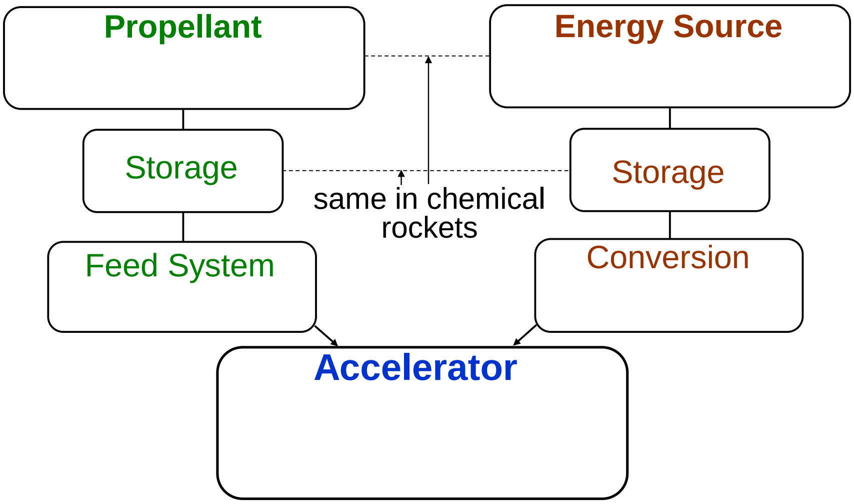
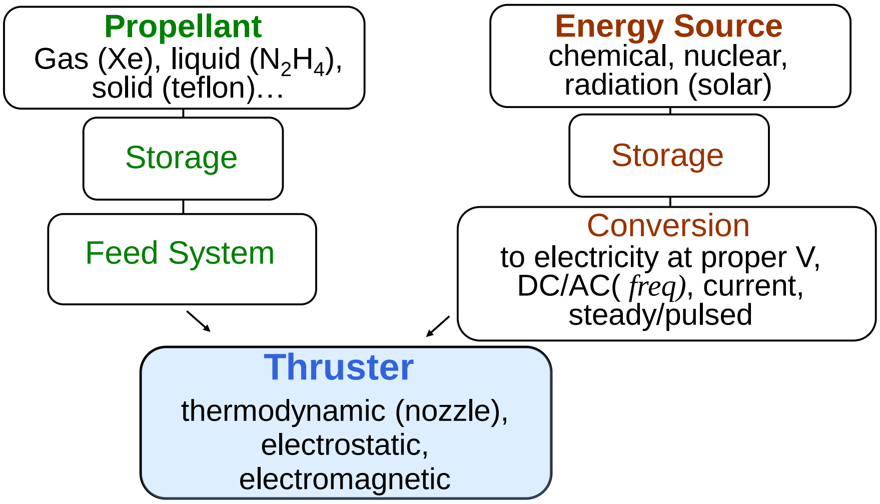
Electric Propulsion (EP)

Overview

Basics Rocket Propulsion Elements



Electric Propulsion System Elements



Propellant
Gas (Xe), liquid (N_2H_4), solid (teflon)…

Storage

Feed System

Energy Source
chemical, nuclear, radiation (solar)

Storage

Conversion
to electricity at proper V, DC/AC(*freq*), current, steady/pulsed

Thruster
thermodynamic (nozzle), electrostatic, electromagnetic

Electric Propulsion - Accelerators

	Electrothermal	**Electromagnetic**	**Electrostatic**
Accel. Force	Pressure, ∇p Electrically heat propellant and use nozzle expansion (resistojets, arcjets)	Lorentz, $\vec{j}\times\vec{B}$ Magnetic and elec. fields accelerate ionized propellant (MPD, pulsed plasma thrusters)	Electrostatic, $\vec{F}_e$ Static E field (alone) accelerates charged particles (ion engines, colloidal and Hall(?) thrusters)
I_{sp}(s)	300-1,500	1,000-10,000	2,000-20,000+
$\frac{\text{Thrust}}{\text{Weight}}$	$<10^{-3}$	$<10^{-4}$	$<10^{-4}$–10^{-6}

already covered

Comparison to Chem./Nucl. Rockets

Propulsion Technology	**Orbit Insertion**	**Orbit Maintenance and Maneuvering**	**Attitude Control**	**Typical Steady State I_{sp} [sec]**	**Thrust [N]**	**Advantages**	**Disadvantages**
COLD GAS		√	√	60-250	0.1- 50	-Simplicity -Safe -Low Contamination	-Low Specific Impulse
CHEMICAL							
(a) Solid	√			280-300	0.1 to 12x10^6	- High Thrust - Heritage	-Moderate performance -Combustion complications -Safety concerns
(b) Liquid							
Monopropellant		√	√	140-240			
Bipropellant	√	√	√	305-460			
Dual Mode	√	√	√	313-322			
Hybrid	√	√		250-350			
NUCLEAR THERMAL	√	√		750-6000	Up to 12x10^6	High Specific Impulse	-Unproven -Politically unattractive -Expensive -Low Thrust/weight
NON CHEMICAL							
Electro-Thermal (Arcjets, Resistojet)	√	√		300-1500	0.0001 to 20	Very high specific impulse	- High system mass - Low thrust level Limited heritage
Electro-Magnetic (Plasma)	√	√		1000-10,000			
Electro-Static	√	√		2000-100,000			

