Incorporation of the Mini-Magnetospheric Plasma Propulsion System (M2P2) in a Manned Mission to Mars

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ABSTRACT

This paper presents two variations of a manned mission to Mars incorporating the Mini-Magnetospheric Plasma Propulsion (M2P2) System, under development at the University of Washington by Professor Robert Winglee, as a less expensive, flexible alternative to the traditional nuclear propulsion systems proposed in the NASA Mars Reference Mission. The M2P2 produces a magnetic plasma bubble that interacts with the ambient solar wind to produce an energy-efficient, high specific impulse thrust. Two scenarios are presented to show the versatility of the M2P2 propulsion system. The first consists of a standard mission similar to the NASA Mars Reference Mission, in which cargo is sent to the Martian surface prior to the piloted mission. The second scenario is a non-traditional mission, in which a single, piloted mission is sent to Mars with multiple landers. These landers would be able to explore multiple sites on the surface of Mars. Multiple orbit trajectories with varying total and Martian surface stay times have been calculated to show the time flexibility of this advanced propulsion system versus the limited launch windows dictated by traditional propulsion systems. The minimum round trip time is shown to be 1.7 years, with potentially 50% less departure mass from low Earth orbit than required by the Mars Reference Mission.

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Nomenclature

F – Thrust
g – Local gravitational acceleration
M – Mass
P_r, P_ϕ - Radial and tangential components of thrust
r – Radius from central gravitational body
θ – Flight path angle
ϕ – True anomaly
ΔV – Change in velocity
DIPS – Dynamic Radioisotope Power System
ECLSS – Environmental Control and Life Support System
EDV – Earth Descent Vehicle
ETV – Earth Transfer Vehicle
GEO – Geosynchronous Earth Orbit
ISRU – In-Situ Resource Utilization
ISS – International Space Station
LEO – Low Earth Orbit
M2P2 – Mini-Magnetospheric Plasma Propulsion
MAV – Mars Ascent Vehicle
MDV – Mars Descent Vehicle
MMH – Monomethyl Hydrazine
MTV – Mars Transfer Vehicle
THCS – Temperature and Humidity Control System
WAVAR – Water Vapor Adsorption Reactor
WM – Waste Management
WRM – Water Recovery, Management

1. INTRODUCTION

A mission to Mars is often thought of as the next step in human exploration of space. An integral part of making a mission to Mars possible is developing a feasible propulsion system. The traditional nuclear propulsion methods suggested by “The Reference Mission of the NASA Mars Exploration Study Team” [1] has the disadvantages of being restricted to short launch windows, causing long mission duration and high costs. With the implementation of an advanced propulsion system such as the Mini-Magnetospheric Plasma Propulsion (M2P2) System, the mission would enjoy the benefits of flexible launch capabilities, reduced mission durations, and lower costs. Two different scenarios for the M2P2 Mission to Mars are presented here. Both demonstrate the low mass requirements and the adaptability of the M2P2 System. The first scenario demonstrates how a Mars Reference-type mission would look using the M2P2. The second scenario shows how the M2P2 can be adapted to an unconventional, “one-trip” mission.

1.1.The Mini-Magnetospheric Plasma Propulsion (M2P2) Device

The Mini-Magnetospheric Plasma Propulsion (M2P2) device is a system, developed by Professor Robert Winglee at the University of Washington [2], which uses energy from the solar wind to provide enhanced propulsion for the spacecraft. The M2P2 uses a solenoid (Figure 1) to create a magnetic field into which plasma is injected, resulting in an inflated “magnetic bubble” tens of kilometers in diameter. In much the same manner as the Earth’s magnetosphere, this bubble intercepts and deflects the solar wind, which has a velocity between 350 and 800 km/s, although it can occasionally travel as fast as 1000 km/s. Unlike the Earth, however, the momentum acquired by the M2P2 from the solar wind is sufficient to raise or lower the orbit of the spacecraft. This acquired momentum results in a radial force on the spacecraft. In a multiple M2P2 ship configuration, varying the pointing of the magnetic field of the M2P2 devices can generate a tangential force component, up to an angle of 15^o [2] off the radial direction from the sun.

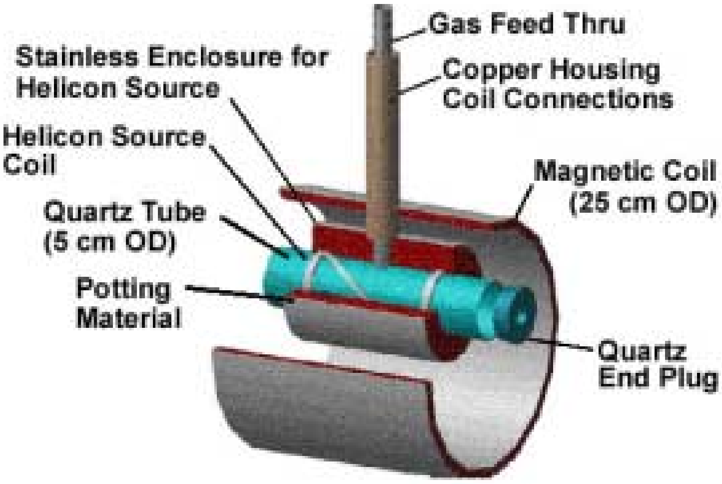


Fig. 1: The components of the M2P2 lab prototype [2].

