MW-Class Electric Propulsion System Designs for Mars Cargo Transport

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Multi-kilowatt electric propulsion systems are well developed and have been used on commercial and military satellites in Earth orbit for several years. Ion and Hall thrusters have also propelled robotic spacecraft to encounters with asteroids, the Moon, and minor planetary bodies within the solar system. High power electric propulsion systems are currently being considered to support piloted missions to near earth asteroids, as cargo transport for sustained lunar or Mars exploration, and for very high-power piloted missions to Mars and the outer planets. Using NASA Mars Design Architecture 5.0 as a reference, a preliminary parametric analysis was performed to determine the suitability of a nuclear powered, MW-class electric propulsion system for Mars cargo transport. For this initial analysis, high power 100-kW Hall thrusters and 250-kW VASIMR engines were separately evaluated to determine optimum vehicle architecture and estimated performance. The DRA 5.0 cargo mission closed for both propulsion options, delivering a 100 t payload to Mars orbit and reducing the number of heavy lift launch vehicles from five in the baseline DRA 5.0 architecture to two using electric propulsion. Under an imposed single engine-out mission success criteria, the VASIMR system took longer to reach Mars than did the Hall system, arising from the need to operate the VASIMR thrusters in pairs during the spiral out from low Earth orbit.

Nomenclature

AISP = Advanced In-Space Propulsion
DAV = Descent/Ascent Vehicle
DDU = Direct Drive Unit
DRA = Design Reference Architecture
EDL = Entry, Descent and Landing
ETDD = Exploration Technology and Demonstration Program
HAT = Human Architecture Team
HEFT = Human Exploration Focus Team
HLLV = Heavy Lift Launch Vehicle
IMLEO = Initial Mass in Low Earth Orbit

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I_{sp} = Specific Impulse
LEO = Low Earth Orbit
MEL = Master Equipment List
MPD = Magnetoplasmadynamic
NaK = Sodium-Potassium
NEP = Nuclear Electric Propulsion
NTP = Nuclear Thermal Propulsion
NTR = Nuclear Thermal Rocket
PIT = Pulsed Inductive Thruster
PPU = Power Processing Unit
SHAB = Surface Habitat
Sol = Martian solar day ≈ 1.0275 Earth day
TRL = NASA Technology Readiness Level
VASIMR = Variable Specific Impulse Magnetoplasma Rocket

I. Introduction

Inspiring generations of scientists, engineers, visionaries and dreamers, the human exploration of Mars remains a priority long term goal for the world's space agencies. The latest National Aeronautics and Space Administration (NASA) Reauthorization Act[1] states that planned capabilities supporting initial human exploration missions beyond low-Earth orbit will "…provide the foundation for pursuit of international and other collaborative activities in the conduct of these and potential follow-on missions to the lunar surface and deep-space destinations, such as asteroids and ultimately the surface of Mars." In a companion to this paper, Mercer *et al.*[2] describe vehicle design options for a 300-kW electric propulsion system for a crewed mission to a near earth asteroid; in this paper, we discuss design options for a MW-class vehicle for pre-deploying cargo to Mars in support of human exploration.

The use of high power electric propulsion for cargo and even crewed missions to Mars is not a new concept; multiple prior studies have investigated various design options tied to a myriad of assumed mission architectures.[3,4,5,6,7,8,9] In this analysis we investigate the use of nuclear electric propulsion (NEP) for the cargo portion of the Mars Design Reference Architecture 5.0, the most recent NASA mission profile for the human exploration of Mars. In the following sections a brief overview of the mission architecture is presented, followed by a description of the power and propulsion system options evaluated during this preliminary study and a discussion of the resulting vehicle trades and optimized system designs. The paper concludes with a brief summary of results and suggestions for further analysis.

II. Mars Cargo Reference Mission

The *Human Exploration of Mars Design Reference Architecture 5.0* (DRA 5.0) was selected to bound the analysis and establish a common basis for comparison. Published in 2009, DRA 5.0 is the latest NASA Mars reference mission, and provides an integrated design approach along with the mission goals, systems, and challenges facing the first three human expeditions to Mars.[10] Of particular interest to this paper is the pre-deployment of two cargo elements encompassing the descent/ascent vehicle (DAV) and the surface habitat (SHAB), which would be launched, assembled, and checked out in low Earth orbit (LEO). Once verified, the vehicles would loiter in LEO until an Earth-Mars departure window opens, at which point they would be injected into a minimum energy transfer to Mars. After an approximately 350-day transit they would aerocapture into a highly elliptical Mars orbit, from which the DAV would autonomously perform entry, descent and landing (EDL) operations at the desired landing site, while the SHAB remained in orbit awaiting the arrival of the crew. Nuclear thermal propulsion was chosen as the baseline in-space propulsion system for both cargo and crew, using a common core stage of three 25-klbf (111-kN) NTP engines on all vehicles. Each cargo vehicle has an IMLEO of 246.2 t and a total of five Ares-5 heavy lift launches, carried out over 120 days, are required to place the cargo vehicle elements in LEO. Once in LEO, the elements rendezvous and dock to create the two cargo vehicles used to transport the cargo payloads to Mars. Each cargo vehicle has an overall length of 72.6 m, including the 30-m long aerocaptured payload. The total combined payload mass, including the aeroshell, EDL system, lander descent stage, and surface payload, is approximately 103 t. Using cryogenically stored liquid hydrogen as a propellant, the cargo vehicle NTP engines run for approximately 39 minutes and consume a total of 91 t of propellant. An overview of the DRA 5.0 long-stay mission architecture is depicted in Fig. 1, and additional details may be found in Ref. 10.

Because NEP vehicles have often been proffered as a means for economical cargo delivery to the Moon, Mars, and other planetary destinations, a limited study was undertaken under the auspices of the ETDD High Efficiency

Space Power Systems Project with support from the ETDD Advanced In-Space Propulsion Project to ascertain the utility of a MW-class nuclear electric propulsion (NEP) vehicle to perform the baseline Mars cargo mission outlined in DRA 5.0. In early July 2011, the COMPASS (Collaborative Modeling for Parametric Assessment of Space Systems) team at the NASA Glenn Research Center performed a detailed parametric trade study and design analysis to optimize delivery of the Mars DRA 5.0 cargo payloads using NEP. Various nuclear power systems and electric propulsion systems were considered, although due to limited time and funding only high power Hall thrusters and VASIMR engine options were evaluated in the initial analysis. Other potential high power plasma thrusters, such as the pulsed inductive thruster (PIT) and magnetoplasmadynamic (MPD) thruster, will be considered for future COMPASS trade studies. A consideration of very high power electric propulsion for the piloted portion of the Mars exploration mission is also under consideration, pending additional resources.

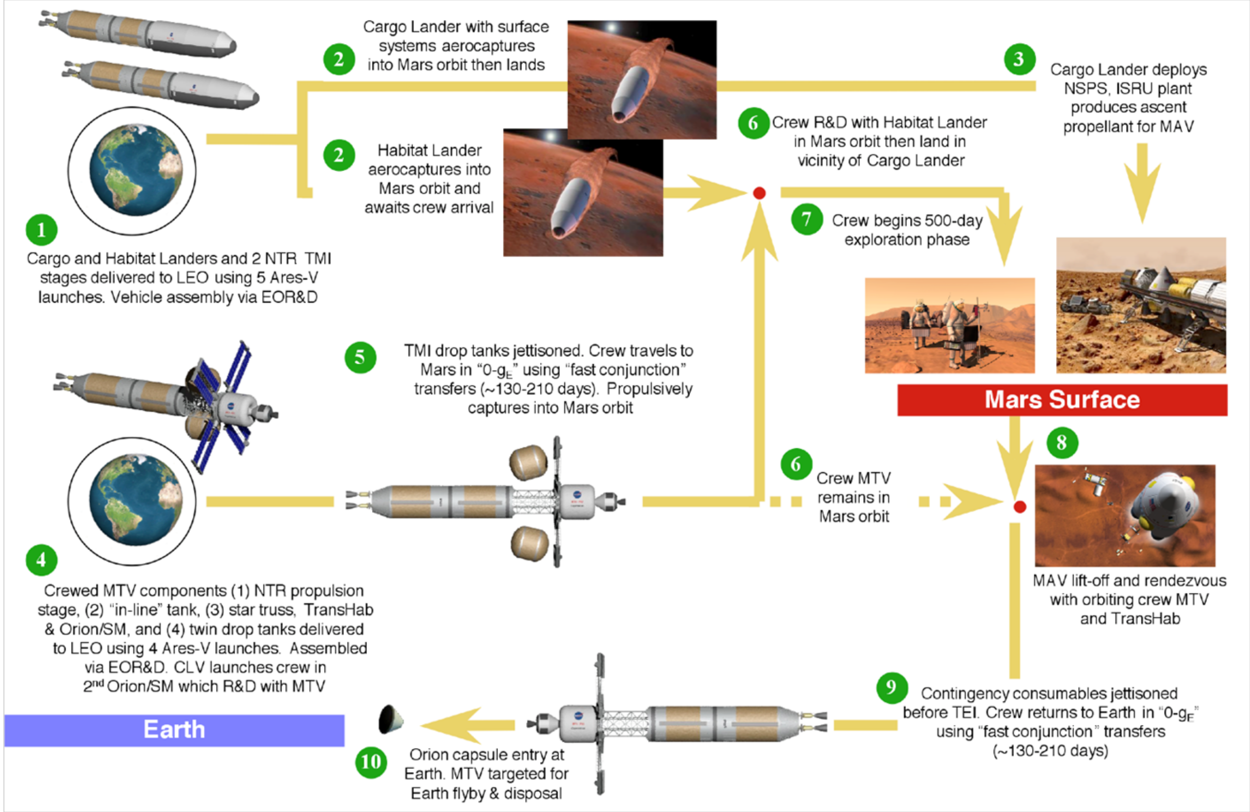


Figure 1. Mars DRA 5.0 mission profile with baseline NTP[11]

