PREMARS: PLANT AND ROCKET EXPERIMENT FOR MARS AURORA RESEARCH SUPPORT

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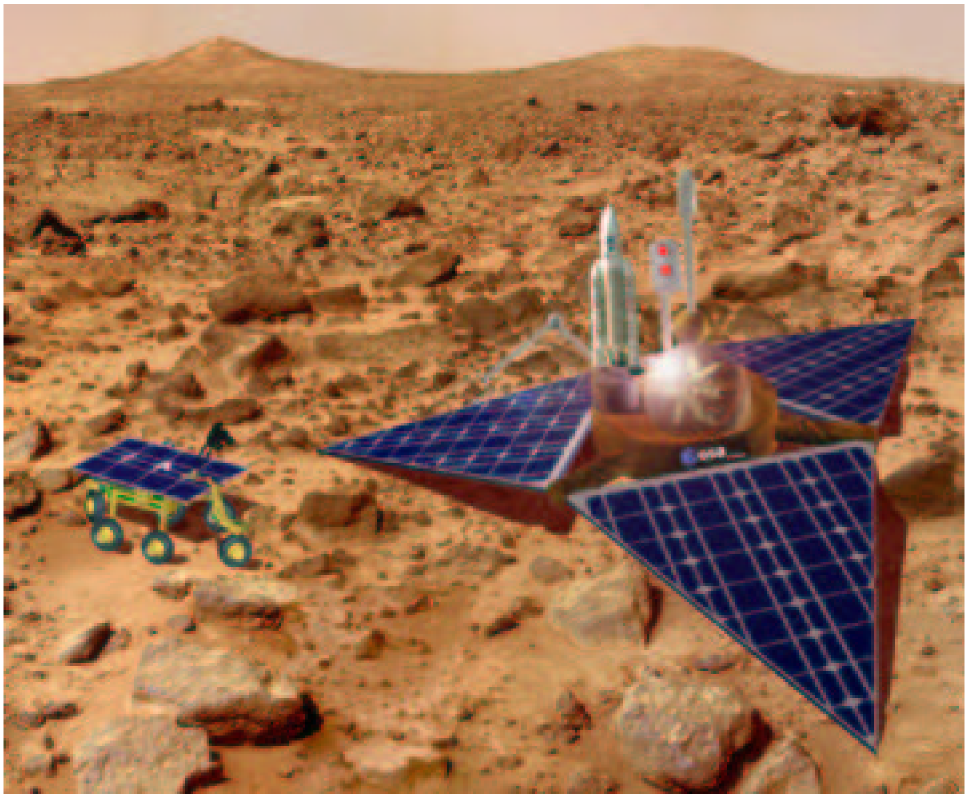

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The technologies necessary to support a human Mars mission need to produce life-sustaining resources (food, water, and fuel) using the Mars local environment. A mission is proposed that demonstrates these technologies by launching a rocket using fuel generated by in-situ propellant production (ISPP) techniques and by growing a plant in a greenhouse on Mars using only local soil, atmosphere, and water. The mission requirements are discussed and the trade space analysis for each subsystem is shown. Most necessary hardware has already been designed, built, and tested on Earth. The mission is designed using technologies that have been in use for over one hundred years and is also designed to maximize student involvement.

Key words: Mars, Plant, Rocket, In-Situ, ISRU, ISPP, ♂.

1. INTRODUCTION

1.1. About This Document

This document is written in response to the European Space Agency (ESA) Aurora Student Design Competition (ESA, 2003) and is designed to meet the category guidelines for “New Enabling Technologies”. This document should conform to ESA publication guidelines as discussed in Daly (2001).

1.2. Document Layout

This document is divided into the following five major sections: The Introduction (Section 1), Mission Overview (Section 2), Requirements (Section 3), Mission Trade Space (Section 4), and the Conclusion (Section 5).

The Mission Overview (Section 2) provides a discussion of the goals of the mission and the timeline required for the mission.

The Requirements (Section 3) discusses the necessary tasks each individual element or subsystem of the mission must perform to achieve the goals.

The Mission Trade Space (Section 4) provides an in-depth discussion of each sub-system. Alternatives to each subsystem are discussed and a justification is provided for the final decision used to create the Requirements section.

1.3. Design Philosophy

Primary Design Philosophy: This mission was designed as a simple proof-of-concept. The goal of the mission is not to grow crops with sufficient nutrients for a multi-man base, nor to launch a sample return, it is only to demonstrate that these feats are possible. This can be done by the growth of one flower and the short flight of a simple rocket.

Secondary Design Philosophy: This mission is designed to maximize student involvement, which has the benefits of reducing development costs while training young scientists and engineers. Undergraduate students have already designed, built, and flown complete satellite systems for school projects (Solomon et al., 1996). Students have also built and operated plant growth modules that have flown on the STS, and ISS (WCSAR, 2003). Even though this is a Mars mission, which is more complex, it is still simple enough that students can design and construct most parts with some professional guidance.

1.4. Definitions

The following acronyms and vocabulary are used in this document.

- COSPAR: Committee On SPAce Research
- ESA: European Space Agency
- GPR: Ground Penetrating RADAR
- GRS: Gamma Ray Spectrometer
- HEND: High Energy Neutron Detector
- IDDS: Inchworm Deep Drilling System
- MARSIS: Mars Advanced Radar for Subsurface and Ionosphere Sounding
- MER: Mars Exploration Rover
- MC: Mars Orbiter Camera
- NASA: National Aeronautics and Space Administration
- ISPP: In Situ Propellant Production
- ISRU: In Situ Resource Utilization
- ISS: International Space Station
- RADAR: RAdio Detection and Ranging
- sol: One Martian day
- STS: Space Transport System
- THEMIS: THermal EMIssion Spectrometer
- **Factories** are the chemical production units that convert Martian air and H_2O to Gas or Fuel.
- **Fuel, Gas** is ethylene (C_2H_4)
- **Greenhouse** is the closed and self-contained robotic system that houses the plant, the environmental controls to grow the plant, sensors, and nutrient delivery systems.

