AA 284a
Advanced Rocket Propulsion

Lecture 17
Electric Propulsion

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Electric Propulsion Fundamentals

- Chemical systems are capable of delivering very high thrust forces, but the energy storage capability in the chemical bonds limits the maximum exhaust velocity, thus the Isp.
- Concept has been discovered by pioneers: Tsiolkovski, Goddard, Oberth.
- First demonstrated by Vladimir Glusko, USSR
- Electric propulsion systems require large power source which limits their use.
- Commonly used in applications requiring very high Isp's, but low thrust densities.
  - Satellite propulsion
  - Interplanetary missions
- Very low thrust, heavy power supply leads to very low acceleration (10^{-4}-10^{-6} g's): influences flight strategy- spiral trajectory
- Three general kinds:
  - Electrothermal: Use electric energy to thermalize the propellant (Isp limited by order of speed of sound)
  - Electrostatic: Use electric fields to accelerate ionized propellant (speed of light)
  - Electromagnetic: Use electromagnetic fields to accelerate plasma propellant (speed of light)

Electric Propulsion – Common Types

	Common Propellants	Isp, sec	Power Range, W	Thrust Range, mN	Typical Efficiency, %
Electrothermal					
Resistojet	N2H2, NH3	~300	500-1500	100-500	80
Arcjet	N2H2, H2	500-2,000	300-100,000	200-2,000	35
Electrostatic					
Ion	Xe	3,000	50-2500	10-200	70
Hall Effect	Xe	1,500-2000	1500-5000	80-200	50
Electromagnetic					
Pulsed Plasma	Teflon	1,000	1-200	1-100	5
MPD	NH3, H2	2,000-5,000	$1{,}000\text{-}4\ 10^6$	$1{,}000\text{-}2\ 10^6$	25

Electric Propulsion – Important Equations

- Electric Propulsion System Efficiency:
  - Conversion of electric energy to kinetic energy

$$\eta = \frac{\dot{E}_k}{P_e} = \frac{\dot{m} v_e^2}{2 P_e} = \frac{T v_e}{2 P_e} = \frac{T\, Isp\, g_o}{2 P_e} = \frac{T^2}{2 \dot{m} P_e}$$

$\eta : Efficiency$

$P_e = Elecric\ Power$

$T : Thrust$

$\dot{m} : \Pr opellant\ Flow\ Rate$

$v_e : Exit\ Velocity$

- Note that the effect of the exit pressure on the thrust force has been neglected. This is accurate for most systems, but not all types including MPD, resistojets
- **Basic Analysis:** Required burn time - mission duration

$$\Delta V = \frac{T}{\overline{M}} t_b \qquad T = \frac{2 P_e \eta}{v_e}$$

  - Combine

$$t_b = \frac{v_e \Delta V}{2\eta \left(P_e / \overline{M}\right)}$$

$\overline{M} : Averege\ Mass - Spacecraft$

$t_b : Mission\ Time$

$\Delta v : DeltaV\ of\ Mission$

  - Specific power, P_e/M, is critical to limit mission time
  - This analysis is only valid if the propellant mass is a small fraction of the initial mass

Electric Propulsion – Important Equations

- Power Supply – Specific Power:

$$\alpha = \frac{P_e}{M_{pwr}}$$

α : *Specific Power*
M_{pwr} = *Mass Power Plant*

- M_{pwr} includes the mass of the power system, propellant feed system and the engine itself

$$M_{pwr} = \frac{P_e}{\alpha} = \frac{\dot{m} v_e^2}{2\eta\alpha} = \frac{M_{prop} v_e^2}{2\eta t_b \alpha}$$

M_p : *Payload Mass*
M_{prop} : *Propellant Mass*
M_i : $M_p + M_{prop} + M_{pwr}$

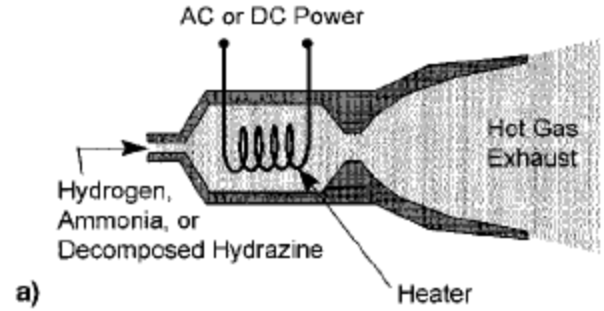
- With the use of rocket eqn.

