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MASSIVE: a fuel production mission in the framework of Martian ISRU

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Abstract

Mars Automated Supply System via ISRU for Venture Expeditions (MASSIVE) is a preliminary mission design in the framework of planetary ISRU aimed to consolidate fuel production technologies to support future manned mission to Mars. MASSIVE is designed to produce the required propellant to power a 3 astronauts MAV from surface up to LMO. The plant is designed to be operational for more than 5 years, the time during which the propellant production will continue with the simultaneous further characterization of the landing area. The mission is designed to fit the full system into one single SLS launcher with a proposed launch date in 2035 to touchdown in Gusev Crater in Jan 2036. The launch configuration is conceived as a single cylindrical lander containing the elements composing the Mars surface segment and the 1.4 tons spacecraft attached to the lander. The separation between the spacecraft and the lander takes place 3 days before the atmospheric entry when the lander continues its impact trajectory to Mars while the spacecraft will perform a Mars Orbit Injection maneuver to reach its operational orbit around the planet. The lander touches down with a vertical final descent, after being slowed down by an IAD and a subsonic parachute. During the plant deployment, the spacecraft performs scientific investigations on the landing site to study the H_2O concentration, while acting as a relay between MOC and lander. The operational configuration on the surface consists of an excavation rover and the plant. The rover is deployed by a ramp from the lander, and in its nominal daylight operations, it will excavate and bring the regolith to the plant, where it will also be recharged between the working cycles. The regolith is processed in a microwave oven, which dehydrates it collecting the H_2O while a pump collects the CO_2 from the atmosphere. A microchannel Sabatier and an H_2O electrolyzer will then take CO_2 and H_2O as reagents to produce O_2 and CH_4, which are cryocooled and stored in a liquid state in the tanks. The full system is expected to produce up to 38 tons of propellant within 2040, when the first manned missions to Mars are planned. This paper details the mission design with subsystem specifications and concept of operations from launch to disposal, providing an insight into its feasibility and current limitations.
Keywords: ISRU, Mars, Mission design, Fuel production

List of acronyms

ADCS	Attitude Determination and Control System
EDL	Entry Descent and Landing
IAD	Inflatable Aerodynamic Decelerator
ISRU	In Situ Resource Utilization
LEOP	Launch and Early Orbit Phase
LMO	Low Mars Orbit
LMOS	Low Mars orbit Segment
MASSIVE	Mars Automated Supply System via ISRU for Venture Expeditions
MAV	Mars Ascent Veichle
MOC	Mission Operation Center
MOXIE	Mars Oxygen ISRU Experiment
MSS	Mars Surface Segment
NASA	National Aeronautics and Space Administration
PPP	Propellant Production Plant
SLS	Space Launch System
TRL	Technology Readiness Level
WEP	Water Extraction Plant

1. Introduction

Mars Automated Supply System via ISRU for Venture Expeditions (MASSIVE) is a preliminary mission design in the framework of planetary ISRU aimed to consolidate fuel production technologies to support future manned missions to Mars. MASSIVE is designed to produce the required propellant to power a 3 astronauts MAV

from surface up to LMO. The plant is designed to be operational for more than 5 years, the time during which the propellant production will continue with the simultaneous further characterization of the landing area.
The work originated in a university context as a project related to the Applied Space Mission Analysis and Design course taught by Professor Michèle Lavagna at Politecnico di Milano. The purpose of the work is to conduct a Phase 0/A study by identifying the feasibility and a preliminary design of a mission given its mission objectives and high level requirements.
Mission objectives:

- Prepare next manned mission to Mars by:
  - Consolidating ISRU technologies for fuel production on Mars.
  - Prepare surface infrastructures to support manned mission return.
- Provide further characterization of the potential landing area of the future manned missions.

High level objectives:

- A full scale automated ISRU plant for fuel production to support an ascent phase for a three astronauts capsule up to LMO shall be delivered on surface.
- The plant shall be automatically operated and monitored from Earth.
- Infrastructure for products management and storage to withstand for more than 5 year operations shall be settled on the surface.
- Launch date shall be later than 2028.

The work was addressed with a top-down approach starting with high-level preliminary studies of the environment, the processes needed to meet the requirements, and the state of the art, to then proceed with more detailed studies at the system/subsystem level. The goal is to investigate the mission feasibility under the identification of the main elements and critical technologies involved, its development timeline and key features associated with risks and their impact on the mission scenario.
The objective of the paper is to summarize the work conducted, focusing in particular on the process and considerations made to arrive at the defined mission concept and system architecture. The paper starts with a presentation of the literature research on past missions and the mission environment, and then focuses on defining the payload needed to accomplish the mission objectives. This is followed by the mission architecture and the presentation of the most relevant trade-offs for future studies, concluding with a presentation of the overall system and production strategy.

2. Literature research

To get an overview of the state of the art while learning from prior experience, previous missions related to ISRU technologies and more general ones conducted on Mars were analyzed. Since martian ISRU technologies are relatively young, additional research was performed regarding current mission studies and concepts.

2.1. Martian ISRU

The most relevant experiment ever flown concerning ISRU on Mars is MOXIE [7]. This payload, mounted onboard the Perseverance rover (Mars 2020 mission), aims to a successful dissociation of CO_2 from the Martian atmosphere to obtain diatomic oxygen. The success of this experiment sets the stage for future ISRU missions. In addition, the results indicate that this system is easily scalable to large production rates [8]. Despite the success of this experiment, this is only one of the chemical transformations required to produce a viable fuel/oxidizer couplet. Further chemical processes should therefore be tested in relevant environments.

2.2. General past missions to Mars

A detailed study of all past and present missions to Mars and the technological solutions employed was performed. The study of those missions was useful both to ensure compatibility with systems that are still active on Mars which can serve as support for MASSIVE. The research also served to have an overview of the major criticalities related to the exploration of Mars and the solutions that have already been found. Finally, this investigation was utilized to understand which technological solutions were usually applied and why, through reverse engineering studies.

