MAV-Ops

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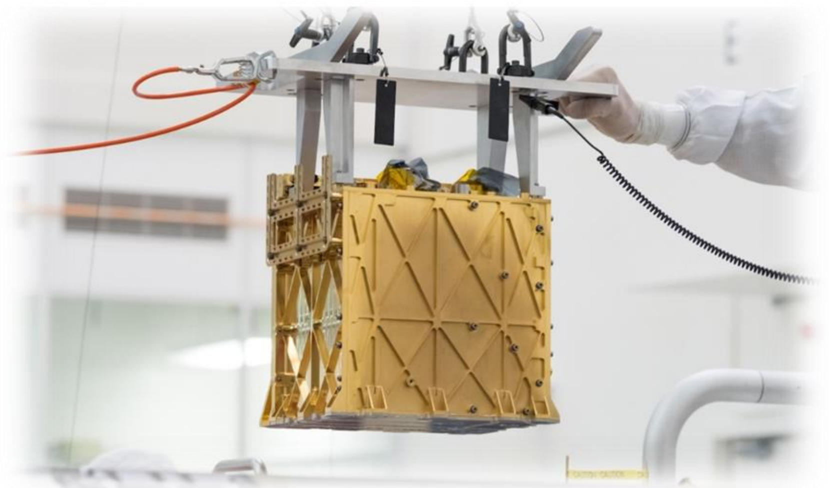
Executive summary

The manned exploration of Mars is a very ambitious goal that requires a large amount of resources such as the oxygen needed to breath and fuel the Mars Ascend Vehicle. To overcome these limitations, ISRU practices come useful. We know that carbon dioxide constitutes about 96% of Martian atmosphere and it is the candidate for oxygen extraction through a Solid Oxide Electrolysis reaction. The MOXIE demonstrator proved this concept on board of the Perseverance Rover in April 2021. The full-scale device, L-MOXIE, will be almost 200 times larger and the power generation system must be totally redesigned. In this work we evaluate the power requirements of L-MOXIE leveraging a process simulation developed in Aspen Hysys, obtaining a consumption of 22.8 kW. Our design effort focuses on the generation, transmission and storage of electric energy, as well as oxygen handling and storage. We employ a forcing technique based on C-K theory pillars to broaden the spectrum of options retrieved from the literature review and from the partial solutions we build a morphological chart. Three concepts are then generated based on nuclear, grounded solar, and orbiting photovoltaic power generation systems. A trade-off analysis is performed to assess them, and the orbiting photovoltaic concept is excluded due to the low scores obtained in the MAUA. The feasibility analysis of the two concepts gives an overall payload of 8253 kg for the nuclear and 4471 kg for the solar, including the batteries.