- **Lander** is the base station that integrates most of the subsystems. The lander generates power for everything except the rover that has its own power supplies. The lander houses the Factories, Rocket, Greenhouse, and Earth communication systems.

- **Rover** is the mobile robotic platform.

- **Water** is liquid H_2O, frozen water-ice, or the "dirty ice" mixture of Martian soil and water-ice. The water form is either clear from the context, not important, or a more specific term is used.

2. MISSION OVERVIEW

2.1. Motivation

Food and water are necessary to support human life. In temperate climates on Earth nothing else is needed but in hostile climates such as Mars, food and water is not enough and energy is critical for survival. This energy is used to create heat, process the hostile environment to a hospitable state, and help perform other tasks necessary for survival.

Gaseous fuel as an energy form is useful because it can easily power a rocket for sample return or the return of the human team. Using ISPP techniques the mass and cost of the mission are reduced because less hardware needs to be delivered to the Martian surface (Zubrin et al., 1996). While a human Mars mission *may* include energy from solar, nuclear, fuel-cell, and other energy sources, it *must* include fuel for at least some part of the return vehicle propulsion system.

A chemical factory will produce fuel (C_2H_4 and O_2) with Martian material and local energy generation based on solar power only. This is advantageous because nothing else other than the solar panel and the chemical factory needs to be imported to Mars. In theory, there is no limitation for the fuel production.

Human Mars mission design concepts have been proposed that do not use the local resources available on Mars (Cohen et al., 1989). Due to the increased cost and complexity of this type of mission (Zubrin et al., 1996) it is suggested that ESA utilize in-situ resource utilization (ISRU) techniques with the Aurora program.

To validate the concept of growing food on Mars with in-situ resources only, we propose a greenhouse system for plant growth in soil, water, and Martian atmosphere with the same chemical factory used for the fuel production.

In this design, PREMARS is not a two part mission (plant growth and fuel production) but is a single system transforming Mars in-situ resources and power to food and fuel, the two main elements necessary for a human presence on the red planet.

2.2. Mission Objectives

Mission objectives are plant growth through one complete life cycle (seed to flower) and flight of a rocket. These two goals will be verified by cameras located on the lander.

2.3. Mission Scenario

1. Land at a location that meets the water, temperature, and solar energy requirements. Deploy solar panels for energy and rover for water.

2. Set up experiments and support systems.

    - Initiate water acquisition system. This may be atmospheric, lander-mounted drill, rover-mounted drill, or robotic drill system. The water is extracted from the soil by heating it to a vapor.

    - Set up greenhouse. This involves putting soil in the greenhouse, filling the water reservoir, planting the seed, and sealing the system.

    - Initiate fuel production. The chemical factory produces the rocket fuel (C_2H_4 and O_2).

3. Monitor greenhouse and fuel factory. Adjust systems as necessary to aid mission success.

4. End of Mission

    - Sterilize greenhouse.

    - Launch rocket to demonstrate fuel usability.

2.3.1. Mars Environment

Mars environmental parameters relevant to this mission are listed in table 1.

2.3.2. Mars Water Model

We use a Mars water model based upon the Mars Odyssey Gamma Ray Spectrometer (GRS) results as described by Boynton (2002). This model is approached from a pessimistic view assuming results are only valid at the current low resolution of the GRS instrument and that at a higher resolution the supply is not "global" poleward of approximately 40 degrees but instead "sparse". A more in-depth discussion of this and other possible water scenarios is discussed in Section 4.1.

We expect to solidify these assumptions with the arrival of the MARSIS instrument on-board the Mars Express satellite in January 2004 (Picardi et al., 1999).

Table 1. Mars Environmental Parameters

Atmosphere	
Pressure	5-10 mbar
Gas	95% CO_2, 3% N2, 2% Ar
Others	Electrostatic charging
Ground	
Diurnal temperature cycles	low thermal inertia atmosphere has low heat capacity, high diurnal temperature cycles, f.e. -15° C to -75° C
Temperatures	at +40° latitude over the year
Average	-55° C
Minimum	-110° C
Maximum	-10° C
Solar Radiation	No radiation $<$ 200nm, UV part $>$ 200 nm does strongly vary, infrared 25 W/m^2 for a normal day, 120 W/m^2 during a dust storm

2.3.3. Fuel

The fuel is created by a factory. Martian atmosphere is mined for CO_2 and with water acquired on Mars produces the ethylene rocket fuel as discussed in Zubrin et al (1997).

2.3.4. Plant

The plant type has been selected as *Arabidopsis thaliana*. We choose this based upon the fact that *A. thaliana* is a widely studied plant and has a huge knowledge base to support it. It has had its genome mapped, and has already been studied in the context of a Mars greenhouse mission (MacCallum et al., 2000). It is possible to genetically modify the plant for low light, low water, small size, small weight, and high stress environments, all of which should be expected on a Mars mission (Scheurger et al., 2002).

3. MISSION REQUIREMENTS

3.1. PREMARS Mission Statement

The mission statement is listed in Table 2.

Table 2. PREMARS Mission Statement

Primary	Demonstrate life support techniques using Mars in-situ resources. This is achieved by: · Plant growth using Martian water and soil · Rocket flight using Martian fuel	
Secondary	Plant	Learn about Mars soil properties
	Rocket	Use ISPP technologies
	H_2O	Acquire or create
	All	Student involvement

3.2. Lander Requirements

The lander accommodates all sub-systems for the mission. This includes but is not limited to the greenhouse, chemical factory and the rover in a launch configuration.

The lander interacts with the rover to transport a 5 kg sample system from the rover to the chemical factory. The lander system accommodates a Mars orbiter communication link and data storage.

The lander system provides the energy for all sub-systems including the rover.

Lander information are also summarized in Table 5.

