

AE6450 Fall 2004  
Lecture #14  
Electric Propulsion

The "jet" or exhaust power ( $P_{jet}$ ) of any thruster is:

$$P_{jet} = 1/2 g_c I_{sp} F$$

Thus, for a situation where we wish to fix the thrust at a constant value, as specific impulse increases, the jet power must also increase.

Jet power is in turn a function of the total "bus" electric power ( $P_e$ ) and the overall efficiency ( $h$ ) of converting electric power into jet power:

$$P_{jet} = P_e h$$

..The mass of the electric power system (as well as power conditioning and thrusters) is proportional to the total "bus" electric power:

$$M_{power} = a P_e$$

where  $a$  is the overall system specific mass (typically in kg/kW electric).  
Finally, ..

$$M_0 / M_b = \exp (\Delta V / g_c I_{sp})$$

The propellant mass ( $M_p$ ) is simply the difference between  $M_0$  and  $M_b$ :

$$M_p = M_0 - M_b$$

# Designing Electric Propulsion

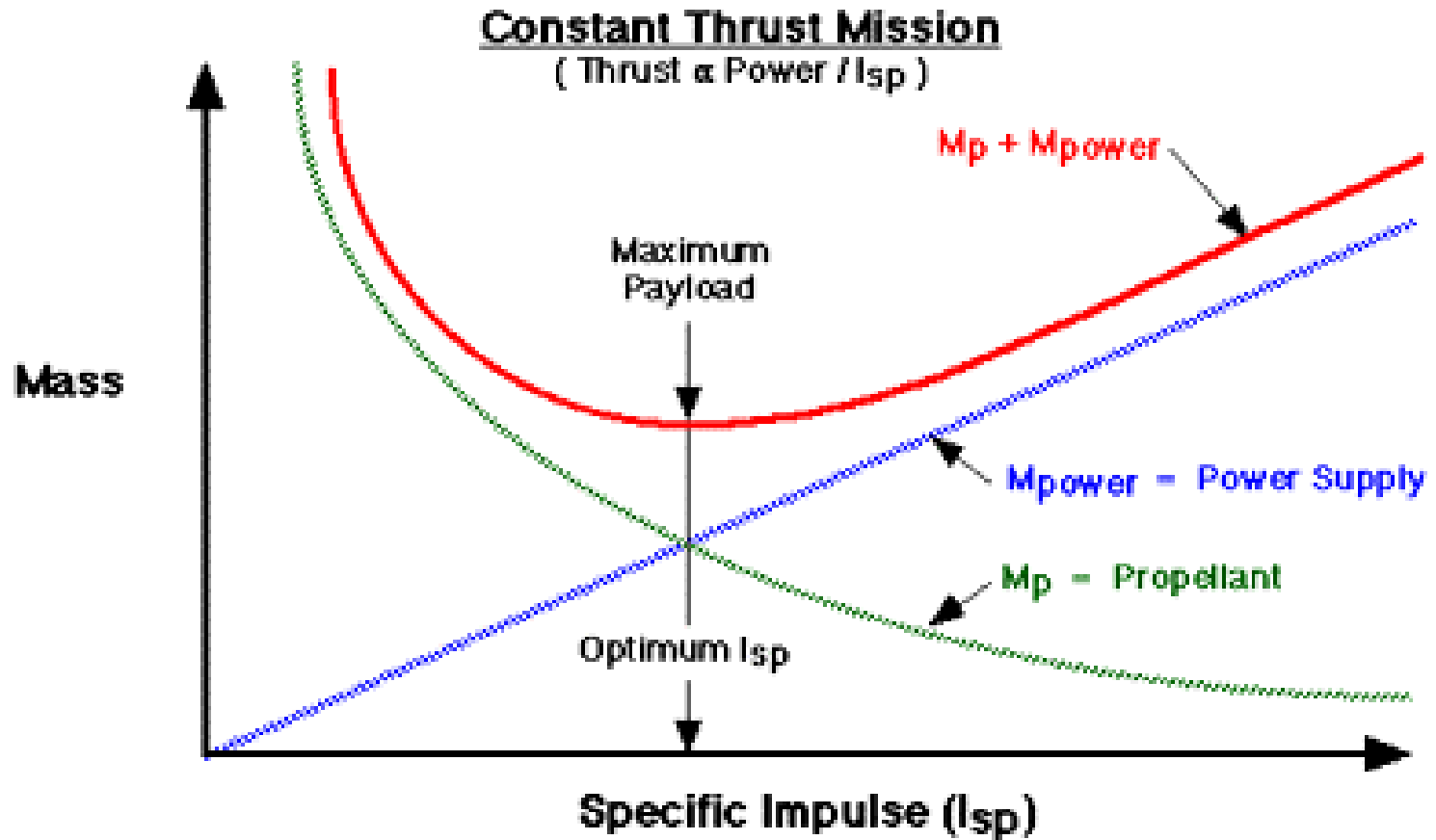
## Path A: Power Source Based on Chosen Thruster and Mission