Key Words

Mars exploration, ISRU, Power generation system, MOXIE, Feasibility study



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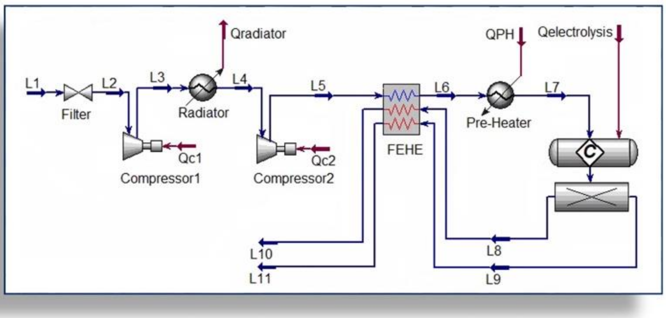
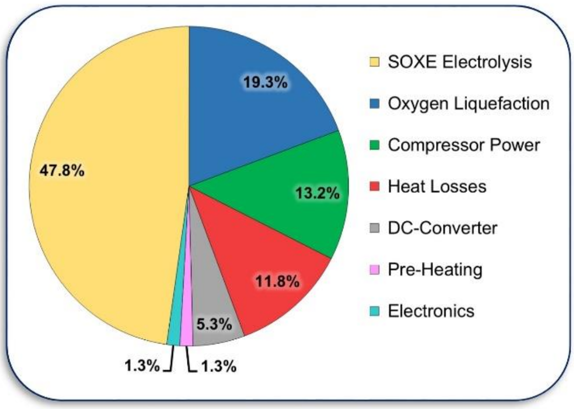
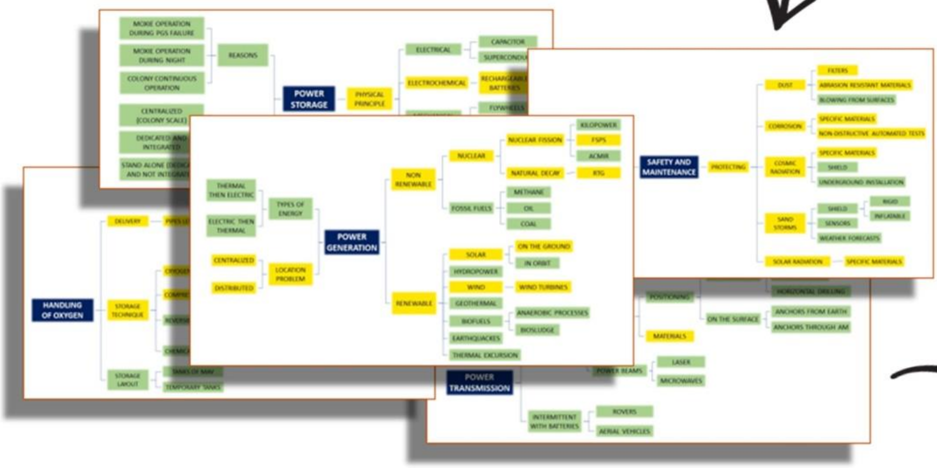
L-MOXIE simulation in Aspen Hysys