III. Assumptions and Constraints

Due to limited time and resources, the GRC COMPASS team considered a reduced initial set of power and electric propulsion options. A prior analysis by Frisbee[7] developed a few years prior to the release of DRA 5.0 investigated the use of solar power for MW-class electric propulsion cargo missions to the Moon and Mars, and compared vehicle designs for engine arrays of 25-kW$_e$ xenon-fed ion thrusters, 25-kW$_e$ bismuth-fed Hall thrusters, 200-kW$_e$ class lithium-fed MPD thrusters, and 200-kW$_e$ class pulsed inductive thrusters. Partially to complement this prior study, and to take into account additional advances in high power Hall thruster development and other advanced propulsion systems, the COMPASS team was asked to focus on nuclear electric power designs using 100-kW$_e$ class xenon-fed Hall thrusters and 200-kW$_e$ VASIMR engines as propulsion options. Future COMPASS studies will evaluate 1-MW$_e$ NEP Mars cargo vehicle design options using 200-kW$_e$ PIT and MPD thrusters.

A. Study Approach

The goal for the COMPASS study was to develop a 1-MW$_e$ class NEP cargo vehicle design to deliver approximately 100 t of cargo to a 1-Sol elliptical Mars orbit, without the use of aerobraking. The initial constraints included the use of one heavy lift launch vehicle (HLLV, in place of the now cancelled Ares 5 rocket) to lift the

NEP vehicle, and one HLLV to lift the cargo payload. As a first approximation, the study assumed an approximately 40 t NEP stage dry mass with up to 60 t of propellant. The NEP vehicle and 100-t payload are separately launched to a 407 km low Earth orbit and the two elements are docked, with the NEP vehicle as the passive docking element. Once attached, the assembly spirals to Earth escape and thrusts to Mars. At Mars, the vehicle spirals down to a highly elliptical 1-sol parking orbit, from which the set of DRA 5.0 cargo elements are deployed.

The COMPASS study utilized an integrated and interactive team of subsystem experts to iteratively design and assess the spacecraft in terms of mission performance, mass constraints, volume constraints, and overall system interactions. As such, the various technology options are not assessed at single operating points, but are configured to optimize the system as a whole. Figures of merit considered in the study include mass and cost, technology readiness levels, simplicity, and robustness, with the use of single fault tolerance or at least a graceful degradation of capability. Preliminary study products include concept of operations, spacecraft design concept, master equipment list, a rough cost estimate (currently in work and not reported here), and primary risks. An initial vehicle system design was developed to facilitate the COMPASS design trades, as shown in Fig.2.

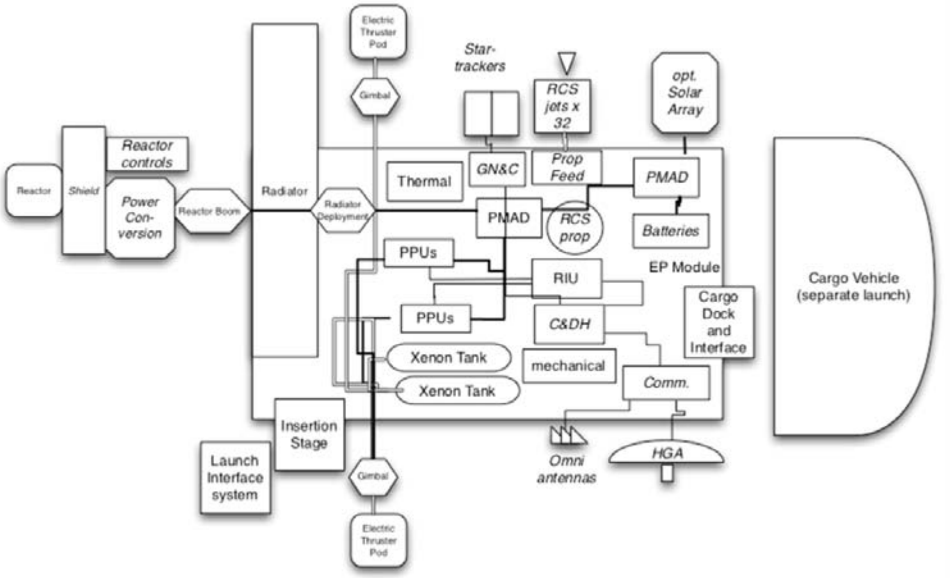


Figure 2. Strawman NEP cargo system

B. Power System Options

The nuclear power system used as a starting point for the COMPASS evaluations is based on an evolutionary development path that flows from currently planned fission surface power systems through moderate power reactors for NEP applications to eventual high power, multi-megawatt fission space power systems. Each of these mission classes share three basic building blocks that will be validated in NASA's Fission Power System (FPS) Project Technology Demonstration Unit:[12] (i) liquid metal cooled, fast-spectrum reactors with pin-type fuel elements; (ii) dynamic power conversion with alternating current power management and distribution; and (iii) large scale, lightweight heat pipe radiator panels. Near-term fission surface power systems for operation at 10-kW$_e$ to 100-kW$_e$ would use a liquid metal (NaK) cooled reactor with uranium dioxide (UO_2) fuel and a stainless steel structure, composite radiators with water heat pipes, and Stirling or Brayton power conversion. Moderate power systems providing 100-kW$_e$ to 1-MW$_e$ would use a liquid metal (lithium) cooled reactor with uranium nitride fuel and a refractory alloy structure, while retaining Brayton or Stirling power conversion systems and composite radiators with water heat pipes. For high power, multi-megawatt in-space applications a Li liquid metal cooled reactor using uranium carbide fuel and refractory alloy structure is envisioned, with advanced Brayton or Rankine power conversion and carbon-carbon radiators with sodium or potassium cooled heat pipes.

A set of preliminary design options for an evolvable, moderate power system are provided in Table 1, with the first column listing power system design parameters for a HEFT-defined 300-kW$_e$ class EP system suitable for human expeditions to a near Earth asteroid (NEA); the specifications for the proposed NEA mission are provided in a companion paper at this conference by Mercer et al.[2] Evolving from this near-term capability to the MW-class power levels required for Mars cargo delivery, the table presents a variety of preliminary design options that were considered by the COMPASS team in configuring an optimal NEP cargo vehicle power system. Common to each of the moderate power designs is an operational design life of 5-years, with a refractory alloy reactor based on the SP-100 design.[13] The reactors use uranium-nitride (UN) fuel, with lithium coolant in the primary loop. The payload and vehicle structure are shielded from the reactor by a combination of distance and an integral lithium hydride and tungsten shadow shield located near the reactor. For the cargo vehicle, the nominal distance from reactor to payload was determined to be 50 m, which trades distance and shield mass to maintain minimum overall system mass. A 22° half-angle cone for the shield design provides protection for the deployed vehicle radiators in flight.

Four Brayton power converters with helium-xenon (HeXe) working fluid and sodium-potassium (NaK) secondary loops each provide 270-kW$_e$ for a total power of 1.08-MW$_e$. Composite radiators panels with titanium-water (Ti-H2O) heat pipes are used to reject waste heat. The rejection of waste heat from the reactor and power conversion system is accomplished using a NaK-pumped loop that distributes waste heat to radiator panels, which in turn are made up of titanium/water heat pipes. An inherent feature of the Brayton cycle is that heat rejection can occur over a fairly wide temperature range, allowing some of the higher temperature heat rejection required by the propulsion system to share some of the radiator panels with the power system.

Additional similarities and trade options investigated by the COMPASS team are listed in Table 1. Based on a fairly conservative approach toward in-space power capabilities, the COMPASS team chose Case 1 as representative of a near-term evolutionary step toward a nuclear electric propulsion power system. This case more closely represents an evolutionary step from the current TRL-4 ETDD FPS system concept, without placing significant requirements on additional technology development to achieve a 1-MWe power levels. A more detailed discussion of the power system trades and corresponding analysis leading to the selection of a final design configuration is presented in Section IV.

