

EMMI - Electric Solar Wind Sail Facilitated Manned Mars Initiative

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Abstract

The novel propellantless electric solar wind sail (E-sail) concept promises efficient low thrust transportation in the solar system outside Earth's magnetosphere. Combined with asteroid mining to provide water and synthetic cryogenic rocket fuel in orbits of Earth and Mars, possibilities for affordable continuous manned presence on Mars open up. Orbital fuel and water eliminate the exponential nature of the rocket equation and also enable reusable bidirectional Earth-Mars vehicles for continuous manned presence on Mars. Water can also be used as radiation shielding of the manned compartment, thus reducing the launch mass further. In addition, the presence of fuel in Mars orbit provides the option for an all-propulsive landing, thus potentially eliminating issues of heavy heat shields and augmenting the capability of pinpoint landing. With this E-sail enabled scheme, the recurrent cost of continuous bidirectional traffic between Earth and Mars might ultimately approach the recurrent cost of running the International Space Station, ISS.

Keywords: E-sail, Mars, manned spaceflight, asteroid mining, propellantless propulsion

1. Introduction

Manned missions to Mars have been in the planning stage since the onset of space age (Portree, 2001; Dorney and Scimemi, 2012). Current proposals include national space agency plans as well as private sector efforts. The European Agency, ESA, as well as the National Aeronautics and Space Administration, NASA, have both expressed interest in manned Mars flights.

Private sector ventures, such as MarsOne or Mars Direct have more ambitious schedules, but are struggling with resource limitations. All of the above base the transportation on traditional propulsion including heavy launchers.

The E-sail (Janhunen, 2010) is a novel propellantless propulsion concept which is based on using the solar wind. It is estimated to be very efficient in terms of impulse versus propulsion system mass (Janhunen et al., 2013b). The E-sail can transport cargo payloads in the solar system at reasonable speed and at low cost because the propulsion system is lightweight and does not consume any propellant.

The alternative technological path that we propose in this paper could provide means for affordable and continuous trafficking of cargo and passengers between the Earth and Mars and thus continuous presence of human beings on the surface of Mars. Because of the exponential nature of the rocket equation, by hauling water from the asteroids and converting it to fuel, one could decrease the transportation cost tremendously. Other assets required by our proposed E-sail facilitated manned Mars presence include the possibility to use the water as a radiation shield, potable water and a source of breathable oxygen. We call the scheme presented on this paper the E-sail facilitated Manned Mars Initiative (EMMI).

The purpose of the paper is to analyse EMMI schemes at high level of abstraction by attempting to identify the leading terms (drivers) of their mass and risk budget. In particular cases, we shall also dwell on some details, but full engineering design of the needed space assets is outside the scope of the paper.

2. Electric solar wind sail

The electric solar wind sail (E-sail) provides thrust in the solar wind without consuming fuel (Janhunen et al., 2004, 2006; Janhunen, 2010). The E-sail and its possible uses have since been extensively researched (Janhunen et al., 2014), outlining outer planet exploration (Janhunen et al., 2013a), asteroid towing (Merikallio and Janhunen, 2010), and NEO sample return (Quarta et al., 2012).

The E-sail thrust is acquired by Coulomb repulsion between charged solar wind particles and highly charged tethers. Since the tethers are made of very thin, around 25–50 μm wires, the power to keep the tethers charged can be produced by solar panels of modest size (a few square metres) (Janhunen, 2010).

3. Asteroid mining

At the centre of the E-sail facilitated Manned Mars Initiative (EMMI) is the utilisation of the propellantless ΔV provided by the E-sail to haul water from asteroids into orbits of Earth and Mars. A “standard” large 1 N E-sail can travel from the Earth to the asteroid belt in a year, and bring back three tonnes of water in 3 years (Quarta and Mengali, 2010). One E-sail vessel is capable of repeating the journey multiple times within its estimated lifetime of at least ten years.

3.1. *Extracting water from asteroids*

We outline here a baseline scheme for extracting water from the asteroids. An alternative method will be discussed in the following section. In this section we introduce a twin container, of which the other part is heated with electric power generated by solar panels. The evaporating water vapour is condensed in the other container.

