Evaluation of High-Power Solar Electric Propulsion Using Advanced Ion, Hall, MPD, and PIT Thrusters for Lunar and Mars Cargo Missions

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ABSTRACT

This paper presents the results of mission analyses that expose the advantages and disadvantages of high-power (MW_e-class) Solar Electric Propulsion (SEP) for Lunar and Mars Cargo missions that would support human exploration of the Moon and Mars. In these analyses, we consider SEP systems using advanced Ion thrusters (the Xenon [Xe] propellant Herakles), Hall thrusters (the Bismuth [Bi] propellant Very High I_{sp} Thruster with Anode Layer [VHITAL], magnetoplasmadynamic (MPD) thrusters (the Lithium [Li] propellant Advanced Lithium-Fed, Applied-field Lorentz Force Accelerator ($ALFA^2$), and pulsed inductive thruster (PIT) (the Ammonia [NH_3] propellant Nuclear-PIT [NuPIT]). The analyses include comparison of the advanced-technology propulsion systems (VHITAL, $ALFA^2$, and NuPIT) relative to state-of-the-art Ion (Herakles) propulsion systems and quantify the unique benefits of the various technology options such as high power-per-thruster (and/or high power-per-thruster packaging volume), high specific impulse (I_{sp}), high-efficiency, and tankage mass (e.g., low tankage mass due to the high density of bismuth propellant). This work is based on similar analyses for Nuclear Electric Propulsion (NEP) systems.[1-3]

Lunar Cargo Mission

Figure 1 illustrates the results of preliminary analyses for the Lunar Cargo mission. In each case, the Ion (Herakles) system is used as a reference for determining overall mission performance in terms of initial mass in low Earth orbit (IMLEO) and trip time between a 400-km altitude low Earth orbit (LEO), comparable to the altitude of the International Space Station, and a 100-km altitude low Lunar orbit (LLO). In these systems, there is a complex interplay between thruster I_{sp} and efficiency, and overall vehicle mass and trip time. Generally, lower values of I_{sp} favor trip time because, for a given power, thrust increases (and trip time decreases) as I_{sp} decreases. However, this trip time benefit can be somewhat negated if the thruster efficiency drops off at low I_{sp}, as it does with Ion thrusters (e.g., a 3% decrease in thruster efficiency over the I_{sp} range of 5,000 to 7,000 lb_f-s/lb_m). Also, low I_{sp} adversely impacts mass due to the exponential increase in wet mass through the Rocket Equation. Thus, we see that the Ion system has an optimum I_{sp} around 6,000 lb_f-s/lb_m where both mass and trip time are lower than at higher or lower values of I_{sp}. In contrast, the relatively constant efficiency of the advanced-technology thruster actually favors a lower I_{sp}, resulting in them being the lightest at an I_{sp} of 5,000 lb_f-s/lb_m. Also, as discussed below, the relatively low power-per-thruster of the Ion thruster results in a very large parts count, and ultimately dry mass, for the Ion propulsion system. Finally, all the 0.9-year round-trip SEP Cargo Vehicles have a lower IMLEO than the expendable Chemical (O_2/H_2) Cargo Vehicle, although the high-T/W Chemical system has a

much shorter trip time (e.g., 3 days LEO-to-LLO in Apollo, or 5 days for a minimum-energy LEO-to-LLO DV).

