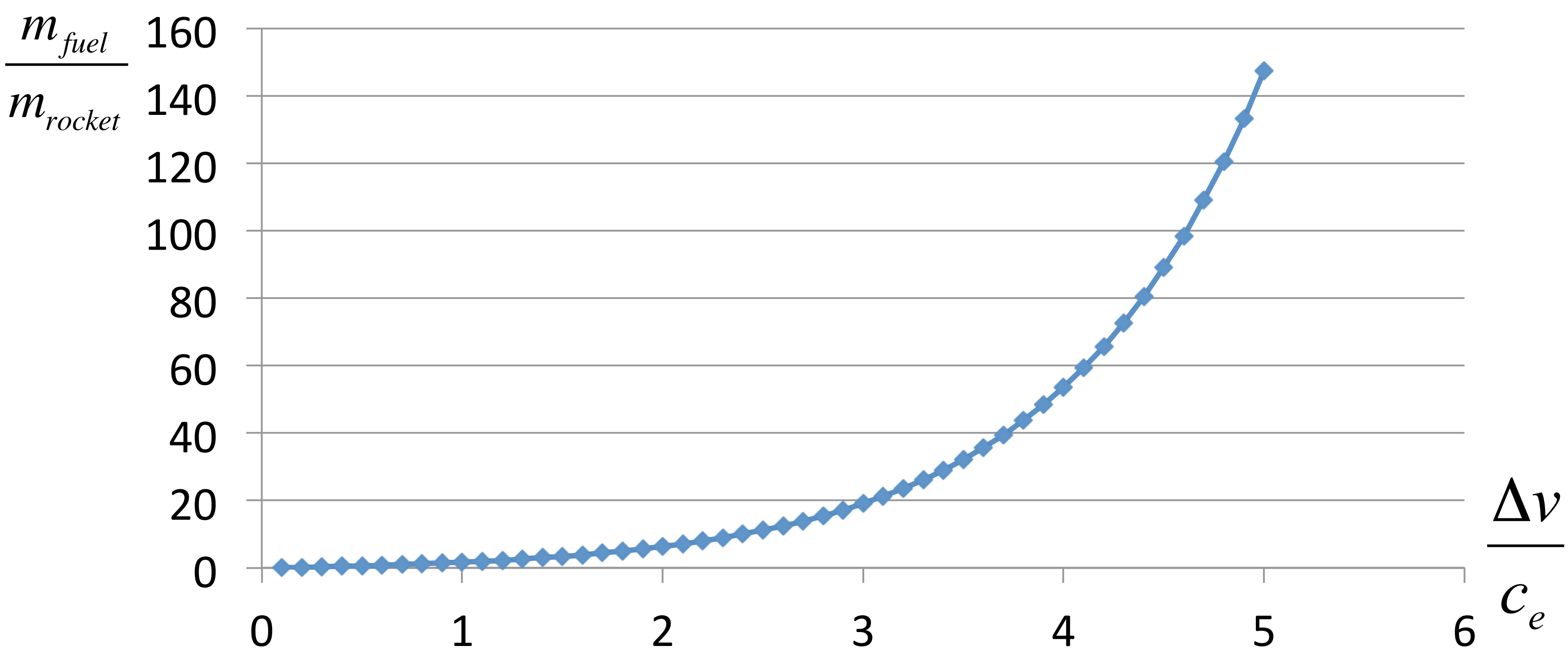

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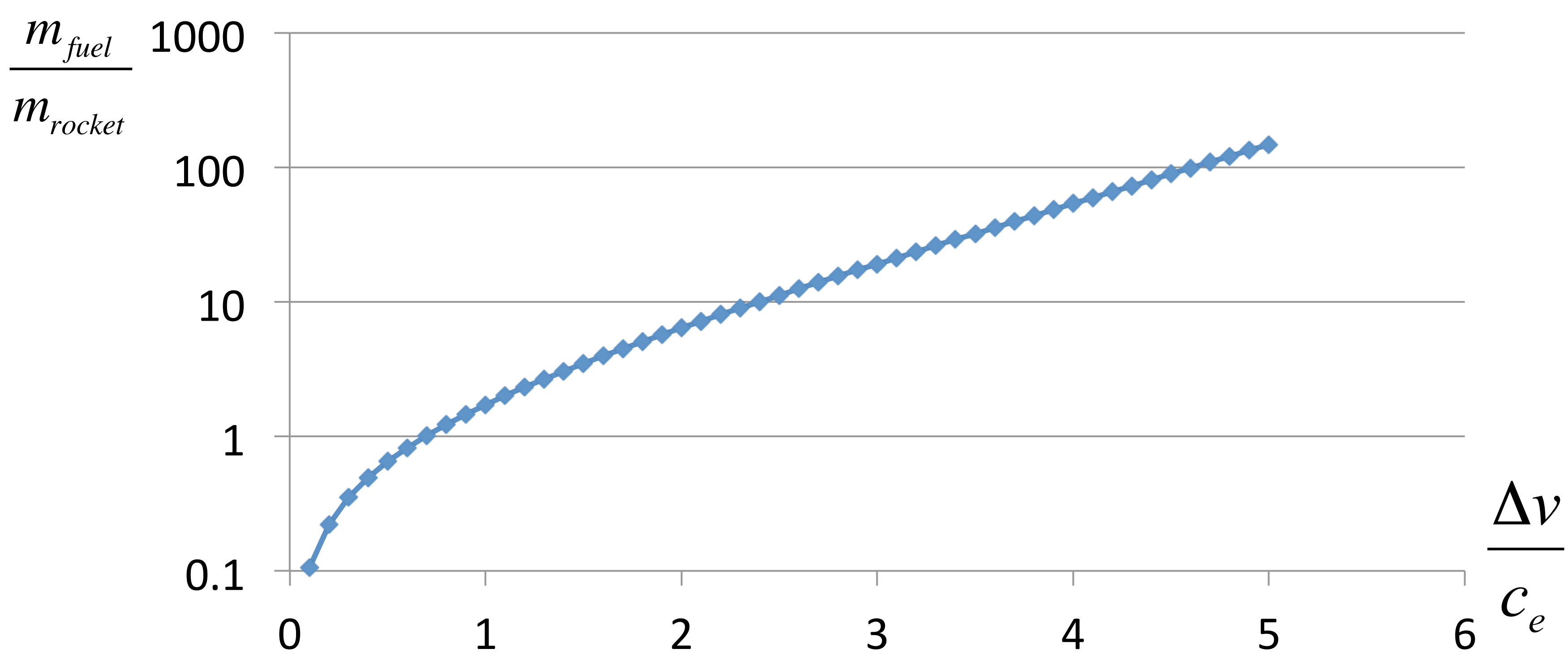

Rocket Equation: Example

How much fuel do we require to send a 1000 kg rocket to the Moon (Δv = 16 km/s) using a chemical rocket (c_e = 4 km/s)?

$$\frac{m_{fuel}}{m_{rocket}} = e^{\left(\frac{\Delta v}{c_e}\right)} - 1$$

$$m_{fuel} = m_{rocket}\left[e^{\left(\frac{\Delta v}{c_e}\right)} - 1\right]$$

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$$m_{fuel} = m_{rocket}\left[e^{\left(\frac{\Delta v}{c_e}\right)} - 1\right]$$

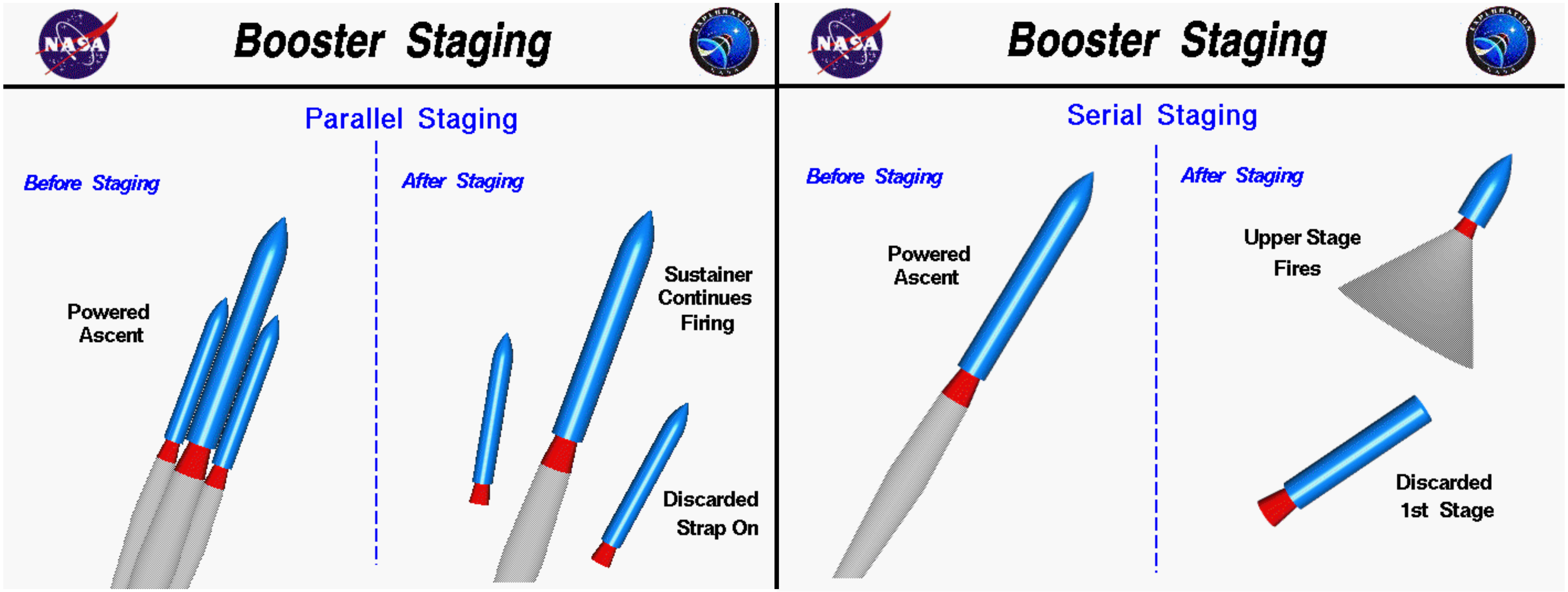
$$m_{fuel} = 1000kg\left[e^{\frac{16km/s}{4km/s}} - 1\right]$$

$$m_{fuel} = 1000kg[e^4 - 1]$$

$$m_{fuel} = 53{,}600\ kg$$

Staging

We can use *staging* as a trick to help improve the situation.