1.2. Benefits of the M2P2

The M2P2 was chosen as an advanced propulsion system for this mission because it offers several considerable advantages over chemical or nuclear propulsion: the M2P2 provides a constant force, while at the same time using very little fuel compared to the amount that would be needed with conventional rockets. Thus, by using a M2P2, a crew arrives at Mars more quickly than if they were simply launched from Earth and coasted along a Mars intercept trajectory, and more efficiently than if they were to use chemical rockets. Using the M2P2 to provide thrust also allows the mission to leave Earth at a lower velocity, conserving fuel for both manned and unmanned spacecraft. In addition, the magnetic bubble created protects the crew from a substantial amount of particle radiation.

The M2P2 has an advantage over solar sails in that it is both smaller and lighter. The M2P2 requires only a solenoid and plasma injection system, which have a combined mass of less than 70 kg. Also, as the M2P2 travels away from the sun, the magnetic bubble self-adjusts to the fluctuations in the solar wind so that the total force transmitted to the ship remains constant. This feature is not available with solar sails, as the force transmitted to a ship with a solar sail falls off at the same rate as the photon flux, i.e., inversely as the square of the distance from the sun [2].

2. APPLICATIONS TO A MISSION TO MARS

Another benefit of using M2P2 systems is that of having more frequent launch windows. With traditional chemical or nuclear propulsion the launch windows for Mars arrive approximately once every two years [1]. This creates a strict time schedule on any multi-phased mission to Mars. Our research shows that when using a M2P2 system, launch windows occur several times a year. This allows for a greater flexibility in the pre-placement of supplies for future manned missions. The frequent launch windows also allow for the ability to choose between many different surface stay and total mission durations. We have calculated some examples of these different mission times, and some feasible ones are given in Table 1.

Reducing the ΔV's required during an interplanetary mission is an ongoing challenge. We propose that it is possible, due to the low thrust nature of the M2P2 device to effectively tailor the approach to a target planet so as to result in a lower required ΔV in a planet's sphere of influence. The ΔV for several different missions, a Hohmann Transfer, the Mars Reference Mission [1], and a M2P2 mission, which will be discussed below, are shown in Table 2. The ΔV required for the

Table 1: M2P2 mission times

Days				Years
Departure	Surface	Return	Total	
223.4	448	180.2	851.6	2.33
249.4	363	203.8	816.2	2.24
268.9	290	207.4	766.3	2.10
287.2	204	228.3	719.6	1.97
305.5	108	256.3	629.2	1.72
324.5	1	324.5	616.2	1.69

M2P2 device to leave Earth from LEO is around 3.25 km/s. As the craft approaches Mars the M2P2 system can be used to tailor the approach to achieve a ΔV of less than 2.5 km/s, and leaving Mars a chemical ΔV of 2 km/s results in acceptable Earth return trajectories. These are compared to the other missions in Table 2. Because of the low thrust nature of the M2P2 , it has to be operated in a different fashion to chemical propulsion systems. First, it must be left on for long periods of time in order to produce any significant change in the trajectory of the spacecraft. Second, the orbits attainable are vastly increased, and we have found that varying the amount of time the M2P2 is turned on can drastically change the mission travel and surface stay times.

By comparing the M2P2 system to a typical mission to Mars using nuclear propulsion we have found that a M2P2 mission requires less mass and is more flexible overall, because of the variety of trip durations and launch windows available. We are no longer constrained by long surface stays; thus we can be creative when designing missions to Mars using the M2P2 system. We have decided to present two variations on a mission to Mars using an M2P2 system (See Sections 2.1 and 2.2). The first mission, Scenario I, is similar to the Mars Reference Mission in that it is a “typical” mission, in which the time at Mars is spent on the surface. The second mission (Scenario II) is different from the Mars Reference Mission in that it takes advantage of the short required stay. It leaves a manned ship in orbit around the planet and sends a crew to the surface in a small lander for four weeks, returns them to the ship and sends another lander down for another 4 weeks. Because the surface stay is shorter, less maintenance is required and therefore fewer man-hours are needed for equipment upkeep. We have chosen to present each mission with only a crew of 4 for comparison’s sake, as opposed to the Mars Reference Mission, which has a crew of 6 [1]. Table 3 compares the total masses of the Mars Reference Mission, which uses nuclear propulsion [1], and the M2P2 missions. The M2P2 missions require less mass than the Mars Reference Mission, mostly due to lower chemical propellant mass requirements. As can be seen from Table 3, using M2P2 systems can result in a significant mass savings over conventional approaches. Scenario I is able to reduce by over 100,000 kg the amount that needs to be lifted to LEO. Scenario II is able to reduce, by over 50%, the mass needed in LEO to complete the Mars Reference Mission [1].

Table 2: Mission ΔV comparison

Mission	Chemical ΔV (km/s)			
	Leaving Earth	Arriving Mars	Leaving Mars	Total
Hohmann Transfer	3.6	2.26	2.26	8.12
Mars Reference	5	0	4	9
M2P2	3.2	2.5	2	7.7

Table 3: LEO departure mass comparison

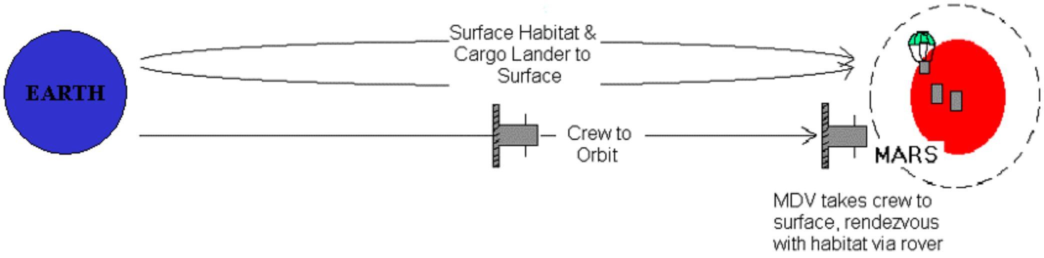
	Mars Reference Mission (Crew of 6) (kg)	M2P2 Scenario I (Crew of 4) (kg)	M2P2 Scenario II (Crew 4) (kg)
Cargo I	134,473	90,300	N/A
Cargo II	147,472	120,750	N/A
MTV	137,406	101,310	173,440
Total	419,351	312,360	173,340