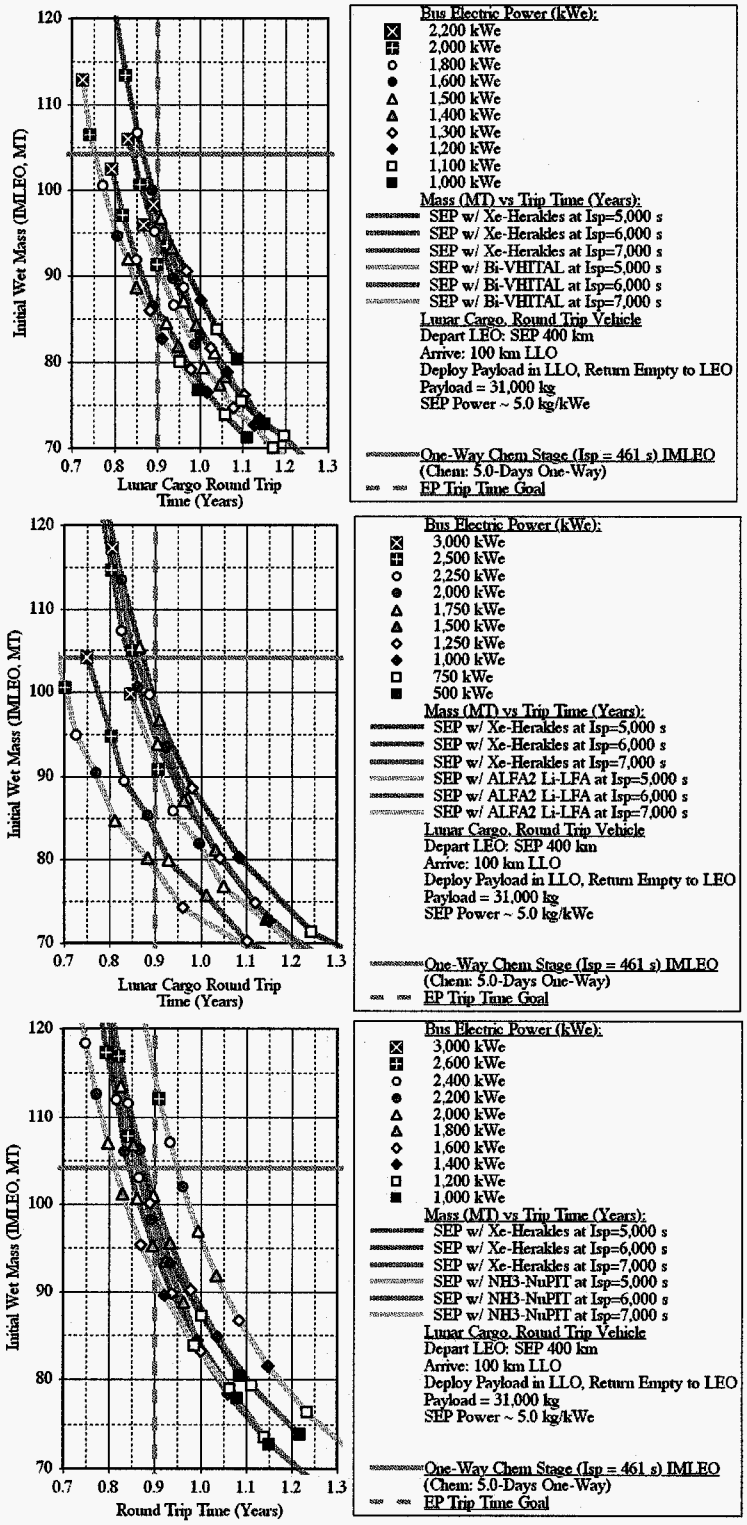

Figure 1. Variation in IMLEO and Round Trip Time for the SEP Lunar Cargo Mission.

Another important element of mission feasibility is the overall system complexity, as quantified in this study by a parts count for the propellant storage and feed system, plus the number of thrusters and PPUs. Figure 2 illustrates the propulsion system parts count as a function of the total or bus power level. Also shown in Figure 2 are the power levels required to achieve the target round-trip trip time of 0.9 year. Here, we see that the Ion system, with its relatively low power-per-thruster, has a has a significantly greater parts count than any of the advanced thruster options. (Note that because we have kept the ALFA^2 and NuPIT power-per-thruster constant, independent of I_{sp}, the parts count curves for the three ALFA^2 and NuPIT I_{sp} cases fall on top of each other.) Finally, the relatively modest ΔV of the Lunar Cargo Mission results in a modest propellant load, so the limited lifetime (throughput) of the VHITAL and ALFA^2 thrusters is not an issue for the Lunar mission; in fact, the throughput of the VHITAL thruster could be on the order of 17% of its baseline value and still only require a single set of VHITAL thrusters per mission.