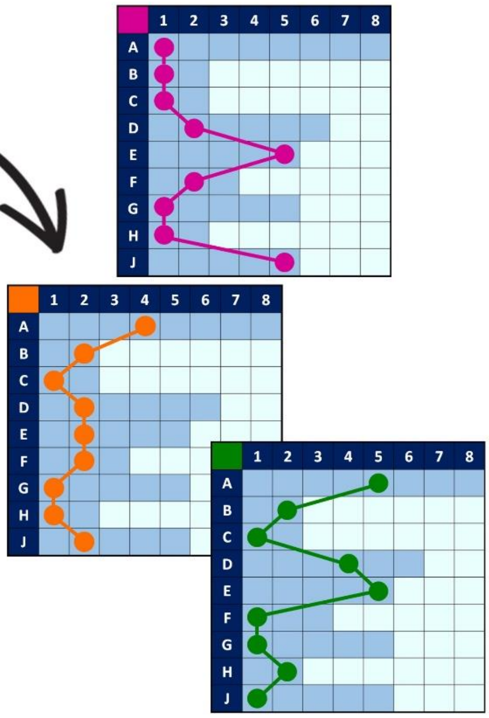
L-MOXIE consumption of 22.8 kW



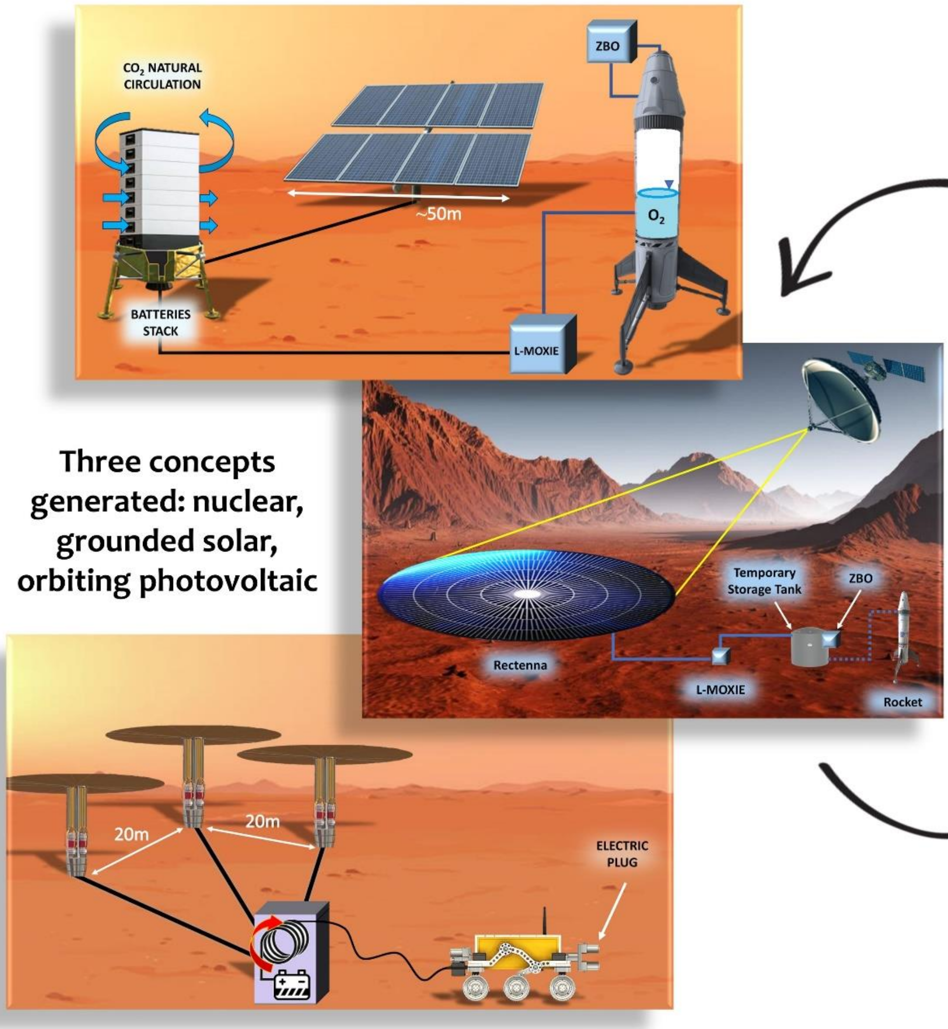
Forcing technique based on C-K theory pillars



Morphological charts for concepts generation



Three concepts generated: nuclear, grounded solar, orbiting photovoltaic



MAUA and scoring activity

	Nuclear (Kilopower)	Grounded Photovoltaic Panels	Orbiting Photovoltaic Panels
Mass	0.44	1	0.01
Safety	0.8	1	1
Deployability	1	1	0.6
Reliability of energy supply	1	0.75	0.75
Risk	1	0.9	0.8
Compactness	0.4	1	0.01
Technology readiness level	0.7	1	0.3
Flexibility and modularity	1	0.75	0.85
Cost	0.75	1	0.3
Loss	0.97	1	1
Total	0.77	0.95	0.54
Result	✓	✓	✗

Project description written by the Principal Academic Tutor

Human exploration of Mars will almost certainly use an In-situ resource utilization (ISRU) system to produce oxygen from the Martian atmosphere for crew breathing and, most importantly, to make propellant for a Mars Ascent Vehicle. The MOXIE experiment on the Mars2020 (Perseverance) rover will demonstrate this technology at ~0.5% of the scale required for a human mission. Scaling MOXIE technology (solid oxide electrolysis) to a human-scale mission will require several tens of kilowatts of electrical power. Moreover, it presents numerous operational challenges.

A Mars Ascent Vehicle (MAV) will land autonomously on Mars with enough methane to fuel the ascent but a near-empty liquid oxygen (LOX) tank. The oxygen producing and liquifying equipment will most probably be pre-installed in the MAV, in such a way that astronauts arriving in the next 26-month cycle can remove this equipment from the MAV and possibly repurpose it for surface operations. Other configurations may be considered as part of the study, as can the potential use of robotics, both autonomous and teleoperated from Earth.