$$\frac{M_i}{M_p} = \frac{e^{\Delta V / v_e}}{1 + \left(1 - e^{\Delta V / v_e}\right)\left(v_e^2 / 2\eta t_b \alpha\right)}$$

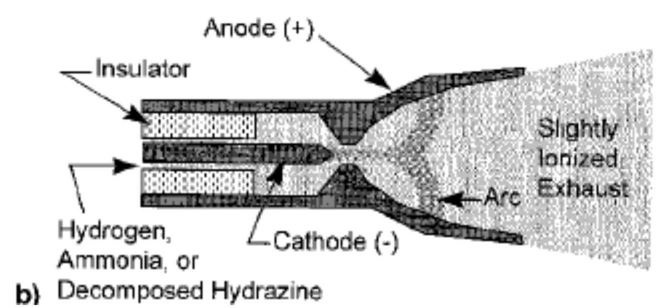
- Note that for a given initial mass to payload ratio there is an optimum $\Delta V / v_e$
- There is an optimum Isp for a given system/mission for electric propulsion systems
  - This is because increasing Isp increases power plant mass, but reduces propellant mass
  - A balance which does not exist in a chemical rocket

Electrothermal Systems

- Resistojet:
  - Resistively heat the propellant using a heat exchanger
  - Simple, but low performance system
  - Performance limited by the melting temperature of of the heat exchanger.
  - Isp better than monoprops and cold gas thrusters
  - Mature technology



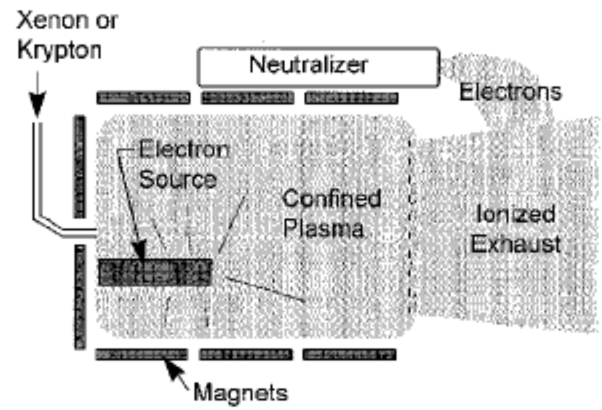
- Arcjet:
  - Arc discharge heats the propellant
  - Arc is generated by
    - Low DC voltage high current
    - High frequency high voltage
  - Local heating and thermal losses limit efficiency
  - Electron life limits life to about 1,500 hours
  - Mature technology



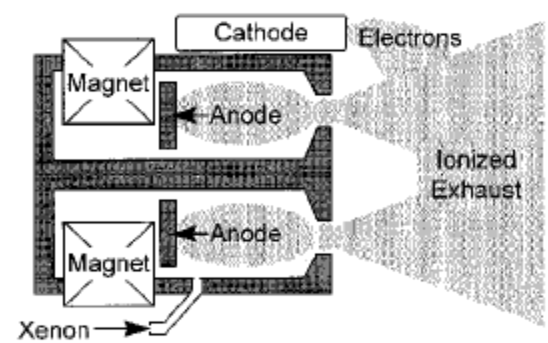
Electrostatic Systems

$$\vec{F} = e\vec{E} + e\vec{v}_e \times \vec{B}$$ Coulomb force

- Ion Engine:
  - Propellant is ionized
    - Electron bombardment
    - Radiofrequency excitation
  - Accelerated using high electrostatic potential (~1,000V)
  - Low density ion field (not a plasma)
  - Plume is neutralized to prevent charge built up
  - High power requirement limits usage
  - Mature technology



