Making Cents of Space Travel: The Economics of In-Space Propulsion

Manju Bangalore
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Chemical rocket

- Thrust
- Fuel
- Oxidizer
- Low temperature
- Low fuel efficiency
- Exhaust

Electric rocket

- Thrust
- Fuel
- Solar panels
- Electricity
- High temperature
- High fuel efficiency
- Exhaust

Electric rockets are more fuel efficient. Use electricity rather than chemical combustion to produce hot exhaust gases.
Overall Project

- Create equations for delta \( v \) and trip time as functions of power, mass, specific impulse, and efficiency

- Develop excel-based spacecraft model including mass and costs for all subsystems
Procurement of Equations

- Utilized SEPSOT, MATLAB, and Excel
- Cases vary by orbit, specific impulse, efficiency, shadowing, and power
**Graphs for Equations**

**Figure 1.** Power versus ΔV for GTO to GEO with shadowing on.

**Figure 2.** Power versus ΔV for GTO to GEO with shadowing off.

**Figure 3.** Trip time in terms of acceleration for GTO to GEO shadow on.

**Figure 4.** Trip time in terms of acceleration for GTO to GEO shadow off.
GTO to GEO Equations

Delta V

$\Delta V = 2.65$

Trip Time

as a function of start mass, power, efficiency, and specific impulse:

$$t = (2 \times 10^{-5}) \left( \frac{2\eta p}{m_0 g I_{sp}} \right)^{-1.018}$$
Incremented Apogee

\[ c = -0.44 \ln(a) + 5.6203 \]

\[ t = (c)(2 \times 10^{-5}) \left( \frac{2 \eta p}{m_0 g I_{sp}} \right)^{-1.018} \]
When does low-thrust propulsion make more sense than chemical?

We have to look at mass utilization and the time-value of the mission to find the optimal solution.
Sensitivity Analyses

- Power
- Start mass
- Specific impulse
- Efficiency
- Cost
- Revenue ($k/kg) of payload
- Launch costs (for specific vehicles)
<table>
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<tr>
<th><strong>Spacecraft Model</strong></th>
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| **Propulsion Wet Mass, kg** | 979.339566. This was found by adding the tank mass, the propellant mass, and the total propulsion dry mass. |
| **SEF Radiator Mass, kg** | 17.76669339. This was found by subtracting the PPU efficiency from 1 and multiplying it by the maximum SEF power and 1000, dividing it by 5.67 x 10⁻⁸, multiplying it by radiator emissivity, dividing it by the difference of the radiator temperature to the fourth and the environment temperature to the fourth, dividing it by two, and multiplying it by the radiator areal density. |
| **Battery Mass, kg** | 0.001333333 |
| **Power BOP Mass, kg** | 40. This is an estimate. |
| **Avionics Mass, kg** | 50. This is an estimate. |
| **Dry Mass w/o Structure and Tanks, kg** | 912.7709984. This is the sum of the total propulsion dry mass without tank, the array mount and tint mass, the SEF radiator mass, the battery mass, the power BOP mass, the avionics mass, and the solar array mass. |
| **Structure Mass, kg** | 139.4382183. This is calculated by multiplying the structures percentage by the sum of the dry mass without structure and tanks and the tank mass. |
| **Delta V, km/s** | 2.65. This is derived from the SEFSPOT curves. |
| **Ideal Final mass, kg** | 3655.3632362. This was found by taking the exponential of the product of 1000 and the AV and the reciprocal of the gravitational constant multiplied the specific impulse and multiplying it by the initial mass. |
| **Starting specific power, W/kg** | 0.01. This was found by dividing the maximum SEF power by the start mass. |
| **Starting acceleration, m/s²** | 4.417308-07. This was found with the Rocket Equation. The calculation was 2 times the efficiency and power of the spacecraft divided by g, the initial mass, and the specific impulse. |
| **Total Propellant Mass, kg** | 373.713861. This is the propellant residual mass added to the difference of the start mass and final mass. |
| **Propellant Residual Mass, kg** | 29.27712275. This is the difference of the start and final spacecraft mass multiplied by the propellant and residual percentages. |
| **Required Propellant, kg** | 344.4307183. This is calculated by subtracting the final mass from the initial mass. |
| **Tank Mass, kg** | 16.81712375. This is calculated by multiplying the total propellant by the tank mass fraction. |
| **Trip Time, Days** | 66.77740889. This is derived from the SEFSPOT curves. |
| **Total SEP Wet Mass, kg** | 1442.740201. This is the sum of the dry mass without the structure and tanks, the structure mass, the task mass, and the propellant mass. |
| **Non-SEP Mass, kg** | 2557.2397999. This is the total SEP wet mass subtracted from the initial mass. |
| **Partial SEP Cost, $K** | $94,240.71. This is the sum of costs of the solar array, the product of the hardware per string and the |
Falcon 9

launch cost

Graph showing net revenue in $M vs. specific impulse in seconds for different percentages: 100%, 80%, 60%, 40%, and 20%.
Atlas V 551

thruster quantity
Applicability

Will be used to guide future space architecture assessments.
thank you!