Power may be produced by solar arrays, by nuclear power plants (e.g. NASA's Kilopower Reactor [1]), or by some other means. Deploying and operating the power system will be a challenge, as will connecting it to the ISRU oxygen production system. Nuclear power plants must be located at least 1 km away from the MAV and positioned in craters with no direct line of sight to the MAV. Solar panels could be closer, or perhaps even attached to the MAV, but in this case, they would have to be designed so that the crew could detach or stow them before the MAV takes off.

The challenge for this ASP project is to evaluate different potential systems and subsystems, such as cabling, power systems, interfaces, robotic movers, etc. and to develop plans for how the systems could be deployed and operated. MIT-based mentor(s) will provide a background for ISRU design and operation. The principal disciplines that will be involved are: power, mechanical, structural, materials, and robotics. Each potential system design needs to be analyzed not only for technical feasibility (i.e. Will the system work once it is configured?) but also for operational feasibility (i.e. How will the system be deployed and activated?). Students will develop operational scenarios for deploying and operating each of the systems that is being studied.

Team description by skill

The team is composed by four engineering students, that brought different skills and expertise to the project:

Paolo Arnaudo is an Automation Engineering student at PoliTo. He focused on the telecommunication systems in space archite+cture and he drafted the orbiting photovoltaic concept.

Marco Castaldi is a Mechanical Engineering student at PoliTo. He worked on the nuclear concept, proposing also a deployment strategy and performing the feasibility analysis.

Lorenzo Quadri is an Aeronautical Engineering student at PoliMi. He worked on the grounded solar concept performing also the feasibility analysis. He is responsible of the communications with the stakeholders.

Vito Andrea Sangiorgio is a Chemical Engineering student at PoliMi. He developed the process simulation of the L-MOXIE in Aspen Hysys and he carried out the power consumption estimation.

Goal

The MAV-Ops project is subdivided into different goals depending on the project advancement. First, the team is asked to understand the importance of In-Situ Resource Utilization (ISRU) for human exploration of Mars and why ISRU has large power and energy requirements. Then, the team will evaluate alternative power generation systems and alternative power transmission systems. It is also required to include operational feasibility as part of systems design and develop operational scenarios for deploying and operating each of the systems that is being studied. Moreover, the evaluation of how robotics could help, both during deployment and eventually during continued operation is considered a plus. The team is finally asked to demonstrate the ability to communicate the findings of the project that could be potentially beneficial to NASA and other agencies/groups planning ISRU activities.

Understanding the problem

In the framework of space exploration, Mars discovery and colonisation play an important role. One main limitation to achieve this purpose is given by the difficulties in bringing all the resources needed for the manned mission, especially oxygen. For this reason, the technological demonstrator Mars Oxygen ISRU Experiment (MOXIE) has been developed to test the Oxygen production on Mars and it is mounted on rover Perseverance. In April 2021, MOXIE successfully accomplished its first demonstration producing 5.37 grams of O_2 during the mission Mars2020. The next step after the MOXIE prototype is the development of a large-scale oxygen generator, called L-MOXIE, that produces the oxygen needed for the return journey of the Mars Ascent Vehicle (MAV) to Earth. The L-MOXIE is expected to generate ~200 times more oxygen than the prototype, with a similar design of the oxygen generator but a completely different power generation system.

In this context, the MAV-Ops project wants to propose, through an exhaustive and comparative analysis, possible optimal designs for a real scale system. The first research challenge is the estimation of the electric power consumption of L-MOXIE to produce the oxygen flowrate required to fill MAV tanks.

