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Surface Energy Production Issues for the Refueling of Starships

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Abstract

In order to produce a sufficient quantity of propellant on the surface of Mars for the return of a Starship (SpaceX) to Earth, there are various means of energy production. Musk wishes to use photovoltaic panels as a primary source of energy to meet this need. According to the work of Cooper et al, solar panels in conjunction with batteries or fuel cells are indeed very effective, perhaps even more than nuclear energy on the kW per kg basis. However, there are several drawbacks: The solar energy received on Mars is half that received on Earth due to the greater distance from the sun. A huge surface of solar arrays would thus be required, which is highly impractical for the deployment, even using very thin layers. Moreover, solar panels produce energy only during the day and the deposit of dust could dramatically affect their efficiency. According to our calculations the total mass of ISRU systems plus power systems would be between 180 and 247 tons, depending on the rate of water molecules present in the Martian soil. As a consequence, the feasibility of the proposed strategy is doubtful and new options might have to be investigated.

Keywords: fuel production, ISRU, energy

Acronyms/Abbreviations

NASA: National Aeronautics and Space Administration

DRA: Design Reference Architecture (from NASA)

IMLEO: Initial Mass in Low Earth Orbit

1. Introduction

We address the problem of supplying energy on the surface of Mars in order to refuel Starships space vehicles for their return to Earth [1,7]. The scenario follows 13 steps. First (1) the crew is sent into orbit, where the rocket separates into a booster (Super Heavy) and an upper section (the Starship) (2). The booster returns to Earth, where it is refueled (3) and a new unmanned vehicle (Starship tanker) (4) takes off and reaches the orbit to transfer propellant onto the previous Starship (5). Once the Starship's refueled, the Starship begins its interplanetary journey to Mars (6). After an aerocapture manoeuvre (7), it lands on Mars (8). Once the propellant production for the return trip is completed using local resources (9), the launcher takes off again (10) for the return to Earth (11). Finally, another aerocapture manoeuvre is implemented (12) and it lands on Earth (13).

In this study, it is proposed to focus on stages (9) and (10), which are dedicated to propellant production on Mars and take-off for the return to Earth. It is therefore assumed that each of the preceding steps has been carried out correctly. Moreover, in SpaceX's plans, the architecture involves the refueling of two Starships,

making the task more complex. Similarly, launch windows and trip durations are assumed to be close to standards, which implies to consider 6 to 8 months of interplanetary travel. This leaves a limited mission duration on Martian soil around 368 days. This duration depends on a number of complex factors. An approximate duration is used for our calculations.

In the next sections, it is proposed to estimate the mass of ISRU systems as well as power systems and to discuss the feasibility of refueling the Starships.

2. Requirements

2.1 Propellant production requirements

Knowing the amount of propellant to be produced will give an idea of the energy required to produce it. The Tsiolkovski equation is used (1).

$$\Delta v = V_e \times \ln \frac{m_i}{m_f} \quad (1)$$

- Δv is the velocity change between the start and end of the propulsive phase;
- V_e is the gas ejection velocity. For the Raptor engine, the proposed value is 3.644 km/s (average Isp of 371s).
- m_i is the initial mass of the rocket before the propulsion phase;
- m_f is the final mass of the rocket after the propulsion phase. It is assumed to be equal to 200 tons (dry mass+payload).

The velocity change can be easily calculated [3]. See (2).

$$\Delta v = v_{esc} + \Delta v_{loss} + \Delta v_{inj}$$

$$= (5.03 + 0.5 + 0.833) \\ = 6.633 \text{ km/s} \quad (2)$$

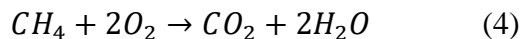
Assuming a residual propellant mass of 10 tons noted m_r , the required initial mass of propellant can be inferred, see (3).

$$m_{propellant} = m_i - (m_f + m_r) \\ = \\ = 200 \times e^{\Delta v/V_e} - 210 \approx 1012 \text{ t} \quad (3)$$

This calculation gives an idea of the amount of propellant to be produced on Mars over the duration of the trip. Given that SpaceX's plan is for a two-ship voyage, we need to multiply the mass found by 2, as the previous result is for a single launcher.

2.2. ISRU requirements

In Situ Resource Utilization (ISRU) is seen as an almost unavoidable option for the journey to Mars [2,3,4,5,8,9,10,11,12,13]. Bringing all the propellant needed for a return trip from Mars to Earth seems impossible. We would need to employ means and technologies that we haven't yet mastered. Let us examine the equation for the combustion of methane (4):



As can be observed, the mass of oxidizer is much greater in proportion than that of fuel: 64g of O₂ for 16g of CH₄, i.e. 4 times more. It is in general better to have more oxygen to improve the efficiency of the combustion process, with a 4.5 ratio.