Table 1. Preliminary Power System Design Options

	HEFT Human NEA[2]	**Case 1** Mars Cargo	**Case 2** Mars Cargo	**Case 3** Mars Cargo
Design Life (yrs)	2	5	5	5
Net Power (kWe)	315	1015	1015	1015
Reactor Power (kWt)	1150	3700	2700	2700
Reactor Coolant	Li	Li	Li	Li
Reactor Materials	Nb-1Zr/UN	Nb-1Zr/UN	Nb-1Zr/UN	Nb-1Zr/UN
Reactor Outlet (K)	1200	1200	1500	1500
Shield Materials	LiH/W	LiH/W	LiH/W	LiH/W
Shield Dose	50 rem/yr	25 krad	25 krad	25 krad
		10^11 nvt	10^11 nvt	10^11 nvt
Shield Half Angle (deg)	22	22	22	22
Reactor Separation (m)	30	50	50	50
Power Conversion	Brayton	Brayton	Brayton	Brayton
PC Materials	Superalloy	Superalloy	Refractory	Refractory
Converter Power	2 x 100%	4 x 25%	4 x 25%	4 x 25%
	340 kWe each	270 kWe each	270 kWe each	270 kWe each
Heat Rejection Coolant	NaK	NaK	NaK	NaK
Radiator Materials	Composite	Composite	Composite	Composite
	Ti-H2O HPs	Ti-H2O HPs	Ti-H2O HPs	Ti-H2O HPs
Avg Radiator (K)	450	450	450	450
Radiator Sink (K)	230	230	230	230
Radiator Area (m2)	560	1800	1100	1100
PMAD (VAC)	480	480	480	1000
Mass Estimate:				
Reactor (kg)	1250	2000	1700	1700
Shield (kg)	2500	1900	1500	1500
Power Conv (kg)	1000	1900	2000	2000
Heat Reject (kg)	2650	7500	5000	5000
PMAD (kg)	1050	4000	4000	2900
TOTAL (kg)	8450	17300	14200	13100
Sp Mass (kg/kWe)	26.8	17	14	12.9

To provide a common basis for assessing the various propulsion systems, the power system was assumed to provide a fixed DC voltage to all of the propulsion systems, with any further power conditioning being performed by the electric propulsion system power processing unit (PPU). To this end, the Brayton power conversion system provided 3-phase AC power at 1200 Hz and 450 – 550 V to a conventional diode rectification system, resulting in a DC voltage of 600 V for the VASIMR system and 750 V for the Hall thruster system.

C. Electric Propulsion System Options

Although the initial intent of the COMPASS study was to evaluate multiple high power electric propulsion options, due to limited time and funding the first set of propulsion trades focused on high power Hall thrusters and a 200-kW_e VASIMR engine. Commercial kW-class Hall thrusters have been successfully flown on a variety of satellites[14] as well as a lunar orbiter mission,[15] and laboratory model Hall thrusters have been operated at power levels over 50-kW_e,[16] most recently as part of the FY11 ETDD Advanced In-Space Propulsion Project. The VASIMR thruster, originally developed at MIT and later at the NASA Johnson Space Center, is continuing under commercial development by the Ad Astra Rocket Company,[17] and a 200-kW_e version has recently been proposed as part of an electric propulsion testbed experiment on the International Space Station.[18] Future trades may consider the pulsed inductive thruster (PIT)[19] and lithium-fed MPD thruster,[20] both of which have been demonstrated in the laboratory.

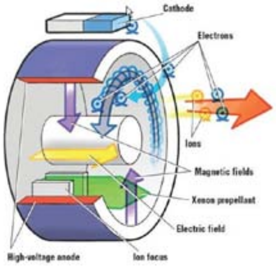


Figure 3. Hall thruster principles of operation.

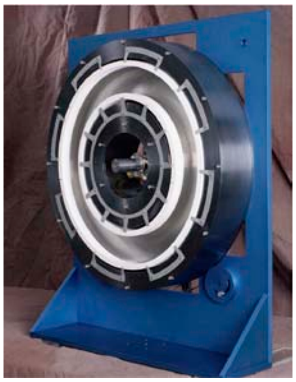


Figure 4. NASA-457M 50 kW Hall thruster

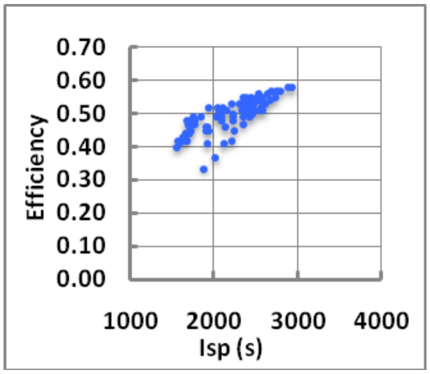


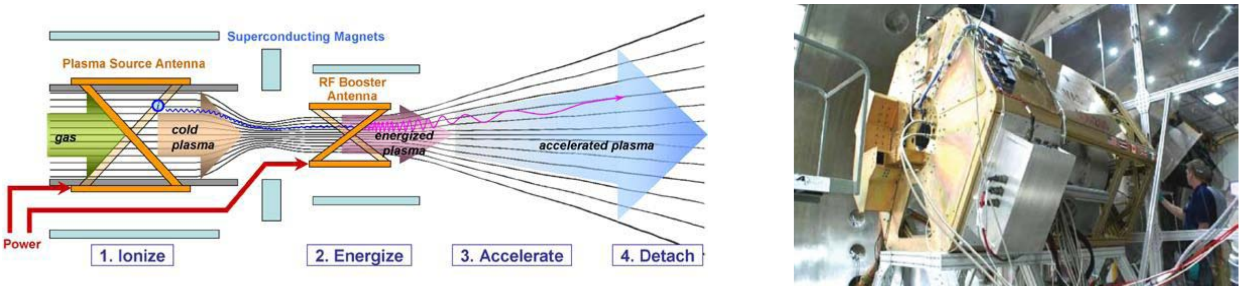
Figure 5. Hall thruster performance range for NEP design

High Power Hall Thruster

The Hall thruster consists of an annular cylindrical channel and uses an applied radial magnetic field to trap orbiting electrons and an axial electric field between the trapped electrons and a backplane anode to produce electrostatic acceleration of the propellant ions (Figure 3). The magnetic field is created by coils wound around magnetic cores on the axis and outer circumference. The electrons are supplied by an external hollow cathode. Hall thruster performance scaling is similar to that of ion thrusters, with I_{sp} dependent on the applied voltage and the molecular weight of the propellant. There is extensive flight experience with Hall thrusters, both internationally and domestically, with the latest flight thruster being the Aerojet BPT-4000, operating at 4.5 kW_e.[21]

The current COMPASS study assumes an evolutionary 100 kW_e Hall thruster design based on prior high power Hall thruster concepts.[16] Although preliminary scaling analysis of nested (concentric) channel Hall thrusters indicate these systems might be attractive for high power operation,[22] the baseline thruster unit assumed in the COMPASS analysis used a single channel Hall thruster based on the known NASA-457M thruster. The NASA-457M (Figure 4) was designed for a nominal operating point of 50 kW_e, but reached power levels approaching 100 kW_e during limited laboratory testing. The performance data used to determine the thruster operating point with xenon propellant for the NASA DRA 5.0 Mars cargo mission are shown in Figure 5.

The use of nuclear power allowed the thruster PPU electronics to be replaced with a simpler direct drive unit (DDU), which is designed to operate at a single set DC voltage provided by the power system PMAD. This set voltage was determined by the operating voltage of the Hall thruster, which in turn was driven by the propellant mass and trip time constraints of the mission. To successfully close on a solution for the Mars cargo mission required an I_{sp} of 3340 s; this is somewhat beyond the design goals of the NASA-457M, but was deemed achievable at a voltage of 750 V. Another option considered during the study was the use of krypton as propellant, due to its lighter atomic mass and availability compared with xenon propellant. This option was quickly ruled out on the basis of the increased propellant storage/tankage mass and volume penalties. Based on the NASA-457M, the thruster mass was estimated to be 136 kg; the DDU mass was calculated to be 35 kg/unit.



(a) (b)

Figure 6. (a)VASIMR conceptual design and operation; (b) 200-kW test article.

VASIMR Thruster

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is an electrodeless thruster that utilizes two types of plasma waves to ionize and heat a plasma propellant, which is then exhausted through an expanding magnetic nozzle. The operating concept is shown in Figure 6a and the 200-kW laboratory model thruster is shown in Figure 6b. Argon gas is injected into a chamber surrounded by a strong (~ 0.7 T) magnetic field, and is ionized by low power (30 kW) helicon waves to a plasma density approaching 10^{20} m^{-3}. The plasma flows along the magnetic field, and in the region where the field strength exceeds 1-Tesla, ion cyclotron waves are injected into the plasma to further heat the ions. The plasma is then expanded along the decreasing field of the magnetic nozzle, which serves to convert perpendicular plasma particle thermal energy to axial kinetic energy and therefore thrust.