2.1 Scenario I

Scenario I is presented to show how The Reference Mission [1] would be modified if the advanced M2P2 propulsion system were used. Scenario I is similar to The Reference Mission in that multiple launches are made from Earth, in an attempt to reduce the mass of the manned spacecraft, and to take the first step in establishing a permanent human base on the surface of Mars. Two cargo vehicles and a manned spacecraft are sent from Low Earth Orbit (LEO), as shown in Figure 2. The first cargo vehicle carries a nuclear reactor, one large rover, food and water for the surface stay, science equipment, an *In Situ* Propellant Production Plant with storage tanks, and a dry Mars Ascent Vehicle (MAV) [3]. The second cargo vehicle takes a surface habitat to the surface of Mars. These cargo missions will be powered by solar panels and utilize the M2P2 system. Once at Mars, the transfer vehicle aerobrakes in the Martian atmosphere and aerocaptures, then uses rockets and parachutes to land on the surface [3]. Once the transfer vehicle has landed safely on the surface, the rover carries the nuclear reactor to a site far from the landing site. At the landing site the *In Situ* Propellant Production Plant is set up and begins making rocket propellants, methane and oxygen [3]. The third vehicle leaves Earth after the first two have reached the Martian surface. This third vehicle consists of the piloted Mars Transfer Vehicle (MTV), which also acts as the Earth Transfer Vehicle (ETV), and the fuel needed to escape Earth Orbit and capture at Mars. The MTV contains a Mars Descent Vehicle (MDV), an Earth Descent Vehicle (EDV), a rover, living quarters, food and water for four astronauts while *en route* to Mars and for the return to Earth. The solar panels are deployed in Geosynchronous Earth Orbit (GEO).

Finally, the crew of four is brought to the MTV on a carrier such as the Space Shuttle Endeavor [4]. The MTV utilizes M2P2 propulsion on the way to Mars. At Mars, the MTV uses aerobraking combined with a small chemical burn to capture in Mars orbit. Once in Mars orbit the astronauts will leave the MTV/ETV using the MDV. The landing site will be within walking distance of the *In Situ* Propellant Production Plant, Habitat, and MAV. In the event that the landing site is missed, the astronauts will have spacesuits and an unpressurized rover that can travel up to 150 km. Food and water for the surface stay will already be at the habitat. Power for the surface stay is provided by the nuclear reactor. The astronauts spend the entire duration of their stay on the surface of Mars.

Due to the extended surface stay and the pre-located cargo missions of Scenario I, a significant reduction in mission mass is attained by using *In Situ* Resource Utilization (ISRU). To produce water for both the astronauts and for the production of return propellant a Water Vapor Adsorption Reactor (WAVAR) [7] was decided upon. This device is capable of extracting the natural water vapor out of the Martian atmosphere, which contains 0.03% water by volume. This water will then be used by the crewmembers for life support needs and also by a Sabatier process [1,3,8] to produce propellant for the return trip. The water from the WAVAR process is decomposed into hydrogen and oxygen through electrolysis. The oxygen is then liquefied and saved in a tank for later use. The hydrogen is combined with carbon dioxide from the Martian atmosphere to produce methane and water using the Sabatier process [1,2,8]. The methane is stored in cryogenic tanks to be used in the Mars ascent and Mars escape burns, while the water is again decomposed through electrolysis and sent back through the process. These two processes allow the fuel and water needed on the surface and for the return trip to be produced at Mars and removes the need to include the return propellant and some of the required water in



CARGO I
Nuclear Reactor for Surface
Unpressurized Rover
Surface Habitat
Food and Water for 100 Days
Science Equipment
Mars Ascent Vehicle
In Situ Propellant Production

MTV
Living Quarters
Mars Descent Vehicle
Unpressurized Rover
Earth Descent Vehicle
M2P2 Systems
Solar Panels
Food and Water for 440 Days

CARGO II
Surface Habitat

Fig. 2: Scenario I.

the initial launch from Earth. Further research and development of ISRU processes is needed, and these processes must be demonstrated before a full-scale human Mars exploration program can be launched. Current plans call for methane/oxygen propellant ISRU strategies to be implemented on an unmanned Mars sample return mission in about a decade.

The Mars Ascent Vehicle delivered on the cargo mission provides the crew a way to leave the Martian surface and dock with the transfer vehicle. The dry mass of the ascent vehicle module is approximately 3,300 kg [8]. The MAV fueled with the *In Situ* Propellant returns the astronauts to the ETV [3]. The MAV will carry back enough fuel for the MTV/ETV to escape Mars orbit and will itself run on *In Situ* Propellant. The ETV uses *In Situ* Propellant to escape Mars Orbit. Once back inside Earth's sphere of influence the astronauts are ejected from the ETV in the EDV and make for an Apollo type re-entry or a docking maneuver with the International Space Station. Table 4 gives an itemized breakdown of the mission components and their masses for this scenario and compares it to Scenario II.