With the previous estimates made on the quantity of propellant to be produced (2025 tonnes for two Starships) and considering a duration of stay on Martian soil of 368 days, of which only 338 are for propellant production (production must be completed 30 days beforehand for safety reasons), it is possible to determine the daily quantity of propellant to be produced: approximately 6 tons (2025/338).

Several NASA studies have tried to characterize the size and mass of the systems in charge of producing propellant, as well as the required energy and power [2, 3,4]. We propose to extrapolate data from the 2009 NASA report, in which there are estimates of the mass and power of ISRU systems for the production of 32 tons of propellant (CH₄/O₂) [3, page 111]. In this report, NASA is proposing to bring to Mars robot excavators, a unit for extracting water from Martian soil, a chemical unit exploiting the Sabatier reaction and water electrolysis, and a system for liquefying and storing methane and oxygen. It is possible to land in an area where water ice is present in large quantities a few centimetres or metres below the surface. In most cases,

however, there are no exploitable ice pockets, so we have to try to extract the water molecules directly from the Martian soil. Thanks to the Martian robotic missions, we have discovered that the average water molecule content is in the order of 3 to 8%. This is low, but sufficient to attempt extraction, provided a large quantity of Martian soil is collected, hence the need for robotic excavators. The principle is relatively simple: collect a few kilograms of soil and enclose it in a container. The water is heated to over one hundred degrees Celsius to vaporize it, then cooled down into liquid form on contact with a cold spot and collected. The very dry soil is then removed and replaced by a new sample brought in by a robot excavator.

Importantly, as clearly explained by NASA, the needs depend on the amount of water present in the soil. Both cases are considered, 3% and 8%, see Table 1.

Remark: The ideal solution would be to find lots of ice underground and to exploit that ice. Although it is possible to land in the north of the hemisphere where many icy terrains have been found, it is assumed here that the landing site could be anywhere, eventually close to the equator of Mars to maximize the efficiency of photovoltaic cells.

Table 1: Mass and power requirements in NASA scenario [3, page 111], for the production of 32 tons of propellant.

H2O 3% rate		
System	Mass (tons)	Power (kW)
Excavating robots	1.183	1.53
Water extraction systems	0.615	31.9
ISRU O ₂ and CH ₄ prod.	0.545	23.11
Liquefaction systems	0.03	4.38
Total	2.3	61

H2O 8% rate		
System	Mass (tons)	Power (kW)
Excavating robots	0,704	0,8
Water extraction systems	0,474	15,81
ISRU O ₂ and CH ₄ prod.	0,527	24,26
Liquefaction systems	0,03	4,38
Total	1.7	45

Assuming the required amount of hydrogen is 5% of the total amount of propellant (4g of hydrogen out of 80g in total in equation (4)), as hydrogen is only one ninth of the mass of a water molecule, the required amount of water that has to be collected for the Sabatier reaction is 0.45 times the mass of required propellant, therefore 14.4 tons in NASA scenario and 910 tons here. In the NASA report, almost 17 tons of water are considered, which is slightly different from 14.4 tons but NASA included

some water for life support systems. Some margins also have to be taken. A preliminary estimation of the mass and power requirements of ISRU systems can be obtained by a linear extrapolation of the NASA values shown in Table 1. The chosen multiplicative factor is 53.5 (910/17). The results are presented Table 2. Scaling up the systems allows in general to save some mass, which is true for the tanks for example, but for power requirements, a linear extrapolation is probably a good approximation.

Table 2: Mass and power requirements for the extraction and exploitation of 910 tons of water for the production of 2024 tons of propellant. Linear extrapolations from NASA estimates, which were based on the extraction and exploitation of 17 tons of water.

H2O 3% rate		
System	Mass (tons)	Power (kW)
Excavating robots	63.3	82
Water extraction systems	32.9	1, 707
ISRU O2 and CH4 prod.	29.2	1, 236
Liquefaction systems	1.61	234
Total	127	3, 259

H2O 8% rate		
System	Mass (tons)	Power (kW)
Excavating robots	37.7	42.8
Water extraction systems	25.3	846
ISRU O2 and CH4 prod.	28.2	1, 298
Liquefaction systems	1.605	234
Total	92.8	2, 421

3. Electric power generation

3.1 Context and options

As previously calculated, ISRU requires a huge electric power capacity, between 2.4 and 3.3 MW. In this section, we look at the various options for generating the required electrical energy.

The vast majority of Mars mission architectures have sought to base surface energy production on the use of nuclear fission [2,3,4,5,11,12]. Other authors, however, suggest the use of photovoltaic panels [5,7,8,9,10].