- Hall Effect Thruster
  - Gridless electrostatic propulsion system
  - External hallow cathode ring shaped anode: ~300 V
  - Magnetic field spirals electrons ionizing the gas
  - Ions are accelerated by the electric potential
  - First developed and extensively used by Russians
  - Currently being used extensively in the Western world
  - Optimum Isp in1,500 s, low voltage and moderate power consumption makes this a very attractive option.
  - New Application: Orbit raising for GeoSats



Electrostatic Systems – General Scaling

m_{ion} : Ion Mass

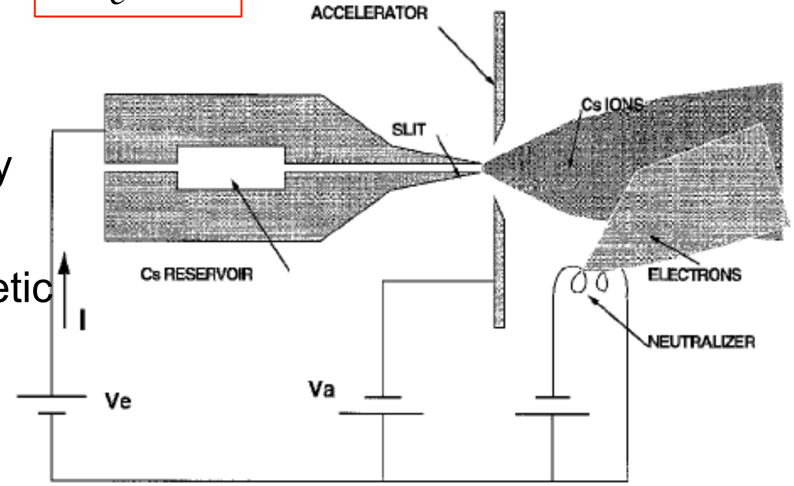
q : Ion Charge

J : Current

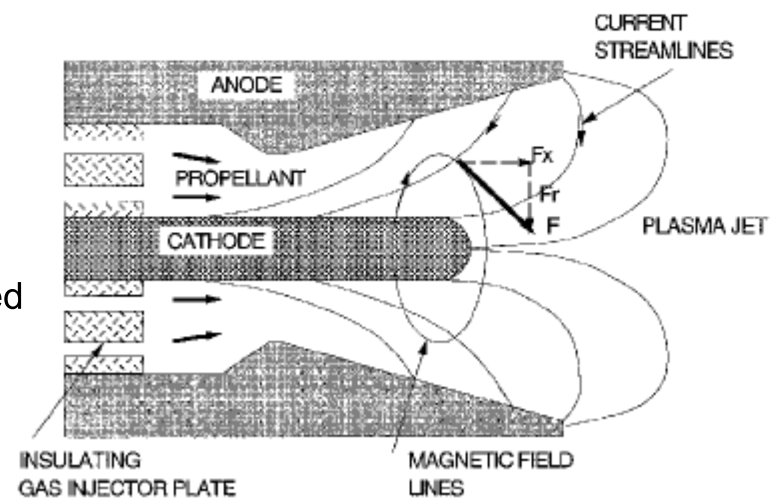
- Ion velocity and Isp: $v_e = \left(\frac{2qV}{m_{ion}}\right)^{1/2}$ $\quad Isp = \frac{1}{g_o}\left(\frac{2qV}{m_{ion}}\right)^{1/2}$
- Current mass flow rate relationship: $\dot{m} = J\frac{m_{ion}}{q}$
- Thrust relationship $T = \dot{m}v_e = J\left(\frac{2m_{ion}V}{q}\right)^{1/2}$
- Propellant selection $T \propto \sqrt{m_{ion}/q}$ $\quad Isp \propto \sqrt{q/m_{ion}}$
- In order to maximize thrust, one must use large MW and low ionic charge
- The mission duration can be estimated to be $t_b = \frac{\Delta V}{(P_e/M)\eta}\left(\frac{V}{2}\frac{q}{m_{ion}}\right)^{1/2}$
- Note that P_e=V J+ *power for ionization*
- *Reducing mission duration requires:*
  - *Low values for voltage and ion charge to mass ratio*
  - *High efficiency and specific power*

Electromagnetic Systems $\vec{F} = e\vec{E} + e\vec{v}_e \times \vec{B}$ Lorentz force