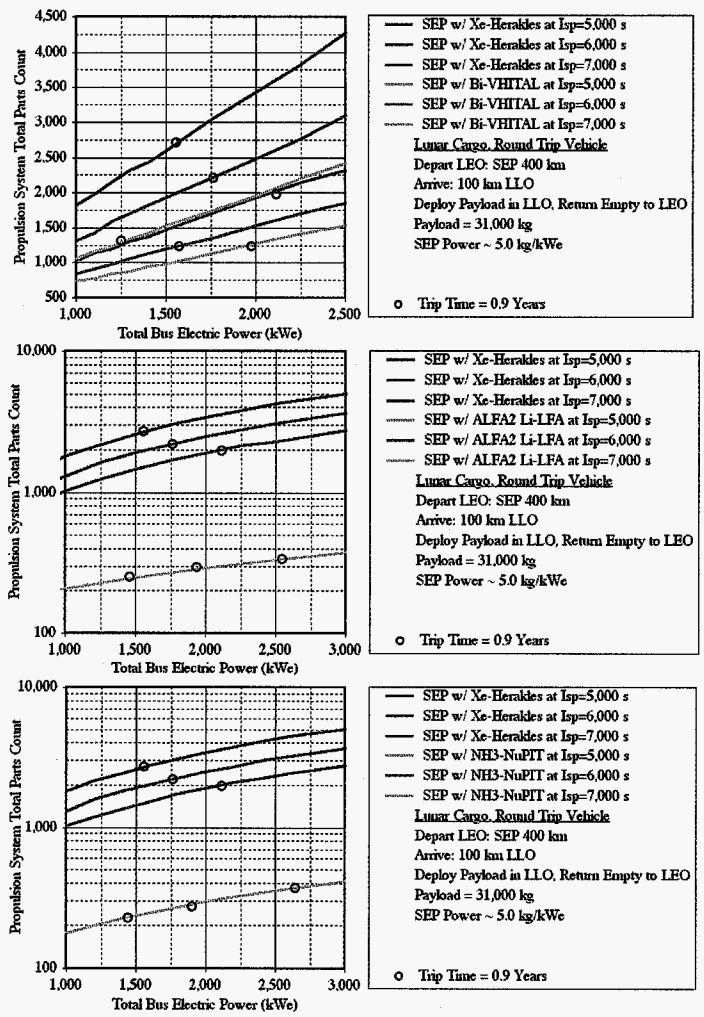

Figure 2. Electric Propulsion System Parts Count vs Total Bus Electric Power for the SEP Lunar Cargo Mission.

Figure 3 illustrates the mass breakdown for the various elements of the SEP vehicle at the values of total or bus power level required to meet the requirement of a 0.9-year round trip (to enable a 1-year delivery cycle with one SEP vehicle). Typically, as I_{sp} decreases, the power level (and thus power system mass) required for a given trip time decreases. However, decreasing I_{sp} also results in a higher propellant mass; thus, there can be a complex interaction between trip time, I_{sp}, power system mass, propellant mass, and total vehicle mass (IMLEO). The various SEP systems have a sufficiently high I_{sp} that reducing their I_{sp} significantly reduces their power system mass, which compensates for the slightly higher propellant mass due to lower I_{sp}. For the Ion system, the optimum (minimum-IMLEO) I_{sp} is around 6,000 lb_f-s/lb_m. By contrast, the VHITAL, ALFA2, and NuPIT systems have the lowest IMLEO at the lowest I_{sp} considered here, 5,000 lb_f-s/lb_m. Part of the difference in behavior between the Ion and advanced-technology systems is that Ion thruster efficiency drops off significantly at t lower values of I_{sp}; by contrast, the assumed efficiency for the advanced systems drop only slightly over the I_{sp} range of 5,000 to 7,000 lb_f-s/lb_m. Also, when compared to the advanced systems at the same 5,000- lb_f-s/lb_m I_{sp}, the higher power required for the Ion system is due to its higher propulsion system dry mass (because of the Ion thruster s lower power-per-thruster as I_{sp} decreases). Finally, the Chemical stage has minimal dry mass but very large propellant mass due to its low I_{sp} (as compared to the I_{sp} of the electric thrusters).

Mars Cargo Mission

As with the Lunar Cargo cases, we see similar relative performance between the various electric propulsion systems for an SEP Mars Cargo Mission, as shown in Figure 4. For this mission, the LEO-to-low Mars orbit (LMO) ΔV is typically on the order of 16 km/s, which is roughly the same as that for a round-trip Lunar Cargo mission. However, in the Mars Cargo case, the Cargo payload is carried through the full ΔV (whereas the Lunar Cargo is only carried through a ΔV of ~8 km/s); thus the optimum I_{sp} is around 7,000 lb_f-s/lb_m. For this mission, higher I_{sp} values result in the need for a higher power to achieve a given trip time such that the increase in power system mass (and corresponding increase in thruster, PPU, etc. mass) essentially negates any propellant (and propellant tankage) mass savings afforded by the higher I_{sp}.