3. Landing site selection & environment overview

From the analysis of the Martian environment several sites have proved to be suitable for the mission. The possibilities identified and the final selection are shown in Fig. 1. A trade-off matrix was compiled for the choice of the identified site based on several criteria that are here listed: site accessibility, telecommunications coverage, sunlight conditions, weather conditions, scientific interest and collection terrain.
The selected site corresponds to Gusev Crater $[14.5° S\, 175.4° E]$. This site has been previously explored by the Spirit rover [2]. From a geological perspective, the experiments carried out in-situ by this mission confirmed the presence of the basaltic rocks composing Mars's regolith as well as the presence of hydrated minerals [10], optimal for the water extraction process.
The most relevant environmental characteristics of the chosen site are shown in Table 1. It can be seen that

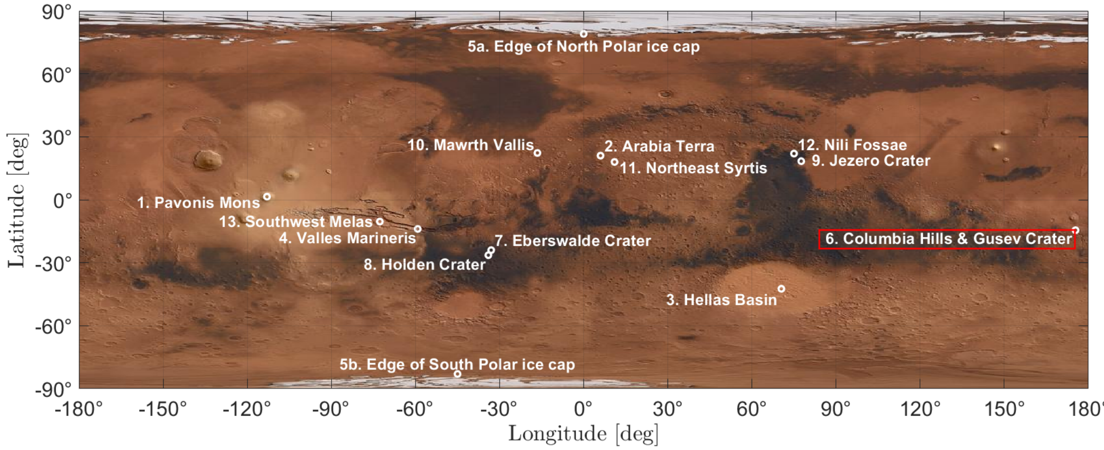

Figure 1: Landing sites considered in the trade-off process

although the equatorial location provides good illumination, the temperature, pressure and density reach very low values that need particular considerations in terms of design.
An additional parameter reported is the rate of atmospheric dust deposition on surfaces, a phenomenon already found to be critical in past missions.

Propriety	Max. value	Min. value	Unit
Atmospheric temperature	250	190	K
Atmospheric density	0.018	0.010	kg/m^3
Atmospheric pressure	665	505	Pa
Surface temperature	295	180	K
Dust deposition rate	0.6×10^{-9}	1.8×10^{-9}	kgm^2/s

Table 1: Environmental proprieties of the Gusev Crater [9]

The presence of dust in the Martian atmosphere might represent a threat considering the storms that often affect parts of the planet. From this point of view, Gusev Crater is in a position that minimizes the probability of being subject to local and regional storms [3]. However, it is not possible to avoid planet encircling storms that strike the entire planet once every two years.
Although the critical issues encountered from an environmental point of view need special design considerations, all the difficulties identified have already been addressed by previous missions.

4. System alternatives & trade-offs

The development of the work started with a study of the payloads and the mission architecture needed to accomplish the mission objectives. The most relevant trade-offs for the payloads definition and overall architecture are here reported.

4.1. Propellant selection

In order to select the most suitable O/F couple to be produced in-situ, the Δv required to bring a Mars Ascent Vehicle of 3 astronauts from the surface to a LMO was computed. The calculation of this impulse was based on the works [4] [12], obtaining a value of $4.6\,km/s$.
In order to select the propellant to be produced the following criteria have been considered: physical properties, heritage, complexity, production rate, flexibility & reliability. The physical properties are paramount to evaluate the performance of the propellant, while the other criteria were studied to consider the production and storage difficulties of each process.
From the studies conducted, four O/F couples were considered and subjected to this trade-off: Liquid oxygen and Liquid hydrogen (LOX + LH2), Liquid oxygen and methane (LOX + CH_4), Liquid oxygen and carbon monoxide (LOX + CO), and Carbon dioxide and magnesium (CO_2 + Mg, hybrid).
Although LOX + LH2 is a viable option, especially in terms of specific impulse, this option was discarded due to the difficulties of storing liquid hydrogen. Therefore, the final choice fell on the liquid oxygen and methane pair, which partly obviated the cryogenic storage challenges while allowing good propulsion performances.
Considering this choice, it has been calculated that 20.1 tons of O_2 and 5.9 tons of CH_4 must be produced to obtain the necessary impulse.

4.2. *Chemical process & payload definition*

For the production of these quantities of substances, it was necessary to identify the chemical reactions required to go from elements in the Martian environment to the finished products. The processes selected are a Sabatier reaction in parallel with water electrolysis. Other options were analyzed, but the one reported proved to be the most chemically efficient and simple from a hardware required standpoint.
The equations for the selected processes are given in Eq. (1).

$$\begin{gathered} CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O \\ 2H_2O \longrightarrow 2H_2 + O_2 \end{gathered} \tag{1}$$