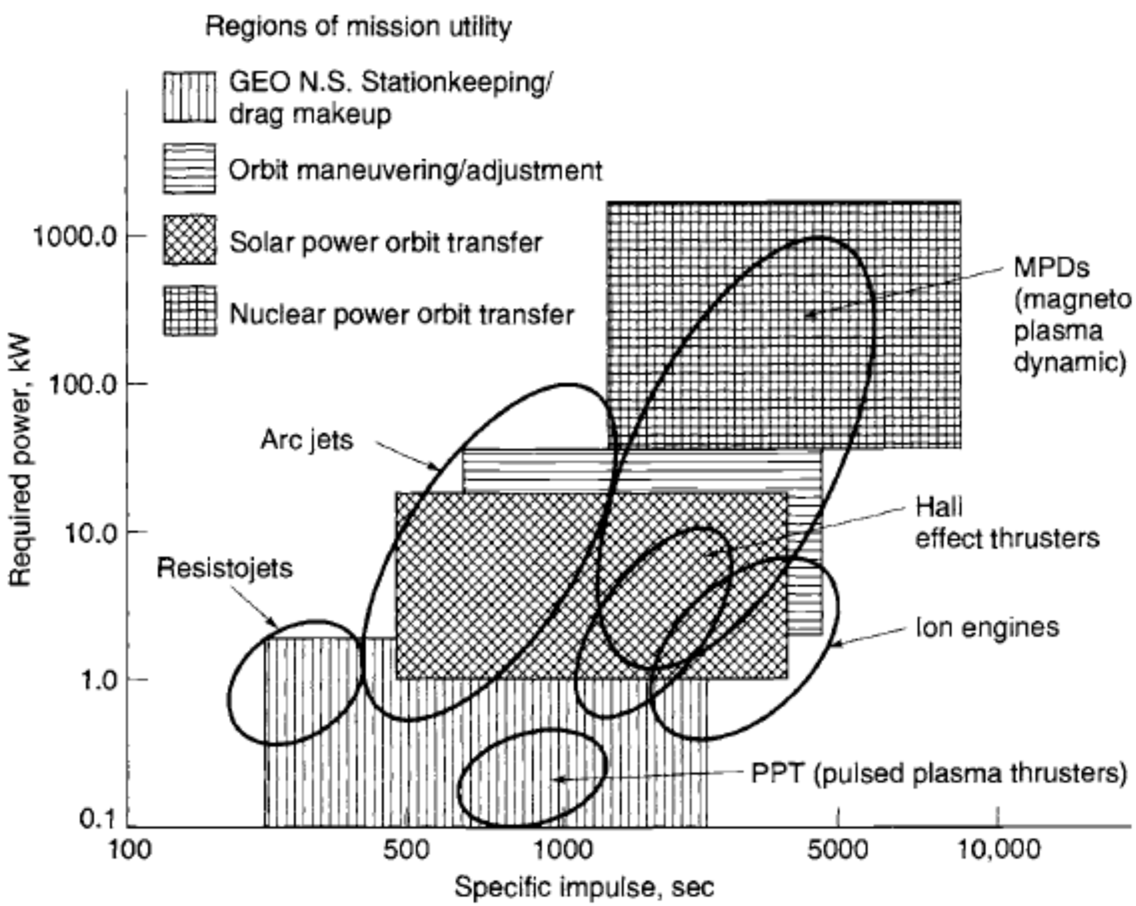
- Pulse Plasma Thruster:
  - Very simple system
  - Solid propellant is formed into a plasma by electric discharge
  - Plasma is accelerated using electromagnetic field
  - Very low efficiency
  - Pulsed mode operation



- Magnetoplasmadynamic (MPD):
  - Large current discharge applied between the two electrodes ionizes the gas
  - Self Induced MPD: Magnetic field is self induced by the current
  - Applied field MPD: Magnetic field externally applied
  - The plasma is accelerated by the Lorentz force
  - Large thrust force possible – requires very large power levels, high Isp feasible
  - Cathode erosion is an issue



Electric Propulsion Systems – Overall Performance



Ref: "Sutton, "Rocket Propulsion Elements"