The VASIMR masses and performance parameters used in the COMPASS evaluations were provided by Dr. Harold White of the NASA Johnson Space Center (JSC), in consultation with Ad Astra. Mass estimates were based on preliminary designs for a potential power and propulsion testbed experiment to be flown on the International Space Station (ISS). Performance was based on recent test data, with an assumed fixed operating condition of 5000 s I_{sp} and 60% efficiency.[23] The most recent test data are shown in Figure 7; however, it should be noted that the data was obtained at varying power levels. The highest achieved performance occurs at highest tested power level of 200 kW_e. Based on these results, a 200-250 kW_e propulsion unit was designed as two 125 kW_e thrusters operating in parallel, with oppositely polarized applied magnetic fields, to minimize possible interaction with the Earth's magnetic field during the initial outward spiral from low Earth orbit. The performance measured at 200 kW_e was assumed to be representative of the units operating at 125 kW_e. This assumption will require validation through additional testing of the current VASIMR laboratory thruster.

The VASIMR module design assumed for the COMPASS study consisted of dual VASIMR thrusters, superconducting magnets, magnet and thruster cooling systems, radio-frequency generators, and associated heat rejection radiators. Two rejection temperatures were identified: 218 °C for the thruster body itself, and 45°C for the power electronics. The total system mass was estimated to be 10 kg/kW_e, or approximately 2.5 t for each 2-thruster unit. The system length reached several meters in the original unified design. The impacts of this unified modular design will be discussed further in the Results section.

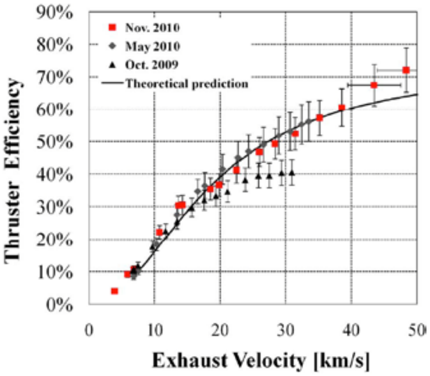


Figure 7. Recent VASIMR performance measurements.

D. Baseline Mission Trajectory

The general mission architecture was described in Section II. The cargo mission requires prepositioning assets in Mars orbit, followed by deployment to the surface of an in-situ propellant plant that will produce and store ascent propellant prior to crew departure from Earth. The DRA 5.0 assumes 300 days of continuous propellant production on Mars using a 30 kW_e nuclear power system. It is also assumes that the initial setup of the ISRU system on the surface will require 30 days. The additional time required for in situ propellant production imposes launch opportunity and trip time constraints on both the cargo and crew vehicles. In general, based on initial trajectory analysis, a cargo vehicle trip time of 2.7 years or less allows the cargo vehicle to depart in the launch opportunity prior to the crew mission and arrive at Mars in time to allow in situ propellant production prior to crew vehicle departure. Longer cargo trip times require the cargo vehicle to depart two opportunities prior to the crew launch date.

The assumed heavy lift launch vehicle capabilities impose an initial mass in Low Earth Orbit (IMLEO) constraint of approximately 100 t for the combined mass of cargo vehicle and propellant. The assumed usable shroud volume for the heavy lift launch vehicle was assumed to be a cylinder 8.5 m diameter x 20 m, based on projected launch vehicle capabilities.[24] In addition, mission success requirements imposed a single fault tolerant requirement on the system; in the case of the propulsion system, this meant that the mission could be completed under single engine out conditions. Reaction control was performed using a blow-down monopropellant reaction control systems (RCS) based on commercially available systems. Two RCS are used for fault tolerance.

During the COMPASS analysis the mission trajectories and trip times for each propulsion system were developed with strict adherence to these requirements, maintaining the team's conservative approach to mission planning. The subsequent impacts of these requirements on the design and performance of each propulsion system are discussed in Section IV below.

E. Baseline Vehicle Design

The cargo vehicle, including payload, power and propulsion, radiator, shielding, and deployable structures, was designed to fit into the launch vehicle shroud and deploy in orbit. The radiator area for heat rejection from the power conversion system was calculated to be 1800 m^2, and dominated the design requirements for shielding and deployment. The vehicle is shown in its stowed configuration in Figure 8a. The design approach incorporates some of the radiator surface on a central, rigid hollow rectangular structure, with additional radiator surface folding out from the central structure in orbit. The deployed Case 1 cargo vehicle is shown in Figure 8b.

Vehicle thrust and steering is accomplished by thrusters mounted near the vehicle center of mass which thrust perpendicular to the long axis of the vehicle. As the vehicle center of mass shifts due to the ejection of propellant, the thrusters are gimbaled to follow the change in center of vehicle mass. This provided some design challenges to ensure the thruster plumes do not impinge on vehicle structures or radiators, which were taken into account in the final vehicle designs for both propulsion options.

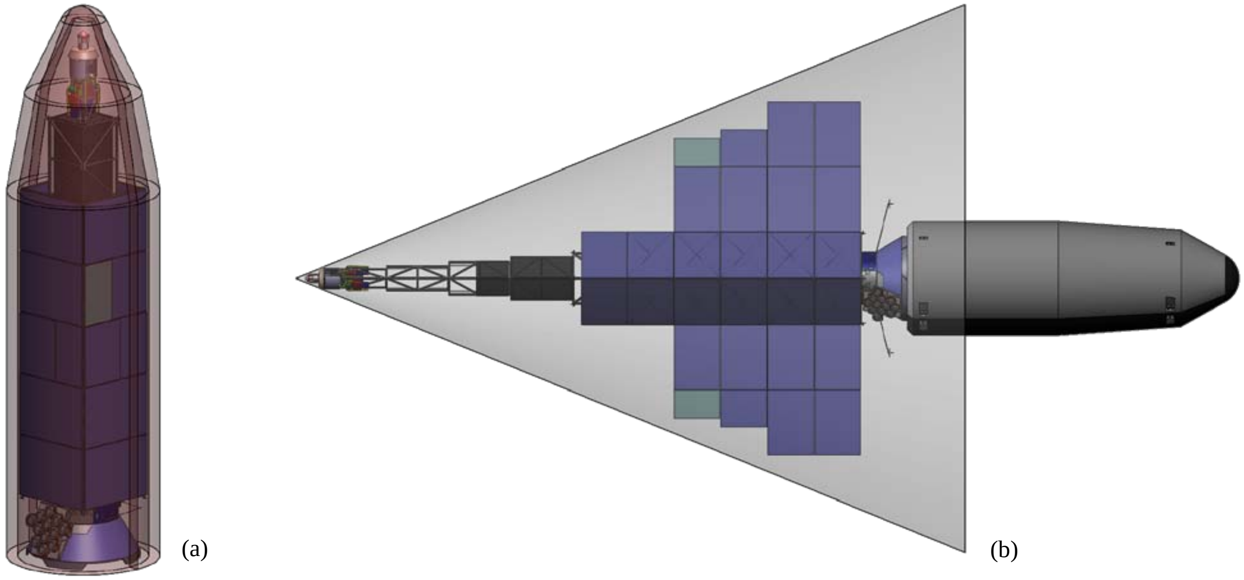


Figure 8. Case 1 NEP Cargo vehicle (a) stowed in the heavy lift launch vehicle shroud, and (b) deployed with shielded region shown

IV. COMPASS Results

The COMPASS team assessed the two propulsion options described above for Mars cargo mission requirements defined by DRA 5.0. Assuming a common reactor system (Case 1 in Table 1), propulsion system configurations and operating parameters (I_{sp}, power level) were iterated to reach an integrated vehicle system design that met mission and launch vehicle constraints. The results, and the important system level trades performed during the analysis, are discussed here. Additional details related to the vehicle designs are provided in the Appendix.

A. Mars Cargo Mission with Hall Thrusters

Ten 100-kW$_e$ Hall thrusters operating with xenon propellant are used to process the 1-MW$_e$ of available system power. Two spare Hall thrusters are included for redundancy to satisfy the engine-out mission success requirements. The vehicle design incorporates the Hall thrusters near the vehicle center of mass, with the thrusters individually gimbaled to maintain thrust through the vehicle center of mass as it changes over the course of the mission. The whole propulsion system mounting platform is installed at an angle of 15°, and the thrusters must be able to travel 20° to maintain their proper orientation. Based on laboratory and flight experience the Hall thruster plume divergence was assumed to be 45°, and the thrusters are situated between two orthogonal radiator panels to avoid plume impingement. Xenon propellant is stored at supercritical pressure in two spherical composite overwrap pressure vessel (COPV) tanks, located in the central rectangular structure of the vehicle. Propellant is distributed using a single high pressure control unit with individual low pressure control units for each thruster string. The overall vehicle design was previously shown in Figure 8b. The optimized design layout for the Hall thruster propulsion option is shown in Figure 9.