These chemical processes are carried out in dedicated payload compartments, as shown in Fig. 4. This payload has been coded as the Propellant Production Plant (PPP), for which the necessary parameters for the design of the whole system have been calculated. The detailed design of the payload itself will be subject to further characterisation in future phases of the mission definition.
As can be seen in Fig. 4, the PPP takes in H_2O and CO_2 directly. However, these are not directly extractable from the Martian environment but must undergo beneficiation processes.
Concerning H_2O extraction, this is collected from Martian regolith through a rover which has the specific function of excavating and bringing material to the production and storing plant. Martian regolith contains hydrated minerals from which water can be extracted by heating the regolith in a microwave oven. The water collected is then transferred to the PPP. Given the complexity required by the process of extracting H_2O from the regolith, both in terms of the oven and its interfaces with the rover and the PPP, this element is also considered to be a mission payload coded as a Water Extraction Plant (WEP).
The process is simpler for the extraction of CO_2 from the environment. Since the Martian atmosphere is composed for the 95% of carbon dioxide [9], it is necessary to utilise a compressor to achieve the desired flow and a filter to prevent dust or other unwanted elements from entering the system. Although the detailed design of this apparatus has not been investigated, it is not considered to be a critical point since a similar system has already been tested in relevant environment by the MOXIE experiment [7].

4.3. *System concept definition*

The last set of analysis and trade-offs before entering the more specific level of individual subsystems and operations is done to define the mission concept and its high-level architecture.
This part proved to be one of the most challenging of the study, having to narrow down the endless possibilities for achieving mission objectives to a solution that optimizes the outcome based on the identified drivers. For the sake of brevity, only a few of the possibilities explored and their corresponding criticalities are reported, while the final choice is described in detail in the next sections.

4.3.1. *Landing & launching strategy*

From the early stages of the work it was clear that the mass to be landed on Mars would have been critical. From the result then obtained in the final mass budget, it can be seen that the mass to land is 13 times greater than Perseverance, the heaviest payload to have ever made a soft-land to date [11]. For this reason, landing was considered the bottleneck of the whole mission design process.
To overcome this problem, the possibility of dividing what was to be landed into three separate landing capsules was initially considered. This would have greatly reduced the mass at landing.
However, studying the uncertainty ellipses, it was found that it was not possible to make the three capsule landing at a short distance without compromising the landing safety. Connecting the three modules with cables/pipes or moving them through a ground mobility system to a single point would have completely negated the advantage derived from separating the mass into three blocks.
Reducing the size of the uncertainty ellipses would have required a capture maneuver. This again would have resulted in an excessive increase in mass in terms of propellant, making the mass too high to be launched in a single launch. The possibility of aerocapture/aerobraking was studied but soon discarded, as the density of the Martian atmosphere is too small to slow down large masses except at altitudes for which the state of the art Guidance, Navigation and Control (GNC) technology is not mature enough to handle a safe passage.
Finally, the possibility of multiple separate launches was explored. This certainly has many advantages from a technical point of view, but was found to be too expensive, thus discarded.
Reducing the options to the need to land the entire mass in one lump, the need for the development of technology to enable the landing of high masses on planets with atmospheres was noted. The development of such technology proves to be essential for future exploration of Mars, requiring the transportation of heavy infrastructure to the planet. The development of a new technology also comes in line with MASSIVE's design timeline. With a planned launch in 2040, it is necessary to integrate technologies that are being studied today, as by that time the current state of the art will be obsolete.
One promising system to greatly increase the landable mass on Mars is the Inflatable Aerodynamic Decelerator [13]. This system was integrated in the design so to be

able to perform a single landing. This system will allow considerable speed reduction during the early stages of the EDL phase without excessively altering the mass and volume of the system.
The Launcher selected for the mission is the SLS Block 2 Cargo [6], as it is currently the only one able to launch MASSIVE to Mars.

4.3.2. In-situ power production trade off

The required power output from the Mars plant during the propellant production and storing phase was estimated to be 20 kW. Given this power and the minimum mission duration of 5 years, the two strategies identified for power generation were photovoltaic and nuclear power production. Other innovative power production methods were explored, such as wind power or in-orbit production with laser transfer to ground. However, at the current stage of analysis, these methods do not provide an advantageous energy density compared to those mentioned above. The criteria identified for choosing between photovoltaic and nuclear power source were regulations, energy density, and reliability.
The reliability of solar panels on Mars is extremely low due to dust deposition and storms that obscure solar radiation. Regarding energy density, preliminary sizing was done based on end-of-life performance and secondary batteries needed in both the nuclear and photovoltaic cases. Due to the heavy degradation of solar panels, a mass of about 6 tons was estimated in the case of photovoltaic and 3.5 tons in the case of nuclear, making this more energetically beneficial.
Despite the strict European regulations regarding the use of Nuclear Power Sources, they are significantly more advantageous than solar production.
Two nuclear fusion reactors were therefore implemented as the energy source for the plant on the surface. Kilopowers, currently under development by NASA, were used as a reference [5]. Each of these reactors is capable of developing 10 kW and their design is being carried out specifically for ISRU-type missions to the Moon and Mars, thus making them an excellent fit for the mission. Although their TRL is currently at levels 5-6, the development timeline for the reactors will make them flight-ready before MASSIVE integration begins.

5. System architecture

The mission includes a single spacecraft, composed of three detachable blocks: orbiter, support stage and lander. The deployed configuration is illustrated in Fig. 2. During launch the solar panels of the orbiter are folded to fit into the launcher firings, while during the interplanetary cruise they are unfolded to provide power.
Each block is designed to meet a set of functionalities at all stages of the mission. The lander is mainly active during two phases of the mission. First, during EDL it shall allow a safe landing of all elements required on the Mars' surface. Then, during in-situ activities the equipment present inside the lander carry out the activities to reach the mission objectives, including: managing the regolith, producing propellant and storing it. The lander supports the equipment during their activities by providing electric power supply, data handling, and telecommunication with Earth. The orbiter has multiple functionalities: first, it shall ensure power and communication along the interplanetary phase, then it is used to perform scientific investigations, data relay and monitoring of the landing site.