Once the fuel in the first stage is used, we can drop that stage. Now we no longer need to carry that structure into space.

EX: If 10% of your initial mass is structures and $\Delta v/c_e = 2$:

1 stage: payload fraction = 3.8%

2 stages: payload fraction = 7.5%

Types of Fuel:

There are three types of physical process that we use for fuel in space propulsion.

1. Chemical Reactions: This amounts to triggering an energy releasing chemical reaction in a controlled (or uncontrolled) way. (By *far* the most common method).
2. Plasma Reactions: These thrusters use electric fields to accelerate ions. (Not used for launches, but more common now in trajectory corrections).
3. Nuclear Reactions: Nuclear propulsion relies on fission power to generate massive amounts of energy that propel exhaust at huge speeds. (Hard to control, but can also be an *impulse* drive).

Rocket Equation

To correctly compute the change in speed, we need to use calculus.

Here's the answer written in two ways:

$$\Delta v = c_e \ln\left(1 + \frac{m_{fuel}}{m_{rocket}}\right) \qquad \frac{m_{fuel}}{m_{rocket}} = e^{\left(\frac{\Delta v}{c_e}\right)} - 1$$

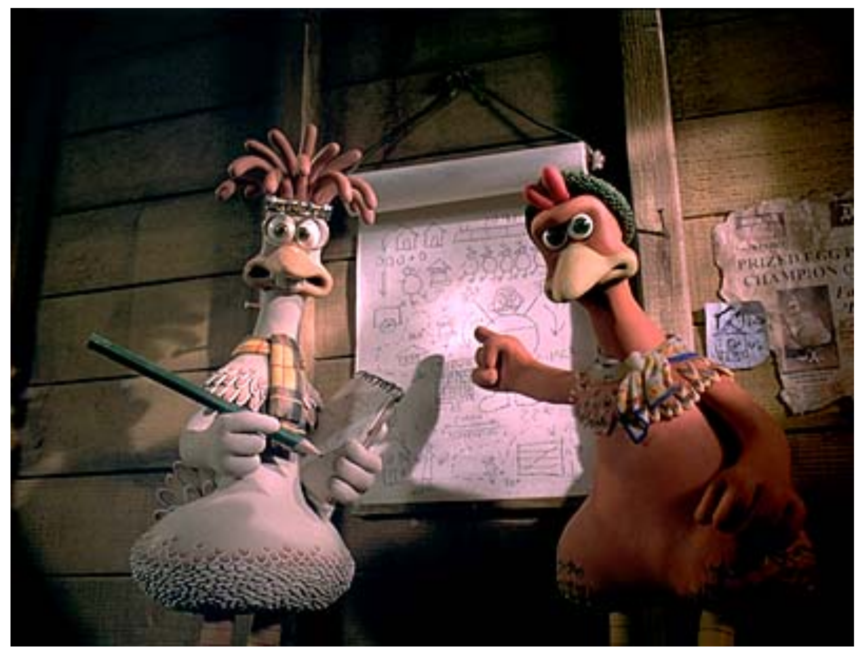
m_{fuel} = fuel mass
m_{rocket} = payload + structure mass
c_e = exhaust speed
Δv = change in spacecraft's speed

We Need More Thrust!

- Thrust is another characteristic of propulsion that we typically will want to maximize
- Thrust is defined as the force generated by an engine or rocket and thus has units of Newtons (N)
- $F = ma$
- $[N] = kg*m/s^2$
- For rockets

$F_{thrust} = c_e*dm$

dm = fuel mass flow rate



Specific Impulse

- Specific Impulse measures the efficiency of a rocket engine.
- It is effectively equal to the thrust divided by the amount of fuel used per unit time.
- It is measured by a quantity called I_{sp}
- For rockets $I_{sp} = c_e/g$ and has units of seconds.

Types of Fuel:

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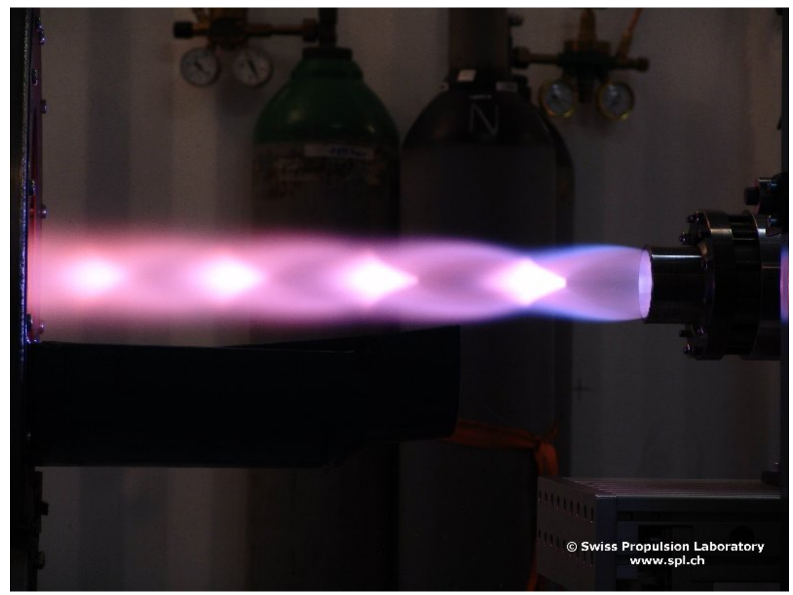
Chemical Rockets

Chemical rockets work by heating a gas through a chemical reaction. This gas is then expanded through a nozzle.

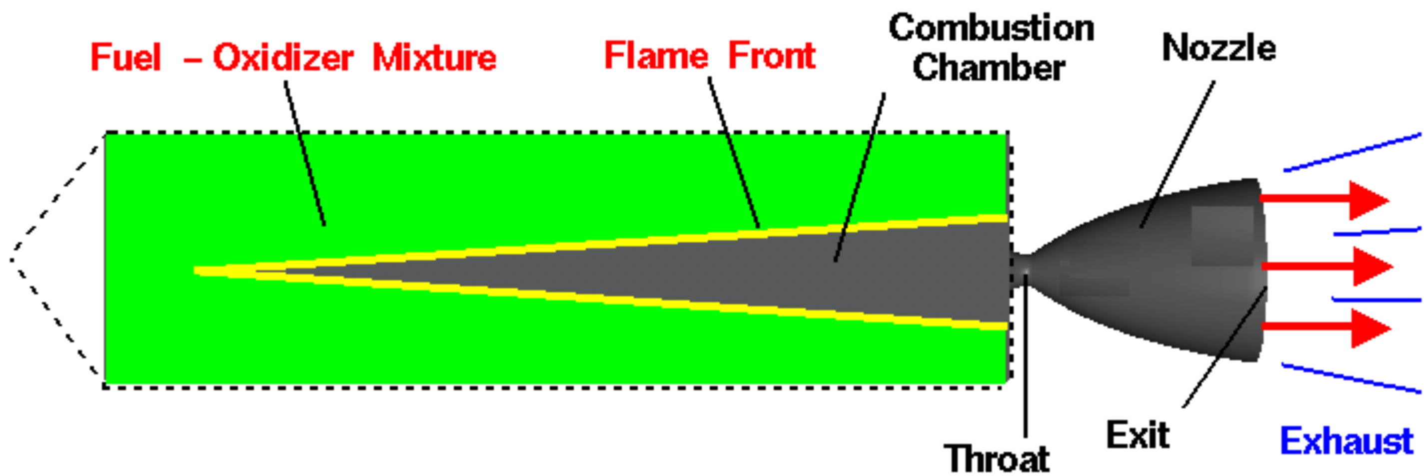
Chemical rockets can be classified based on the form of the fuel they use.