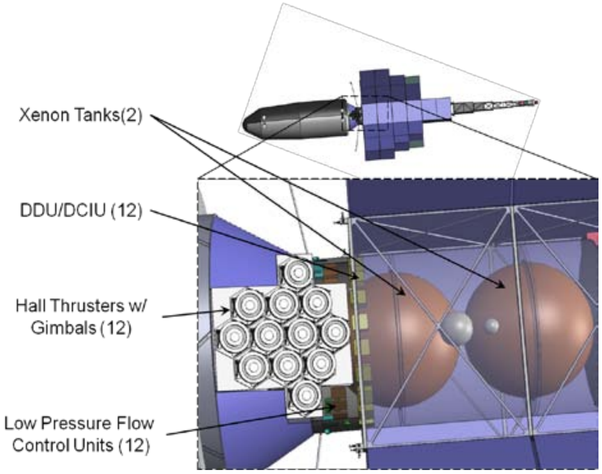


Figure 9. Hall thruster propulsion system vehicle location

The trade between trip time and vehicle mass for the Hall propulsion system over a range of thruster I_{sp} values is shown in Figure 10a. As noted, the mission is constrained by a single engine out criteria, but there are a sufficient number of thrusters to provide a spare capability while maintaining full power processing capability. Based on a series of iterative results, the baseline cargo mission using Hall propulsion requires that the cargo vehicle depart during the launch opportunity preceding the crew launch in order to allow adequate time for ascent propellant production at Mars. The total trip time in this case is approximately 2.7 years, with the trajectory shown in Figure 10b. The mission begins with the cargo vehicle launch in early 2034, a 395-day spiral out from LEO, a 534 day heliocentric trajectory, and a 39 day spiral down to a 1-Sol Mars orbit, arriving in late 2036. The crew leaves in late 2037, once ascent propellant production and storage is confirmed, and arrives at Mars in the first quarter of 2038.

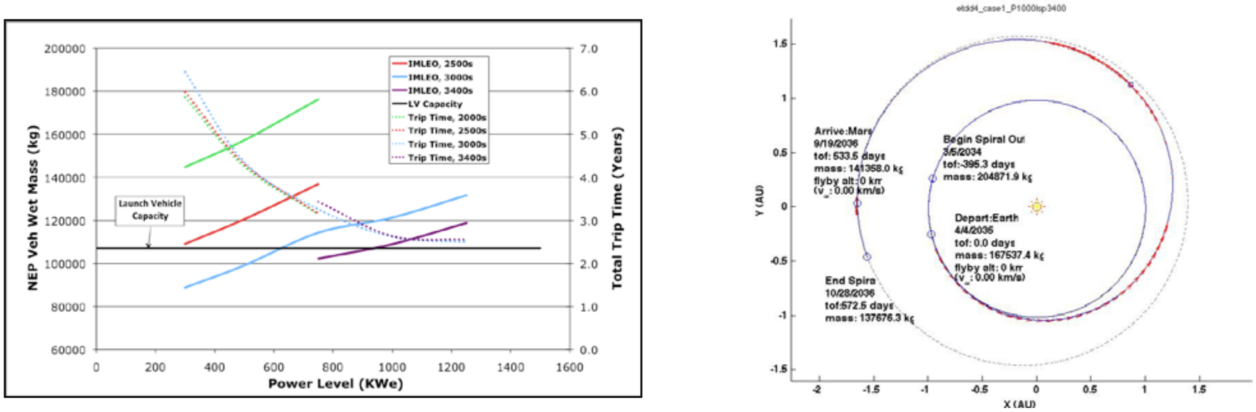


Figure 10. (a) Hall thruster Mars cargo mission trip time/Isp optimization and (b) representative trajectory

B. Mars Cargo Mission with VASIMR Thrusters

To provide a direct comparison with the Hall thruster option, the power for the VASIMR system option was kept constant at 1 MW_e and varying values of VASIMR I_{sp} were examined during the COMPASS trades. To process the required power, a total of eight thrusters, grouped by twos in four 250 kW_e modules, were assumed. A major design factor that subsequently arose in the VASIMR vehicle concept was the much larger volume of the modules, caused primarily by the module length. This volume challenge required several accommodations in both the mission profile and propulsion system design, as discussed below. Argon propellant used by the VASIMR thruster cannot be stored at supercritical pressure due to its relative incompressibility; instead, the propellant is stored cryogenically in two spherical Al/Li tanks insulated with multilayer insulation (MLI) using COTS based cryocoolers. This additional heat removal requirement was incorporated into the existing heat rejection system.

Because the VASIMR modules could not fit into the launch shroud as integrated components, the COMPASS team separated the thruster PPU and radiator from the thruster itself. The modules are mounted gimbaled to accommodate the 30° plume angle observed in experiments. The PPU subsystems were then housed in the central rectangular vehicle structure, with cabling to transmit the required rf power to the thruster added. By imposing this separation of previously integrated module components, and eliminating some of the central support structure, the thruster modules could be situated to allow the vehicle to be stowed in the launch shroud. However, a full analysis of the impact of removing some of the structure on the overall vehicle was not performed in this initial study.

The low temperature PPU radiator provided as part of the VASIMR system could not be incorporated into the existing power system radiator. PPU heat rejection required an additional radiator that, when deployed from the modules, extended outside of the 22° shield cone. To accommodate this additional radiator, the shield angle was increased to 23°; this in turn led to a corresponding increase in the power system mass of 31 kg. The resulting deployed system design with VASIMR thrusters is shown in Figure 11.

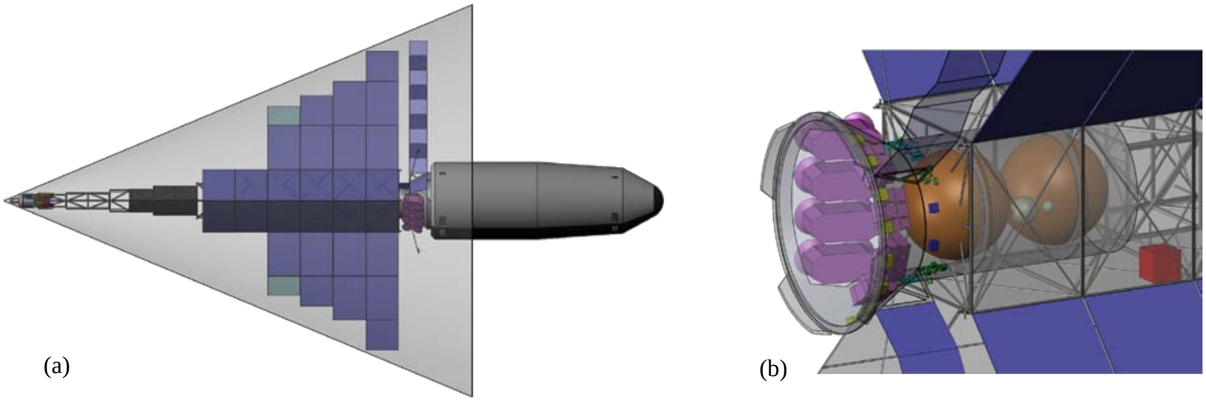


Figure 11. (a) Deployed vehicle design with VASIMR thrusters, with added PPU radiator and increased cone angle. (b) Four VASIMR modules, associated electronics, and propellant system location on cargo vehicle

Due to the constraints of the launch vehicle shroud, the volume required by the thrusters did not allow for required thruster or module redundancy. This impacted the engine out mission requirement, such that instead of engine redundancy, an engine out would reduce the available thrust of the system. This was accounted for in two ways. During the Earth spiral escape phase, even a single "engine out" meant loss of a 250 kW_e module, since the VASIMR thrusters must be run in pairs in the Earth's magnetic field to prevent vehicle torque due to the thruster magnetic fields. In interplanetary space, "engine out" is assumed to be the loss of a single 125 kW_e thruster. As a result, mission success under a VASIMR "engine out" scenario assumed 3 thruster modules (6 paired thrusters) operating at a total power of 750 kW_e during Earth escape spiral, followed by 7 thrusters operating at a total power of 875 kW_e during the interplanetary portion of the trajectory.

With these performance and design constraints, the minimum trip time using the VASIMR propulsion system under an engine out scenario is approximately 5 years, which includes an 815 day spiral out from LEO, a 960 day heliocentric trajectory, and a 66 day spiral down to a 1-Sol Mars orbit. As noted in Section II.D, mission durations of less than 2.7 years are required to launch cargo and crew vehicles in tandem opportunities. The longer travel time under an engine-out condition would require the cargo vehicle to leave two opportunities prior to the crew mission, at the end of 2032, in order to arrive in time to finish producing the necessary ascent propellant. The cargo vehicle would arrive at Mars in the fall of 2035. The performance optimization and trajectory using VASIMR is shown in Figure 12.