2.2 Scenario II

The main goal of Scenario II is to show the M2P2 system can be applied to a non-traditional mission. With Scenario II we will show that with the short Martian stays allowed by the M2P2 system we can eliminate the need to rendezvous with supplies on the Martian surface and can greatly reduce overall mass. Scenario II sends only one vehicle, the MTV/ETV, to Mars (See Figure 3.). Unlike "The Reference Mission" [1], this scenario does not send any cargo to the surface of Mars before the piloted mission arrives. Instead of attempting to establish a permanent Martian base, this scenario focuses on a single comprehensive mission. For the purpose of this study it was decided to send two small two-person landers with all the supplies needed to the surface for four weeks each. One of the advantages to having a mission of this type is eliminating the need to rendezvous with supplies on the Martian surface. This allows a more comprehensive study of the planet by enabling visiting the surface at more than one location (using multiple landers), and reducing pollution of the planet by eliminating the need for a nuclear power source and permanent habitat on the surface. While two of the crew are on the

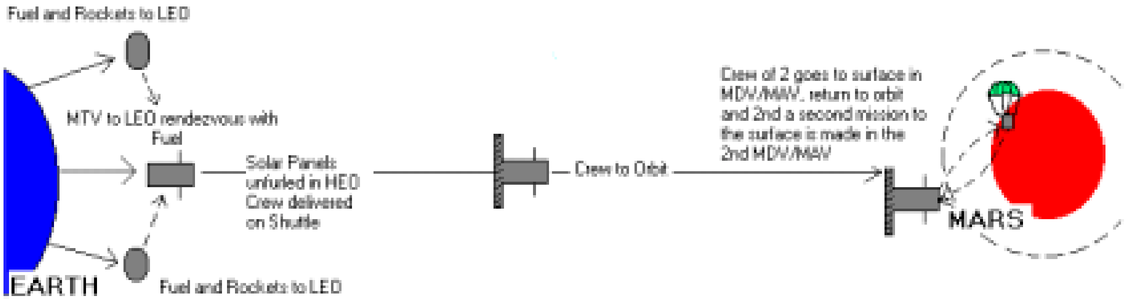


Fig. 3: Scenario II.

surface the other two crewmembers remain in orbit processing data and maintaining the MTV/ETV.

The MTV for Scenario II is assembled in LEO. It carries science equipment, living space, food and water for four astronauts for the entire duration of the trip, inflatable habitats for the surface of Mars, two small MDV/MAV, and an EDV. In Scenario II most of the man-hours at Mars will be in orbit around the planet. After the MTV is in a stable orbit, two of the crew will descend to the Martian surface in a small MDV/MAV. Propellant for the ascent will be carried down to the surface. The MDV/MAV is equipped with an inflatable habitat, batteries, and enough consumables for four weeks. The astronauts will not have a rover on the surface. All science equipment will also be brought from the MTV to the surface. The MDV, which also acts as a MAV, will be used to return to the MTV in orbit. The other two astronauts will make a second trip to the surface in a similar manner as the first. This eliminates the need to rendezvous with a habitat and power source on the surface of Mars, and allows the astronauts to visit two different sites on the Martian surface. Though this trip has the benefit of redundancy with two MDV/MAVs, it does not allow for the possibility of using *in situ* propellant. This varies greatly from the Reference Mission [1], which places the entire crew on the surface for the full duration of the stay at Mars. The return to Earth is done in a similar fashion as Scenario I, except that no *in situ* propellant is used. Again, Table 4 gives an itemized breakdown of the mission components and their masses for this scenario and compares it to Scenario I.

2.3. Transfer Vehicle

The Transfer Vehicle (See Figure 4) consists of several independent sections, which are connected together. Each of these sections contains complete systems for the vehicle. This modular design allows each separate system to be built and carefully tested on Earth before it is lofted into space. Once in space, the components can be assembled into the Transfer Vehicle, and astronauts can be sent up to begin Earth escape procedures. From the exterior, the Transfer Vehicle is a long cylinder with sections of solar panels at one end and an array of long booms in the middle. There are four solar panels, arranged so that they form a plus sign. These panels will constantly face towards the sun, and the rest of the ship extends from the middle of the solar array away from it. Because of this arrangement, there is no possibility of shadows on the panels, which could result in various power difficulties. During the initial stages of escape, the panels are folded and stored within the body of the Transfer Vehicle.

Attached to the center of the solar array is the power control center. This is designed to regulate and control the flow of power to all of the ships component sections. It also contains batteries and other redundant back-up systems. Proceeding away from the sun, the living quarters are attached to the power systems. These are designed for a zero gravity environment, and are thus very space-efficient. The living quarters are shaped as a cylinder, and attached to the outside wall of the cylinder are four storage containers. These contain the necessities for a voyage of such duration. There are also maneuvering thrusters positioned along the circular boundaries of the cylinder. Attached to the other end of the living quarters is the M2P2 machinery. There are 6 booms that radiate from the central axis of the ship, and each of these