<u>Three types of chemical rockets</u>:

1. Solid propellant
2. Liquid propellant
   a. Monopropellant
   b. Bipropellant
3. Hybrid rockets



Solid Propellant Motors

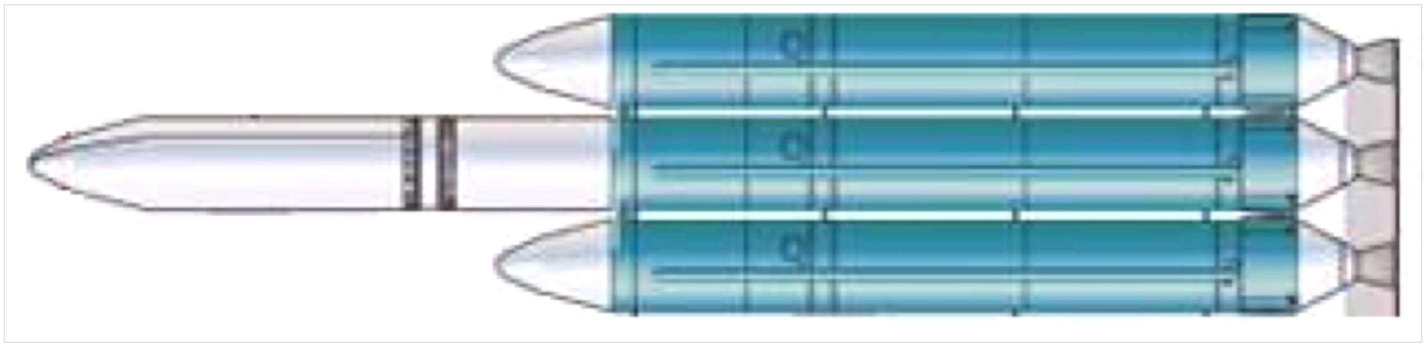


- Fuel and oxidizer are mixed together to form a grain
- Ignited used to start mixture burning
- Exhaust speed = 2.8 km/s
- Propellant example:
  - Ammonium Perchlorate (oxidizer)
  - HTPB or PBAN (fuels)
- Exhaust:
  - Hydrochloric acid
  - Aluminum oxide

<u>Uses</u>:

- Booster Rockets
  - Space Shuttle
  - Delta IV
  - Atlas V
  - Ariane 4 & 5
  - Soyuz
- Model Rockets

Solid Propellant Motors



Boeing Delta IV

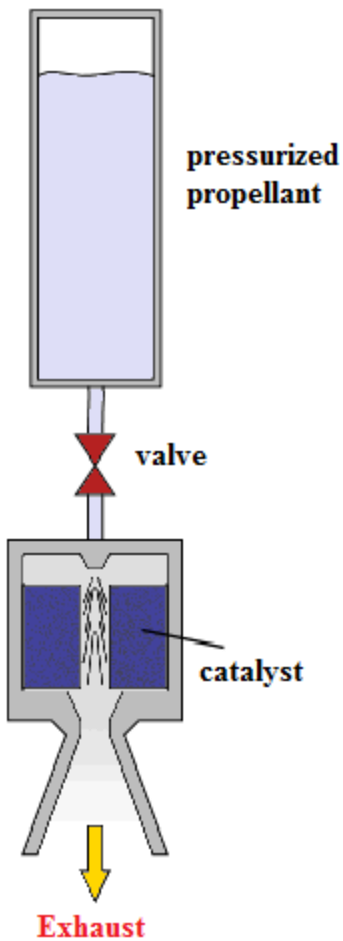
<u>Advantages</u>:

- Very simple design
- Lots of flight heritage
- Reliable
- Compact
- Long storage times
- High payload mass fraction
- Low costs

<u>Disadvantages</u>:

- Impossible to turn off
- Low exhaust speed compared to liquid fuels
- Air pockets can explode, which ruptures the casing
- Seals can rupture causing failure

Liquid Propellant: Monopropellant Engines



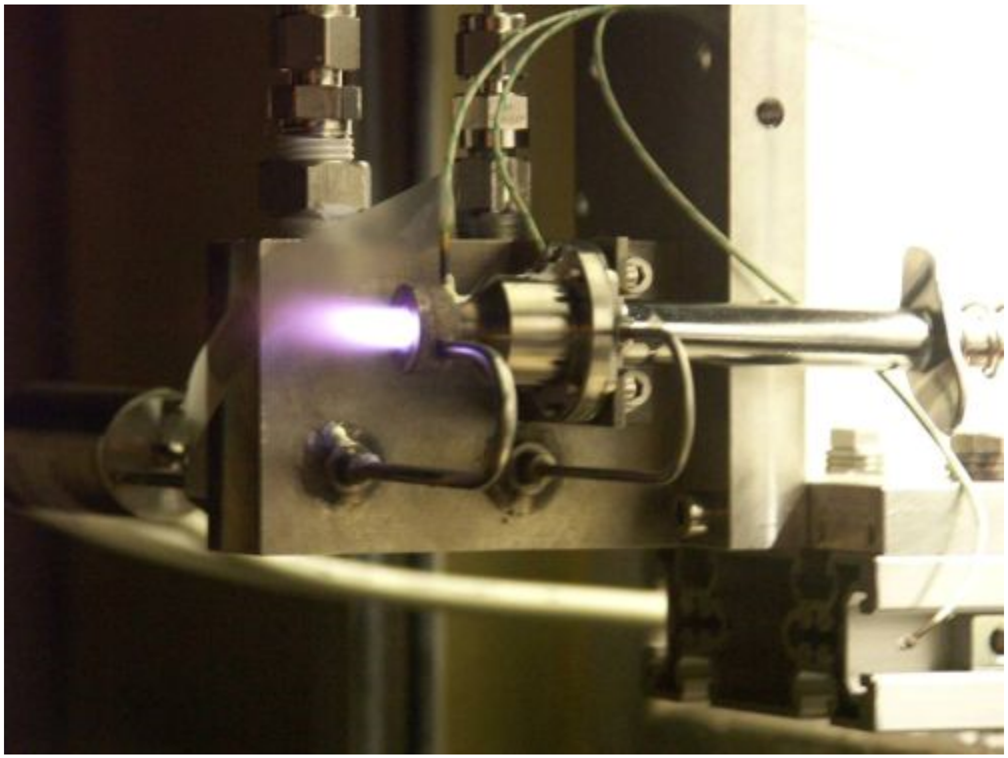
How it works:

1. Monopropellant is passed through a catalyst.
2. Catalyst causes a reaction, which generates heat.
3. The heated products of this reaction are expelled through a nozzle.

Typical fuel is hydrazine (N_2H_4)
Exhaust speed = 2.3 km/s

Usually used for attitude control.

Liquid Propellant: Monopropellant Engines



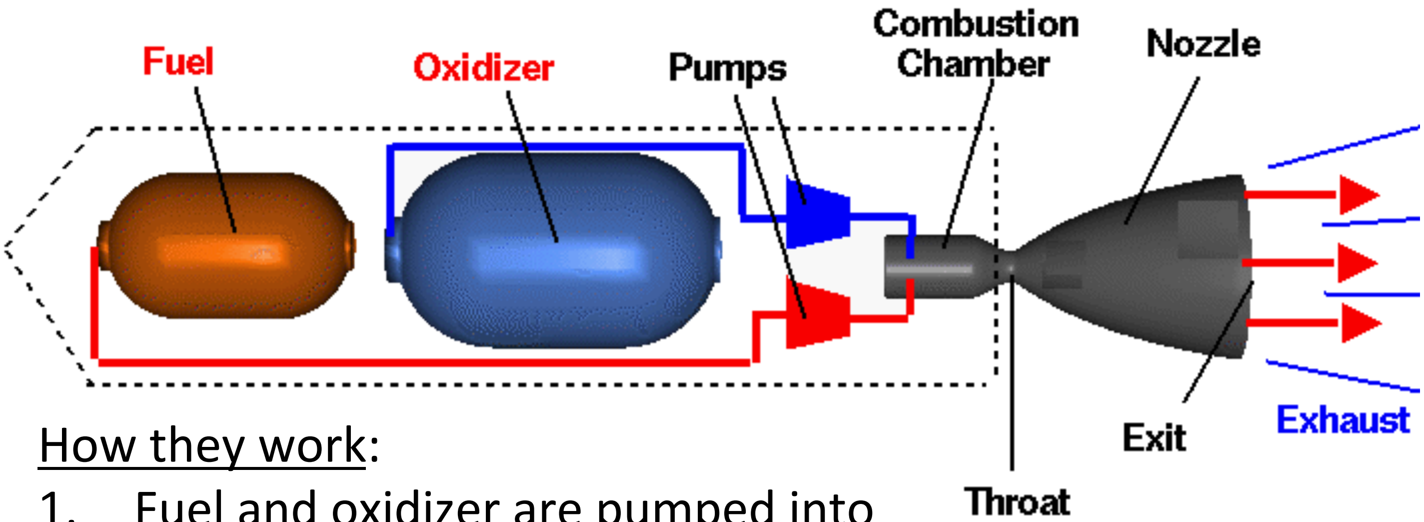
Advantages:

1. Simple design
2. Robust design
3. Reliable
4. Not a lot of plumbing
5. Flight heritage
6. Can turn them off

Disadvantages:

1. Most fuels are toxic
2. Catalyst lifetime issues
3. Low thrust
4. Low exhaust speeds

Liquid Propellant: Bi-propellant Engines



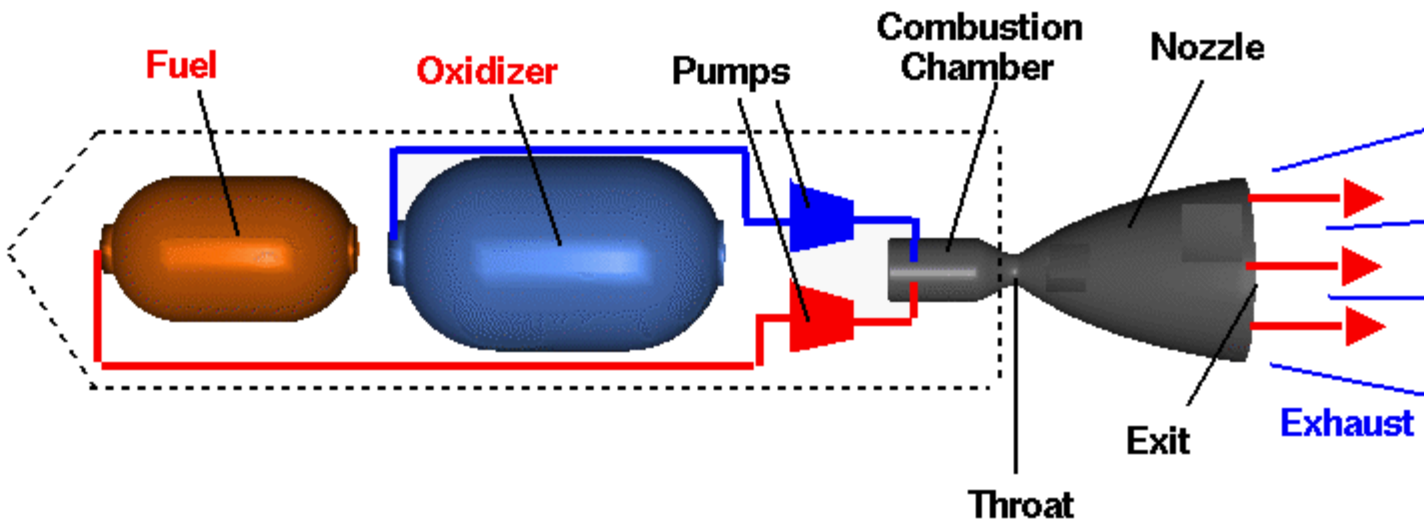
<u>How they work</u>:

1. Fuel and oxidizer are pumped into the combustion chamber
   1. Often use turbopumps
   2. Power tapped off of main combustion
2. Injectors mix propellant to provide stable and thorough combustion
3. Heat is generated from combustion.
4. Heated products are expelled out the nozzle

Liquid Propellant: Bi-propellant Engines

Fuel	Oxidizer	Example
Liquid H_2 (LH2)	Liquid O_2 (LOX)	Space Shuttle Main Engine Saturn V upper stage Delta IV 1st stage Centaur Ariane 2nd stage
Kerosene	LOX	Atlas rockets Delta Titan 1st stage Soyuz rocket
Aerozine 50	Dinitrogen tetroxide	Apollo Service Module Lunar Module Titan rockets Voyager 1 & 2
monomethylhydrazine	dinitrogen tetroxide	Space Shuttle Orbital Maneuvering System (OMS)

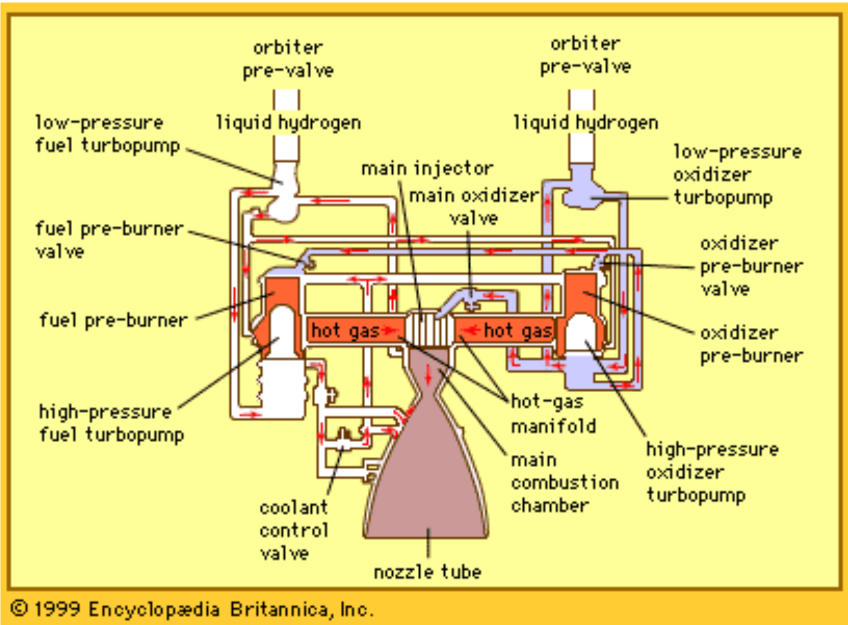
Liquid Propellant: Bi-propellant Engines

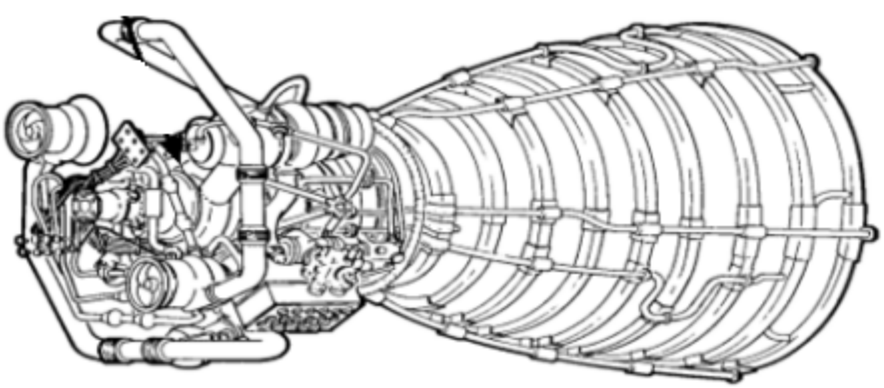


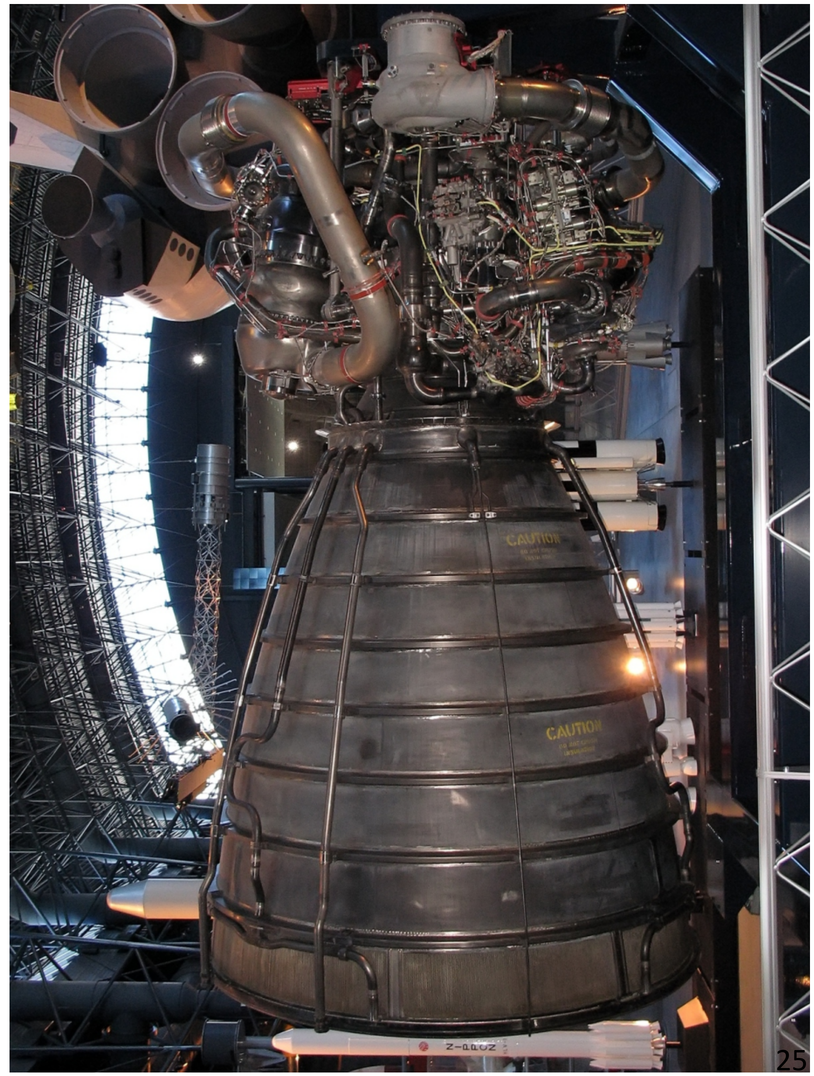
Advantages:
1. Typically more efficient than solid or hybrid rockets
2. High exhaust velocity (3.6-4.4 km/s)
3. Throttled
4. Can turn them off
5. Lots of flight heritage

Disadvantages:
1. More complex than hybrids or solid rockets
2. Cryogenic systems often needed (icing issues)
3. Difficulty storing
4. System complexity

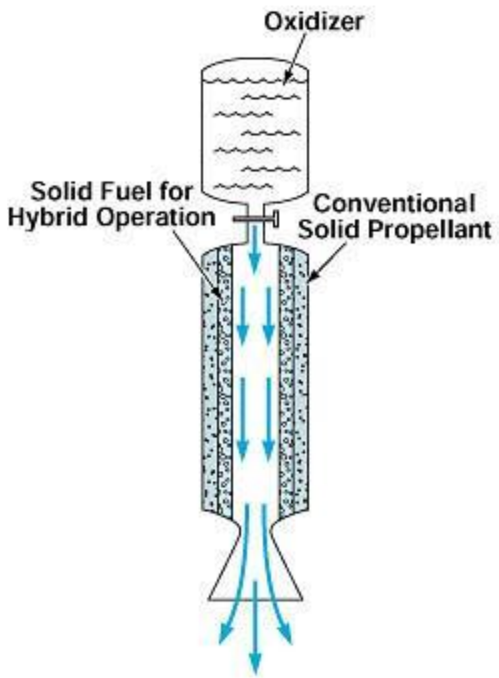
Space Shuttle Main Engine







Hybrid Rocket Motors



A solid fuel is used, but a liquid oxidizer is pumped into the thrust chamber where the solid fuel grain resides.

A combustion reaction occurs heating the reactants, which are expelled through a nozzle

<u>Propellant</u>:

LOX or Nitrous Oxide (oxidizer)
ABS plastic or synthetic rubber (fuel)

A hybrid rocket was used on Space Ship One, which won the X-prize.