The extractor apparatus consists of two container parts connected with a pipe (Fig. 1). The asteroid material is gathered into the other container, which we call an oven from here on. The oven is closed up and tightly sealed, after which it is heated up to about $+50\text{ }^{\circ}\text{C}$ for the water contained in the asteroid material to evaporate (at $+50^{\circ}\text{C}$, water boils at 0.13 bar). The water vapour thus fills the oven and starts flowing through the connecting pipe to the other container (the tank). Temperature of the tank is held slightly above freezing, say at $+5\text{ }^{\circ}\text{C}$, which causes the water vapour to condense on the walls of the tank, but keeps it from freezing and blocking the connecting pipe. After the flow of the vapour recedes, the valve in the connecting pipe is closed and the asteroid material of the oven can be exchanged for another batch of asteroid material. Once the tank is filled up to the desired level, it can be disconnected from the connecting pipe and transported to its final destination. A new, empty tank can be connected to the oven and the process repeated for as long as there are empty tank modules available. These can be transported en masse from Earth to the asteroids with a standard E-sail.

A semipermeable membrane that only lets the water pass in vapour form could be installed on the connecting pipe between the oven and the tank to ensure that the water stays in the tank. This membrane could be heated to keep any larger water mass from forming on top of it (and thus blocking the vapour transfer). Alternatively, the gravity of the asteroid might be enough to help guiding the condensing water towards the end of the tank.

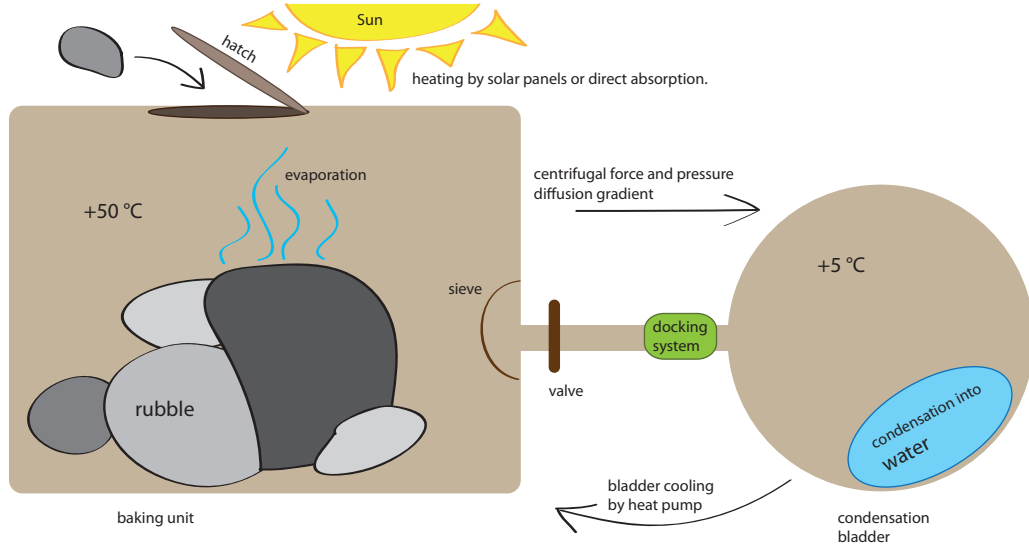


Figure 1: A schematic presentation of the water extractor unit.

The gravity could also be of an artificial (rotational) origin, which could be arranged if the whole extractor apparatus is lifted from the surface of the asteroid and made to spin in space, as is discussed in the section 3.2.

To get a handle on the mass and cost of asteroid mining, let us estimate its energy consumption. The ice-fraction of the asteroid requires 2900 kJ/kg to melt and evaporate into +50°C steam, if an initial temperature of -50°C for the asteroid ice is assumed. Using a heat pump [assuming coefficient of power (COP) of 3] for transferring the condensation heat from the tank in to the oven, we could reduce the energy demand down to 1300 kJ/kg. However, asteroids mainly consist of rocky material, which has to be heated in the process as well, here from the initial -50°C up to the +50°C. Assuming the target asteroid to have water content of 10%, rest 90% being basalt ($c_p = 0.84 \text{ kg kJ}^{-1}\text{K}^{-1}$), the total process would require 2000 kJ/kg. In the case of a dry asteroid with the water content of barely 2%, the energy required to extract a kilogram of water would raise up to 5400 kJ/kg. Moreover, on the surface of Mars the combination of only 2% of soil water content and of that water being released only when the soil is heated up to around 400°C increases the energy requirement up to 20 MJ/kg (Leshin, 2013).