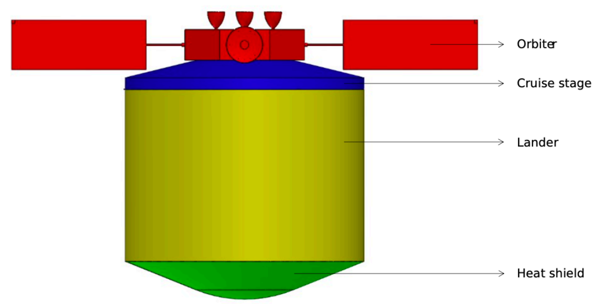

Figure 2: MASSIVE configuration during cruise

5.1. Mass Budget

Given the large quantities of propellant to be produced and stored for several years on the surface, the elements involved in mission design are massive with respect to the payloads delivered to Mars to date. In fact, the tanks and the structure required to support them are large in terms of both mass and volume. Therefore, the biggest constraint considered is the maximum mass that can be launched with current launchers.
Having performed a preliminary design of each of the three main elements composing MASSIVE (orbiter, support stage and lander), the mass budget at launch can be found by summing up all the mass contributions of the elements. The propellant for orbital and attitude manoeuvre has also been estimated and taken into account.
Several configuration trade-offs therefore led to the presented solution, where the mass at launch remains several tonnes below the one allowed on the SLS Block 2 Cargo launcher. It should be noted that system margins were added to each element according to European Space Agency (ESA) margin philosophy [14]. Similarly, a total margin at launch of 20% was added to the entire system, as well as a statistical estimate of 10% to be attributed to the launch adapter, which is required to support the system inside the capsule in the launcher.

Element	Mass [kg]	Margin [%]	Total Mass [kg]
Surface Segment	10916	20%	13100
Landing propellant	536	20%	643
EDL system	5595	20%	7146
Support stage	950	20%	1140
Attitude propellant	150	100%	300
Satellite	1152	20%	1383
Total Dry Mass			23710
+ Launch margin		20%	4742
+ Propellant mass (margins included)			2215
Total Wet Mass			30668
+ Launch adapter		10%	3067
LAUNCH MASS			33039

Table 2: MASSIVE Mass budget

5.2. *Mission segments overview*

There are three key segments composing the overall system architecture: Ground Segment (GS) and space segment, which is divided into Low Mars Orbit Segment (LMOS) and Mars Surface Segment (MSS). In Fig. 3 the layouts of segments together with their interfaces are shown.

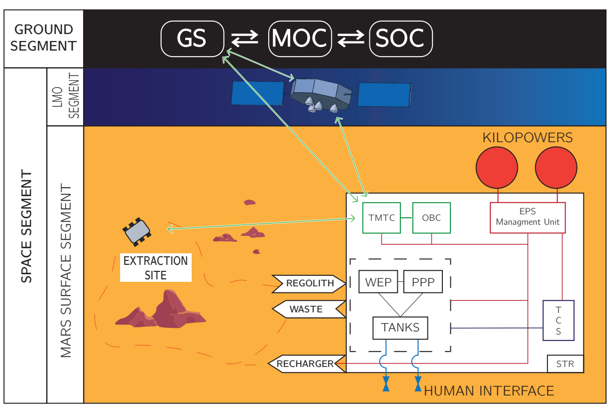

Figure 3: Mission segments and their interaction

5.3. *Mission Segments*

The GS (Ground Segment) is composed of Ground Station, Mission operation Centre, Science Operation Centre and the Polytechnic of Milan. The Ground Station handles the telecommunications coming from Mars, for both LMOS and MSS.

The LMOS is composed by the orbiter, which handles the telecommunications from GS and MSS (both Rover and Plant) and performs the science investigations and monitoring of the landing site.

The MSS is composed by the plant and one rover. The rover collects and brings martian regolith from the surface to the plant, and disposes waste material. The regolith is then processed by the plant, which receives the needed power from EPS of the plant. For the MSS, rover and plant are able to communicate between themselves and the LMOS, but only the plant is able to communicate directly to the GS (to increase redundancy). The Plant hosts the payload of the mission, which is presented in the next subsection.

5.4. *Payload overview*

The payload is composed of three elements: Water Extraction Plant (WEP), Propellant Production Plant (PPP) and Storage System. These are interconnected and are all included in the lander. The overall scheme of the payload is presented in Fig. 4.

The WEP uses the regolith collected from the rover and extracts H_2O which is delivered to the PPP and the H_2O tanks. It works by means of a conveyor belt which brings the regolith inside a microwave oven with the aim of cooking the regolith up to the dehydration point, extracting the trapped molecules of H_2O.

The PPP takes as input the water coming from the H_2O tank and WEP and combines it with the CO_2 coming from the atmosphere via a pump filtration system. At first the PPP electrolyzes the H_2O, the O_2 extracted is cryocooled and stored in the O_2 tanks, then the H_2 obtained reacts with the filtered CO_2 in a microchannel sabatier reactor, producing CH_4, which is then stored in the CH_4 tanks.

The Storage System is composed by a buffer water tank, three liquid oxygen tank and three liquid methane tank. The System keeps water, liquid oxygen and liquid methane at 290 K, 97 K and 121 K respectively. All the tanks are contained within the lander structure to be well protected by the harsh martian environment.

5.5. *MASSIVE elements*

A preliminary design of the elements composing the overall system have been carried out.