After Evans, Telesat Canada internal course

Electric Propulsion (EP)

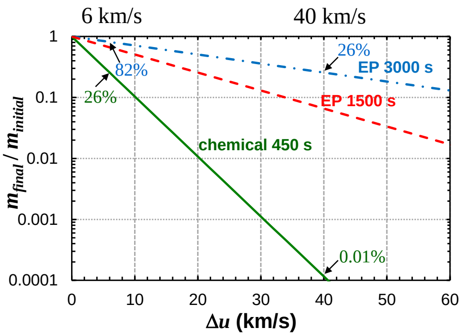
Performance

Potential Advantages for In-Space Propulsion

- From rocket equation $m_{final} / m_{initial} = e^{-\Delta u / u_e} = e^{-\Delta u / I_{sp} g_e}$

In-space Propulsion Requirements

Mission	Typical Δu (km/s)
GEO stationkeeping (15 years)	0.8
LEO to GEO (< 1 day)	4.2
LEO to Mars (9 months)	5.7
LEO to GEO (8 months)	6.0
LEO to Jupiter (9 months)	50
LEO to Mars (1 month)	90
LEO to 1000 Aus (30 Yrs)	175



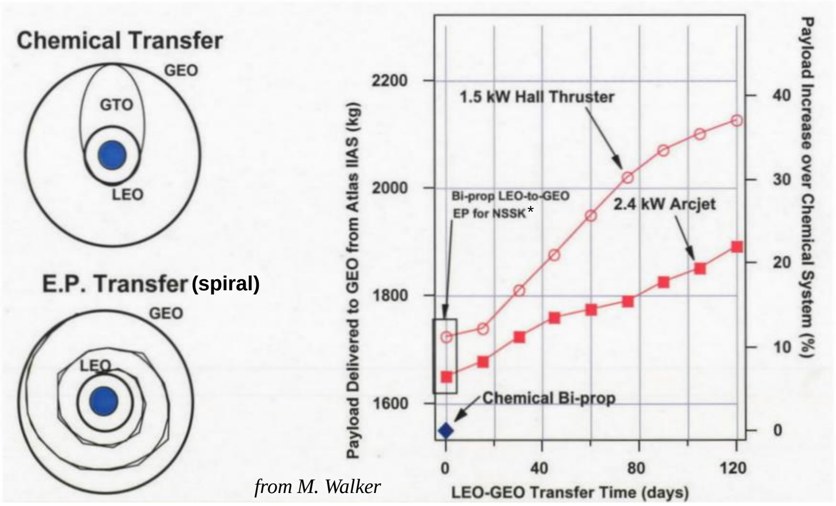
- **EP can provide greater (and reasonable) payload mass fractions**
  - especially for deep space missions, but even for GEO missions
  - lower launch costs, larger payloads,…

  neglects change in gravitational potential of propellant (gravity losses)

Gravity Losses

- Can reduce advantage of EP if propellant is "carried" over large change in gravitational potential
- Example: orbit escape
  - $\Delta u_{long\ duration\ spiral\ burn} \approx 2.3 \times \Delta u_{impulse\ burn}$
  - part of I_{sp} increase needed to meet higher Δu
- Not issue for station keeping (no change in gravitational potential)
- Multiple (short) firings for large orbital changes can also require nearly same Δu as Hohmann (impulsive) transfer
  - short thrust durations at same gravitational end-points as Hohmann transfer

Potential Commercial Advantages



from M. Walker

*NSSK=N-S station keeping

EP Power Requirements

- **Jet Power** $P_j = \tfrac{1}{2}\dot{m}u_e^2$

$$= \tfrac{1}{2}\left(\dot{m}u_e\right)u_e = \tfrac{1}{2}\tau u_e = \tfrac{1}{2}\tau\left(I_{sp}g_e\right)$$