We assume that we can find and choose an asteroid with the desired high

(10%) water content, which leads into baseline electric energy requirement for water extraction of 2 MJ/kg.

3.2. Alternative approach to water extraction

Another, perhaps more elegant, way to extract water from the asteroid material would be to adjust the container temperature by alternating the containers surface albedo and thus by using only direct solar energy. Here the oven would need to be coated by a material whose optical absorptivity is much higher than the infrared emissivity, such as gold or copper, and the tank cooled down by a cold coating, e.g. white paint. The oven would then be filled with asteroid material, or even a small asteroid could be enveloped in its entirety (in the way of recently proposed NASA Asteroid Initiative (Brophy, 2012)), and lifted from the surface and set to a rotating motion. The rotation would ensure that the tank does not shadow the oven for prolonged periods, and more importantly, it creates an artificial gravity keeping the condensed water at the outer wall of the tank. Once the extraction is complete, the oven and the tank would be separated, the oven discarded and the now ice-filled tank left to wait for its carrier E-sail constantly beaconing to ensure it will not get lost.

3.3. Transportation of water by E-sails

Transporting the liquified water from the asteroids to the orbits of the Earth and Mars could be done in lightweight, thin walled container tanks, each weighing a few tonnes when filled. The container has to be specially designed to endure the space environment. The main requirements are containment ability), low mass, resistance to micrometeoroids and tolerance of possible freezing/thawing cycles of the cargo. For these purposes, we propose a layered membrane structure (Figure 2).

The cargo could be brought from C3 down to LEO with the help of gradual aerobreaking without fuel consumption. The thin walled container tank conducts heat to the water mass it is carrying, thus making it heat resistant. The tank could be maneuvered to be in the front on the atmospheric entry so that all the control electronics could be protected behind it.

3.4. Fuel from water

The water, once transported to orbits of Mars and Earth, is split into its constituent H and O by electrolysis or by photocatalytic means (Fatwa, 2013).

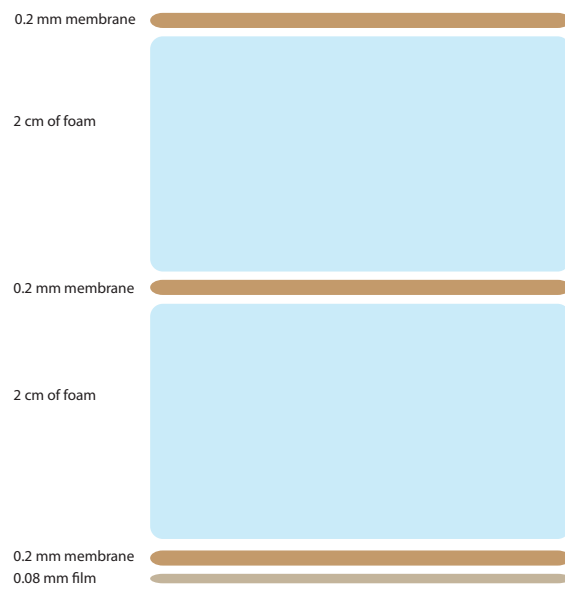


Figure 2: A schematic drawing showing the layers of the tank wall. Multiple layers and a space filler in-between them are necessary preparations for micrometeorite impacts.

After liquefaction, one obtains cryogenic rocket fuel. EMMI is based on manufacturing this LOX/LH2 fuel from the water transported from the asteroids. With 20 kW of electric power one can produce 30 000 kg of LOX/LH2 from water in a year.

However, if liquifying H_2 in temperatures prevalent close to asteroids proves difficult, producing an methane-oxygen fuel could be an alternative possibility. This type of fuel is more complex to produce from asteroid material. Water would also now be split into oxygen and hydrogen, but the pure oxygen would be used to burn carbon containing asteroid material into CO_2 . The carbon dioxide would then be combined with hydrogen in a Sabatier reaction to produce methane and water ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$).

Water to fuel conversion plants would reside in $C3 = 0$ orbit, i.e. barely captured in the gravity well of Earth or Mars. Storages of fuel would be accumulated on these strategic places well in time before they are needed. The redundancy can be built into the system, having a number of smaller tanking stations with combined storage capacity exceeding the required mission fuel amount. Thus malfunctioning of any one fuel production station would not be mission critical. Fuel would also be produced so that it would be ready and waiting before the first humans are sent to space.