3.3. Rover Requirements

The rover must travel a distance of 3km with a maximal range of 1 km around the lander. The rover must return to the lander after traveling away from it.

The rover needs a drilling and sampling system able to transport 5 kg of soil.

3.3.1. Rover Operations Requirements

The rover/lander must detect subsurface water through either the drilling/sampling system or with ground penetrating radar (GPR) techniques. The drilling/sampling system acquires dirt and water ice from up to 1 m depth.

3.4. Greenhouse Requirements

The greenhouse system provides an environment that allows plant growth. It is a self contained system that monitors and adjust chemical and water levels as necessary. It will maintain a temperature minimum of 5° C. It will maintain a pressure higher than the Martian ambient pressure. The greenhouse will sterilize itself at the end of the mission. The water requirements for the greenhouse and plant is 500 mL.

3.5. Factory Requirements

The chemical factory allows extraction and cleansing of water to a liquid form from a “dirty ice” sample. The fuel factory produces the rocket fuel. The fuel factory transports 2 L water as a backup from Earth and stocks it during the mission lifetime.

3.6. Rocket Requirements

The rocket stocks 1 L C_2H_4 fuel during the mission lifetime. The rocket should have a vertical flight from Martian ground to at least 100 m. The rocket mass without fuel should be under 2 kg.

3.7. Rocket Fuel Requirements

The rocket fuel is produced with Martian atmosphere, and is easily stock-able in the Martian environment. 1 L of water is required to produce the rocket fuel.

3.8. Engineering Design Constraints

The total mass of the PREMARS landing system including the roverdoes not exceed 300kg. Estimated entry mass is less than 600 kg.

3.9. Environmental Constraints

All systems operate in a Martian environment near ± 40° latitude. All systems must survive outside ambient temperatures between -100° C and +40° C.

3.9.1. Landing Site

A landing location is not be selected at this time due to the expected in-flux of data from the Mars Express, MER-A, MER-B, and Nozomi robots and spacecraft in addition to the current data stream from the Mars Global Surveyor and Mars Odyssey spacecrafts. The following paragraph discusses the major points to consider when the landing site is eventually selected.

The water distribution model in this paper limits the landing sites to poleward of 35 degrees. The solar panels provide the most power at a sub-solar point, or as close to this point as possible. The sub-solar point is also the best location for the temperature for the greenhouse. Therefore ±40 degrees should be used as the latitude band for the landing site. This mission should exist during a hemispheric summer to maximize temperature and power.

3.10. Life-cycle/Lifetime Requirements

The PREMARS mission duration is the duration of one plant life-cycle and the time to produce the fuel for the rocket launch. The life-cycle of *A. thaliana* is approximately 50 Earth days. The time to produce the rocket fuel is on the order of 5 sols (Martian days). Additional time is necessary for verification and setup of the systems. A small amount of water must be gathered before the seed can be planted. We therefore require 75 sols as an upper limit to the mission duration.

Time for system deploying, search of water is a few day (1 to 5). Time for drilling is 10 days. Time to transport water to the chemical factory is 2-5 days. Time for water and CO_2 extraction and to produce rocket fuel is about 10 day. Time for plant growing is 50 days. (See Table 5.)

4. MISSION TRADE SPACE

This section discusses the options for each element that lead to the requirements (Section 3).

The necessary importation requirements other than the hardware systems (lander, rover, factories, etc.) are the plant seeds and nothing else. Even so, necessary materials (soil, water, chemicals) should also be transported from Earth as backup copies. They should not be used unless local resources fail.

4.1. Water

The water distribution is the primary unknown parameter in this mission.

4.1.1. Recent Water Results

The current situation regarding water in liquid and/or frozen form (ice or snow) on Mars is not known. A survey of publications suggests possibilities from recent liquid surface flows (Motazedian, 2003) and snow-filled craters to almost no water. At a minimum there exists atmospheric moisture (Barth, 1974).

Figure 1 shows dark stains that have appeared on the surface within the past few years.

The flat region in Figure 2 appears to have formed from liquids breaking out of the crater wall, creating gullies as it flows down the crater, and then pooling and freezing at the bottom. The current mission could trade the rover and drill subsystem for a high-precision lander that could target known ice water supplies on the planet.

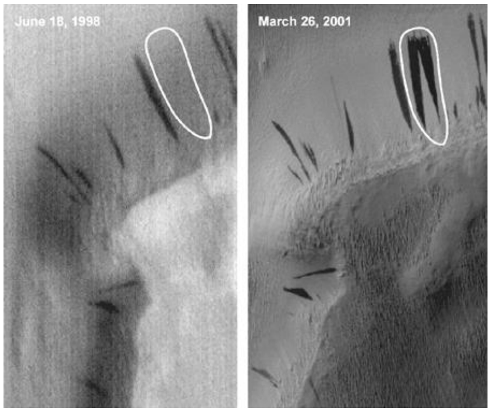

Figure 1. Recent surface flows, probably brine (dirty water). Courtesy of Motazedian (2003). The left image (MOC SP2-37303) was taken June 18, 1998. The right image (MOC E02-02379) was taken March 26, 2001.

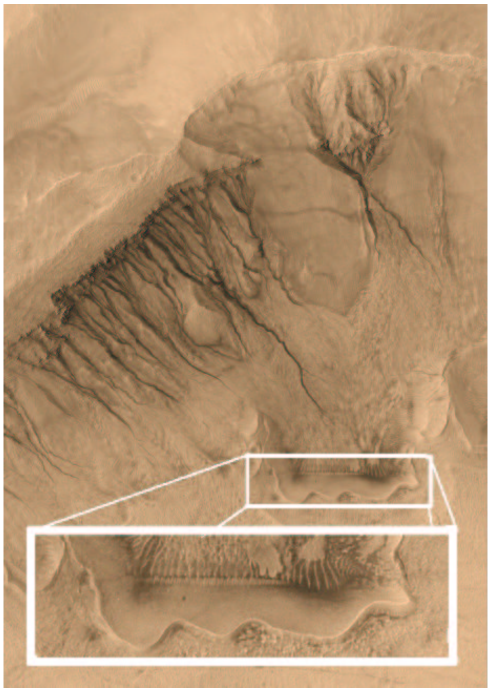

Figure 2. The main image is gullies in a crater wall at (39.0°S, 166.1°W). The white box contains a high resolution view of a flat region at the base of the crater walls, approximately 500 m across (Malin, 2002).

