SPECIFIC MASS REQUIREMENTS FOR HUMAN NUCLEAR ELECTRIC PROPULSION MISSIONS TO MARS

C. G. Morrison[1], W. Ji[2], A. V. Ilin[3], F. R. Chang Díaz[4] and M. D. Carter [5], [1-2]Rensselaer Polytechnic Institute, morric7@rpi.edu, [3-5]Ad Astra Rocket Company, andrew.ilin@adastrarocket.com

Introduction: Electric propulsion technology has rapidly advanced in the last fifteen years enabling missions to deep space with greatly reduced propellant requirements. However, the timescales required for these missions depend on the power source's specific mass.

This research explores the breakthrough power source specific power at which an electric propulsion mission could enable human Mars missions. The adage goes, "If it's not cheaper or better than what's currently available, it will not sell." This research aims to determine the specific mass at which electric propulsion technology matches nuclear thermal and chemical propulsion.

The Importance of Specific Mass: When planning a deep space mission there are two questions that can be asked that can be answered by two equations:

1. How much can be carried?

$$\Delta V = \sqrt{2\mathrm{E}}\, ln\left(1+\frac{\bar{P}_{sc} m_p}{P_{jet}}\right) \qquad \text{Rocket Equation (1)}$$

2. How fast can the mission be performed?

$$\bar{a} = \frac{\sqrt{2}\, P_{jet}\, ln(1+\bar{P}_{sc} m_p / P_{jet})}{\sqrt{E}\, m_p} \qquad \text{Avg. Acceleration (2)}$$

Table 1: Effects of Increasing Variables on ΔV and $\bar{a}$

Variable		$\bar{a}$	ΔV
E	Jet Energy Density [J/kg]	↓	↑
m_p	Initial Propellant Mass [kg]	↓	↑
P_{jet}	Jet Power [W]	↑ then ↓	↓
$\bar{P}_{sc}$	Specific Jet Power [W/kg]	↑	↑

Equations (1-2) break down into four fundamental variables. Maximizing ΔV and $\bar{a}$ maximizes the capability of a spacecraft. The only variable that increases both is the specific jet power. Optimizing the specific jet power optimizes the performance of an electric spacecraft:

$$\bar{P}_{sc} = \frac{P_{jet}}{mass_{spacecraft}} \qquad \text{Specific Jet Power (3)}$$

A slightly modified metric can be defined called the power and propulsion system specific power ($\bar{P}_{PPS}$). Maximizing the power and propulsion system specific power is the best approach to increasing the specific jet power of the spacecraft:

$$\bar{P}_{PPS} = \frac{P_{jet}}{mass_{\text{power source}} + mass_{\text{engine}}} \qquad (4)$$

$$\bar{P}_{PPS} = \frac{\eta_{engine}\, \bar{P}_{power\ source}\, \bar{P}_{engine}}{\bar{P}_{power\ source} + \bar{P}_{engine}} \qquad (5)$$

The equation (5) can then be inverted to be in terms of specific mass rather than specific power:

$$\alpha_{PPS} = \frac{(\alpha_{\text{power source}} + \alpha_{\text{engine}})}{\eta_{\text{engine}}} \qquad \text{PPS Specific Mass (6)}$$

The specific mass (α) of the power and propulsion system is the fundamental metric of an electric propulsion system. Lower specific masses enable further and faster missions.

Mars Mission: The NASA Mars Design Reference Architecture (DRA) has reference architectures for both chemical and nuclear thermal propulsion missions to Mars [1].

Utilizing mission parameters similar to the DRA, electric propulsion missions were planned by Dr. Chang Díaz in his recent publication [2]. Using the data from that paper as well as new data generated using the same methods, breakeven points were found at which electric propulsion matched chemical and nuclear thermal for both the number of days in space and the payload fraction.

Figure 1 illustrates the results for an electric propulsion mission with a 17.6% payload mass fraction corresponding to the nuclear thermal rocket mission from the DRA.

A power and propulsion specific mass of 20 kg/kW can match the 374 in flight days and the 17.6% payload fraction of the DRA's nuclear thermal reference. A power and propulsion specific mass of 24.1 kg/kW matches the 374 in flight days and the 10.7% payload mass fraction of the DRA chemical system. The breakeven power for the electric propulsion system for a 374 in-flight day trip was found to be 5.6 MW of jet power.

The orbital mechanics data reflected in the figure is based upon data for the VASIMR electric propulsion system. The VASIMR engine has better performance due to its ability to throttle over a large range of Isp, the power and propulsion system requirements will be slightly more stringent for other electric propulsion systems.

Power Source Specific Mass: The specific mass of the power source from Equation (6) is dependent upon the electric propulsion technology:

$$\alpha_{\text{power source}} = \alpha_{PPS}\eta_{\text{engine}} - \alpha_{\text{engine}} \qquad (7)$$

Using an engine specific mass of 1.2 kg/kW and an efficiency of 70% [2] and the numbers previously found for the power and propulsion specific mass, the requirements for a power source can be found. Table 2 lists the power source specific mass that matches the nuclear thermal and chemical DRA mission for the parameters listed in this section.