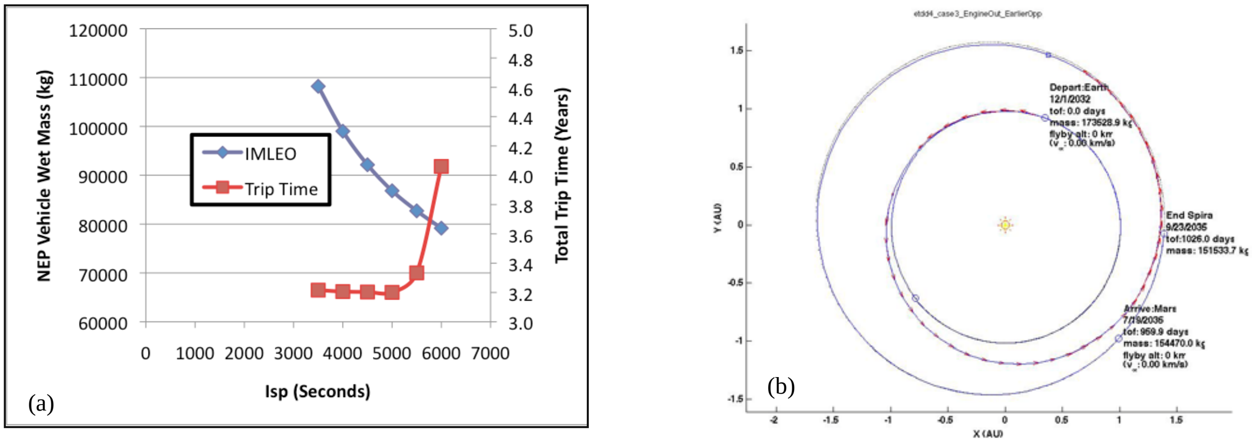


Figure 12. (a) VASIMR thruster Mars cargo mission trip time/I_{sp} optimization and (b) representative trajectory.

C. Discussion

The two propulsion options considered in this preliminary design analysis are compared directly in Table 2. As previously noted, the larger size of the VASIMR system imposes several additional constraints to the integrated vehicle concept, resulting in some redesign of the baseline vehicle. This includes removal of some vehicle structure to accommodate the VASIMR engine modules, incorporation of cryogenic storage for the argon propellant, and an increased reactor shield cone angle to accommodate the low temperature PPU radiator. Additionally, to launch within the mass and volume constraints of the assumed heavy lift launch vehicle, the size of the VASIMR system did not allow for redundant engines, which impacts the single fault tolerance mission performance relative to the Hall thruster propulsion system. This in turn results in the longer trip time for the VASIMR system. It should be emphasized however that the preliminary VASIMR design and operating conditions assumed in this study will likely change with refined definition of the system dimensions, performance, and heat rejection requirements, and further detail on the components, interfaces, and power dissipation requirements may resolve some of the initial performance challenges related to trip time, vehicle size, and vehicle mass.

Table 2. Comparison of Hall and VASIMR propulsion options.

	Units	**Case 1 Hall**	**Case 2 VASIMR**
Type of Engine	-	Hall	VASIMR
Engine I_{sp}	s	3400	5000
Total Power To Engines	kW_e	980	735/858
Number Of Engines	-	10	6-7
Single Engine Power	kW_e	98	122.5
Launch Date	-	3/4/34	9/8/30
Earth Departure	-	4/4/35	12/1/32
Mars Arrival	-	9/19/36	7/19/35
Orbit Achieved	-	10/27/36	9/23/35
Spiral Out Duration	Days	395	815
Heliocentric Duration	Days	534	960
Spiral Down Duration	Days	39	66
Total Mission Duration	Days (Yrs)	968 (2.7)	1841 (5)
Launch Mass	kg	204854	200872
Earth Departure Mass	kg	167529	173614
Mars Arrival Mass	kg	141354	154546
Final Mass	kg	137675	151608
Total Prop	kg	67179	49264
Total Delta-V	m/s	13250	13796

While every effort was made to maintain a common power system, standard DRA 5.0 cargo mission profile, and presumed launch vehicle capabilities, it is clear that choosing other options may result in different discriminators between the propulsion systems. This analysis should therefore be taken more as a guide to NEP development requirements in support of future high power missions, as opposed to a preference for developing one propulsion system over another. For example, changing launch vehicle requirements may allow a redundant VASIMR module, which would alter the resulting engine out assumptions and reduce the mission trip time calculated during the study. Alternatively, the packing issues uncovered in the study may lead toward more efficient VASIMR designs that could comfortably fit redundant dual thruster modules within the current heavy lift launch vehicle constraints. Similar insights would be expected for other high power EP options such as the PIT and MPD thruster, where design issues may be uncovered that will help guide developers toward more robust, compact NEP flight systems. In addition, more advanced power system options could lead to higher power operation or smaller radiator areas, thereby changing mission trip times or vehicle configurations.

The master equipment list for the Hall and VASIMR thruster systems and for the evolutionary nuclear power system used in the current COMPASS study is included in the Appendix. As previously noted the current state of the art for each of the high power thrusters is approximately TRL-3 to 4, and for the power system approximately TRL-4, requiring significant development and testing in multiple subsystems to advance toward MW-class propulsion applications.

Although the Hall thruster is based on a flight demonstrated propulsion technology, high power Hall thrusters require several advancements to be flight ready. Commercial Hall thrusters operate at power levels below 10-kW$_e$, and only limited laboratory thruster testing has occurred at the power levels of interest to this study. In addition, the assumed specific impulse of 3400 s represents an achievable but higher operating value than commonly employed with xenon propellant. Xenon supercritical storage in large scale composite spherical tanks is based on existing commercial technologies that have been demonstrated at a smaller scale, and there may be challenges to scaling the tanks to the levels required for a long duration, high power mission. The high power Hall PPU/DDU represents an even greater unknown, as only scaled high power laboratory models and modules have been developed to date.

Likewise, the VASIMR concept encompasses several technologies that are currently at a laboratory level. The thruster performance has only recently been measured during ground tests, using plume impact methods in place of thrust stand measurements. The published performance with variable I$_{sp}$ was provided at varying power, and the full throttling profile for the VASIMR has not yet been mapped. The high power radiofrequency transmitters will require additional development to operate in required space thermal and vacuum conditions, and the concept will require space rated superconductors for high field electromagnets. Such designs will need to demonstrate sufficient mission life under cryogenic conditions with no quenching.

V. Concluding Remarks

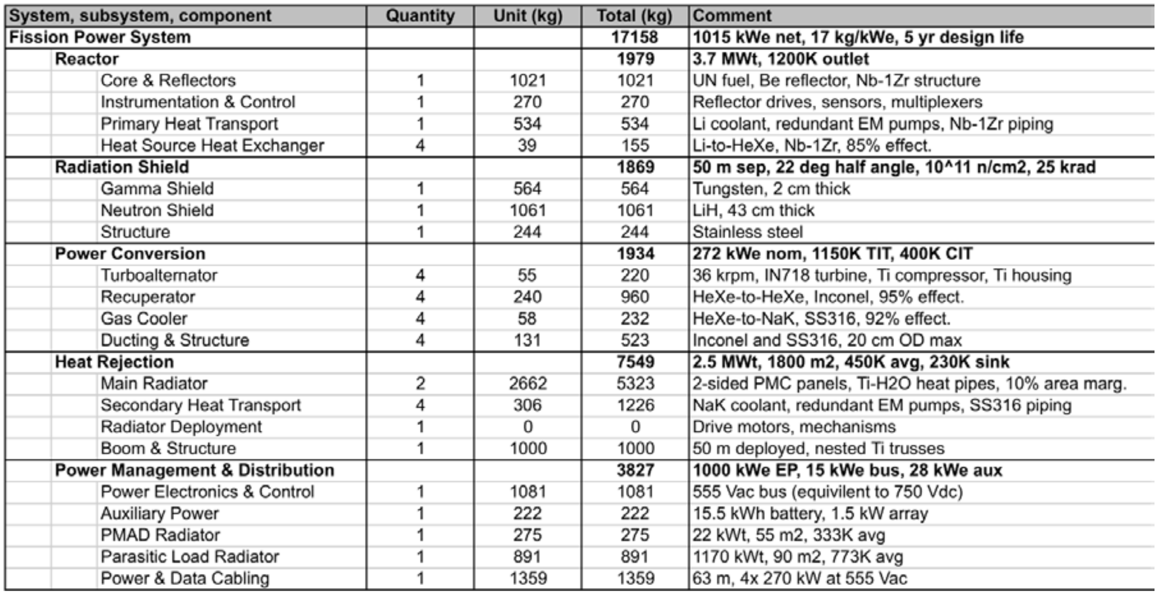
This paper describes the results of a recent COMPASS study performed at the NASA Glenn Research Center to evaluate vehicle design options and performance for high power electric propulsion systems under a common set of mission and launch vehicle constraints. For this initial study the COMPASS team used the cargo delivery mission outlined in Mars Design Reference Architecture 5.0 to provide baseline payload requirements, and an assumed heavy lift launch vehicle capable of lifting 100 t to low Earth orbit. Two propulsion options were considered in this preliminary analysis, a 100-kW$_e$ class Hall thruster based on the existing high power NASA-457M laboratory thruster, and a 125-kW$_e$ VASIMR thruster based on the experimental 200-kW$_e$ VASIMR200x laboratory thruster. A common MW-class space nuclear reactor power system design based on a conservative evolution from the ETDD Fission Surface Power Technology Demonstration Unit was used for both vehicle designs. The mission required delivery of a 100 t payload to a 1-Sol Mars orbit, with sufficient time to land a propellant manufacturing system on the surface of Mars to generate propellant for crew ascent. Once propellant manufacture and storage was confirmed, the crew would depart Earth for Mars. A further constraint imposed on the COMPASS team was to design a cargo vehicle that minimized the required number of launches from Earth to LEO. In response, the team developed a profile that used two heavy lift launches, one for the payload and one for the NEP vehicle. Once in orbit the payload would dock with the propulsion stage, and the assembled vehicle would begin a spiral out of LEO and on to Mars.