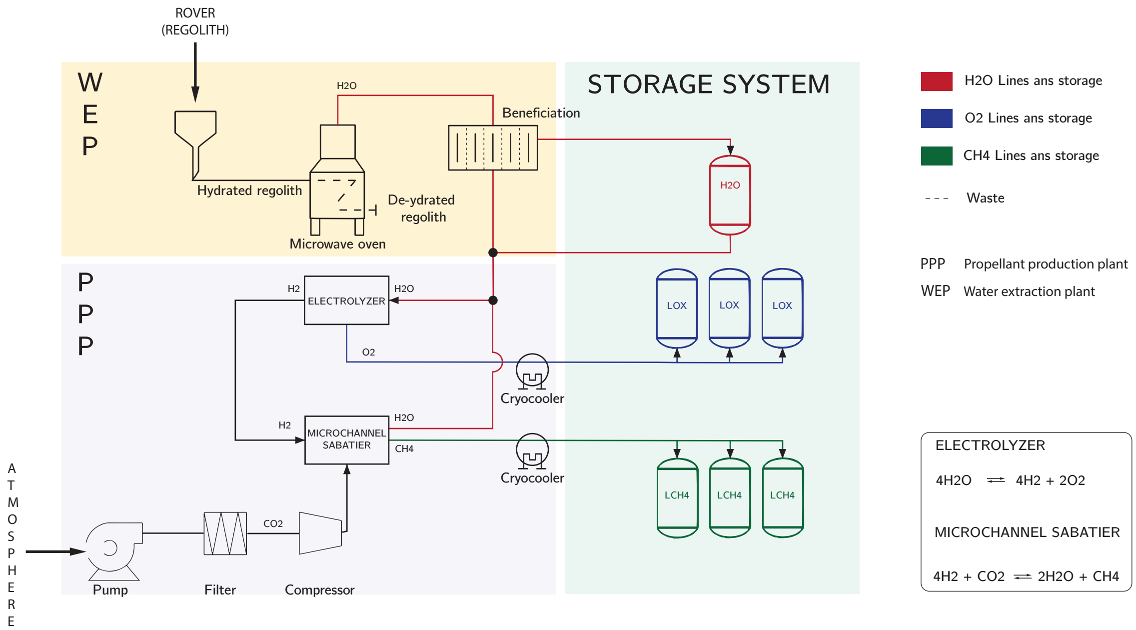

Figure 4: Payload scheme

Since the orbiter (Fig. 5) is the interface between the launch vehicle adapter and the spacecraft, the starting point of the configuration is the 3 m diameter central structure tube. The external structure is octagonal and is placed around the central tube to allow several external support panels for the equipment. A set of tiltable solar panels ensure enough power for operations along the overall mission. The propulsion system of the orbiter is employed to slow the system after the interplanetary arc, and to avoid impingement of the engines plume with other elements, all the thrusters of the main propulsion are placed on the same face. To reduce centre of mass fluctuation, all tanks are placed in the central cylinder, in a symmetrical manner. An HGA and a UHF antenna are used for communication purposes. Concerning the ADCS, sun sensors and star trackers are selected and positioned to ensure a clear field of view.
The nadir-pointing payloads mounted on the orbiter are: a high resolution imaging camera for landing site reconnaissance, a Short Wave Infra Red camera for the characterization of the landing site via mineral and thermophysical property mapping, in addition of a polarimetric synthetic aperture radar (P-SAR). Finally, daily global images would be provided by a context camera with a wide field of view, in order to provide short-term in-situ weather forecast and in particular warning of dust storms.
The support stage (Fig. 6) is placed on top of the lander, and it represents the interfaces between the latter and the orbiter. During EDL, the top part of support stage faces zenith to ensure two main functions: first, the wrap around antenna allows to communicate with the orbiter, then the parachute system is positioned in the top centre position to face zenith and to be aligned with the center of mass of the lander.

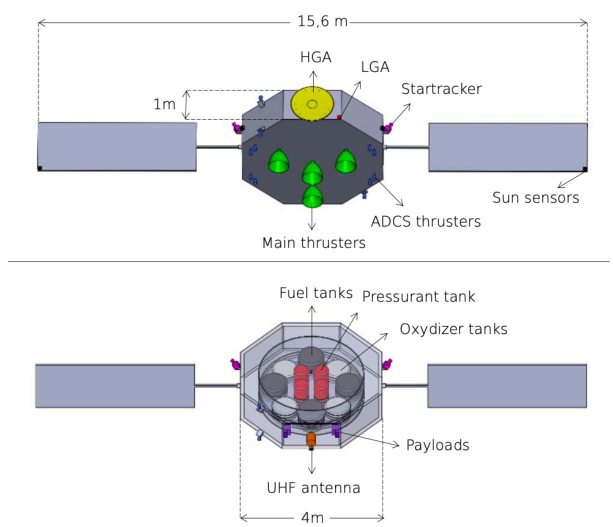

Figure 5: Orbiter configuration

Since the parachute system is attached to the support stage, when the parachute detaches from the lander it carries away the support stage as well. Below the top surface of the support stage, the ADCS tanks are placed near the central position in a symmetric manner to reduce the variations of the centre of mass. These tanks feed the ADCS thrusters which is composed of two sets of pyramidal thrusters, diametrically opposed to ensure the largest momentum arm for attitude corrections.

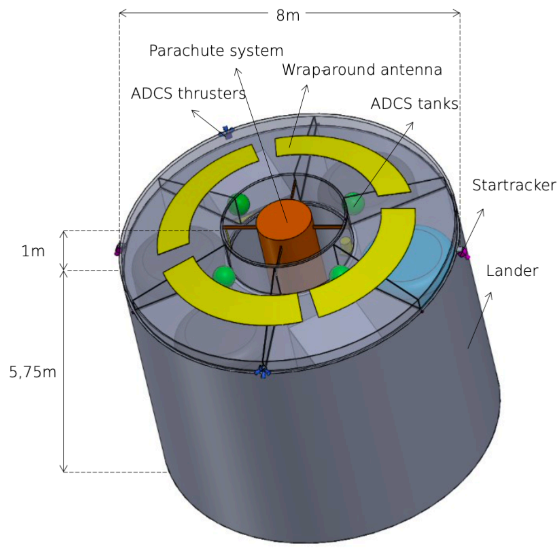

Figure 6: Support stage configuration

The lander configuration is a cylindrical monolithic module which contains all the surface elements. The weight is distributed to keep the center of mass aligned with the symmetry axis of the cylinder. The closed configuration (Fig. 7) protects the surface elements from the space environment, as well as the martian environment once landed on the surface.