- Increase in I_{sp} (or u_e) entails increase in power
  - – $\propto u_e^2$ for constant flowrate
  - – $\propto u_e$ for constant thrust
- Comparison for thrust of 1000 lb_f (4.5 kN)
  - – chemical rocket (I_{sp}=350s) $\Rightarrow P_j$ = 7.7*MW*
  - – EP rocket (I_{sp}=3000s) $\Rightarrow$ **P_j = 66 *MW***
- EP systems tend to be **power-limited**
  - – so low thrust (and acceleration)

Required Supply Power

- **Supply Power** $$P_s = \frac{P_j}{\eta_T}$$ ← total efficiency of energy conversion
- Overall conversion efficiency has 3 main components

$$\eta_T = \eta_S \; \eta_{pp} \; \eta_{th}$$

energy conversion - of raw energy source to electricity

- ~100% for photovoltaics – direct conversion of photons (does NOT include fraction of solar radiation that can be converted to electricity by typical solar array, ~18-25%)
- 10-40% for nuclear thermal, thermodynamic cycle limits = lots of waste heat

power preparation and conditioning electronics (losses in electronics)

- ~92% (electrostatic)
- ~98% (steady arc jets)

thruster efficiency - only part of delivered electrical energy converted to KE

30-75%

Thrust Efficiency, η_{th}

- Typical values (varies with I_{sp})

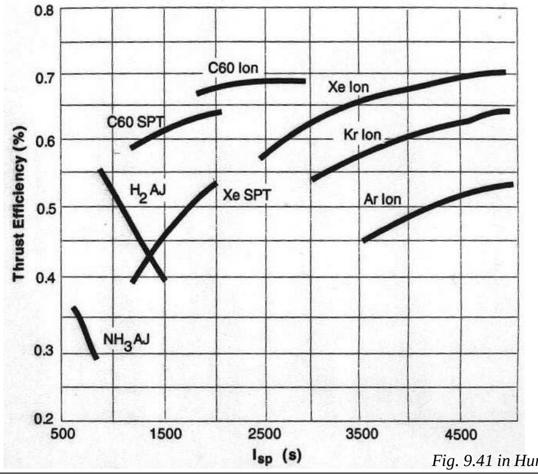


Fig. 9.41 in Humble, Henry and Larson

Mass Requirements

- What limits available power to EP systems?
  - mass of power plant and associated systems
- If power plant mass is significant fraction of propellant mass, then some advantages of higher specific impulse operation are lost
  - “payload” may consist mostly of power plant/electronics for propulsion system

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Mass Requirements (con’t)

- **Power source mass**

$$Mass_{powersource} \cong \underset{\uparrow}{\beta_s} P_s \longleftarrow$$

nearly linear relationship

specific mass (e.g., kg/kW)

Note: sometimes α used for specific mass, but also used by others for specific power (kW/kg), i.e., $\alpha = 1/\beta$

- β_s~7-25 kg/kW$_{elec}$ for solar arrays (depends on cell design, substrate)
- β_s~2-4 kg/kW$_{thermal}$ for nuclear reactors (depends on shielding)
  - to reject waste heat, also require additional mass for radiators β_R~0.1-0.4 kg/kW$_{waste\ heat}$

Mass Requirements (con't)

- **Power preparation and conditioning**

$$Mass_{pp} \cong \beta_{pp} P_{pp}$$

- Large variation with type of EP device (especially if need high voltage or power, and short pulse forming electronics/switches)
  - β_{pp}~0.2 kg/kW$_{elec}$ for typical arcjets
  - β_{pp}~20 kg/kW$_{elec}$ for PPT (pulsed plasma thrusters)

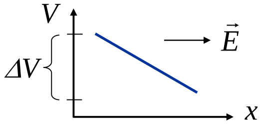
Electric Propulsion (EP)

Background

Electrostatics - Definitions

- V – potential or voltage (sometimes ϕ) ($Volts$)
- E – electric field (V/m, $N/Coulomb$)
- q – charge (C) ($q_{e^-}=1.602\times10^{-19}\ C$)
- Force $\vec F = \vec E q$
- Potential Energy $\int F dx = \int qE dx = q\Delta V$
- J – current (A, $Coulomb/s$)
- j – charge current density (A/m^2, $Coulomb/m^2 s$)
- n – number density ($1/m^3$)

$$\vec E = -\nabla V \left(= -\frac{dV}{dx} \right)$$

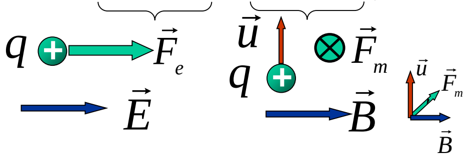


$$j = nqu$$

Forces on a Charged Particle

- To examine how to use electrical energy to accelerate a propellant, consider acceleration of a particle with mass ***m*** and charge ***q***