Table 4. Mass budgets of Scenarios I and II

Scenario		I Mass (kg)	II Mass (kg)
Cargo			
	Nuclear Reactor [1]	3,960	-
	Unpressurized Rover [1]	500	-
	Food and Water [3,	1,490	-
	Science Equipment [1]	1,700	-
	Aerobrake [8]	2,000	-
	M2P2 Systems	1,300	-
	Power Systems	2,450	-
	Mars Ascent Vehicle [8]	2,400	-
	In Situ Prop. Production [2]	9,000	-
	Structure	5,500	-
	Propellant	60,000	-
Total		90,300	N/A
Habitat			
	Surface Habitat [8]	32,000	-
	M2P2 Systems	1,300	
	Power Systems	2,450	-
	Aerobrake [8]	2,000	
	Structure	4,000	
	Propellant	79,000	
Total		120,750	N/A
MTV			
	EDV(s) [8]	3,000	3,000
	Power Systems	4,260	4,260
	M2P2 Systems	1,600	1,600
	Food & Water	8,350	9,830
	EC/LSS [10,11]	3,400	3,400
	Communication [3]	350	350
	MDV(/MAVs) [3,8]	3,000	6,000
	Fuel for MDV(/MAVs)	1,000	4,000
	Unpressurized Rover [1]	550	-
	Science Equipment [3]	-	900
	Batteries [3]	1,000	2,900
	Inflatable Habitats [10]	-	900
	Ship Structure	5,200	5,200
	Aerobrake	2,500	2,500
	Propellant	67,100	128,500
	Total	101,310	173,340
TOTAL		312,360	173,340

houses two (2) M2P2's. Like the solar panels, these are folded when leaving earth. In addition to the M2P2's, these booms house the communications dishes of the M2P2 project, allowing a clear path to Earth.

The other side of the M2P2 system is attached to a cylindrical section of the Transfer Vehicle which functions differently depending on which permutation of the Mars Mission is employed. It holds a Mars Lander system, which is propelled from the craft and transports the crew from orbit to Mars. This is not used during the Transfer stage of the mission, and so is activated at Mars. The end of the lander section is attached to the main engine, which is used for orbital capture and escape. Most of the space is for a large fuel tank, containing hydrazine. The section of the ship oriented farthest from the sun holds the main rocket engines used for capture and escape, and the propellant tank. This is used to leave both Earth and Mars, as well as slow the Transfer Vehicle at Mars.

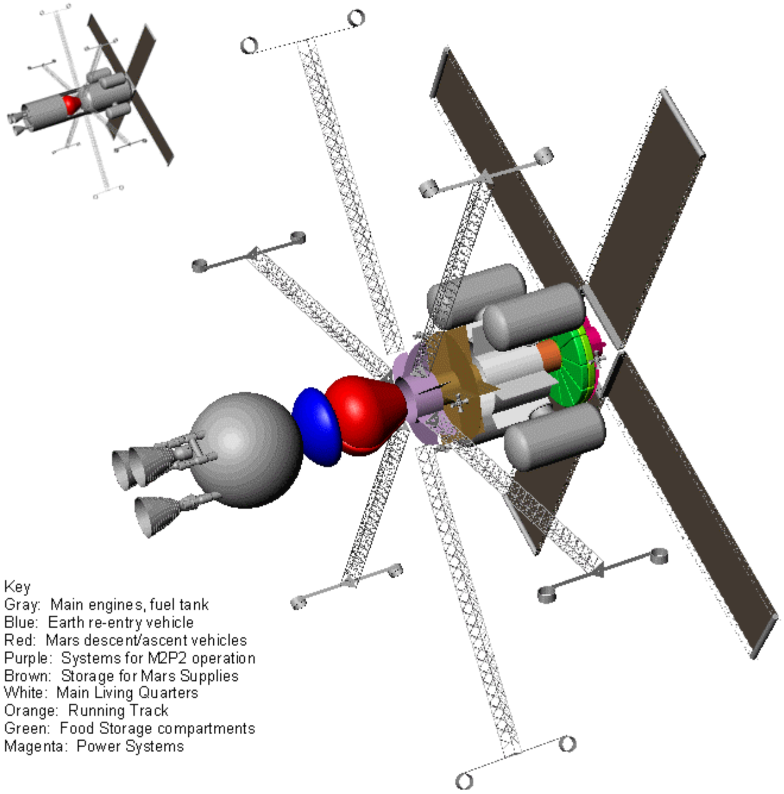


Fig. 4 The transfer vehicle.

3. PROPULSION SYSTEM

3.1. Requirements for the M2P2 system

In both scenarios the ship has twelve M2P2's; adjusting the amount of power going into each device can vary the resulting force. By combining the twelve M2P2's a specific force of 1 N per 200 kg is produced at Earth and a specific force of 1 N per 100 kg is produced at Mars. This specific force results in the required force of 280 N near Earth to complete Scenario II in 1.8 years. Each individual unit will have to produce 24 N and this falls within the current capabilities of the M2P2 device. In order to generate 24 N each device requires 3 kW of electrical power, which results in a total of 36 kW required by the twelve M2P2's near Earth and 18 kW near Mars (this allows for the size of the solar panels to remain constant over the mission duration), these values were determined to be acceptable power requirements based on what could be attained using the latest generation of solar panels (see Section 4). Using twelve M2P2's also allows for a small level of redundancy, if one or two units should fail, power can be rerouted to the remaining M2P2's in order to maintain the required 280 N. Each device, including the surrounding electronics, has a mass of 66 kg, for a total mass of 400 kg. The M2P2's are held twenty meters away from the ship so that the high plasma densities at the devices do not interfere with the ship or the astronauts. The M2P2's are supported on Stacking Triangular Articulated Compact Beams (STACBEAM) that have the ability to retract when needed [3]. The beams have a combined mass of 600 kg [3].

The M2P2 is capable of using a variety of propellants. Virtually any easily ionizable gas can be used [2]. Suitable propellants include H_2, He, N_2, Ar, CH_4, NH_3, and CO_2. While hydrogen and helium make excellent ionizable propellants, they are not stored easily for long periods of time. In order to have a reasonable storage density, hydrogen and helium would have to be stored in liquid form. This would require cryogenics, which involves a large mass and power cost.