Based on this common set of assumptions, the COMPASS team evaluated vehicle designs and mission profiles for a propulsion system comprised of 12 high power Hall thrusters (10 operational and two spares), and a system of eight VASIMR thrusters grouped into four modules, the latter to provide cancellation of potential magnetic field interactions between the thrusters and the Earth's magnetic field during the spiral out of LEO. Due to current VASIMR size and mass estimates, there was insufficient launch vehicle capacity to provide a redundant propulsion module. This meant that, in case of engine out, the system would have to operate with 3 modules (6 thrusters) until the LEO spiral was complete, after which seven VASIMR engines could be used for the transit to Mars. This in turn resulted in the VASIMR system taking longer to perform the spiral and transit. The Hall cargo vehicle required approximately 2.7 years to get to Mars, and could launch in the opportunity preceding the launch of the crew vehicle. Due to the engine out requirement for mission success, the VASIMR cargo vehicle would have to launch two opportunities prior to crew departure, requiring approximately 5 years to reach Mars orbit at reduced power.

Although the primary goal of this study was to assess the relative performance of various high power electric propulsion concepts, the results also demonstrate that the use of MW-class NEP for the baseline Mars DRA 5.0 cargo mission could reduce the number of heavy lift launches from five to two HLLVs. However, additional analysis would be required to optimize an NEP vehicle design for cargo delivery to Mars, and for the higher power levels required for the crew portion of the mission. The baseline DRA 5.0 architecture assumed the same set of nuclear thermal propulsion elements could be used for both crew and cargo missions, offering an attractive system commonality. Whether the development cost of higher power NEP systems for both cargo and crew can be offset by reduced launch costs will ultimately depend on the scenario chosen for the sustained human exploration of Mars. The current analysis offers some initial trends for consideration as those missions continue to be developed.

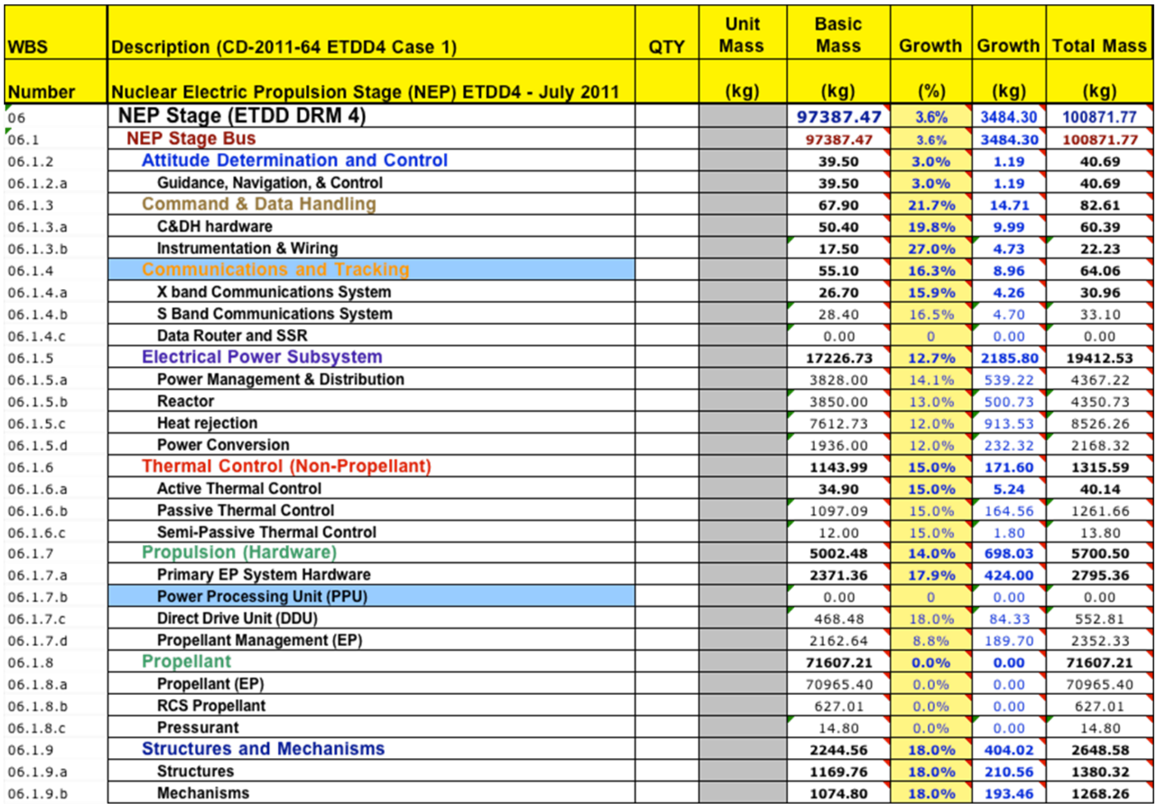
Appendix: Master Equipment Lists

Table A.1. Power System Master Equipment List



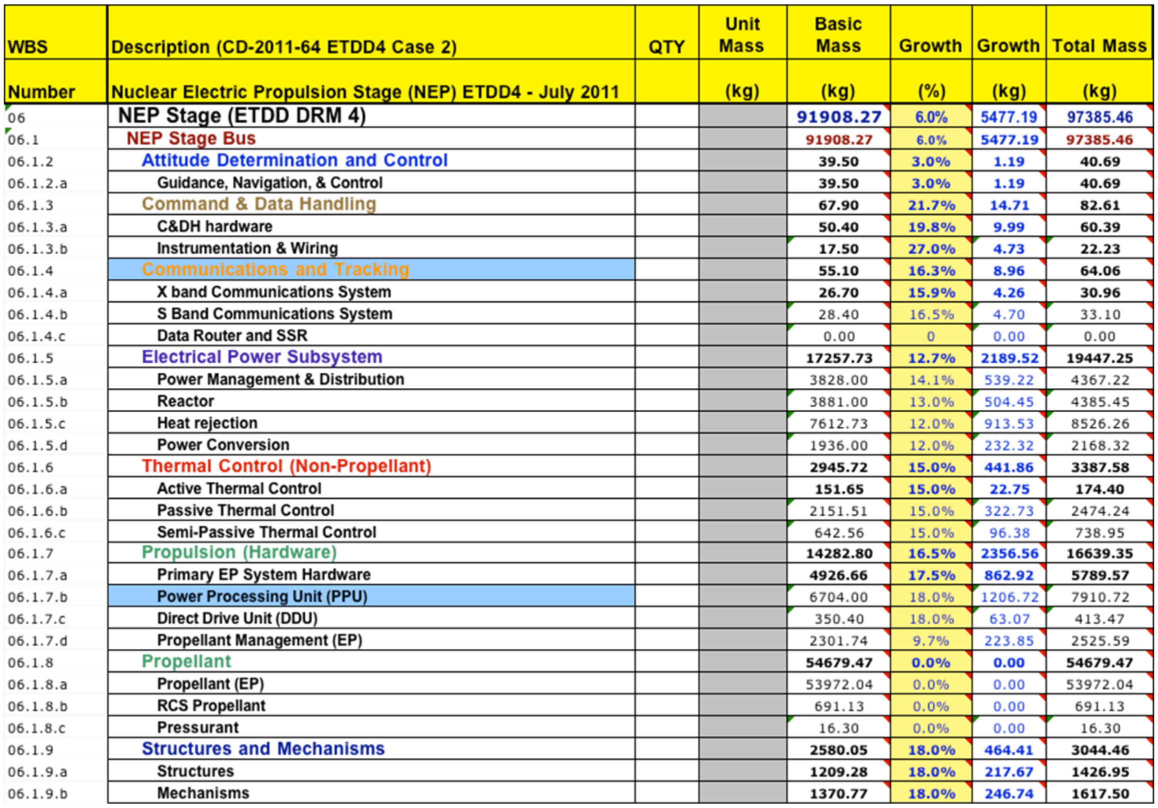
System, subsystem, component	Quantity	Unit (kg)	Total (kg)	Comment
Fission Power System			**17158**	**1015 kWe net, 17 kg/kWe, 5 yr design life**
Reactor			**1979**	**3.7 MWt, 1200K outlet**
Core & Reflectors	1	1021	1021	UN fuel, Be reflector, Nb-1Zr structure
Instrumentation & Control	1	270	270	Reflector drives, sensors, multiplexers
Primary Heat Transport	1	534	534	Li coolant, redundant EM pumps, Nb-1Zr piping
Heat Source Heat Exchanger	4	39	155	Li-to-HeXe, Nb-1Zr, 85% effect.
Radiation Shield			**1869**	**50 m sep, 22 deg half angle, 10^11 n/cm2, 25 krad**
Gamma Shield	1	564	564	Tungsten, 2 cm thick
Neutron Shield	1	1061	1061	LiH, 43 cm thick
Structure	1	244	244	Stainless steel
Power Conversion			**1934**	**272 kWe nom, 1150K TIT, 400K CIT**
Turboalternator	4	55	220	36 krpm, IN718 turbine, Ti compressor, Ti housing
Recuperator	4	240	960	HeXe-to-HeXe, Inconel, 95% effect.
Gas Cooler	4	58	232	HeXe-to-NaK, SS316, 92% effect.
Ducting & Structure	4	131	523	Inconel and SS316, 20 cm OD max
Heat Rejection			**7549**	**2.5 MWt, 1800 m2, 450K avg, 230K sink**
Main Radiator	2	2662	5323	2-sided PMC panels, Ti-H2O heat pipes, 10% area marg.
Secondary Heat Transport	4	306	1226	NaK coolant, redundant EM pumps, SS316 piping
Radiator Deployment	1	0	0	Drive motors, mechanisms
Boom & Structure	1	1000	1000	50 m deployed, nested Ti trusses
Power Management & Distribution			**3827**	**1000 kWe EP, 15 kWe bus, 28 kWe aux**
Power Electronics & Control	1	1081	1081	555 Vac bus (equivilent to 750 Vdc)
Auxiliary Power	1	222	222	15.5 kWh battery, 1.5 kW array
PMAD Radiator	1	275	275	22 kWt, 55 m2, 333K avg
Parasitic Load Radiator	1	891	891	1170 kWt, 90 m2, 773K avg
Power & Data Cabling	1	1359	1359	63 m, 4x 270 kW at 555 Vac