<u>Advantages</u>:

1. Can shut down
2. Simple to use
3. Safe propellants

<u>Disadvantages</u>:

1. Complex fuel flow/ combustion.
2. Lower performance than bi-propellant
3. Little/no flight heritage

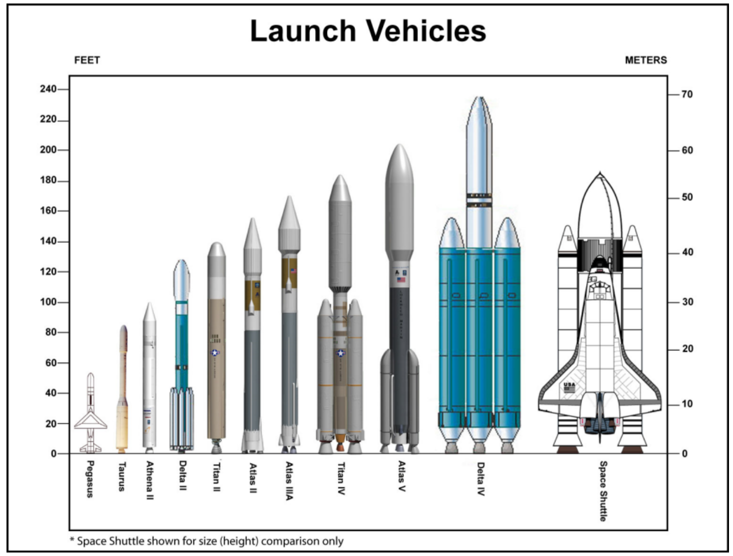
Chemical Propulsion

Three types:
Solid propellant
Liquid propellant
Hybrid propellant

Lots of flight heritage
Launch vehicles
Orbit Transfer thrusters
Station-keeping

Performance:
High or low thrust
Exhaust speeds =
2-5 km/s

Launch Costs



Launch Vehicle	Payload to LEO	Total Cost (million)	Cost/lb
Delta IV	56,800 lb	$294 (2008)	$5200
Titan IV	47,790 lb	$525(2008)	$11,000
Atlas V	27,000 lb	$294(2008)	$10,900
Ariane 5	35,273 lb	$120 (2008)	$3400
Space Shuttle	53,600 lb	$450 (2008?)	$8400
Falcon 9	**23,050 lb**	**$56 (2011)**	**$2400**

Launch Costs

Let's imagine that you're on the space station and you want to buy a liter of water. How much would it cost to bring it to you?

One liter of water = 2.2 lbs.

2.2 lbs. x $3400/lbs. = $7480

That's pretty pricy.

We need to find a way to make space travel more affordable.

Chemical Propulsion

Mission	Required Δv*	$m_{initial} / m_{payload}$ (c_e = 5 km/s)
Earth orbit to Mars and return	14 km/s	16
Earth orbit to Mercury and return	31 km/s	148
Earth orbit to Jupiter and return	64 km/s	3.6×10^5
Earth orbit to Saturn and return	110 km/s	3.6×10^9

*Assumes Hohmann transfer with no staging or gravity assists.

Chemical rockets are limited to exhaust speeds of 2-5 km/s.

***Can we do better than that*?**

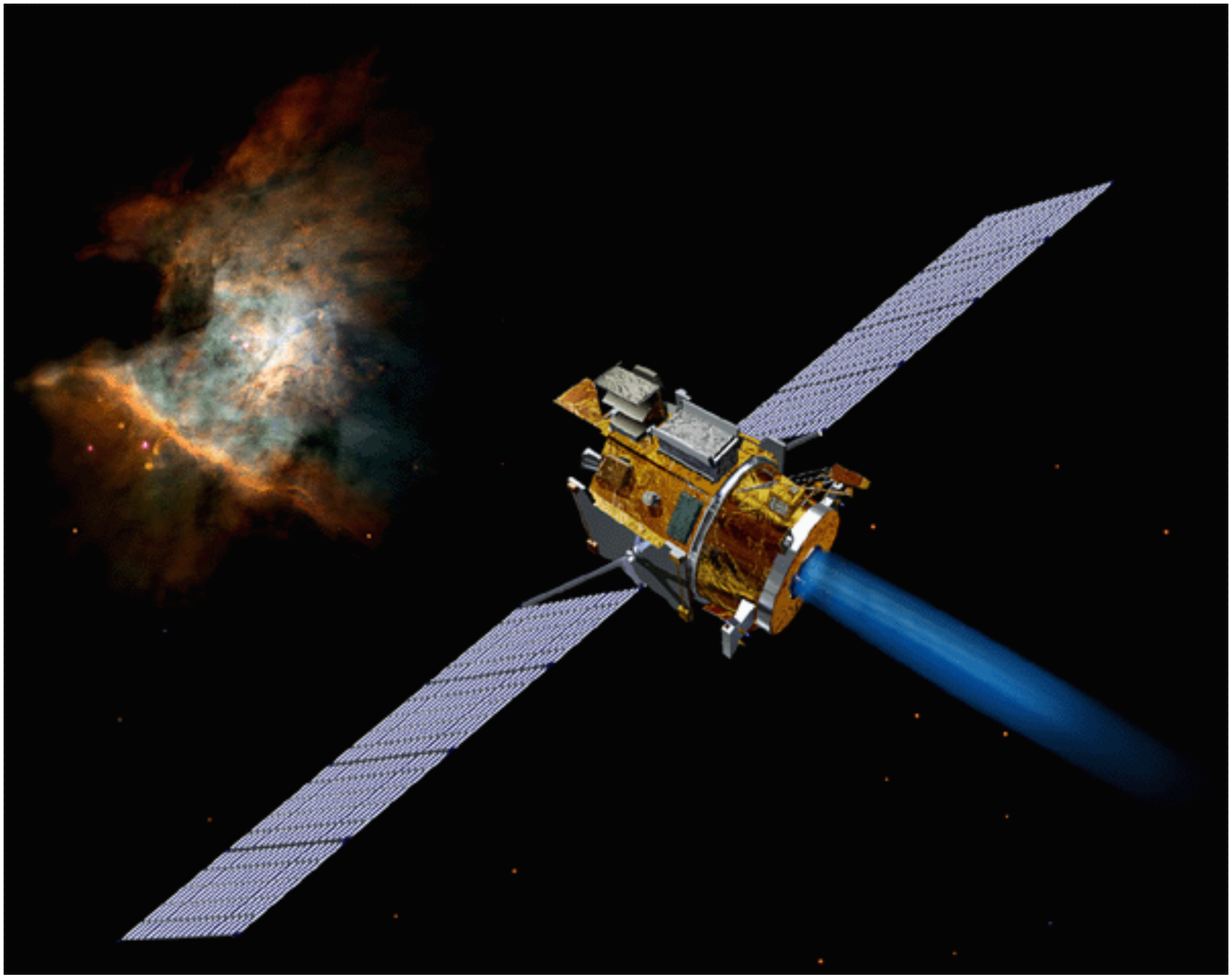
Chemical Propulsion

Mission	Required Δv*	$m_{initial} / m_{payload}$ (c_e = 5 km/s)	$m_{initial} / m_{payload}$ (c_e = 25 km/s)
Earth orbit to Mars and return	14 km/s	16	1.8
Earth orbit to Mercury and return	31 km/s	148	3.5
Earth orbit to Jupiter and return	64 km/s	3.6×10^5	12.9
Earth orbit to Saturn and return	110 km/s	3.6×10^9	81.5

*Assumes Hohmann transfer with no staging or gravity assists.

Chemical rockets are limited to exhaust speeds of 2-5 km/s.

Electric Propulsion (EP)



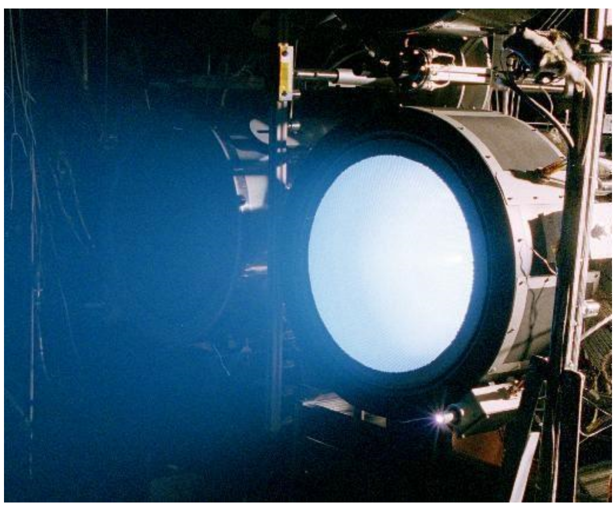
Beyond Chemical Propulsion

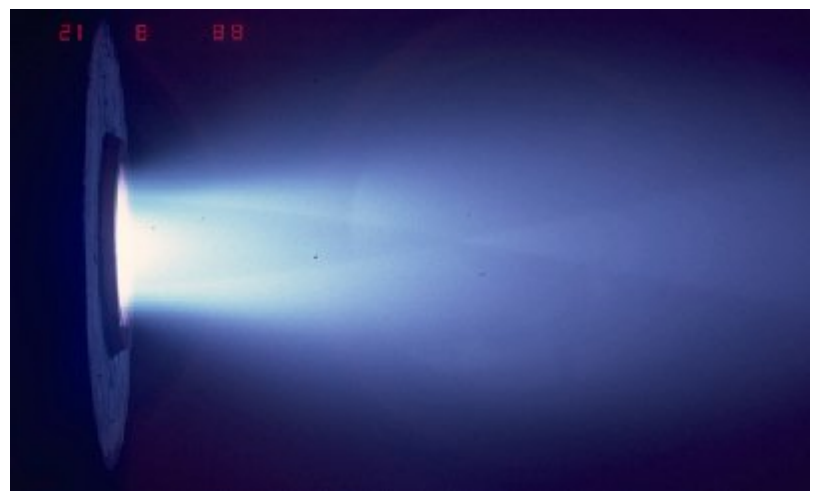
Electric propulsion uses onboard electrical power to generate an accelerate a plasma to generate thrust.

Historical Note: First conceived by Goddard in 1906!