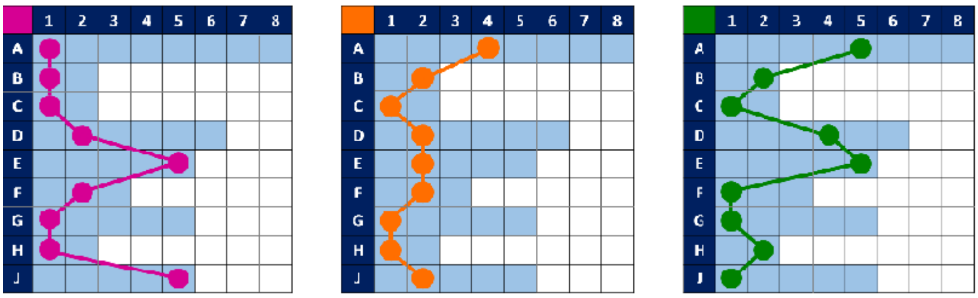
Then it is important to understand the environment and the boundary conditions on the Red Planet where the In Situ Resource Utilization (ISRU) will operate. The main variables influencing the system design concern the Martian climate. Indeed, the atmosphere is composed by more than 95% of CO_2, which is the raw material for the oxygen generation, and it is much more rarefied than on Earth [2]. The lower temperatures compared to Earth require a study on gas density and temperature fluctuations throughout the day. The choice of the power generation technology, based on these considerations, is the core of the whole power generation system design. Several technologies are in principle applicable and among them the two most established are the nuclear and solar technologies. Once the electric energy has been produced, it is necessary to design an adequate power transmission system connecting the L-MOXIE to the power generation system. For photovoltaic technology, a broad range of alternatives exist, and the transmission system would be relatively simple. However, in case of nuclear reactors an appropriate infrastructure must be designed. A power storage system is needed to mitigate the power fluctuations and guarantee continuous functioning of the L-MOXIE. If case of intermittent power generation, a large storage system must be designed, possibly based on rechargeable batteries. The oxygen produced by the L-MOXIE must be stored for months on Mars. An established technique in aerospace applications employs the oxygen cryogenic liquefaction. The liquid is then stored in insulated vessels with Zero Boil-Off (ZBO) system to avoid any loss of precious gas [3]. Regarding safety and maintenance, the preventive and protective measures against the atmospheric events must be accurately designed to avoid unexpected system's damaging.

The deployment of the system must be planned in detail to ensure that the final arrangement of the power generation system could be successfully achieved. For instance, if nuclear power is employed, the reactor must be moved away from the spacecraft to preserve humans from the nuclear radiations when they will land on the surface of Mars. The whole control system must be automated and operated remotely having no crew on the first months. The structure of the ISRU system must be robust to resist the atmospheric events and at the same time the payload must be as light as possible. Metallic materials such as aluminum, chromium and stainless-steel special alloys can be employed for construction purposes.

Exploring the opportunities

First, a process simulation of L-MOXIE is developed in Aspen Hysys thanks to the experimental data obtained from the MOXIE demonstrator at JPL laboratories [4]. The estimation of the power consumption for L-MOXIE is carried out leveraging the simulation and a power consumption of 22.8 kW is obtained, including liquefaction. This value is slightly below the previous estimations due to the lower compressor requirements. Using a forcing technique based on the principles of the C-K theory, multiple partial solutions are explored and proposed for the main items of the system, namely the power generation, power transmission, power storage, oxygen handling and storage, safety and maintenance. Exploiting these results, a morphological chart is built and exploited to develop three design concepts: the nuclear concept, the grounded solar concept, and the orbiting solar concept.