Table A.2. Hall Option Master Equipment List



WBS	Description (CD-2011-64 ETDD4 Case 1)	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Number	Nuclear Electric Propulsion Stage (NEP) ETDD4 - July 2011		(kg)	(kg)	(%)	(kg)	(kg)
06	NEP Stage (ETDD DRM 4)			**97387.47**	3.6%	3484.30	100871.77
06.1	**NEP Stage Bus**			**97387.47**	3.6%	**3484.30**	**100871.77**
06.1.2	**Attitude Determination and Control**			**39.50**	**3.0%**	**1.19**	**40.69**
06.1.2.a	**Guidance, Navigation, & Control**			**39.50**	**3.0%**	**1.19**	**40.69**
06.1.3	**Command & Data Handling**			**67.90**	**21.7%**	**14.71**	**82.61**
06.1.3.a	**C&DH hardware**			**50.40**	**19.8%**	**9.99**	**60.39**
06.1.3.b	**Instrumentation & Wiring**			**17.50**	**27.0%**	**4.73**	**22.23**
06.1.4	**Communications and Tracking**			**55.10**	**16.3%**	**8.96**	**64.06**
06.1.4.a	**X band Communications System**			**26.70**	**15.9%**	**4.26**	**30.96**
06.1.4.b	**S Band Communications System**			28.40	16.5%	4.70	33.10
06.1.4.c	**Data Router and SSR**			0.00	0	0.00	0.00
06.1.5	**Electrical Power Subsystem**			**17226.73**	**12.7%**	**2185.80**	**19412.53**
06.1.5.a	**Power Management & Distribution**			3828.00	14.1%	539.22	4367.22
06.1.5.b	**Reactor**			3850.00	13.0%	500.73	4350.73
06.1.5.c	**Heat rejection**			7612.73	12.0%	913.53	8526.26
06.1.5.d	**Power Conversion**			1936.00	12.0%	232.32	2168.32
06.1.6	**Thermal Control (Non-Propellant)**			**1143.99**	**15.0%**	**171.60**	**1315.59**
06.1.6.a	**Active Thermal Control**			**34.90**	**15.0%**	**5.24**	**40.14**
06.1.6.b	**Passive Thermal Control**			1097.09	15.0%	164.56	1261.66
06.1.6.c	**Semi-Passive Thermal Control**			12.00	15.0%	1.80	13.80
06.1.7	**Propulsion (Hardware)**			**5002.48**	**14.0%**	**698.03**	**5700.50**
06.1.7.a	**Primary EP System Hardware**			**2371.36**	**17.9%**	**424.00**	**2795.36**
06.1.7.b	**Power Processing Unit (PPU)**			0.00	0	0.00	0.00
06.1.7.c	**Direct Drive Unit (DDU)**			468.48	18.0%	84.33	552.81
06.1.7.d	**Propellant Management (EP)**			2162.64	8.8%	189.70	2352.33
06.1.8	**Propellant**			**71607.21**	**0.0%**	**0.00**	**71607.21**
06.1.8.a	**Propellant (EP)**			70965.40	0.0%	0.00	70965.40
06.1.8.b	**RCS Propellant**			627.01	0.0%	0.00	627.01
06.1.8.c	**Pressurant**			14.80	0.0%	0.00	14.80
06.1.9	**Structures and Mechanisms**			**2244.56**	**18.0%**	**404.02**	**2648.58**
06.1.9.a	**Structures**			**1169.76**	**18.0%**	**210.56**	**1380.32**
06.1.9.b	**Mechanisms**			**1074.80**	**18.0%**	**193.46**	**1268.26**

Table A.3. VASIMR Option Master Equipment List



WBS Number	Description (CD-2011-64 ETDD4 Case 2) Nuclear Electric Propulsion Stage (NEP) ETDD4 - July 2011	QTY	Unit Mass (kg)	Basic Mass (kg)	Growth (%)	Growth (kg)	Total Mass (kg)
06	NEP Stage (ETDD DRM 4)			91908.27	6.0%	5477.19	97385.46
06.1	NEP Stage Bus			91908.27	6.0%	5477.19	97385.46
06.1.2	Attitude Determination and Control			39.50	3.0%	1.19	40.69
06.1.2.a	Guidance, Navigation, & Control			39.50	3.0%	1.19	40.69
06.1.3	Command & Data Handling			67.90	21.7%	14.71	82.61
06.1.3.a	C&DH hardware			50.40	19.8%	9.99	60.39
06.1.3.b	Instrumentation & Wiring			17.50	27.0%	4.73	22.23
06.1.4	Communications and Tracking			55.10	16.3%	8.96	64.06
06.1.4.a	X band Communications System			26.70	15.9%	4.26	30.96
06.1.4.b	S Band Communications System			28.40	16.5%	4.70	33.10
06.1.4.c	Data Router and SSR			0.00	0	0.00	0.00
06.1.5	Electrical Power Subsystem			17257.73	12.7%	2189.52	19447.25
06.1.5.a	Power Management & Distribution			3828.00	14.1%	539.22	4367.22
06.1.5.b	Reactor			3881.00	13.0%	504.45	4385.45
06.1.5.c	Heat rejection			7612.73	12.0%	913.53	8526.26
06.1.5.d	Power Conversion			1936.00	12.0%	232.32	2168.32
06.1.6	Thermal Control (Non-Propellant)			2945.72	15.0%	441.86	3387.58
06.1.6.a	Active Thermal Control			151.65	15.0%	22.75	174.40
06.1.6.b	Passive Thermal Control			2151.51	15.0%	322.73	2474.24
06.1.6.c	Semi-Passive Thermal Control			642.56	15.0%	96.38	738.95
06.1.7	Propulsion (Hardware)			14282.80	16.5%	2356.56	16639.35
06.1.7.a	Primary EP System Hardware			4926.66	17.5%	862.92	5789.57
06.1.7.b	Power Processing Unit (PPU)			6704.00	18.0%	1206.72	7910.72
06.1.7.c	Direct Drive Unit (DDU)			350.40	18.0%	63.07	413.47
06.1.7.d	Propellant Management (EP)			2301.74	9.7%	223.85	2525.59
06.1.8	Propellant			54679.47	0.0%	0.00	54679.47
06.1.8.a	Propellant (EP)			53972.04	0.0%	0.00	53972.04
06.1.8.b	RCS Propellant			691.13	0.0%	0.00	691.13
06.1.8.c	Pressurant			16.30	0.0%	0.00	16.30
06.1.9	Structures and Mechanisms			2580.05	18.0%	464.41	3044.46
06.1.9.a	Structures			1209.28	18.0%	217.67	1426.95
06.1.9.b	Mechanisms			1370.77	18.0%	246.74	1617.50

Acknowledgments

The authors thank Dr. Carolyn Mercer, manager of the ETDD HESPS Project at NASA Glenn Research Center, for funding the COMPASS study reported here; Dr. Sonny White and Jeff George of the NASA Johnson Space Center for providing information and design inputs related to the VASIMR thruster; Mr. Sal Distefano of the NASA Jet Propulsion Laboratory for his participation in the study; and the members of the NASA GRC COMPASS team that contributed their considerable skills and knowledge to this effort: Les Balkany, Anthony Colozza, John Dankanich, Jon Drexler, Robert Falck, James Fincannon, James Fittje, John Gyekenyesi, Geoffrey Landis, Mike Martini, Tom Packard, Thomas Parkey, Paul Schmitz, Jeff Woytach, Joe Warner, Glenn L. Williams, Anita Tenteris, and especially Melissa McGuire and Carl Sandifer. We gratefully acknowledge the support of the Exploration Technology Development and Demonstration Program within the Exploration Systems Mission Directorate.

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