**Specify Mission – Select Thruster – Select Power Source  
Design Thermal Mgmt System – Design Power Conditioning System –  
Assess Performance**

## Path B: Power Source Based on What is Available from Spacecraft

**Specify Mission – Select Power Source - Select Thruster –  
Design Power Conditioning - Design Thermal Mgmt System –  
System – Assess Performance**

# Optimum Specific Impulse



Courtesy: Robert.H. Frisbee, JPL

<http://www.islandone.org/APC/Electric/impulse.gif>

# System Analysis

Thrust or Jet Power:  $P_j = \frac{\dot{m}_p U_e^2}{2}$

$$\dot{m}_p = \dot{m}_i \left[ 1 - e^{\frac{-\Delta V}{U_e}} \right]^2$$

$\dot{m}_i$  : Initial mass

Required sourcepower  $P_s = \frac{P_j}{\eta_T}$

System inert mass  $m_{inert} = \beta P_s = \frac{P_s}{\alpha}$

$\beta$  : Specific mass of propulsion system (Kg/W)

$\alpha$  : Specific power of propulsion system (W/Kg)

If thrust duration (assuming constant thrust) is  $\tau$ ,

$$\dot{m}_p = \frac{m_p}{\tau}$$

$$m_{inert} = \frac{\beta U_e^2 m_p}{2\eta_T \tau}$$

$$m_{pay} = m_f - m_{inert} \quad \text{where } m_f \text{ is final mass achieving } \Delta V$$

$$\Rightarrow \frac{m_{pay}}{m_i} = e^{\frac{-\Delta V}{U_e}} - \left[ 1 - e^{\frac{-\Delta V}{U_e}} \right] \frac{\beta U_e^2}{2\eta_T \tau}$$

**Design goal: maximize payload mass fraction. Define:**

$$U_0 \sqrt{\frac{\eta_T \tau}{\beta}}$$

$$\Delta V^* = \frac{\Delta V}{U_0}$$

$$U_e^* = \frac{U}{U_0}$$

$$\Rightarrow \frac{m_{pay}}{m_j} = e^{\frac{-\Delta V^*}{U_e^*}} - \frac{1}{2} \left[ 1 - e^{\frac{-\Delta V^*}{U_e^*}} \right] U_e^{*2}$$

**Propulsion system mass per unit of jet power:**

**Jet-specific mass**

$$\beta_j = \frac{\beta}{\eta_T} = \frac{1}{\alpha\eta_T}$$

**Optimal exhaust speed:**

$$U_{e0} = k \sqrt{\frac{\tau}{\beta_j}}$$

**Where  $k \sim 1$**

If  $\beta_j$  is too high, or the allowable thrust time is too low, optimum speed may be less than that from chemical rockets.

May still use electric propulsion for missions with electric power supply;

Primary electric propulsion will not benefit from power system sharing until it is a large scale mission with many MW of power

Possible uses -> station-keeping (no benefit to impulsive thrust)  
-> lifting large structures (low g; continuous thrust)

$$\left( \Delta V \approx 2.3 \Delta V_{impulsive} \right)$$

-> Electric primary propulsion needs  $I_{sp} > 1000s$  to compete

with modern chemical system  $I_{sp}$  (450s)

# Electromagnetic Propulsion

Electromagnetic force per unit volume on a gas carrying current in a magnetic field

$$\vec{F}_m = \vec{j} \times \vec{B}$$

$\vec{B}$  magnetic induction field in gas (Tesla)

$\vec{j}$  Electric current density In gas (A/m<sup>2</sup>)

$\vec{F}_m$  N/m<sup>3</sup>

# Electromagnetic Propulsion Systems

**Unsteady vs. Steady**

**Self-field vs. Applied Field.**

**Self Field:**

**Discharge currents whose own magnetic fields are high enough for efficient thruster performance without needing external applied magnetic fields. High power (MW)**

**Available in short pulses from capacitor bank: unsteady operation.**