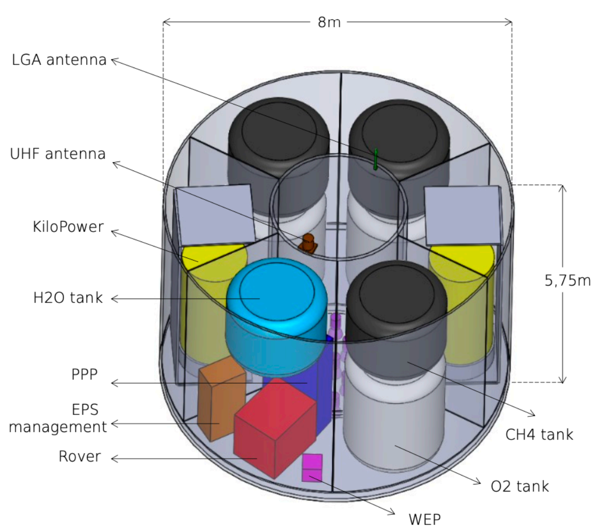

Figure 7: Lander packed configuration

Tanks are symmetrically distributed and attached to the skeleton of the structure, made with aluminium honeycomb layer surrounded by aluminium alloy. The 8 m diameter allows it to fit into the launcher and keep all the payload on the bottom level, to interface with the martian soil once landed. During operations, a new configuration Fig. 8 is allowed by sliding rails that can open in order to deploy the two 10 kW-kiloPower reactors, which are responsible for the power generation of the entire system. Together with the nuclear reactors a small ramp is deployed, to allow the rover to descend and begin its nominal operations of regolith excavation on the surface. The WEP interfaces directly with the PPP and they are both attached to the lander's bottom level.

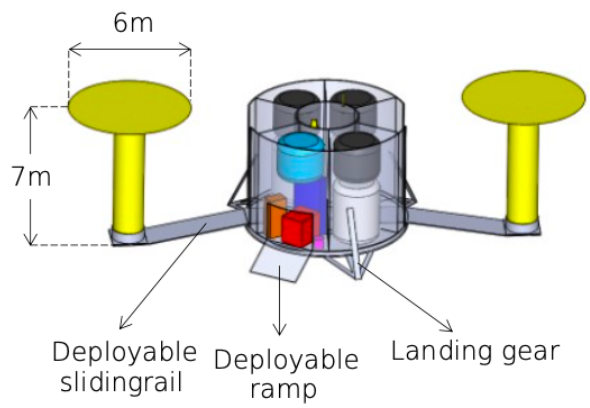

Figure 8: Lander deployed configuration

6. Concept of Operations

The ConOps involve a complex set of operations and interfaces between the system segments and vehicles. The mission is subdivided into 8 main phases (Fig. 9)

1. LEOP (∼15 days): this phase starts with launch and includes all the operations involved in the earliest stage of the interplanetary trajectory from Earth to Mars;

2. Transfer To Mars Phase (∼202 days): from exit of Earth SOI to the entry of Martian one;

3. Mars Orbit Operations Phase (∼3 days): this phase concerns all the operations to be executed in order to safely place the satellite in its operational orbit, as well as safely bringing the lander in an impact trajectory with Mars;

4. EDL Phase (∼3 minutes): the entry, descend and landing phase which finishes with touchdown;

5. Deployment Phase (∼TBD hours): dedicated to deploy the plant and its elements once reached the surface;

6. Commissioning Phase (∼21 sols): time required to commission and perform health check on the overall system, such as performances and nominal functionalities;

7. Production & Storage Phase (∼years): main part of the mission dedicated to the production and storage of CH_4 and LOX;

8. Disposal Phase (∼days): end of the mission and switch off of the plant.

6.1. *Concept of operations until touchdown*

The operations before touchdown are divided into two main parts. Firstly, the mission analysis study allows to understand the launch window and the required time of flight to reach Mars. The window for minimising excess velocity at the output of the terrestrial SOI is found to be 10 June 2035 – 02 July 2035. The interplanetary trajectory is then propagated with the assumption of departing the 24th of June 2035.

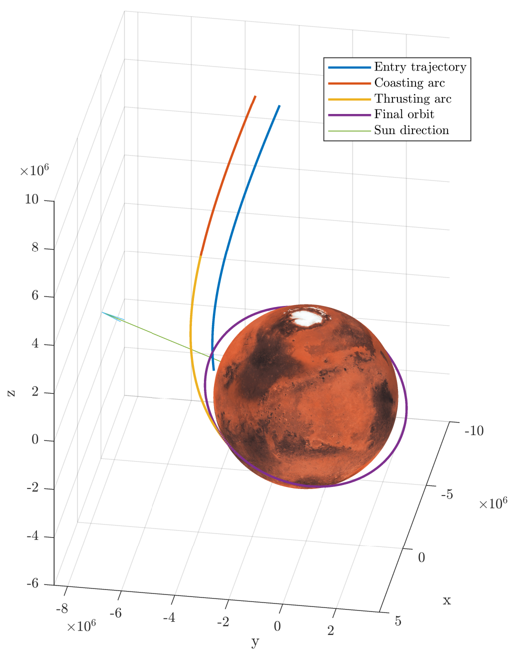

Figure 10: Mars orbit operations

After the interplanetary phase, the Mars Orbit operations phase begins (Fig. 10) with the separation of the orbiter from the lander, which aims to reach its nominal working orbit around the planet. From launch to atmospheric entry the operations have an overall duration of 202 days. Then, three days before the lander's atmospheric approach (set at t = 0 s) the orbiter is detached from the support stage. The orbiter starts its mars orbit insertion at t = -495 s, thrusting for 36 minutes, up to t = +1667 s. In the meantime the lander performs the EDL, which starts at t = 0 s and finishes at t = +203 s.