Advantages:
High exhaust velocity
High propellant efficiency
High spacecraft speeds

Disadvantages:
Power intensive
Very low thrust (*in space only*)
Acceleration takes time
Potential lifetime issues





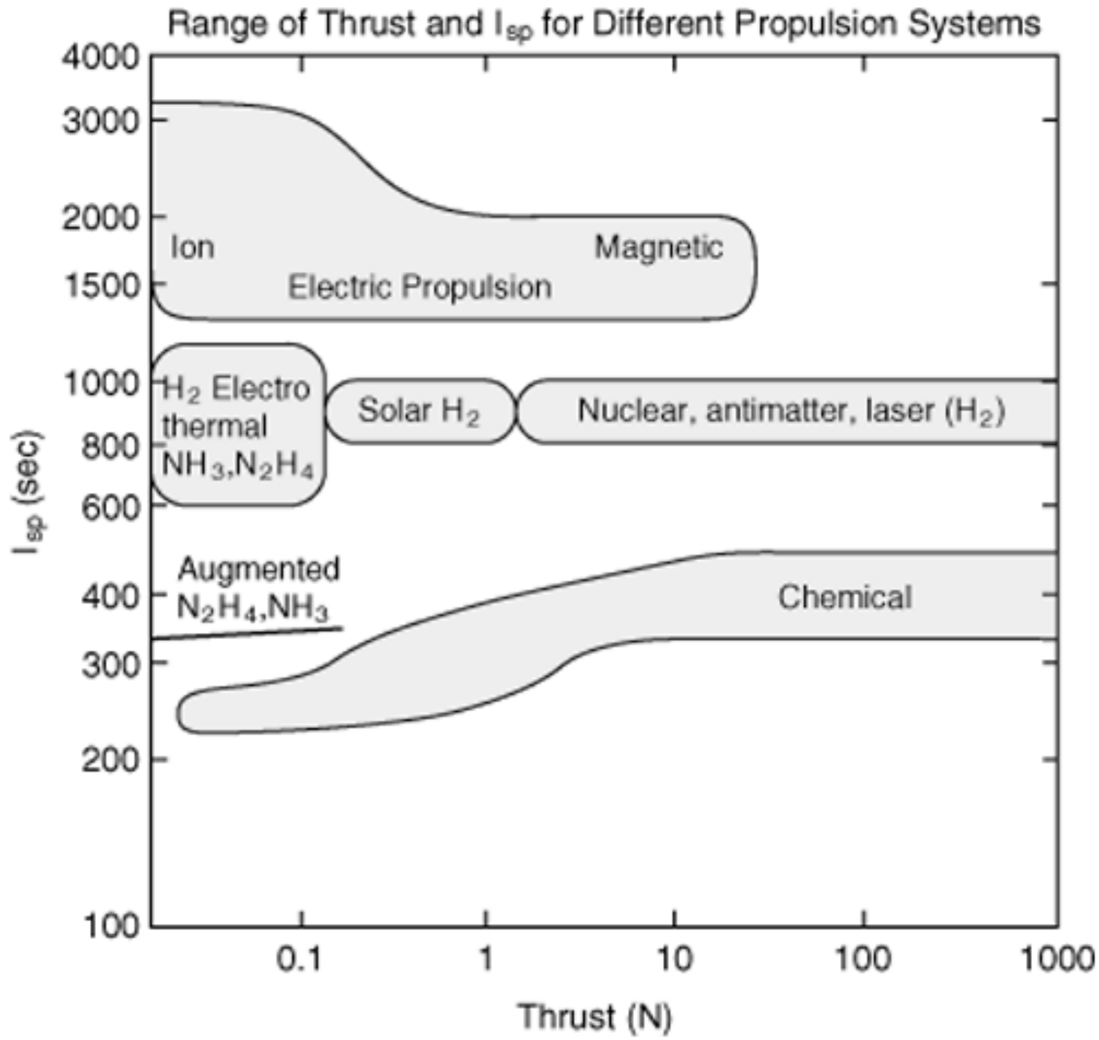
Types of Electric Propulsion

1. *Electrothermal* – uses electricity to heat a neutral gas
   examples: arcjet

2. *Electrostatic* – uses a static electric field to accelerate a plasma. Static magnetic field are sometimes used to help confine the plasma, but they are not used for acceleration. *examples*: gridded ion thruster

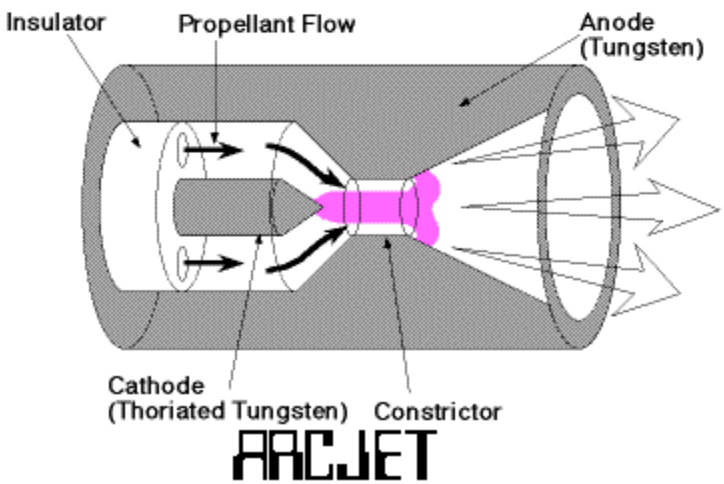
3. *Electromagnetic* – uses electric and magnetic fields to accelerate a plasma. *examples*: hall thruster, pulsed plasma thruster

Types of Electric Propulsion



Specific Impulse (I_{sp}) = c_e/g

Electrothermal: Arcjet

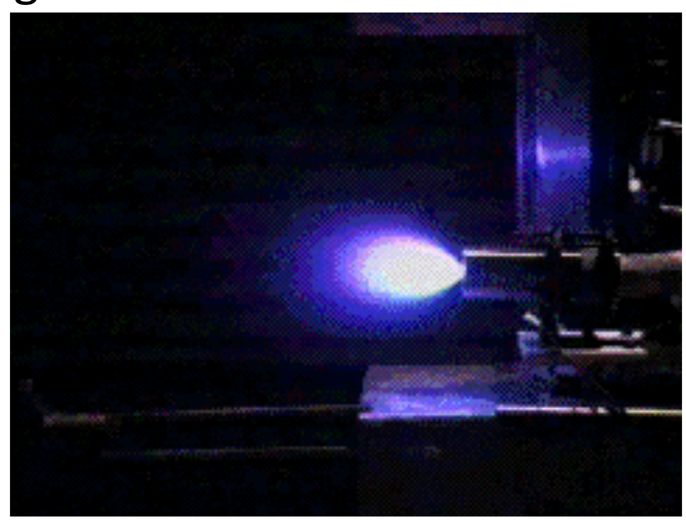


How they work:

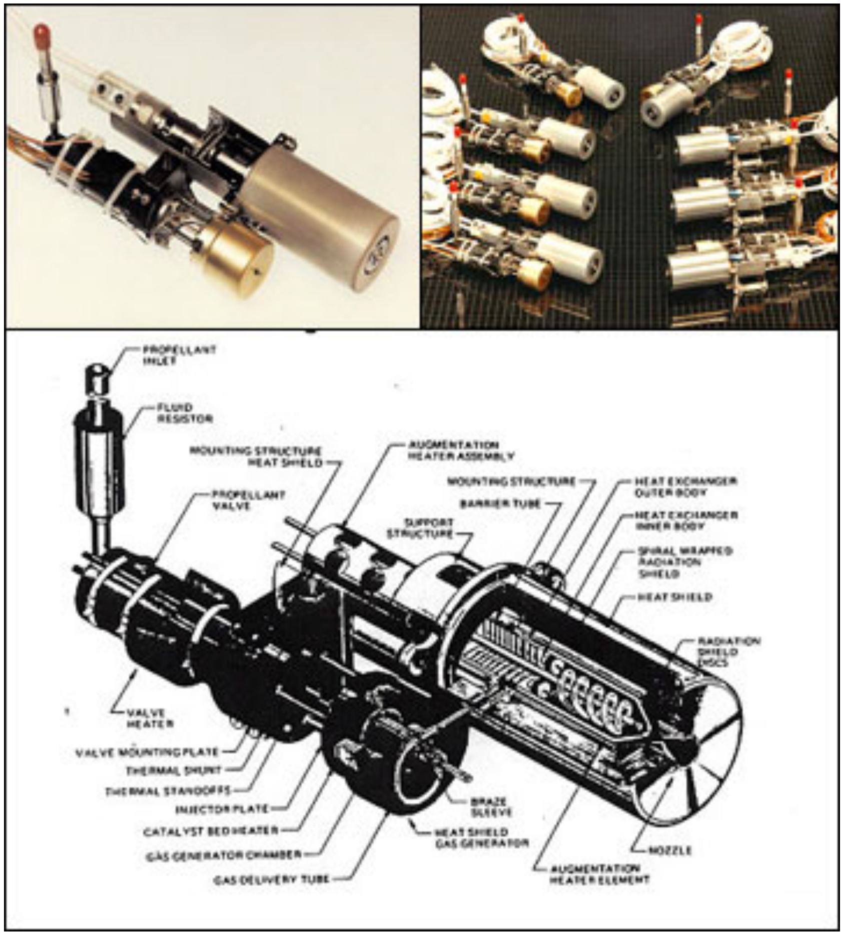
1. Neutral gas flows through the propellant flow.
2. An electrical arc forms between the anode and cathode.
3. A small amount of the neutral gas is ionized to form the arc.
4. The remaining gas is heated as it passes through the arc.

Propellant:	Hydrazine Ammonia
Exhaust speed:	4-10 km/s
Thrust range:	200-1000 mN*
Power required:	400 W – 3 kW
Efficiency:	30-50%

* 1 mN is about the weight of a sheet of paper.