We have chosen to use hydrazine (N_2H_4) as propellant, because it can be ionized and has a long history of use onboard many robotic and man-rated space missions. Although hydrazine is more massive, on a molecular scale, it can be easily ionized into its light element constituents and can be easily stored in liquid form using current propulsion tank technology. Hydrazine will also be used for the attitude control thrusters. This redundancy will result in a more efficient propellant storage system.

Each M2P2 device requires 0.25 kg of hydrazine per day. For our ship's twelve M2P2 devices, a total of 3 kg of hydrazine per day will be required. This propellant requirement is a result of plasma leakage from the edges of the M2P2 bubble. This leakage is caused by energy from the incident solar wind heating the ions within the mini-magnetosphere; these heated ions (with their large gyro-radius) can become demagnetized near the boundary of the magnetosphere and lost from the system.

3.2. M2P2 Missions

In order to generate several different M2P2 missions quickly, a computer program was written. This program was written in Matlab and was used for all mission calculations. The input variables for this program were the number of days the M2P2 operates. It was quickly discovered that the best way to utilize the M2P2 is to allow the spacecraft to travel beyond Mars orbit and then rendezvous with the planet as the spacecraft was falling back toward the sun. This allows for a faster realignment of the planets so that the return mission can leave Mars, resulting in shorter total mission times and also for a reduced ΔV required at Mars. When the M2P2 is first on as it is leaving Earth, the shortest mission and lowest ΔV's result when the tangential force is vectored opposite the direction of motion. As the craft approaches Mars the M2P2 is again turned on with the tangential force vectored in the direction of motion. This second use of the M2P2 allows for a reduction in the radial velocity of the spacecraft, due to the mostly radial force, as it reaches Mars and an increase in the tangential velocity to better match that of Mars.

To calculate the path of the spacecraft as a function of time the equations of motion of Stuhlinger for low thrust missions [5] were used (See Figure 5). The force of the propulsion system is F, and the angle the force is vectored off the radial direction is θ. The local gravitational force is g and φ is the true anomaly. These equations were solved together using Matlab. From the solution the position and velocity of the spacecraft as a function of time was determined.

For the return trip, it was found that if the M2P2 is turned on as the craft is leaving Mars with the tangential force vectored opposite the spacecraft's momentum, the true anomaly that the return trip traveled though is greatly reduced. This allows for mission times of about 2 years without having to use large chemical burns. Before the spacecraft leaves Mars orbit, the M2P2 is turned on, which over the course of several days places the ERV in a highly elliptical orbit about Mars, thereby decreasing the chemical burn requirements. As the spacecraft nears Earth, the M2P2 is used in order to slow the radial velocity of the craft as it falls in toward the Sun and to reduce the tangential velocity, for a smaller chemical burn requirement at Earth. An example of

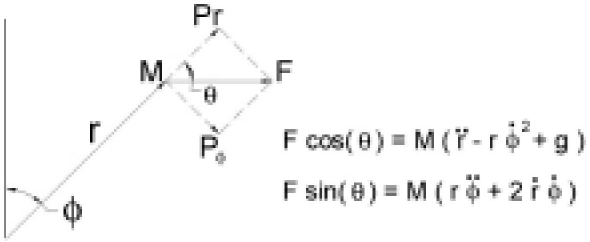


Fig. 5 Polar coordinate system used in trajectory analysis [5].

one of these missions is shown in Figure 6.

The main benefit of using M2P2 devices is the ability to launch human missions to Mars which last less than two years. This particular mission results in a total mission duration of 670 days. The trip outbound lasts 249 days, followed by a surface stay on Mars of 130 days, and a 290-day return trip. As can be seen in Figure 6 the mission travels beyond the orbit of Mars before actually entering orbit around Mars. This is done to allow for both a reduction in the ΔV required to enter into orbit around Mars and to allow for the correct positioning of the planets to result in a shorter mission time. After the spacecraft leaves Mars on its way back to Earth, the M2P2 is again turned on in order to reduce the tangential velocity of the craft. This reduction decreases the true anomaly the mission travels though on the return voyage, allowing for a total duration of under two years. The times for this trip are compared to the Mars Reference Mission [1] and a Hohmann Transfer [6] in Table 5. These missions also demonstrate the wide adaptability of the M2P2 device to a variety of missions.

The cargo missions were also designed using M2P2 systems to capitalize on the availability of additional launch windows not available to chemical or nuclear propelled missions. The ability to use the M2P2's to reduce the ΔV's required (thereby reducing the amount of propellant that needs to be carried), and the fast transit times, are another benefit of using the M2P2 systems on the cargo missions. Using a M2P2 system it is possible for the cargo to arrive on Mars 135 days after leaving Earth, however a longer transit time may be more desirable due to launch window spacing. This time is equivalent to chemical or nuclear propellants, but can be done with a lower amount of propellant, thereby saving mass.