Due to the fact that the ESA Aurora project desires to have a human presence on Mars regardless of the water situation, this mission is relevant regardless of the validity of the current water model.

4.1.2. Water Models

This mission is been designed in a modular way. Should the water model be incorrect the mission can still be flown with only minimal changes. If there proves to be less water than currently assumed, the water requirements for the plant and fuel factory are small enough that the drill system proposed in this mission can be exchanged for an atmospheric water acquisition system. This will have little effect on the overall mass, energy, or functionality of the mission. If there proves to be more water than the current model assumes then this mission can fly with smaller mass and power requirements than the current design.

We divide the current water estimates on Mars into the following five models. Each model details the assumed planetary supply of water, discusses acquisition/extraction methods, and lists changes required to the current PREMARS mission in order for it to succeed. The model used in this paper is model number 2.

Model 1: Water is ubiquitous on a planetary scale poleward of 35 degrees. Frozen in the top 2 meters, occasional surface flows. Water exists at 35% ± 15% by weight (40% to 73% ice by volume). (Boynten et al., 2002).

Model 1 Changes: The mission is reduced to a Beagle-2 class mission. The rover is not necessary. The lander has a small shallow drill system since by definition, wherever it lands there is water. Detection is not necessary and acquisition is a regular drill system.

Model 2: Water is ubiquitous only at current low space-based resolutions (Boynten et al., 2002) but once on the ground it is necessary to locate it. However it can be found easily due to repetitive and predictable natural processes (for example it is always at the bottom of North-facing crater walls). The water resources will soon be mapped by hi-resolution space detection systems (Picardi et al., 1999).

Model 2 Changes: None required. This is the water model we are using in this paper. Detection is in the form of maps from current (or soon-to-be) orbiting spacecraft. The rover is manually driven to where the ice is located. Acquisition is via the drill system proposed in this paper (Section 4.2).

Model 3: This model is based upon Water Model 2, but the water will not be mapped by the MARSIS instrument or other spacecraft. Solid theories exist regarding predictable supplies (i.e. each crater has a supply given certain latitudinal constraints).

Model 3 Changes: The mission scales up (in mass and cost) to a ExoMars09 (Gardini, 2002) class mission. At a minimum the rover and lander systems must interact with a ground penetrating radar system to find the local water supply. This can continue to scale up to a suite of rovers with detectors, multiple landers like the Netlander mission, and even penetrometers to create seismic events.

Model 4: Water exists but at only at extreme depths (hundreds of meters) and maybe only at a few select locations on a planetary scale.

Model 4 Changes: A deep drilling system is required. We suggest the Inchworm Deep Drilling System (IDDS), a drill system capable of deep drilling and sample return (to the Martian surface from the subsurface) using very little power. See Gorevan (2003) for more information on a wide range of Mars drill systems.

Model 5: Water does not exist on Mars, except as previously detected in the form of atmospheric moisture (Barth, 1974).

Model 5 Changes: Replace the rover and drill system with an atmospheric water acquisition factory. Mass, complexity, and cost are all significantly reduced in this model.

4.1.3. Water Model Discussion

None of the previous Water Models make the mission goals impossible. While larger scale sample return and human missions are significantly affected by the possible water locations and quantities of Mars, the PREMARS mission is less affected due to its small size and requirements.

Water Models 3 and 4 can be grouped together with Water Model 5 so that rather than the lack of water raising the complexity and mass of the mission it can be used to considerably reduce it.

The question is then raised why we do not design the mission based upon Water Model 5. First we discuss the two extreme possibilities for this mission. They are both independent of water models.

Maximum The scaled-up extreme of this mission is a Viking class mission with at a minimum 1 large lander and water detection systems as discussed in Water Model 3. The rocket is scaled to a Mars Sample Return Rocket and the greenhouse grows multiple crops of multiple species of plant.

The reason this mission is not selected is because the complexity involved would prohibit student involvement, increase the chance of a mission failure, and make the budget requirements enormous.

Minimum If we take the PREMARS design to its absolute minimum the primary goals (plant growth, fuel production) can be achieved as follows: The rover and drill system are removed, the greenhouse becomes a petri-dish and the plant a fungus or bacteria, and the rocket is replaced by either a controlled explosion or (signifying the end of the mission) an uncontrolled explosion. The fuel factory can use hydrogen imported from Earth as is usually suggested in ISPP Mars missions.

This minimum mission has many advantages, primarily that it can be flown for a fraction of the cost of the PREMARS mission. However the science return is also a fraction of the science return from the PREMARS mission. It is also important to note that the PREMARS mission can scale up using the current design to supply a human base with food (for at least part of their diet) and to fly a sample return mission. The minimum mission does not scale beyond its small petri dish.

The reason we do not design the mission now based upon Water Model 5 is the same we do not scale it down even farther to support only a petri dish. The benefits of using a rover to mine water (in any form) from the Mars surface is a significant feat that should be attempted. The science return from the rover and drill system are our justifications for using them. If the mass is available we suggest an atmospheric water acquisition system is also delivered to the Martian surface. This can be used in case of rover failure or in addition to the rover.

4.2. Drilling

Based on Water Model 2 we must drill to 2 m depth and collect soil samples which contain approximately 35% water.

A traditional core-drilling device with a diamond drill bit could be adapted for space drilling but will not be suitable for this mission size because of the following reasons: The need of a high axial preload (eventually anchoring of the drilling platform), high energy consumption (at least 50 Watt), drill bit sharpening and replacement, a high increase in energy consumption while drilling in hard rock (up to 300%), and a lot of moving parts.