We chose an Earth-to-Mars trip time goal of 2.2 years to match the Earth-Mars synodic period. Figure 5 again illustrates the general trend of requiring higher power at higher I_{sp} values in order to achieve a desired trip time. We also see the similarity in IMLEO and power between the various electric thruster systems. Also, it is worth noting the different contributions to dry mass between the SEP and Nuclear Thermal Propulsion (NTP) vehicle options (and, correspondingly, the SEP and Chemical vehicles in the Lunar Cargo case). For example, the SEP systems have a significant fraction of their dry mass tied up in the electric power system. However, the actual propulsion system (e.g., thrusters, tankage, etc.) is relatively modest. By contrast, the NTP (or Chemical) vehicle has a much higher propellant load, and correspondingly high propulsion system dry mass, even though it has a minimal power system (for vehicle "housekeeping" needs). (Also, the NTP option requires that the net payload be aerocaptured directly into Mars orbit; thus, an aeroshell is included in the NTP option. By contrast, the SEP vehicles deliver the payload directly into Mars orbit, so an Aeroshell is not needed.) Finally, it is worth noting that the Lunar and Mars SEP Cargo Vehicles have comparable power levels. This suggests the possibility for an evolutionary development program where a Lunar SEP Cargo "Tug" is first developed and deployed, followed by deployment of additional EP vehicles of the same general size for support of human Mars missions.

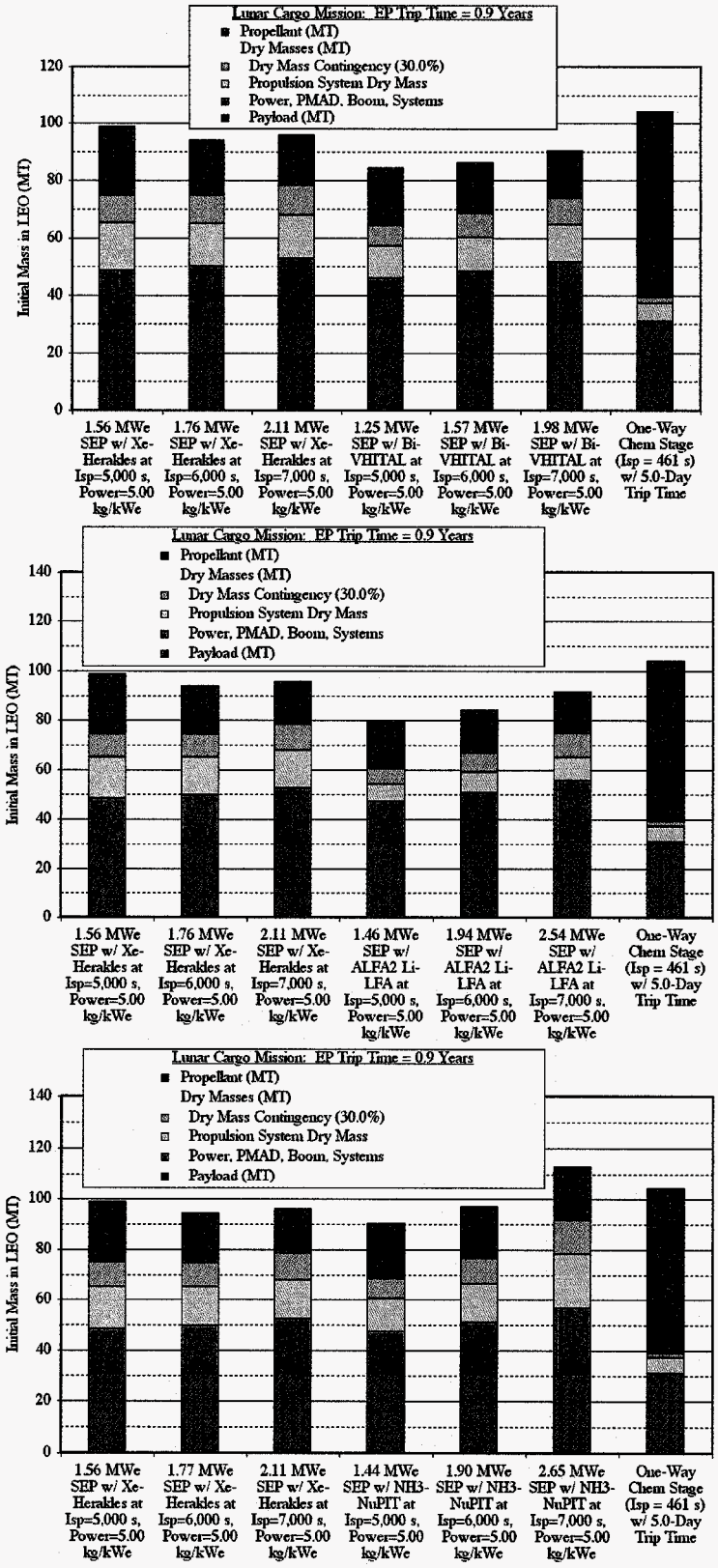

Figure 3. Mass Breakdown for SEP Lunar Cargo Vehicles with a 0.9-Year Round Trip Time.