Electrothermal: Arcjet



<u>Advantages</u>:

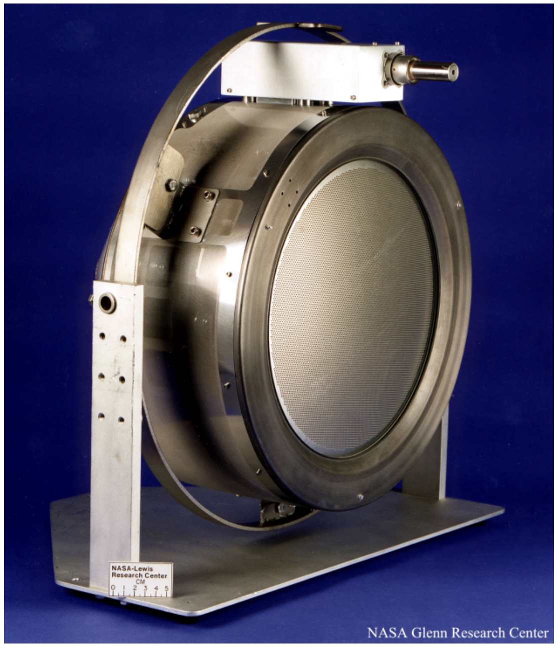
1. Higher exhaust speeds than chemical
2. Scalable to higher power levels
3. Simple design
4. Low voltages
5. Can use hydrazine

<u>Disadvantages</u>:

1. More complex power processing
2. Electrode erosion
3. High current (heat, wiring…)
4. Can use hydrazine

<u>Uses</u> (flown in space):
Station Keeping

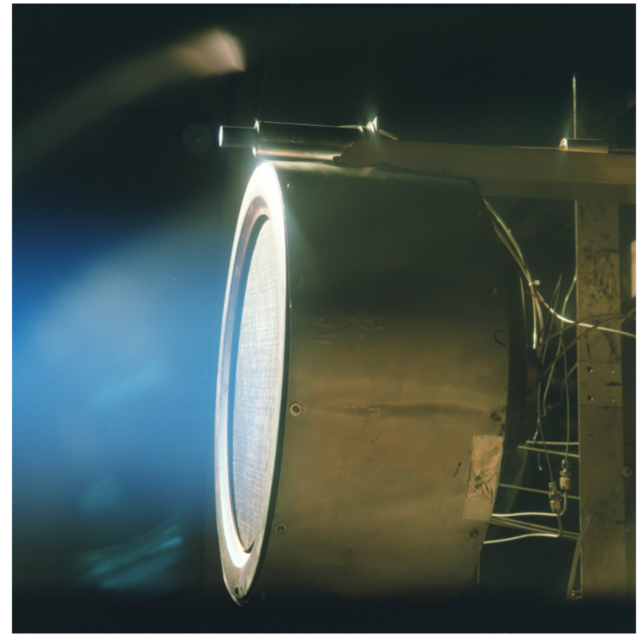
Electrostatic: Gridded Ion Thruster



Vital Stats:

Propellant:	Argon, Krypton, Xenon
Exhaust speed:	15-50 km/s
Thrust range:	0.01-200 mN*
Power required:	1-10 kW
Efficiency:	60-80%

* 1 mN is about the weight of a sheet of paper.

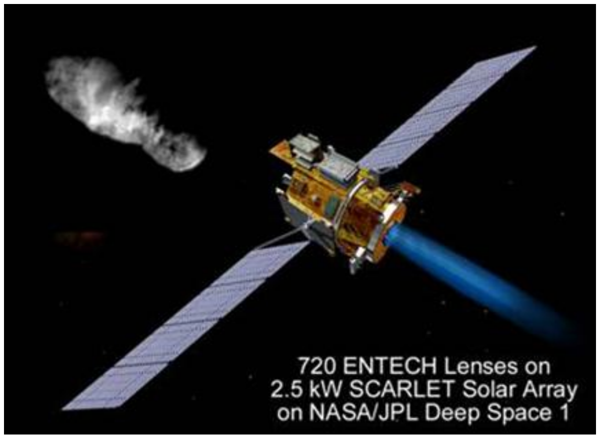


Advantages:
1. High exhaust speed
2. High efficiency
3. Inert propellant

Disadvantages:
1. Complex power processing
2. Low thrust
3. Grid and cathode lifetime issues
4. High voltages
5. Thrust density is limited

Uses:
1. Station keeping
2. Orbital change LEO to GEO
3. Primary propulsion

Electrostatic: Gridded Ion Thruster



Gridded Ion Thrusters have been flown as the primary propulsion of several satellites:

- Deep Space 1 (NASA)
- Dawn (NASA)
- Hayabusa (JAXA)

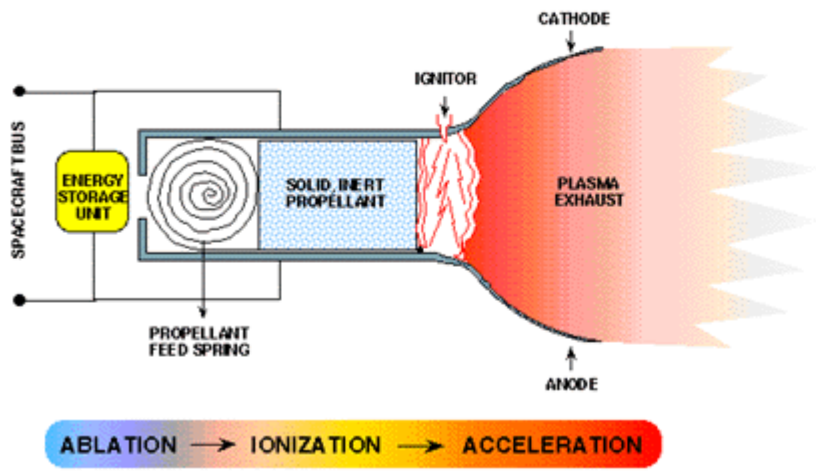
<u>Deep Space 1's NSTAR Thruster</u>:

1. Exhaust speed 35 km/s
2. Used 74 kg of Xenon fuel
3. Low thrust (92 mN) over a long time (678 days)
4. Largest Δv due to thruster (4.3 km/s)

<u>DAWN's Ion Engine</u>:

1. Exhaust speed 31 km/s
2. Low thrust (90 mN) over a long time (longer than DS1)
3. Larger Δv than DS1

Electromagnetic: Pulsed Plasma Thruster (PPT)

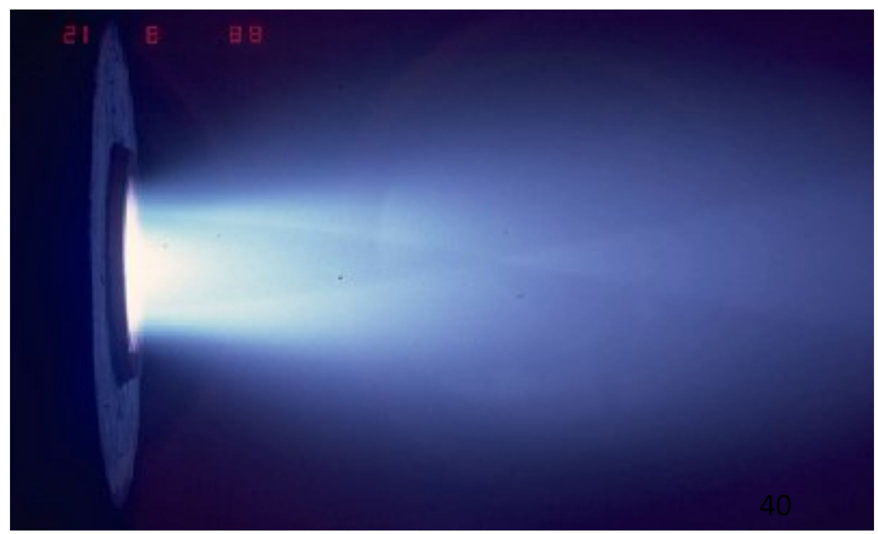


Propellant:	Solid Teflon
Exhaust speed:	6 - 20 km/s
Thrust range:	0.05 - 10 mN*
Power required:	5 -500 W
Efficiency:	10%

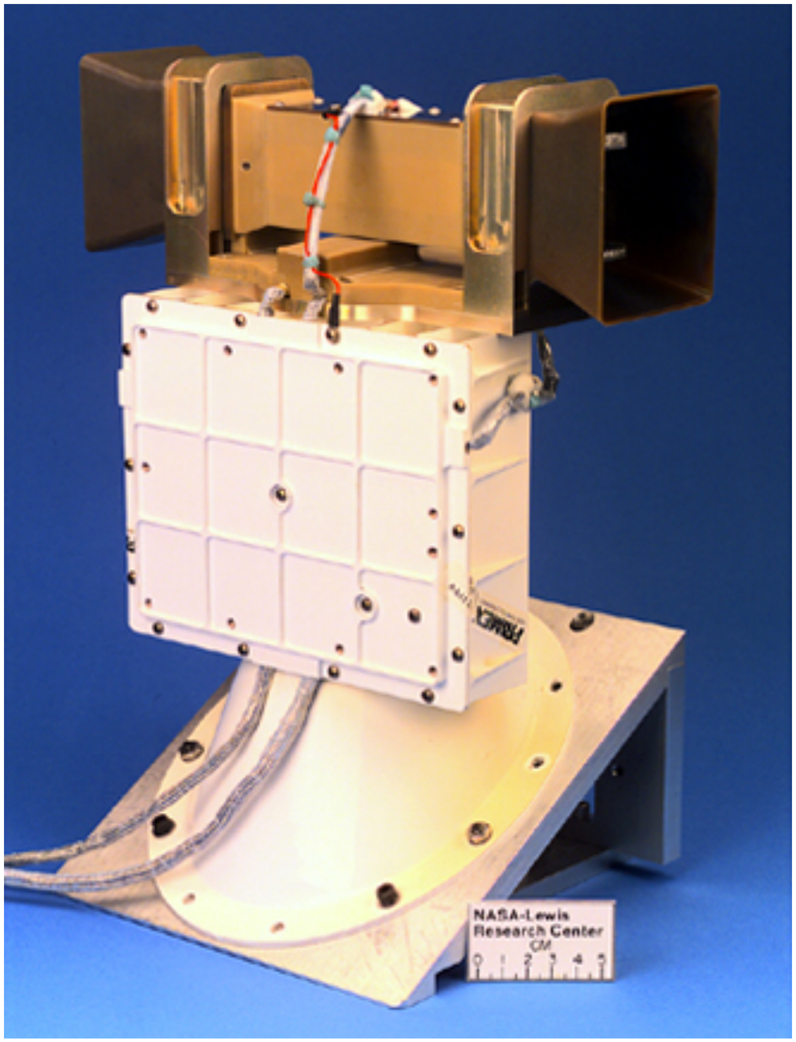
* 1 mN is about the weight of a sheet of paper.