The micro-hammer technology on the Mole on the Beagle-2 mission is built to drill into sand or soil with low resistance (Pinna et al., 2001; Richter et al., 2001). We expect to find an extremely hard permafrost-like ice and soil mixture at about 1 m depth. The top layer of the regolith should be scraped aside as in the Viking experiments. The Beagle-2 Mole will provide valuable data regarding Mars surface physical properties.

4.2.1. Ultrasonic Drill Corer

A drill system with few moving parts, low power requirements, and the ability to drill through hard surfaces and deliver core samples has been developed. It uses ultrasound as the drill technique. It consists of a ultrasonic transducer (horn, stack, backing), a free mass, a bit, and corer (Figure 3). The actuator is smaller than the core outer diameter, thus allowing drilling several meters deep into Martian soil without jamming (Bar-Cohen et al., 2003).

The advantages of this drill are:

- No drill bit sharpening or replacement required
- Low weight (around 1 kg)
- Can be mounted on a rover or robotic arm
- Only a few moving parts, very robust
- More flexible if encountering variable soil densities than traditional drilling systems
- No jamming, no drill walk, and no stable anchored drilling platform required

Figure 3. Ultrasonic Corer with extracted core. Image from Bar-Cohen (2003).

Table 3. Ultrasonic Drill Parameters

Core inner diameter	4 cm
Height	10 cm
Core volume	125.7 cm^3
Drilling velocity	1.25 to 15 cm/hour[a]

[a] Depending on hard (basalt) or soft (sandstone) material

4.2.2. Water Extraction Example

Assumption: Velocity is 6 cm per hour, water content of soil is 40%. We need 100 minutes to fill the corer with 1 core which contains 50 cm^3 of water a few minutes are needed to extract the core and reinsert the drill into the hole (10 min) 1 core with a bulk density of the soil of 1.8g/cm weighs 230g. Thus, the rover will be able to transport 10 cores (2.5 kg) with a total water content of 100 cm^3.

1.5 L water = 25 cycles at 2h per cycle = 50 hour $\approx$ 10 days for water search, extraction and transportation to the lander.

4.2.3. Core Extraction

The extraction is done with the same technology as on the Beagle-2 mission: filling the corer with the powdered cuttings (we should use soil powder, instead of a whole (complete) core for easier soil transport and heating in the water extraction device) extracting the corer with a cable winch installed on the rover or the robotic arm filling the core-contents into the lander.

Energy: We should expect to need about 25-30 Watt in the drilling mode (Bar-Cohen et al., 2003), and the same energy amount as on the Beagle-2 mission for the core-extraction.

Sensors: Another advantage of the ultrasonic-technology is the use of the ultrasonic waves for in-situ characterization of rock properties. Thus, it would be possible to detect the best drilling site by checking the water content of the soil before drilling, which could save on a lot of time and energy.

4.3. Available solar energy

4.3.1. Solar cell output power

Peak power calculation: See Table 4 for Peak Power Calculation. The mission needs less than 400 W mean power during daylight.

Table 4. Solar Cell Power Estimates

	$P_s = S \cdot I \cdot \eta_s \cdot \eta_{atm} \cdot \eta_{60days}$ W/m^2	
P_s	W	Maximal output power
S	m^2	solar cell size
I	W/m^2	insolation
η_s	20%	solar cell efficiency
η_{atm}	65%	attenuation of solar radiance (atm)
η_{60days}	80%	attenuation after 60 sol

With $I > 590$ W/m^2 during spring and summer, maximal output power at 40° N is about 60 W/m^2 with dust deposition on the solar panel.

Mean power estimation: $P_{MEAN} = P_s \cdot 2/\pi \cdot 12h/24h$ W

The mean power can be estimated with a daylight of 12h and a sinusoidal function

P_{MEAN} = 19 W/m^2

E = 0.456 kWh/m^2

Solar cells design: With 40 W/m^2 mean power output from solar cells during daylight, we need about 10 m^2 of solar cells which is approximately 6 to 10 kg (Bailey et al., 2002).

4.4. The Lander

The lander subsystem is detailed in Table 5 where the mass, power, and timeline are shown.

The total lander mass including a rover is less than 100 kg which is under the mass limit of 300 kg. The extra mass will be used by elements not discussed in this paper, such as computers, cables, etc.

The battery technology chosen is Li-ion or NiMh due to energy/mass ratio of about 120 Wh/kg. Batteries are necessary to store the energy to heat the sub-system during the night.

Table 5. Lander

Subsystem	Function	Mass [kg]	Energy	Time [days]	Section
Water search	Detection of ice water	TBD	$<$ 150 Wh	1 to 10	4.1
Rover	Drilling system accommodation	20	on board	1 to 5	4.4.1
	Soils transportation	5		15 to 20	
Drilling system	Soils acquisition	1	30W * 3h/day	5 to 15	4.2
Chemical Factory	Water, soil, atm. & Fuel	10	4000 Wh/day	20 to 30	4.5
Greenhouse	Soil, water, atmosphere	3.5	16 Wh	30 to 80	4.6
Rocket	Fuel storage, use	2.0	fuel	end mission	4.7
Solar Panel	Power provision	10	4560 Wh/day	1 to 80	4.3
Accumulator	Power storage	10	1200 Wh	1 to 80	
Water container	Backup solution	2			
Lander structure	sub-system accommodation thermal isolation	20			
Lander electronic	monitoring and control	2			
Communication box	transmission	2	$<$ 20W	1 to 80	

4.4.1. Rover

A 20 kg rover is necessary to accommodate the drilling system and transport 5 kg martian soil. With a 0.6 m^2 solar panel on top, it is able to have the 30 W necessary for locomotion and then for the drilling system. The time to find water is 1 to 5 days with a maximal travel distance of 1 km (Michaud, 2002).