4. Operations on Mars

It has been estimated from the Curiosity Mars rovers measurements that around 1.5 – 3% of the mass of Martian surface soil is water that can be released by heating the material up to 200 – 400 °C (Leshin, 2013). This water, once extracted, could be split into same kind of fuel to that produced from the water mined from the asteroids, see sect. 3.4, thus allowing to use the same rocket engines (and thus the same vehicles) for lift-off from Mars as for other parts of the mission. This could dramatically further reduce the costs of the mission, albeit also posing additional design restrictions for the spacecraft.

Landing humans on Mars could be circumvented altogether by using remote controlled robotics as proposed in HERRO (Schmidt, 2012): instead of landing, humans would orbit Mars and teleoperate robots on its surface. This approach would significantly reduce the costs and risks and to alleviate the issue of forward contamination of Mars by human-carried microbes.

5. Mission outline

EMMI proposes means for continuous habitation on the Martian surface. Recurrent trips with LOX/LH2 powered transport vehicle between Earth and Mars would transport the exchange crews and their food to and fro in regular intervals. Additional support equipment, food and accessories could be taxied from the Earth with a regular E-sail. The crew transport vehicles would be fueled up on the fuel stations situated in C3's and/or planet-Sun Lagrange points (see sec. 3.4). The Δv required for LEO-Lagrange point transition and for the Lagrange Mars transition is in the scale of 2.5-3.3 km/s, meaning the fuel requirement is about 50 - 60% of the wet mass of the spacecraft if LOX/LH2 is used, moderate Isp of 420 s is assumed and 10 % fuel margin is used.

The mission could thus be done on separate stages, filling up the fuel tank in-between each leg. First, a launcher is used to lift the passengers/payload to LEO where the first tanking occurs. Alternatively, the lift is continued with electric propulsion engines through the magnetosphere. The craft is lifted to L1, L2 or C3, where again fuelling from the awaiting fuel reservoirs occurs. The last leg from C3 to Mars and capture to Mars orbit would again consume the fuel.

The target asteroids would be sought from the vicinity of the Martian orbit, at around 1.5 au, as this is where majority of the mining products are headed. Yearly water extraction pace of roughly 50 000 kg would suffice for a one binannual manned bidirectional trip between Earth and Mars. To achieve this, 3.2 kW of electric power on the asteroid is required. At the distance of 1.5 au from the Sun, this translates into 230 kg of solar panels assuming a horizontal panel on the equatorial surface of a rotating asteroid and a characteristic mass for the solar panels of 100 W/kg at 1 au (Joel Ponzy, private communication). As power is also needed for other purposes, such as moving, communications and countering power system aging, we will assume a 50% higher power consumption, thus arriving at the whole extractor power system weighing 340 kg. We estimate that the whole extraction vessel would in this case weigh around 2000 kg, which is much lower than the expected mass of the orbital fuel factories. This and other key mass figures of EMMI are listed in Table 1.

For the spacecraft carrying the astronauts there is a need for radiation shielding, which increases the mass of the manned vehicle considerably. The water stored on C3 can be used as radiation shield, thus removing the need

Table 1: Some key mass figures of EMMI.

Production and transportation of water per year	50 000	kg
extractor vehicle weight	2000	kg
Transporter E-sail	500	kg
Manned vehicle	50 000	kg
Payload transferred from Earth to Mars	10 000	kg yearly

to launch a heavy shielded manned module all the way from Earth’s surface. The water could then also naturally be used for potable water needs of the crew. Oxygen for breathing could also be manufactured from the water.

5.1. Manned C3 transfer vehicle

The vehicle transporting the crew between Earth C3 and Mars would have a mass of 50 000 kg, including radiation shielding but not including fuel. As sturdy radiation protection is mandatory on manned Mars flights (Zeitlin et al., 2013; Hellweg and Baumstark-Khan, 2007; Cucinotta and Chappell, 2012), 40% of the mass (20 000 kg) would be radiation shielding water, gotten on-board from Earth’s orbit C3 tanking station. Only the crew and their food is needed to be launched from Earth by traditional means; the transfer vehicle would be waiting on C3 with a full tank of LOX/LH2.

The manned transfer vehicle would shuttle in-between Earth and Mars C3 orbits, getting fueled from the LOX/LH2 produced from the asteroid water at the tanking stations residing on these locations.