Table 5: Scenarios I & II compared to Mars Reference Mission

Mission	Days				Years
	Departure	Surface	Return	Total	
Hohmann Transfer	259	454	259	972	2.66
Mars Reference	150	619	110	879	2.41
Scenario 1	250	131	291	672	1.84
Scenario 2	230	60	365	655	1.79

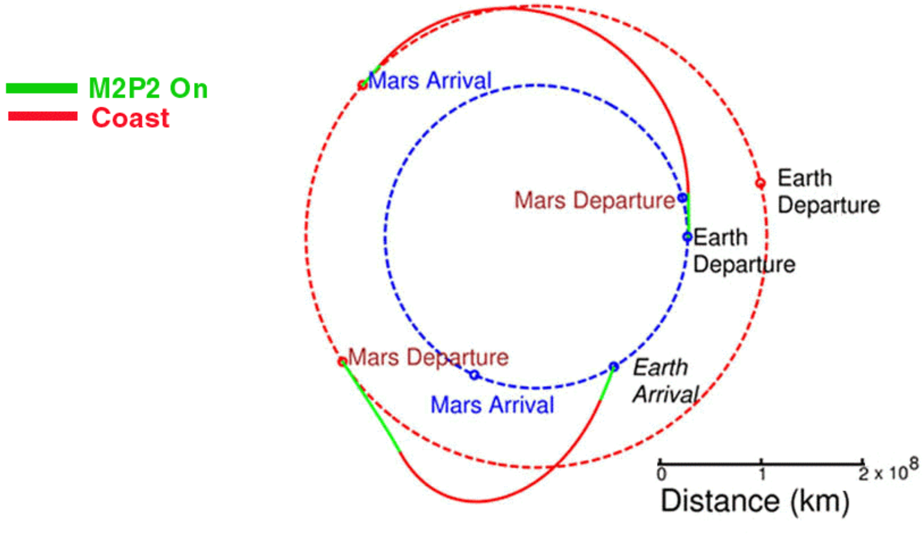


Fig. 6: M2P2 trajectories to Mars.

4. POWER SYSTEM

4.1 MTV Vehicle Power

The MTV uses solar panels as its primary power source. Solar panels are safe for the crew, have been used in space for years with minimal problems, and the power requirements are low enough that the size and mass of the panels does not become prohibitively heavy. The power requirements for the MTV are listed in Table 6. The solar panels are deployed just after passing through the Van Allen radiation belt.

The panels use triple-junction gallium arsenide cells and have cell efficiencies of 26.8%[7]. The solar flux at Mars aphelion is 490 W/m^2 [3]. There the cells generate an electrical output of 131 W/m^2. The solar panels are divided into four sections, each 6 m x 18 m, for a total area of 432 m^2, and generate 57 kW of power at Mars. The specific mass of the panels is 2.09kg/m^2 [2], thus their total mass is 900 kg. While in Mars orbit the M2P2's are no longer used. Thus, the power generated is more than sufficient to power all ship systems, and charge the batteries used in Scenario I and Scenario II. The power system mass is shown in Table 7.

At the distance the M2P2's are separated, the plasma densities near the solar panels are comparable to those in the ionosphere. Plasma densities in the ionosphere have been shown to have no significant effect on satellites in low Earth orbits, and thus should not present a problem to this mission.

Batteries will be used as a power storage point used only as backup in emergencies related to the solar panels. In Scenario II, batteries will also be used for the Mars surface mission. Since the time on the surface for Scenario II will only be a few days, batteries are the most efficient source of power.

4.2. Martian Surface Power Supply

For Scenario I, the power requirement for the surface of Mars is estimated to be 100kW. This includes power for environmental control and life support systems, In Situ Propellant Production and experiments. Similar to the Mars Reference Mission [1] a nuclear reactor will be used for power on Mars. A nuclear reactor was chosen because of the very low solar flux on the Martian surface. The 490 W/m^2 solar flux during transit is modeled for the worst possible case, which occurs at the aphelion of Mars' orbit. The solar flux on the surface of Mars depends on the latitude and the solar declination, which is an angle dependent on the orbit and seasons of Mars. The average solar flux at 35° north on the surface of Mars (using its mean distance from the sun) is 160 W/m^2 [3,8]. Dust storms also play an important role in the modeling of the solar flux on Mars. Dust storms on the average decrease the solar flux by 50% [3]. Based on this, the average solar flux used for sizing the solar arrays on Mars is 80 W/m^2. To produce 100 kW power on the surface would require over 6,000 m^2 of solar panels, which is not a feasible option.

One of the cargo missions sent before the astronauts has a power module. The SP-100 nuclear reactor uses controlled fission of uranium 235 to convert 2.2 MW of reaction power to 100 kW electrical power [8]. Despite the 4% thermal to electric efficiency of the SP-100, this unit still provides a higher energy density (about 40 kg/kW) compared to solar panels. This unit is also capable of high peak-power mode (500 kW) for short durations. A battery of nickel-hydrogen cells will supplement the SP-100 during peak power loads. Table 8 below shows the mass breakdown for the power unit.

Table 6. MTV power requirements

System	Requirements
M2P2	36 kW
Life support	9 kW
Communications	9 kW
Heating	3 kW
Total	57 kW

Table 7. MTV power system mass

	Mass (kg)
Solar Panels	900
Support Structure	3040
Equipment	320
Total	4260

Table 8. Nuclear reactor

Reactor	640 kg
Radiation Shield	860 kg
Heat Transport	445 kg
Reactor instrumentation and control	210 kg
Power conversion	315 kg
Heat rejection	835 kg
Power conditioning, control, and distribution	370 kg
Mechanical and structural elements	285 kg
Total	3,960 kg

The SP-100 unit has an approximate mass of 4,000 kg and when stowed is about 6 meters long and 4 meters in diameter. This power plant is capable of providing continuous power for a minimum of seven years. With minor modifications, the SP-100 can last 15 years at full power [8].