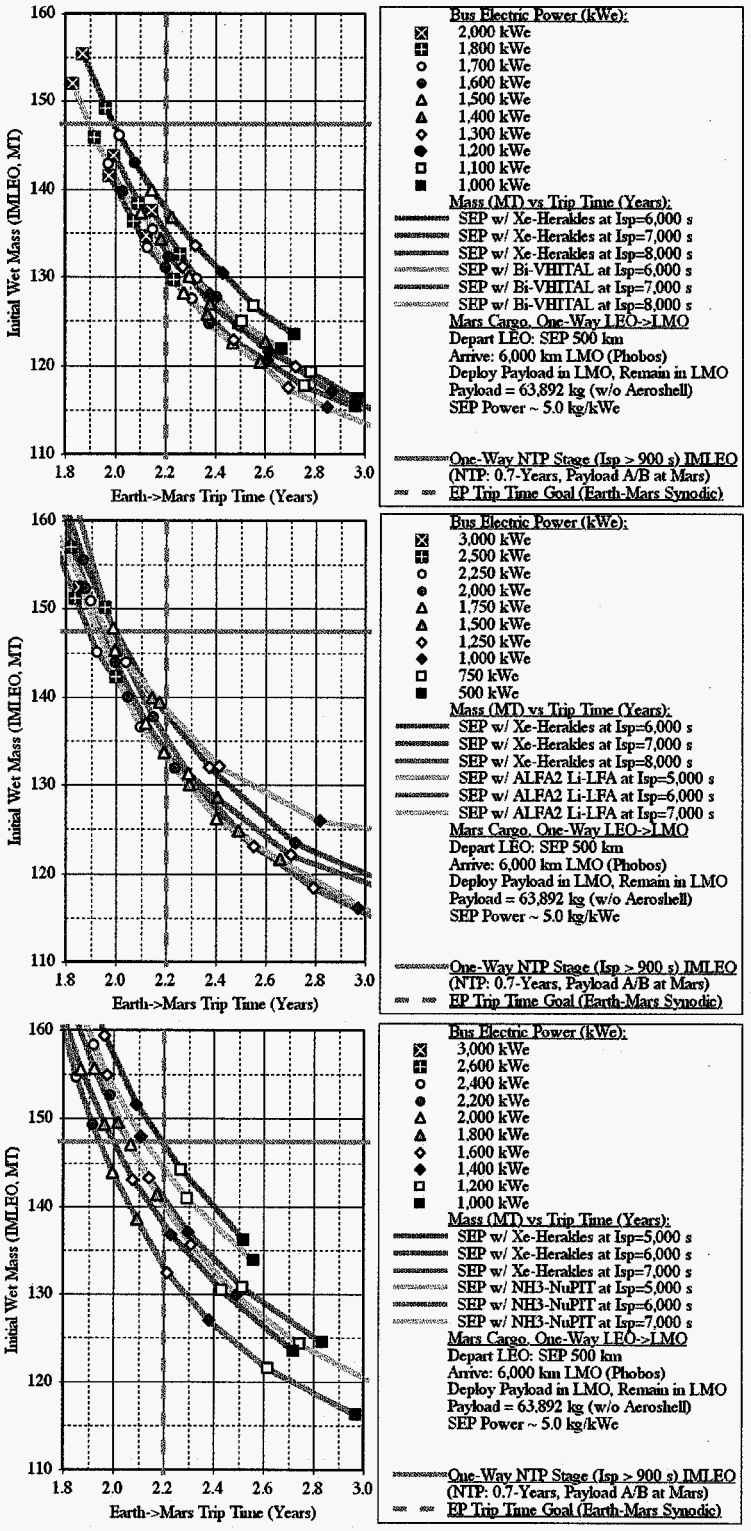

Figure 4. Variation in IMLEO and Trip Time for the SEP Mars Cargo Mission.