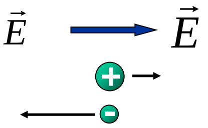
$$m\frac{d\vec u}{dt} = \underbrace{\overbrace{q\vec E}^{\text{Elec. Field}}}_{\text{Electrostatic Force}} + \underbrace{q\left(\overbrace{\vec u \times \vec B}^{\text{Mag. Field}}\right)}_{\text{Lorentz Force}} + \underset{\text{Collisional Force (Momentum Transfer)}}{\vec p} \qquad (1)$$



Motion of Charged Particle in E&B Fields

- How does charged particle move in electric and magnetic fields
- **Electric field only**
  - electron lighter, higher accel.

$$\frac{d\vec{u}}{dt} = \frac{q}{m}\vec{E}$$

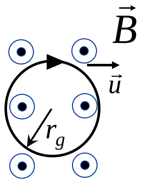


- **Magnetic field only**
  - particle gyrates (centripedal accel.)
  - radius of gyration
    Larmor radius
  - frequency of gyration
    cyclotron frequency
  - no work; B and F perpendicular

$$\frac{d\vec{u}}{dt} = \frac{q}{m}\left(\vec{u}\times\vec{B}\right)$$

$$r_g = \frac{m\left|\vec{u}\times\vec{B}\right|}{qB^2}$$

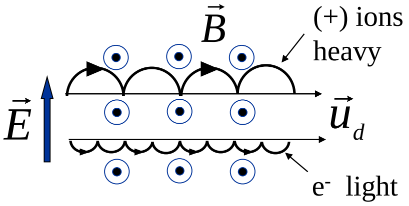
$$\omega_g = \frac{qB}{m}$$

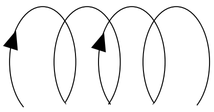


Motion of Charged Particle in E&B Fields

- **Crossed E and B fields**
  - E field accelerates (+) particle upward
  - B field causes acceleration perpendicular to u
  - overall result is drift velocity normal to E and B

$$m\frac{d\vec{u}}{dt} = q\vec{E} + q\left(\vec{u}\times\vec{B}\right)$$





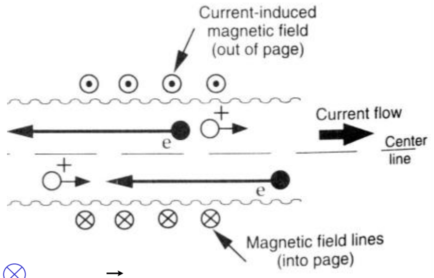
$$r_g \propto m$$

$$\omega_g \propto 1/m$$

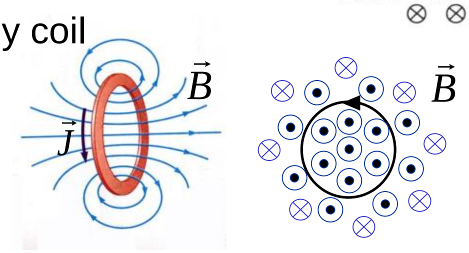
$$\vec{u}_d = \frac{\vec{E}\times\vec{B}}{B^2}$$

Induced Magnetic Fields

- In general, current flow induces a B field
  - B field induced by linear current



  - B field induced by coil



From *Space Propulsion Analysis and Design*, Humble, Henry and Larson, 1995

Plasmas

- Gas composed of equal “amount” of negatively and positively charged particles
  - electrically neutral
  - negative particles usually e^-
  - positive particles are positive ions
  - most of gas molecules often remain neutral (weak plasma, or partially ionized gas)
- **Momentum equation for plasma**

$$\rho\left(\frac{\partial\vec{u}}{\partial t}+\vec{u}\cdot\nabla\vec{u}\right)=-\nabla p+\vec{j}\times\vec{B}$$

↖Current Density (A/m^2)

$$\nabla\vec{u}\equiv\left(\nabla u_1,\nabla u_2,\nabla u_3\right)$$

Induced E Fields – Hall Effect

- **Electron acceleration**
  - – lighter e^- accelerate more quickly and accommodate to flow field (most of *j*)
  - – collisional coupling (momentum) of electrons to heavies (ions and neutrals) is weak

$$\Rightarrow \vec{E} = \eta\,\vec{j} - \underbrace{\vec{u}\times\vec{B}} + \underbrace{\vec{j}\times\frac{\vec{B}}{n_e e}} - \frac{\nabla p_e}{n_e e} \qquad (2)$$

plasma resistivity (Ωm)

$$\eta = m_e \nu_{ce} / n_e e^2$$

collision freq. electrons with heavies

Induced E field due to plasma motion

Hall Effect accelerates heavy particles in charge neutral plasma

electron pressure term