Relating to the landing sequence, the capsule will enter the atmosphere interface at 130 km with 5.585 km/s. Once it reaches Mach 5, after 104 s, it will deploy the IAD (Inflatable Aerodynamic Accelerator). Further decelerated, at Mach 1 and 116 s, it will deploy the subsonic parachute at 4.66km from surface. Finally, at 188 s and 376 m from surface, it will decelerate using thrusters achieving a touch- down velocity of less than 1 m/s after 203 s from entry.

Time	Height	Velocity	Events
0 s	130 km	5585 m/s	Entry at $\gamma = 16.85$ deg
104 s	7.17 km	1202 m/s	Detach heat-Shield, deploy IAD
116 s	5.61 km	241 m/s	Detach IAD, deploy subsonic parachute
188 s	1.32 km	56.35 m/s	Detach subsonic parachute, fire thrusters
203 s	0.95 km	0.04 m/s	Touch-down

Table 3: EDL Concept of Operations

6.2. *System commissioning & surface operations*

After touchdown the plant transmits the signal to MOC which operates with green light for commissioning (if a successful landing occurs). A key factor in this operation is the forecast: the plant shall be deployed only in case of no sandstorms. This phase has a duration of 21 sols. During deployment of the plant, the orbiter operates the commissioning of the payload in order to be ready for landing site investigation. The deployment of the plant involves the opening of kiloPowers rails and their full deployment, the outgo of the rover through a dedicated ramp and the establishing of path for the regolith from the rover to the WEP. The overall plant then processes the health check and performance monitoring to ensure that the overall system and payloads are working correctly and according to the expected performances. In the meantime the orbiter proceeds with the investigation of the landing site: the data is sent to Science Operation Center which performs analysis to identify the water spots on the surface. The coordinates are then sent back to the plant which stores them in order to redirect the rover in the points where water percentage is higher. This is the nominal phase of the mission: during this phase the plant works nominally with the rover collecting the regolith and delivering it to the plant which processes it to produce the chemicals. This phase duration depends on

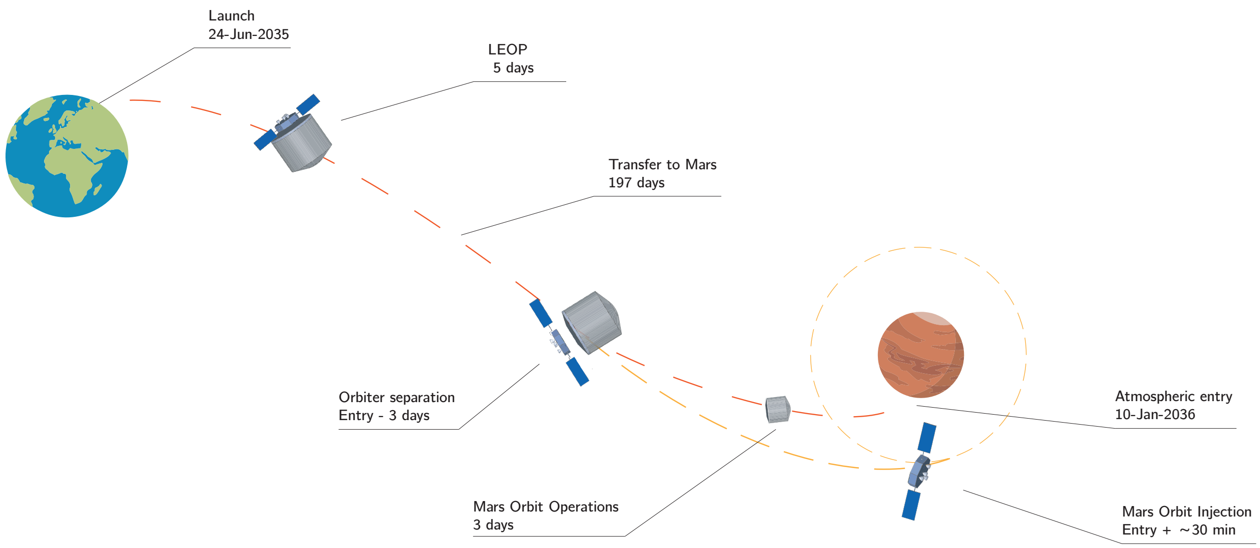

Figure 9: Concept of operations from launch to touchdown

different factors, mainly the water percentage. Once the production goal is met, the plant preserves the tanks with fuel to wait for the first human mission arrival. Finally, once the mission objectives has been fulfilled the plant is posed in hibernation mode to support future missions and being switched on under request.

7. Propellant production & system performance

Once the required elements for production have been identified, they need to be integrated and employed in order to fulfill the mission objective following some main criteria: flexibility, ensured by having an adjustable production rate depending on power and number of reactors/rovers; durability & reliability: the system shall be capable of working beyond the mission objective fulfillment, to aim to have a reusable plant to decrease further more complexity and costs of future missions.

Parameter	Value
Temperature	-40 C°
Regolith density	1500 kg/m^3
Regolith specific heat	608 J/kgK
Water percentage in regolith	1.28 %
Regolith dehydration enthalpy	152940 J/kg
Efficiency of the processes (WEP)	70%
Efficiency of the processes (PPP)	50%

Table 4: Parameters of the production strategy evaluation [1].

7.1. *Assumed data and constraints*

The best production strategy is designed as a function of several input data. The initial assumptions made are those reported in Table 4. These conditions represent the worst case condition for the analysis, therefore it is expected that the production will have better performances. Taking this assumptions as input for the analysis, infinite options and different good combinations are still identifiable (Fig. 11) because the working hours and days per year are still a parameter to select.