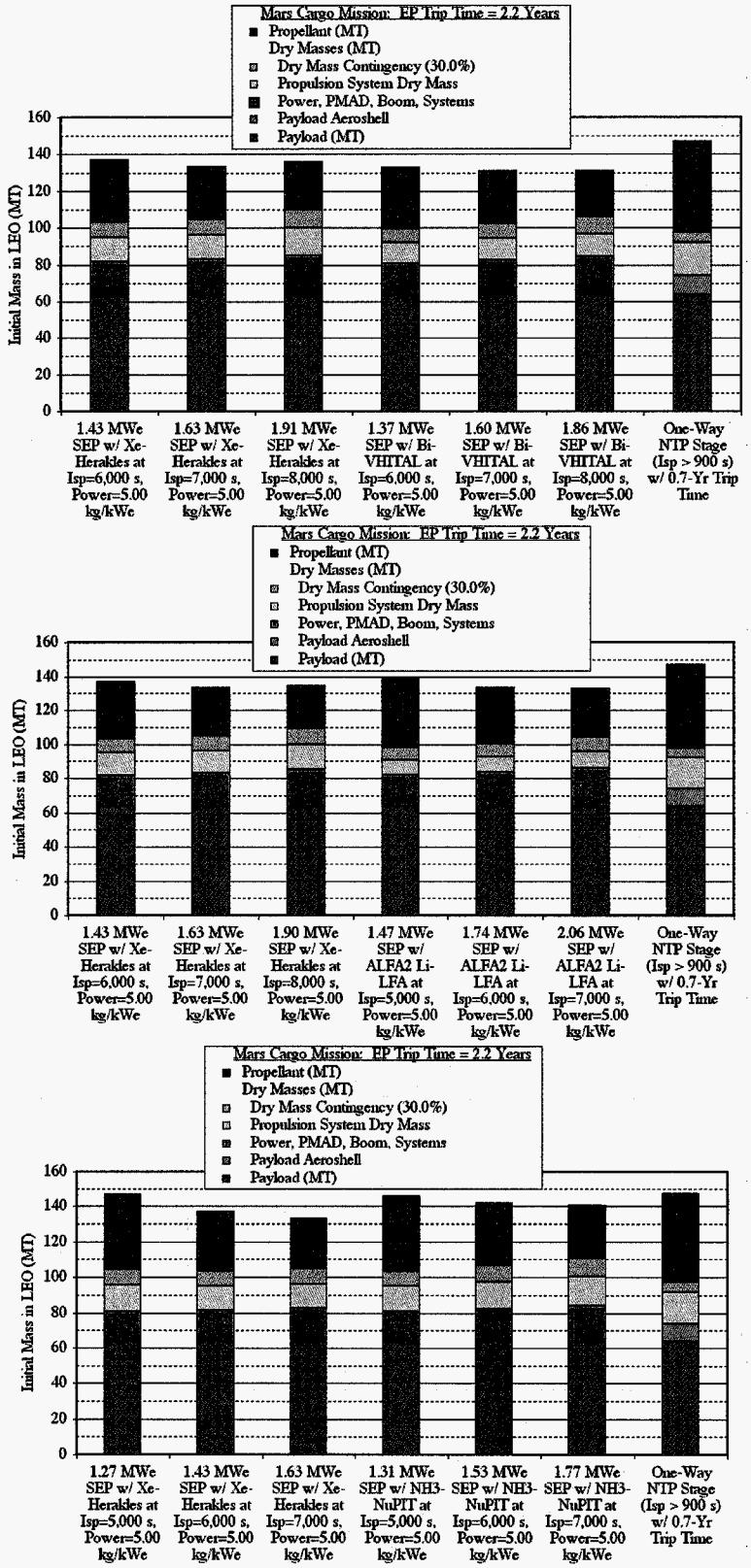

Figure 5. Mass Breakdown for SEP Mars Cargo Vehicles with a 2.2-Year Earth->Mars Trip Time.

Conclusions

Based on the results of these analyses, it is our general conclusion that there is no single advanced electric propulsion technology that is best for all combinations of missions, masses, trip times, specific impulses, power levels, payload masses, and so on. It is emphasized that the results presented here show only the *potential* impact of the various advanced VHITAL, ALFA[2], and NuPIT technologies on mission performance; these results have been based on assumed improvements over the state-of-the-art performance and lifetime of these systems. These assumed improvements must be demonstrated in the laboratory to validate the mission advantages shown here, and to provide the technology base that will be required to enable future bold Robotic and Human Solar System exploration missions of the 21st Century. Further mission analyses using updated performance parameters should be performed as new information becomes available from the thruster research programs to provide a higher fidelity assessment of relative benefits.

References

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