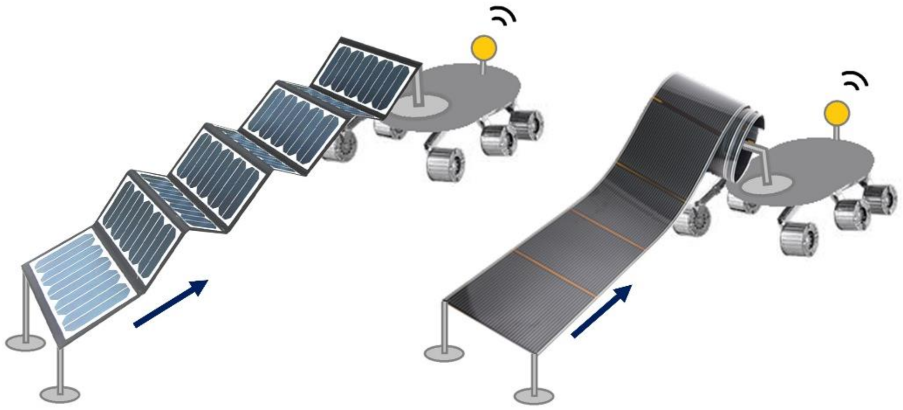
	1	2	3	4	5	6	7	8
(A) POWER GENERATION	KILOPOWER	ACMIR	RTG	GROUNDED SOLAR	ORBITING SOLAR	WIND TURBINES	GEOTHERMAL	THERMAL EXCURSION
(B) ENERGY PATHWAY	THERMAL THEN ELECTRIC	ELECTRIC THEN THERMAL						
(C) LOCATION	CENTRALIZED	DISTRIBUTED						
(D) POWER TRANSMISSION	UNDERGROUND CABLES	CABLES ON THE SURFACE	LASER POWER BEAMS	MICROWAVE POWER BEAMS	ROVERS	AERIAL VEHICLES		
(E) POWER STORAGE	CAPACITORS	RECHARGEABLE BATTERIES	COMPRESSED AIR	THERMAL	NO STORAGE			
(F) ARCHITECTURE	CENTRALIZED, COLONY SCALE	DEDICATED AND INTEGRATED	STAND ALONE, DEDICATED NOT INTEGRATED					
(G) OXYGEN STORAGE	CRYOGENIC LIQUEFACTION + ZBO	COMPRESSED GAS	REVERSIBLE ADSORBERS	CHEMICAL STORAGE AS OXIDIZER	SENSORS + WEATHER FORECAST			
(H) STORAGE LAYOUT	TANKS OF MAV	AUXILIARY TANKS						
(J) PROTECTIVE DEVICES	BLOWING FROM SURFACES	VACUUM CLEANING	UNDERGROUND INSTALLATION	RIGID SHIELD	INFLATABLE SHIELD			



Top: Morphological chart built by a combination of the partial solutions obtained through the forcing technique based on C-K theory pillars. *Bottom:* concepts generated for the nuclear, grounded solar, orbiting photovoltaic concepts.

Generating a solution

Employing the Multi Attribute Utility Analysis (MAUA), the three concepts are assessed through a set of criteria defined by the team and a subsequent scoring activity is carried out. The analysis gives satisfactory results for the grounded solar concept and for the nuclear one, while the score of the orbiting photovoltaic is rather poor and for this reason it is abandoned. The feasibility analysis and the seizing of the nuclear and grounded photovoltaic concepts is then carried out defining the masses and volumes at stake. The nuclear concept includes 3 Kilopower reactors with a size of 10 kW each. This system is expected to work in continuous without any energy storage. The overall weight of the reactors is 8253 kg which is rather impacting on the overall spacecraft. The Kilopower reactors must be installed around 500 m from the human settlement for safety reasons. The cabling between the reactor and the L-MOXIE, that should be located next to the MAV, requires special attention and a system constituted by deployable tubes is proposed. To protect the reactors from sandstorm an inflatable shielding system is considered in this work. The concept based on grounded solar panels has a smaller plot because it is not necessary to separate the PGS from the MAV. The area of the solar panels is estimated to be 1428 m^2 and a configuration with rolled or "accordion" panels is proposed to ease their deployability. Having a discontinuous solar irradiance, the system requires a battery of 340 kWh to allow a continuous functioning of L-MOXIE. The overall solar system weights 4471 kg, 1071 kg of panels and 3400 kg of batteries. The concept based on orbiting solar panels has a low TRL and the MAUA showed that at this stage it is unfeasible. However, it gives good insights for the possible PGS of a future human colony on Mars.



Detail of the deployment phase for the two proposed rolled and "accordion" solar panels configurations.

Main bibliographic references

[1] Gibson, M.A., Poston, D.I., McClure, P., et al., 2018. The Kilopower reactor using Stirling Technology (KRUSTY) nuclear ground test results and lessons learned. In 2018 International Energy Conversion Engineering Conference p. 4973.

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