<u>How they work</u>:

1. Arc ablates material off the Teflon surface.
   a. Material is ionzied
   b. Current flows through the arc.
2. Current generates a magnetic field.
3. Magnetic field and current interact to accelerate the plasma.



Electromagnetic: Pulsed Plasma Thruster (PPT)



Advantages:

1. Simple design
2. Low power
3. Solid fuel
    a. No propellant tanks/plumbing
    b. No zero-g effects on propellant

Disadvantages:

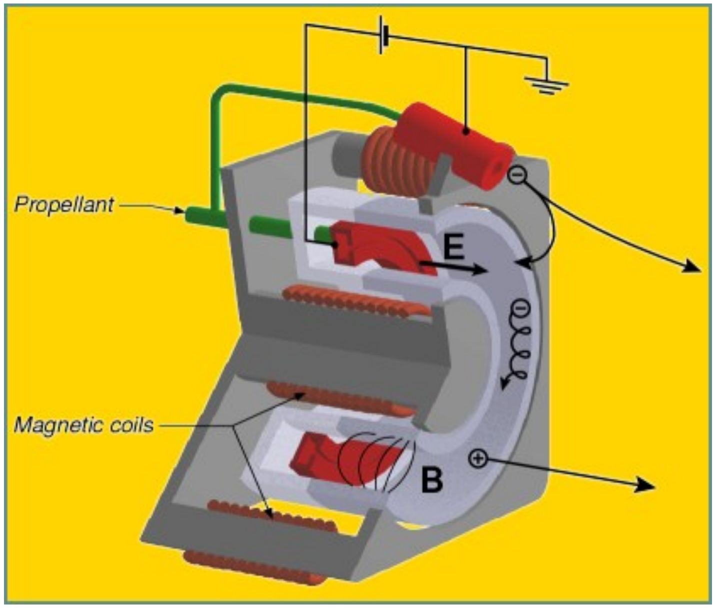
1. Low thrust
2. Low efficiency
3. Toxic products

Uses (flown in space):

Station keeping

Precision pointing

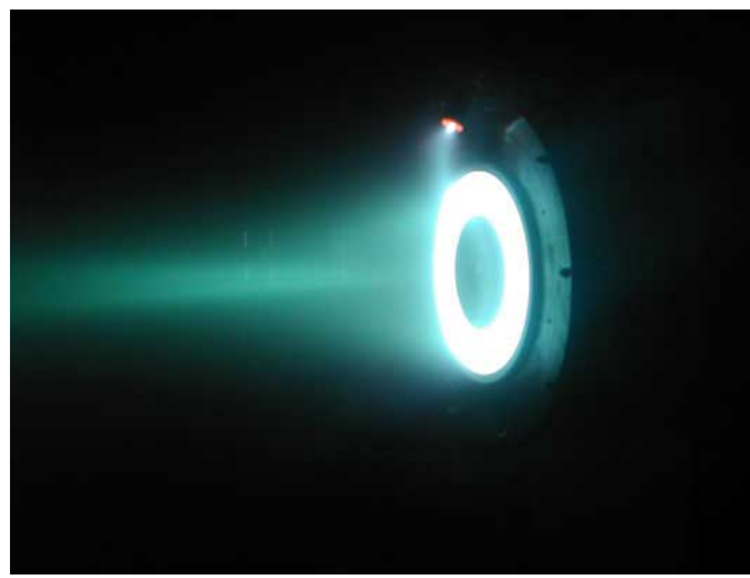
Electromagnetic: Hall Thruster



How they work:

1. Cathode releases electrons which ionize propellant.
2. Electrons from ionization move in a circular pattern (create current).
3. Current interacts with radial magnetic field to produce ion acceleration.
4. Cathode electrons neutralize the beam.

Propellant:	Xenon or Argon
Exhaust speed:	15 - 20 km/s
Thrust range:	0.01 - 2000 mN*
Power required:	1 W - 200 kW
Efficiency:	30-50%

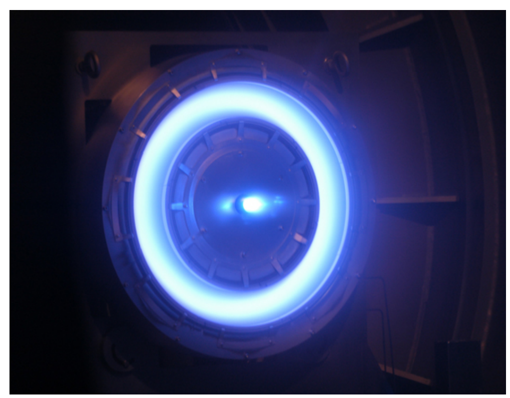


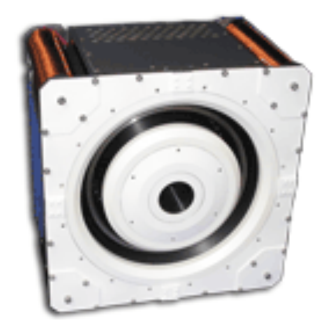
* 1 mN is about the weight of a sheet of paper.

Electromagnetic: Hall Thruster

Advantages:
1. High exhaust velocity
2. Simple power supply
3. Inert propellant
4. High efficiency
5. Desirable exhaust velocity

Disadvantages:
1. High beam divergence
2. Lifetime issues (erosion)





Uses (flown in space):
Station keeping
Orbital transfer (LEO to GEO)
Primary Propulsion (SMART-1)

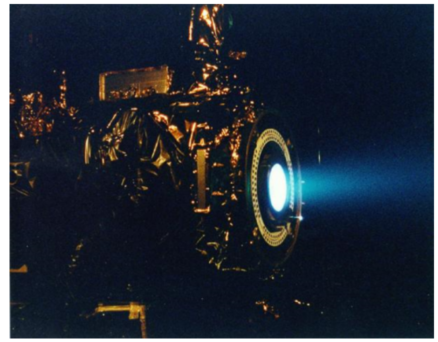
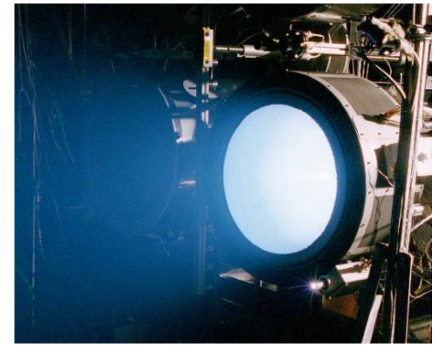
EP Summary

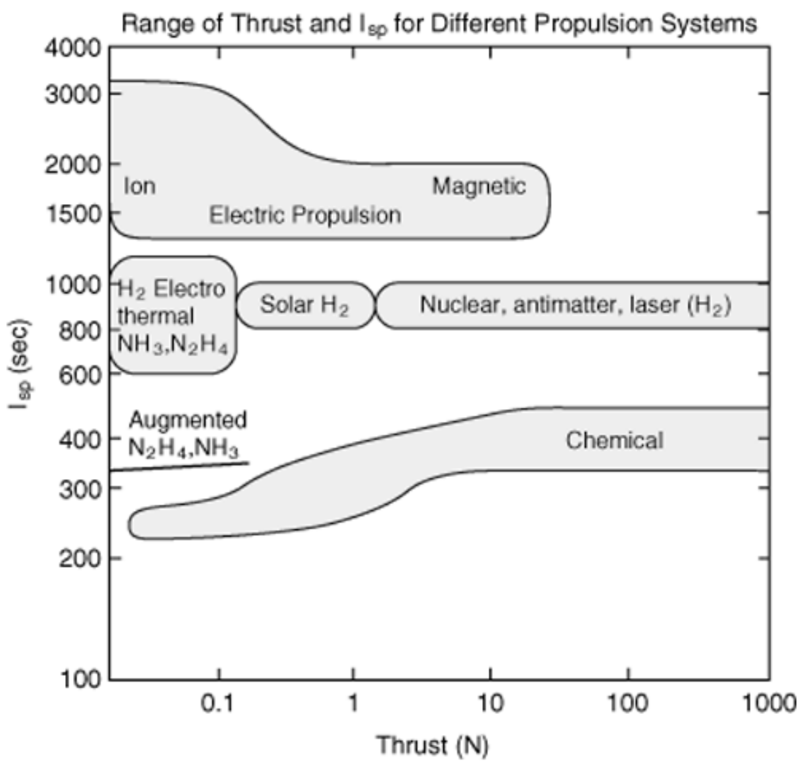
Types of EP:

Electrothermal: resistojet, **arcjet**

Electrostatic: **gridded ion thruster**

Electromagnetic: **Hall thruster**, **PPT**, MPD thruster, **VASIMR**



Advantages:

High exhaust velocity

High propellant efficiency

High spacecraft speeds

Disadvantages:

Power intensive

Very low thrust (*in space only*)

Acceleration takes time

Potential lifetime issues