4.5. Chemical Factories

The chemical factory must produce the O_2 for the plant and 1 L fuel (C_2H_4) for the rocket. 1 L C_2H_4 (liquid) = 0.57 kg = 20 mol. The water requirements are:

$0.018 \text{ kg/mol} \cdot 20 \text{ mol} \cdot 2\ (2H_2O \Rightarrow C_2H_4) = 0.72 \text{ L } H_2O$

0.5 L water is needed for the plant (Section 3.4). The total mission water requirement is therefore 1.5 L.

The factory needs to heat 1.5 L water from ice to gas: $5.1e^6$ J with 80% efficiency = 1430 Wh.

The energy requirements to convert 1.5 kg from ice to gas from is show in Table 6. The first line is the energy to heat the ice, the second is the state-change from ice to liquid water, the third is heating the water, and the fourth is the state-change from liquid to gas.

Table 6. Water Conversion Energy Requirements

ΔT [°C]	Energy Required
$-55 \rightarrow 0$	55° K · 1.5 kg · 2060 J/kg = 170,000 J
$0 \rightarrow 0$	1.5 kg · 330,000 J/kg = 495,000 J
$0 \rightarrow 100$	100° K · 1.5 kg · 4184 J/kg = 627,000 J[a]
$100 \rightarrow 100$	1.5 kg · 2,300,000 J/kg = 3,450,000 J

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[a] Water boils at less than 100°C due to the lower pressure. The exact temperature is not calculated nor is it important as the state-change energy is much more than the temperature change energy

The hydrogen factor needs 476 Wh/mol · 20 mol / 30% = 31750 Wh ⇒ 260 W for 10 days at 12 hour per day.

The heating system needs:

- gas heating: 150 Wh/mol · 20 mol / 90% = 3333 Wh
- reactor heating: 36.5 Wh · 10 day = 365 Wh

Table 7 lists the mass and power for each of the elements of the Chemical Factory subsystem. We estimate a 10 day production timeline (starting at the same time as the greenhouse).

Based on Table 7 we estimate 10 kg total mass for the Chemical Factory subsystem. Total energy should be less than 400 W during the 10 mission day (operation time of 12h per day).

4.5.1. Hydrogen Factory

Hydrogen is the one key element that has been difficult to acquire on Mars. Most mission designs and literature assume the importation of hydrogen from Earth. We attempt to demonstrate a more complete form of ISRU by acquiring the hydrogen locally. The authors believe this is possible due to the recent results from the GRS instrument and expect confirmation from MARSIS. In an attempt to maximize mission success the authors recommend that hydrogen is also imported. This hydrogen should be vented/destroyed when the local hydrogen is acquired. Only in case of an error with the rover to acquire the H-rich water would the Earth supply be used. The standard method of H importation (using the empty fuel tanks of the rocket (Zubrin et al., 1994)) is recommended.

4.5.2. Chemistry

Hydrogen vs. Water: Given the complexity involved with hydrogen it is easier to work with water (and import it as a backup system) and not H_2. We intend to use electrolysis of the water to obtain oxygen (for the plant and combustion).

1. This method provides all necessary material and is more reliable.

Table 7. Chemical Factories Mass and Power

System	Function	Mass [kg]	Power [W]	Energy [Wh]
Water factory	Extract H_2O from soil	1.0	12	1430
Hydrogen factory	Extract H_2O,O_2 from water	0.5	260	31750
First stage reactor heating system	CO reaction (T=250° C)	1.0	+E 31	3700
Second stage reactor	Fuel Production	1.0	-E	0
Atmosphere capture CO_2 pump	P = 1 bar (250° C) from Mars atmosphere			
Pump O_2	P = 1 bar	1.0		
Pump H_2	P = 1 - 10 bar	1.0		
Pump C_2H_4	P = 20 bar T = - 50° C	1.0		

2. The transport of water or ice does not require a special container like hydrogen.
3. This is especially important in the case of small containers where the surface area to volume ratio is higher.
4. There is more electrical consumption with this method (for the electrolysis) but it is still within the requirements

Even though one can produce 9 g H_2O starting from one g of H_2 the hydrogen contribution requires a more complex and thus heavier system. Once again due to the minimalist water and chemical requirements of the PREMARS mission we are less heavy while using water to replace the hydrogen.

Diurnal Cycle Condensation Carbon dioxide freezes and -78°C. The nighttime temperature may be in this range. In theory it is possible to use the day/night temperature variation cycle to freeze the CO_2 and introduce it as a solid into the engine.

1. The pressure in summer is between 5 mbar and 10 mbar. The catalysts function from 1 to 8 bar (lower pressures work but are less efficient).
2. Introduction of CO_2 will increase the temperature while changing to a gaseous state without the use of compressors.
3. An excess of CO_2 in the reactor is beneficial in our case.

Description of the Reactor: Two reactors are used in series (Zubrin et al., 1997; Zubrin et al., 1994).

1. The first is a Reverse Water Gas Shift (RWGS) reactor: $CO_2 + H_2 = CO + H_2O$ (endothermic) + 9 Kcal/mol. 15% conversion rates are easily achieved.
2. The second reactor produces the ethylene: $2\,CO + 4H_2 = C_2H_4 + 2\,H_2O$ (exothermic) -49.4 Kcal/mol.
3. The output of the first reactor is fed directly into the second.
4. Water is recovered after the second reactor and is returned via hydrolysis. Excess water may be delivered to the Greenhouse.

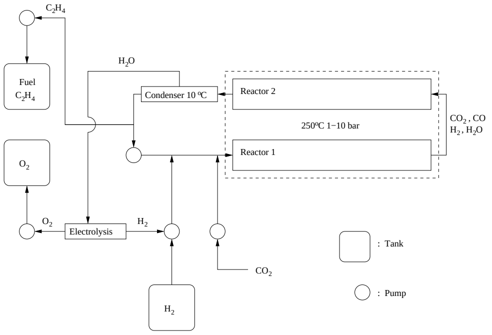


Figure 4. Schematic diagram of the chemical reactor

5. By coupling the two reactions it is possible to maintain the reactors at the required temperature. The second is able to heat the first.