5. ENVIRONMENTAL CONTROL & LIFE SUPPORT SYSTEMS

For this particular mission, current technologies used on the International Space Station (ISS) [12] and the Space Shuttle [4] can be utilized. The Environmental Control and Life Support System (ECLSS) consists of a semi-closed system in which air and water are regenerated and regulated with the use of Air Revitalization, Temperature and Humidity Control System (THCS), and Water Recovery, Management (WRM), and Waste Management (WM) [10,11]. For the mass calculations of each component done by studies of the Advanced Life Support [10], a volume of 50 cubic meters has been allotted to each person. It is assumed that equipment is of the same mass, regardless of the number of crewmembers. Table 9 shows the mass break down for the ELCSS. Comparatively, the Mars Reference Mission [1] is bringing 4661 kg for life support.

Table 9. Environmental Control & Life Support Systems

System	Mass (kg)
Air Revitalization	448
Temperature & Humidity Control	148
Water Recovery & Waste Management	734
Total	1330

5.1 Consumables

The majority of the consumables transported are food and water for the four-member astronaut team. These consumables are housed in disposable modules that are discarded when the module is emptied [3]. From studies in Advanced Life Support [10], the total amount of food and water per day for four humans is 14.84 kg per day. Table 10 shows the mass breakdown of the consumables for a four-member crew. For 671 days, we have calculated the total mass of food and water to be 9,420 kg assuming a 90% water recycling efficiency. This mass plus 410 kg extra is on the MTV in Scenario II for emergencies. This extra food and water will be stored in the MDV/MAV if for some reason the crew must stay on the surface longer than the allotted time. Comparatively, the Mars Reference Mission [1] allots 12058 kg for a 6-member crew. The Ares Explore [3] mission allots 7810 kg for its 4 crewmembers. For Scenario I, the consumables used

Table 10: Consumables for a four-member crew

	Mass per day (kg)	Total for Scenario I (kg)	Total for Scenario II (kg)
Dry Food	2.4	1610	1296
Water	11.64	7810	6286
Oxygen	1.17	840	683
Nitrogen	2	1300	1300

on the return trip to Earth can be sent to Mars on a cargo mission, saving in mass costs to Mars. The astronauts spend 130 days on the surface of Mars, and therefore the food and water for the surface stay can be sent to Mars. A 1% leakage rate is assumed for the Nitrogen and Oxygen, and an 80% recycling efficiency is assumed for the Oxygen. An initial 50kg of Oxygen and 200kg of Nitrogen is also included.

Furthermore standard Atmospheric Revitalization, Control and Supply, Temperature Control, and water waste management will be standard procedures. Humans generate 1.0 kg of CO_2 and consume 0.84 kg of O_2. per day [3]. Therefore, CO2 will need to be eliminated from the habitat and oxygen will need to be produced. WAVAR will produce oxygen [9]. Zeolite sieves will remove CO_2 [9]. The atmosphere within the habitat must be pressurized to 10 psi for the stay on the surface [3,8]. The inside temperature must be maintained at 18-27^{o}C, with humidity at 25-70%[8]. Excess heat must be ventilated to prevent overheating, and will also serve to mix the habitat's atmosphere [8]. Ultrafiltration will be used to filter gray water (laundry, dishwasher, and showering) and wastewater [10,11].

6. COMMUNICATIONS SYSTEM

Communications between the Mars Mission and Earth are facilitated by a fairly standard radio system. In order to penetrate the plasma surrounding the spacecraft, this radio system need only operate in the range of gigahertz frequencies. A design similar to those radios used to penetrate the ionosphere can be employed here. Since the ship ferrying astronauts to Mars will remain in orbit during the surface stay/s, the radio connection to earth may continue through these systems during the crew's Mars exploration. There will, of course, be time periods when the ship will be out of touch with NASA. The longest (approximately 5 weeks) of these periods will occur when the Sun obstructs the communications from Mars to Earth; others occur when Mars is between the spacecraft and earth. During this time, the data gathered by the mission team will reside on the ship computers, and once communication can be resumed with Earth, the information will be transmitted.

Conclusions

The results from this study show that using the M2P2 system on a manned mission to Mars results in increased mission flexibility and a significant mass savings over conventional nuclear or chemical based missions. Use of the M2P2 system in the trajectories shown above significantly reduces the ΔV required to capture at Mars, resulting in a large savings in chemical propellant over conventional missions. The M2P2 can save over 50% of the LEO departure mass required for the Mars Reference mission. Assuming a cost to LEO of $22,000 per kilogram, this saves over $5.4 billion. Another demonstrated benefit of the M2P2 is a reduction of the total mission time to less than 2 years. This shorter mission time decreases the risk from the potential failure of critical sensitive instrumentation and life support systems that will be exposed to harsh environments over very long periods. Also, use of the M2P2 results in a more flexible mission schedule. Several launch windows occur each year and a variety of transit and surface stay times may be chosen to meet mission needs. This is a vast improvement over the once every twenty-six month launch windows of conventional or nuclear propelled missions.

The first M2P2 mission scenario presented, is similar to a conventional approach with an extended surface stay. This mission takes advantage of the M2P2 to reduce the overall mission time of the Mars Reference Mission from 879 days to 670 days. In addition, using the M2P2 over the nuclear propulsion methods used in the Mars Reference Mission results in a large reduction in the amount of mass that needs to be lifted into low Earth orbit. This savings in mass comes almost entirely from the chemical propellants not needed when using the M2P2 devices. The second mission scenario takes an unconventional approach. Instead of the astronauts landing on one site for the duration of the stay at Mars, this approach allows for the exploration of two landing sites by performing two separate landings of shorter duration. The reduction in surface requirements in this mission results in the lowest mass requirements of the three compared missions, a savings of over 50% of the LEO departure mass of the Mars Reference Mission.

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