5.2. Drop to Mars - alternative landing method

The normal way of landing on Mars requires the use of a heat shield to combat the excessive temperatures generated during a high-speed entry into the atmosphere. Given low cost fuel in Mars orbit, however, one could also consider an all-propulsive landing reducing the speed of the spacecraft before it enters the atmosphere. The craft would tank once more in Mars orbit, make a large burn with its engines to nearly cancel its orbital speed and then drop freely into the Martian atmosphere at much lower than orbital speed. This together with a propulsive insertion into orbit around Mars would diminish the mass fraction of the vehicle’s thermal protection system close to zero.

An all propulsive descent would also make it easier to land precisely as it allows greater control over the trajectory. Only a short trajectory through the atmosphere is necessary which reduces the possibility of navigation errors

propagating. In a partly similar concept, an idea of reducing heat shield demands by using propulsive landing to Mars was introduced by Marsh and Braun (2011).

Control over the landing point is an essential aspect once a colony has been built, as landing too near or too far from it could be hazardous. A possibility exists to design the crew transport vehicle, which transports humans between Earth and Mars, to also function on transfers between Martian surface and orbit. This would increase the design requirements on the spacecraft however.

5.3. EMMI timeline

EMMI would first start with launching of asteroid mapping E-sails to scout for suitable water and/or carbon containing asteroids. After the mapping phase (duration approx. 4 years), the mining spacecraft would be sent to selected target asteroid and the mining would start (1 year to transport, 1.5 years to set up operations and to produce the first 50 000 kg of water). A third of the mined water would be transferred to Earth's and a two thirds to Mars orbit. After 8 years from the first launch, one would have 30 000 kg of fuel on the orbit of Earth.

At the first stage of operations, humans would stay on the orbit of the Mars, letting HERRO (Human Exploration using Realtime Robotic Operations, Schmidt (2012)) take care of the surface operations. This would greatly reduce the costs at this stage as the astronaut habitat, life support and return launch from the surface of Mars would not need to be considered. However, HERRO systems would facilitate the mapping of the surface and robotically prepare the base for the future crews that could then land on the surface more prepared.

As EMMI continues, mining operations are expanded to additional asteroids to provide a more continuous and reliable fuel supply. Redundancy can be built up by additional fuel stations on strategic locations. Continuous human presence on the surface and/or on orbit of the Mars would be possible with affordable costs and symmetrically bidirectional traffic.

Once the asteroid mining and fuel transportation system is built, its maintenance would be relatively low cost as all of the craft included are reusable and all the advantages from serial production (lower production and designing costs per unit) could be taken advantage of. Thus only parts that are broken, crew, and life support material has to be put into the system which

makes the maintenance costs roughly comparable to the International Space Station currently orbiting the Earth with continuous manned presence.

6. Development risks

EMMI is based on providing water in Earth and Mars orbits, which is in turn based on E-sail propulsion and on asteroid water mining. These technologies have not yet been demonstrated at high TRL and therefore the EMMI scheme as a whole must be considered at least somewhat risky at the present time. However, demonstration of asteroid water mining and its transportation by E-sail propulsion to planetary orbit is an easily scalable process. This means that it can be first demonstrated in small scale at low cost (many orders of magnitude lower than full EMMI) and then scaled up. Manufacturing cryogenic fuel in orbit is also something that has not yet been done, but we think that few would doubt its feasibility. Thus, demonstration of the E-sail and small-scale asteroid water mining would strongly reduce uncertainty about EMMI's feasibility, and the investment needed would be vanishingly small compared to the cost of manned space activity.

7. Summary and conclusions

We analysed how E-sails could act as critical enabling technology for setting up continuous manned bidirectional traffic to Mars, using asteroid water mining and orbital fuel manufacturing. The most massive and therefore the most costly part of the fuel supply chain are the orbital fuel factories, because splitting water into hydrogen and oxygen takes much more energy than liberating it from asteroid soil. The E-sails are a relatively minor part of the total mass budget. The efficiency of the overall concept stems from the fact that intermediate tankings effectively eliminate the exponential nature of the rocket equation. It is also a significant cost benefit that the orbital water can be used as crew radiation shield. We think that once things are developed, continuous manned presence on Mars (with bidirectional traffic) would be possible at a cost level which is comparable to that of maintaining the International Space Station, ISS.

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