4.6. Plant and Greenhouse

Plant research in space has been going on for over forty years (Porterfield et al., 2000) and ESA has considerable knowledge in the latest generation of space plant growth hardware (Brinckman et al., 1999). However the requirements for greenhouse systems in microgravity (Low Earth Orbit systems like *Mir* and the ISS (Salisbury et al., 2003)) is different than the requirements for a Mars greenhouse.

A greenhouse system for Mars has already been designed. It provides automatic control of all environmental variables, requires no power at night to maintain the minimum required plant temperature, and meets planetary protection requirements (MacCallum et al., 2000). The authors suggest the use of this or a similar system for the PREMARS mission. A robotic garden has already been demonstrated on Earth (Stedman et al., 1996), and proposed for Mars missions (McKay, 2000).

We recommend that the plant growth experiment grows a batch of 3 *A. thaliana* in the greenhouse at one time. A total of 9 seeds will be delivered to the Martian surface so that two backup crops are available.

Growth Cycle: The growth cycle for the plant from seed to flower is approximately 45 days (MacCallum et al., 2000).

Soil and Nutrient Requirements: We estimate 1 L of soil is sufficient to grow a crop of 3 *A. thaliana*.

This document does not discuss the biological aspects of growing a plant in Martian regolith in detail. It is noted that most necessary nutrients exist in the soil in some amount and also that possibly toxic materials do exist. If abundant water is available we suggest the soil be cleansed by flushing with water before the seed is planted. A thorough examination of the Martian regolith and its chemical and physical properties can be seen in (Scheurger et al., 2002).

We also recommend that 1 L of Earth soil is delivered to the Martian surface as a backup in case the first crop fails due to the properties of the Martian regolith. If this occurs the greenhouse can be emptied, filled with the backup Earth soil, and the second crop of 3 plants can be started.

Water Requirements: The fresh weight of *A. thaliana* is approximately 1.0 g. The dry weight is approximately 0.1 g, and the water content is approximately 90% (Essah, 2000). The plant is therefore 10% biomass and 90% H_2O.

Because the greenhouse is a closed system there is no water loss. Therefore the total water requirement of the plant is equal to the maximum instantaneous water usage. This is the amount of water in a mature plant plus the amount of atmospheric moisture in the greenhouse plus the soil water content.

A mature 1.0 g plant that is 90% water means the plant contains approximately 1 mL of water. An upper limit to soil moisture is estimated to be 40%, which means 400 mL of water is necessary for the 1 L of soil.

The atmospheric moisture content of the greenhouse is not considered at this point. We believe the 40% soil water content is a large enough estimate to include it. Furthermore we round the current 401 mL water estimate up to 500 mL as a safety margin. The total estimated water requirements of the greenhouse and plant subsystem is therefore 500 mL.

Since this amount is only required when the plant is in its mature growth stage the initial water requirements at the beginning of the experiment is significantly less. Therefore if the water acquisition system takes time on the order of days or tens of days to deliver the total mission water requirements this does not effect the mission timeline. The plant and greenhouse experiment can begin shortly after landing as long as there is at least a small (10s of mL) water supply.

The water requirements for the plant experiment is small enough that we recommend a backup water supply is imported from earth should the water acquisition system have problems. A few ice cubes transported from earth will have negligible effect on the mission mass and provide a backup system with little chance of error.

Temperature Requirements: The plant dos not require night time heating if the Paragon Space Systems greenhouse is used. The daytime heat requirements are met passively through the design of the greenhouse. The power required to maintain the system is 16 W hours (MacCallum et al., 2000).

4.6.1. Planetary Contamination

We fall under class IVa of the COSPAR policy (COSPAR, 2003) This is the dirtiest level allowed for a lander, because we do not perform any life detection experiments. It is necessary to be cleaner than a Mars orbiter because we do land on the surface. ESA already has experience with this sanitation level (Pinna et al., 2001).

Sterilization: Even though PREMARS is not searching for life, planetary contamination is at least a political problem because we will be introducing a life form onto the Mars surface. Since the greenhouse will be sealed at the beginning of the experiment there should be no contamination of the surface. Viking experiments also demonstrated that the oxidizing properties of the surface are hostile to life for the first few centimeters. Still, the plant chamber will be sterilized at the end of the experiment.

4.7. Rocket

The rocket will fly almost 3 minutes and reach an altitude of nearly 40 km. The body design and materials are chosen such that the total mass stays at approximately 3 kg.

The rocket experiment is a good model to test the validity of in-situ propellant production. Details are available in Table 8.

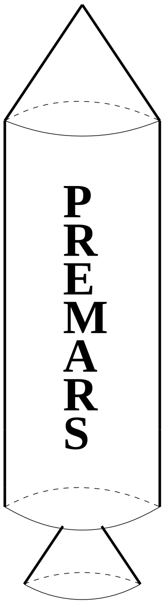
Table 8. Rocket Parameters

Element	Units	Description
Ethylene I_{sp}	s	Specific impulse
O/F = 2.6 : 1	unit-less	Oxygen:Fuel ratio
$g_m = 3.69$	m/s^2	Gravity on Mars
$r = 0.1$	kg/s	Fuel burn rate
$m_{empty} = 2$	kg	Empty mass
$m_{full} = 3$	kg	Full mass
$m(t) = 3 - r \cdot t$	kg	Mass (function of time)
$v(t) = g_m \cdot I_{sp}$ $\cdot ln(\frac{m_{full}}{m(t)}) - g_m$	m/s	No drag loss
$v(t_{burnout}) = 525$	m/s	Burnout at t = 10 s

4.7.1. Fuel

Mars surface and atmosphere can be used to produce rocket fuel.