The aim is to determine which production source best meets the requirements of the Starship project. Namely, a production source capable of producing the amount of propellant required daily, while meeting the logistical constraints of the vessel used in terms of mass and volume. For example, it is necessary to know under what conditions the production material is transported, either within the same vessel as the crew, thus imposing greater constraints in terms of available space and mass, or on-board vessels dedicated to the transport of study tools

(rovers, production systems, etc.), requiring the robotization of installations. In effect, the infrastructures will have to be totally autonomous. However, this also raises the question of landing accuracy.

As many studies have already addressed the problem of electric power generation on the surface of Mars, it is important to take them into account. Probably the most relevant one is the study from Cooper et al, who made an accurate estimation of the mass of systems based on photovoltaic panels and compared that option to an option based the use of nuclear fission systems [1]. It is proposed here to consider their results and to extrapolate the mass of the systems to meet our needs. Nuclear fusion systems, which are not mature technologies, have not been considered here.

3.2 Photovoltaic panels

According to Cooper et al, photovoltaic power systems based on non-tracking thin-film roll-out arrays in conjunction with either fuel cells or secondary batteries for storage are very efficient [1]. Ultra-light arrays have indeed efficiencies of 15% and a mass/area of 0.063 kg/m² [6]. As solar energy works only during daylight, the solar power has to be increased in order to supply electricity to ISRU systems as well as to the secondary energy systems, which would continue supplying electricity to ISRU during night-time. For the production of 2 to 4 MW, 0.5 to 1km² of solar panels have to be deployed, which is a huge surface. The total mass of the panels would be between 31.5 and 63 tons. In addition, the deployment of the panels, which includes time for off-loading the arrays from the Mars surface landing vehicles, time for unrolling the arrays, and also time for placing rocks on the thin arrays to prevent the wind from blowing them away, would be very long.

3.3 Nuclear fission

The two main options are based on the use of Brayton or Stirling engines, which allow interesting mass specific power values.

Recently, in response to the problem posed by the size of nuclear reactors, NASA began developing a project with a very simple concept: KiloPower. Using the well-known technology of nuclear fission, KiloPower is a miniature power plant that can be transported and adapted to Martian conditions. A more powerful version could be capable of producing 10 kW with a mass of around 1,500 kg. Though a possible option would be to send hundreds of 10kW systems to achieve the required number of megawatts, the mass specific power would be too high. A more conventional option is therefore preferable with the deployment of a limited number of heavy nuclear reactors in order to achieve the best mass specific power.

3.4 Comparison of options

The study from Cooper et al provides the comparison between solar systems (non-tracking thin panels plus regenerative fuel cells) and nuclear systems (based on a Brayton engine, which appears to be the most promising) [1]. The results is presented Table 3.

Table 3. Mass specific comparison between solar and nuclear systems for the production of 200 kW (Cooper results) and linear extrapolation of the mass for the production of 2.4 and 3.3 MW.

System	Solar panels based	Nuclear reactor based
Mass specific power for 200 kW production (W/kg)	27.5	27
Mass of systems for 2.4 MW (tons)	87	89
Mass of systems for 3.3 MW (tons)	120	122

4. Discussion

First of all, it is important to notice that our analysis is approximate with numerous assumptions, for instance the rate of water molecules in the Martian soil, the mass specific power of different options (in an earlier version of the paper published by Cooper et al in the 2008 IAC proceedings, lower values were found), and also probably the choice of the chemical transformations to produce methane. If, nevertheless, our assumptions are correct, there are several important findings:

- In terms of mass specific power, the solar based option is very efficient, perhaps even more efficient than the nuclear power option.
- In terms of feasibility, however, the deployment of huge arrays of solar panels (on the order of 1 km²) is doubtful, or it would take such a long time that the average production per day would be severely impacted.
- The total mass of ISRU systems plus power systems would be at least 180 tons (92.8+87) and as high as 247 tons (127+120), depending on the water rate. Furthermore, other systems would be needed to deploy ISRU and power systems on the surface and there would be no margin for life support systems, pressurised rovers, etc. If we assume a payload of 100 tons for each starship, the total mass certainly exceeds the payloads of 2 starships, whatever the power systems option.

5. Conclusion

The main finding of our study is that two cargo starships are probably not sufficient to send ISRU and power systems to the Mars surface. Several options are nevertheless available:

- A simple option could be to add another cargo starship. According to our results, it would probably be sufficient (300 tons payload capacity in total for 240 tons payload).
- Another option is to reduce the amount of propellant that has to be produced. This is possible if the cargo spaceships are completely fuelled in low Earth orbit and if a sufficient amount remains in the vehicle after Mars landing. We did not investigate that option.
- Another idea would be to change the architecture of the mission. For instance, a spaceship could be used as a single stage to orbit vehicle (orbit of Mars) for refuelling another spaceship waiting in Mars orbit. Or a smaller Starship could be used for landing and ascent from the surface, while a standard one could wait in Mars orbit.

Several important difficulties have been identified in this study, but there are still many options to be investigated.

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