Table 2: Power Source Specific Mass Matching DRA Performance Given the Electric Propulsion Parameters Listed in this Section

Propulsion Method	Specific Mass
Chemical Propulsion	15.7 kg/kW
Thermal Propulsion	12.8 kg/kW

In order to clearly demonstrate an advantage over nuclear thermal propulsion, a more stringent power source specific mass requirement of 10 kg/kW is suggested as a basis point for a first generation Mars human electric propulsion power source requirement.

Nuclear power sources are feasible power sources. Figure 2 lists several flown and proposed fission systems. As the power of the systems increases, the specific mass of the systems appears to decrease. Based upon the trend, a nuclear power system with approximately 3 MW unit power and above can meet the 10 kg/kW requirement.

Conclusion: Based upon a comparison to the NASA DRA and orbital mechanics simulations, specific mass requirements were derived that allow an electric propulsion mission to perform on par with chemical and nuclear thermal propulsion.

References: [1] Drake B. (2009) *Human Exploration of Mars Design Reference Architecture 5.0*. [2] Chang Díaz F. R. et al. (2013) *Advanced Nuclear Electric Power and VASIMR Propulsion* [3] Longhurst G. R. et al. (2001) Multi-Megawatt Power System Trade Study. [4] Eades M. et al. (2013) Minimizing System Mass for a Closed Brayton System as a Function of Reactor Specific Mass for Nuclear Electric Propulsion Missions. [5] Litchford R. J. (2011) Multi-MW Closed Cycle MHD Nuclear Space Power Via Nonequilibrium He/Xe Working Plasma [6] Deason, W. et al (2011) Trade Study of a 20 Megawatt Electric Low Specific Mass [7] Gillbrand J. H. (2012) MW-Class Electric Propulsion System Designs for Mars Cargo Transport [8] Mason L. (2013) Nuclear Systems Specific Power Records [9] Taylor R., (2005) Project Prometheus Final Report. [10] El Genk M., (1986) Workshop on Nuclear Applications for Space. [11] Poston D. (2013) Design and Testing of Small Nuclear Reactors for Defense and Space Applications.

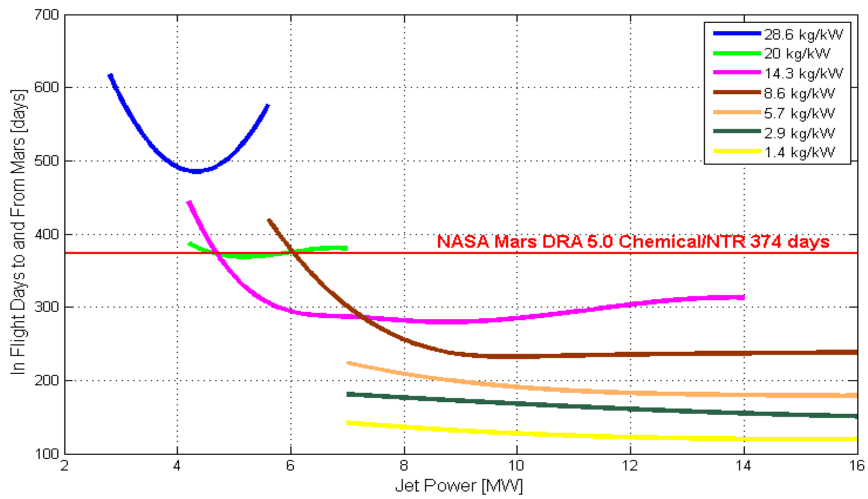

Figure 1: Power and Propulsion System Jet Specific Mass NTR Analysis

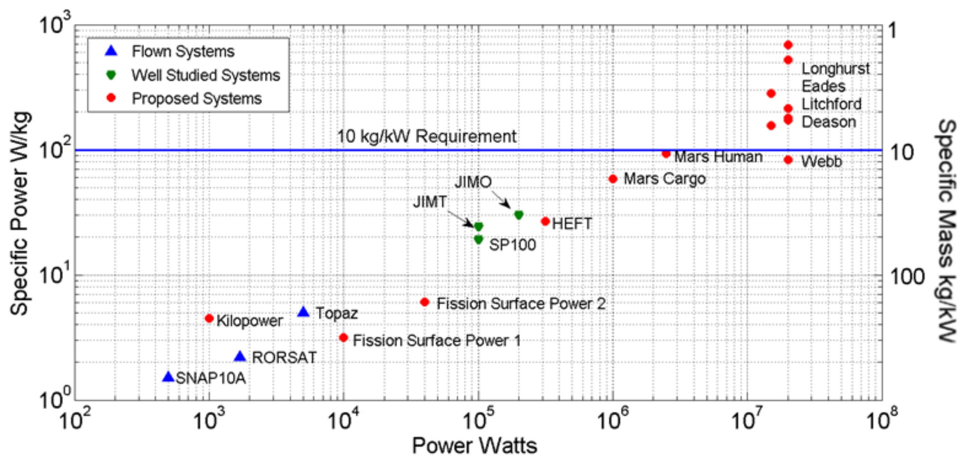

Figure 2: Electric Power vs. Specific Power for Various Nuclear Systems [3–11]