Fuel Type Choice: Among the different types of fuel that can easily be produced in-situ as described in Section 3.2, ethylene (C_2H_4) is well suited for this kind of mission for several reasons: It is storable in a liquid form on Mars at ambient temperature and pressure. This means that the power requirement to store the propellant is much lower than with one of the other types of fuel. The weight of the system is also reduced (because of the smaller tank size) since the density of ethylene is 50 percent greater than liquid methane. Furthermore ethylene has only two hydrogen atoms per carbon while methane has four, this means that less hydrogen is needed for combustion as compared to methane and thus water mining time and energy can be spared. A last feature that makes the use of ethylene/oxygen as a rocket propellant more attractive is the specific impulse which is about two seconds higher than with methane/oxygen.



full mass: 3 kg
empty mass: 2 kg
Propellant: Ethylene C2H4
Height: 1 − 1.5 m
Diameter: 0.1 − 0.3 m

Figure 5.

4.7.2. Launch

To assure the launching of the rocket does not jeopardize further mission science the design of the lander should have the launch pad near non-mission-critical hardware and be shielded in some manner.

4.7.3. Flight

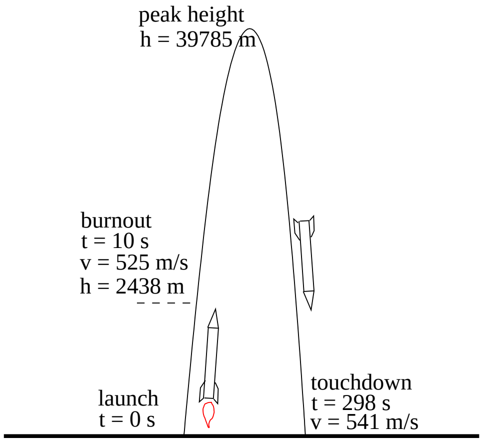


Figure 6.

The altitude reached at burnout time is: $x(t_{burnout}) = 2438m$ which is obtained by integrating the speed with respect to time between $t = 0$ and $t = 10$. The rest of the flight is an unpowered ballistic flight, assumed vertical: $x_{max} = v^2(t_{burnout})/2 \cdot g_m + x(t_{burnout}) = 39785m$. The velocity at touchdown will thus be $v^2(t_{touchdown}) = 2 \cdot g_m \cdot x_{max} \Rightarrow v(t_{touchdown}) = 541m/s$. The time of flight is: $t_{poweredflight} + t_{balistic_{u}p} + t_{balistic_{d}own} = t_{burnout} + (-v(t_{burnout})/g_m) + v(t_{touchdown})/g_m \approx 298s \approx 3minutes$ (Anacker R.,2001).

The first part of the flight is filmed from the lander and the pictures sent back to earth. The success or failure for this part of the mission is based upon these images.

4.8. Mission Schematic

Figure 7 shows a schematic of the mission design and how the different subsystems interact.

5. CONCLUSION

Figure 8. The Little Prince grows a plant in a greenhouse on the Eastern hemisphere of asteroid B612. He also uses an in-situ energy source (volcanic geothermal) to cook food in the South-West. (Saint-Exupéry, 1943).

Sending life to Mars is consistent with the Aurora goals and is a new enabling technology. A near-term plant growth and fuel production experiment would pave the way for future sample return and human missions.

This experiment provides a massive opportunity for public interest and outreach. The significance of growing a plant on another planet will impact the human species as few events in the past have done. It will rival landing on the moon and the first images of our planet from space because it demonstrates our ability to spread life through

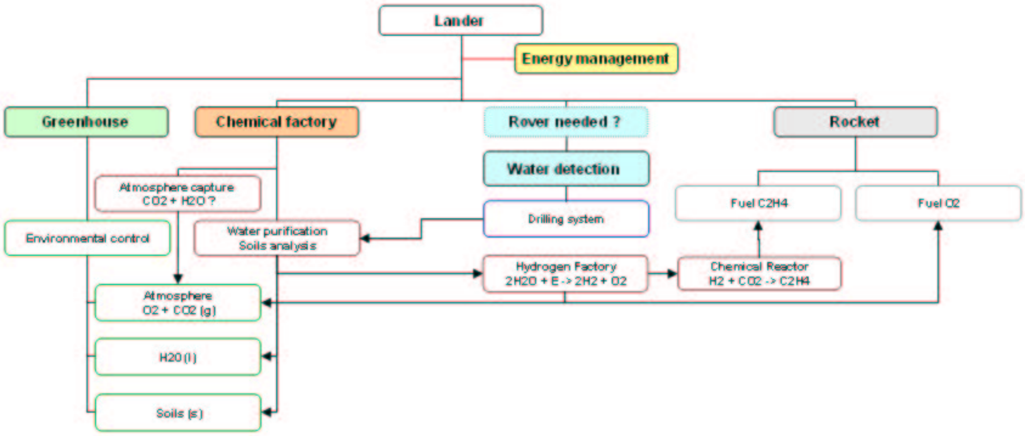


Figure 7. A schematic diagram showing an overview of the mission and how the different elements interact

our solar system. It changes life on Mars from science fiction to reality.

The design is technically feasible. Greenhouses and the chemical equations to create fuel have been used with success on Earth for many years. Furthermore the extensive research literature that already exists on these two experiments provides a broad scientific base to aid ESA with the development of this mission.

5.1. Future Work

Each subsystem of this mission can be worked on both independently and immediately. If the Paragon greenhouse is not used then a robotic greenhouse should be designed and built to meet the requirements discussed in this paper. Testing should ensure that it is a closed system and does not contaminate the surrounding environment.

A Mars soil simulant should be created (Allen, 1998) and tested with *A. thaliana*. The plant should be studied in more detail regarding the Mars environment and possible genetic modifications to aid mission success.

Finally the chemical factory can be built and run in a simulated Martian atmosphere.

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