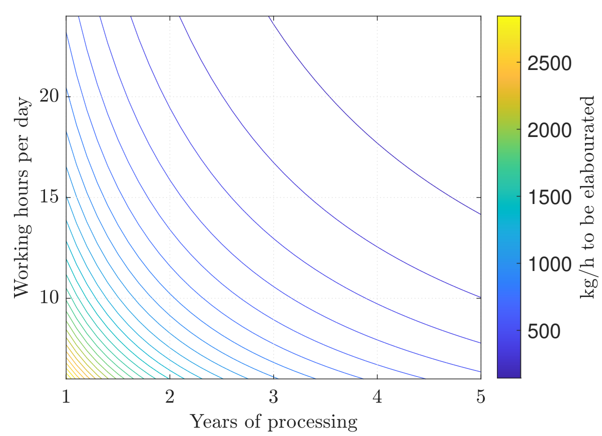

Figure 11: Tons of regolith to be elaborated per hour

Two main constraints have been applied on production:

- the rover shall work maximum 12 h/day: (only-daylight operations) for safety
- the production rates shall be compliant among each other (matching between kg/hr of rovers and oven, to avoid overproduction or overloads)

One design parameter is left to be decided: the kilograms per hour of regolith elaborated by rovers. This allows to have a preliminary sizing of the water tank, the rover itself, and the operations timeline.

7.2. Production strategy evaluation

Initially, different processing strategies have been identified and and analysed. The main concept were:

- Gathering all the water required beforehand and then processing it into propellant;
- Simultaneous extraction, dehydration and processing of all the material
- Daylight extraction and night processing

Each option has positive and negative aspects. In order to select the best strategy which takes into account all the variables, a parametric analysis has been performed in order to identify the best production strategy respecting the constraints imposed. The assumptions and choices made for the logic sequence of the power production needs a careful consideration:

- The plant works at the speed of the slowest subcomponent for that instant of time.
- The Sabatier reaction starts immediately at the beginning in order to minimise the water stored since it is highly power demanding.
- The Sabatier reactor exploits all the energy available which is not used by the baseline, by the oven or by the tanks.
- When the oven collects enough water for the final objective, it stops working, leaving the Sabatier reactor with more energy to exploit.
- A controller allocates the power between the components giving priority to the water production, as it is the bottleneck of the production.
- In the case that the Sabatier consumes all the water available, the controller stops the Sabatier reactor and gives all the power back to the oven.

7.3. Production and plant performance

The optimum condition of chemicals production over time is found to be corresponding to 40 Kg/h (Fig. 12) of regolith elaborated by the rover. In this condition the water tank is not fully used during the production and it can therefore be kept both as a margin in case of failure of some components and as an additional degree of freedom to make the production more flexible.

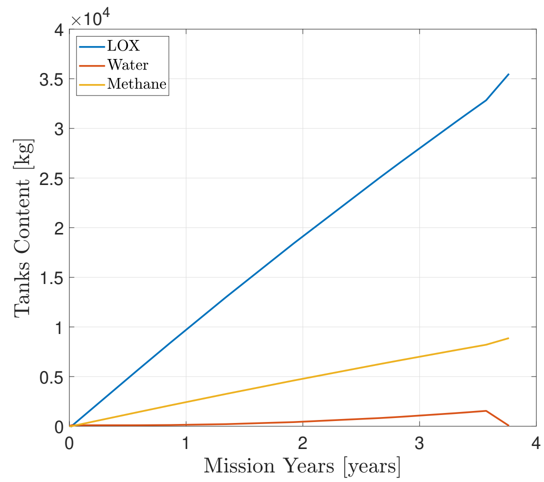

Figure 12: Chemicals production history @ 40 Kg/h

Overall, the mission objective can be met in 3.5 to 4 years; a good time margin is left to take into account possible events causing production to stop such as anomalies or sandstorms. The analysis performed represents a worst case condition and given the copious number of parameters on which the production time depends, it was decided to size the plant according to the worst production case in order to ensure that it can meet the mission objective even in disadvantageous conditions. However, the plant is equipped with a central computer capable of adjusting production and its logic according to the variation of input parameters, such as physical data of the regolith or the quantity itself that is supplied by the digging rover. It therefore has an autonomous central unit capable of adjusting production, which is not only flexible but also scalable, as the input parameters include the amount of regolith to be processed and the amount of energy supplied.

8. Conclusions

With the goal of extending human civilisation beyond Earth's borders, ISRU technologies provide substantial support for future missions. The potential of a facility capable of producing and storing enough fuel to carry astronauts back to orbit is manifold. One of the most prominent benefits is saving on fuel weight at launch, thus increasing the weight of the transportable payload to the surface. The new technologies that are emerging in the space exploration scene make it possible to investigate these seemingly futuristic missions, which are now increasingly accessible. In this context, MASSIVE stands as a forerunner of possible industrial-scale facilities to support the first human colony on the red planet. In the preliminary study of the mission, several points were identified to be critical or relevant, with the aim of investigating them further during more advanced design phases.

8.1. Open points and future work

Among the various aspects of the mission where a more in-depth analysis is needed, the technologies with the lowest TRL and risks mainly spanning over 3 fields:

- EDL, as it is necessary to engineer and demonstrate a prototype capable of performing a vertical and soft landing with a certain precision on the red planet and with a similar order of mass while accounting for the expected plume surface interactions.
- Mechanisms and durability, given the complexity and the dimensions of the mechanisms involved, the extended working conditions as well as interaction with martian weather shouldn't significantly affect the nominal performance.
- WEP, it is required to research and test for multiple years of operations the single elements included in the process such as the microwave oven and belt for regolith transport.

Future work and studies shall focus on these aspects, to optimize the design and the interfaces between the elevated number of elements to optimize performance and durability of production and storage.

8.2. Conclusion

The study of MASSIVE provides a well-rounded assessment of the needs for executing such a project from the earliest stages of planning to operation and end of life. In conclusion, although MASSIVE represents an unprecedented technological challenge, the mission is stated to be feasible. The open points and low TRL elements identified are the starting point for future work and technology improvement required to bring the subsystems to the minimum TRL level required for flight. That being said, in later phases of the mission, it is essential to carry out numerous extensive studies to investigate the identified critical points and major variables in the preliminary design, either confirming or negating the mission's feasibility. MASSIVE mission would drive technological developments to challenging corners, undoubtedly representing a possible candidate as a precursor for the future colonisation of the red planet.

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