

IAC-24-A3-2C-2-x87424

Development Status of Oracle, the ISRU Demonstrator for Oxygen Extraction on the Moon
Francesco Latini^{a*}, Simone Pirrotta^a, Raffaele Mugnuolo^a, Michèle Lavagna^b, Ivan Troisi^b, Alice Dottori^b

^a Agenzia Spaziale Italiana (ASI), Via del Politecnico snc, 00133, Rome, Italy,
francesco.latini@asi.it, simone.pirrotta@asi.it, raffaele.mugnuolo@asi.it

^b Aerospace Science & Technologies Department, Politecnico di Milano, Via La Masa 34, Campus Bovisa, 20156, Milan, Italy

michelle.lavagna@polimi.it, alice.dottori@polimi.it, ivan.troisi@polimi.it

* Corresponding Author

Abstract

Since the beginning of the decade, several space agencies and private industries have set their plans to going back to the Moon: in addition to NASA, who is leading the exploration of the Moon with its Artemis program, ISRO performed the first ever landing on the lunar south pole while JAXA have managed to reach the lunar surface, showing the capability of pin-point landing with extreme accuracy. On the other hand, with the CLPS and LIFT-1 initiatives, NASA aims at supporting private industries to develop their platforms to reach the Moon and bring scientific and technological payloads to perform experiments and collect data. In particular, great importance is given to demonstrating the capability of extracting and using resource locally, allowing a future sustainable human presence on the Moon. In this frame, the Italian Space Agency (ASI) started the ORACLE (Oxygen Retrieval Asset by Carbothermal reduction in Lunar Environment) Project, with the aim to develop an ISRU demonstrator for oxygen extraction from the lunar regolith. The partner for the in-progress Phase A/B1 is the Politecnico di Milano (PoliMi), while the Prime Contractor for the next phases, up to the manufacturing and testing of the Flight Model, is under selection. The process has already been proven in laboratory to produce liquid water from regolith simulant following several steps in two different reactors, one at 1100 °C where carbon oxides are first produced and the second at 250 °C where water vapour is obtained. The present mission is aimed at demonstrating the effectiveness of the selected process in the relevant environment, using actual regolith from the lunar surface. Moreover, the low sensitiveness to regolith composition on the yield of extraction will be demonstrated. The project has successfully completed the first technical reviews (i.e. Mission Definition Review MDR and Preliminary Requirements Review - PRR), when set of Requirements and critical trade-offs were identified. Also, preliminary mass, power and data budgets were estimated along with an evaluation of the subsystems to be included in the baseline configuration. Further refinement is expected for the following phase, directly related to the choice of the service provider among those offering a service launch in the timeframe of 2028. This step is crucial for the identification of the interfaces, especially the one related to the regolith handling system.

Keywords: ISRU, Oxygen, Technological Demonstrator, Moon, CLPS

Nomenclature

This section is not numbered. A nomenclature section could be provided when there are mathematical symbols in your paper. Superscripts and subscripts must be listed separately. Nomenclature definitions should not appear again in the text.

Acronyms/Abbreviations

ASI	Agenzia Spaziale Italiana
CLPS	Commercial Lunar Provider Services
CRB	Carbothermal reactor
FLD	Fluidic pipes, including tanks for gases
HAR	Harness
ISRU	In-Situ Resource Utilization
MCS	Measuring and Control System
MET	Methanator reactor
OBC	On Board Computer

ORACLE	Oxygen Retrieval Asset by Carbothermal reduction in Lunar Environment
PoliMi	Politecnico di Milano
REG	Regolith Management System
STR	Structure
TCS	Thermal Control Subsystem
TRL	Technology Readiness Level
WSU	Water Separation Unit

1. Introduction

The current decade is marked by the worldwide shared will of going back to the Moon to put the basis for future permanent human settlements. This is one of the key points of the Artemis Accords signed by NASA and other space agencies, including ASI, to enable the human presence beyond LEO in preparation for the future colonization of Mars. This challenging initiative

is supported by other programs thought to foster technological developments and scientific data collection to broaden the knowledge regarding the needs to adapt to the lunar environment (lunar dust, temperature, radiations) and the possibility to exploit the available resources. In fact, especially if future manned missions towards Mars are considered, continuous re-supply missions are not sustainable, making the identification, extraction and use the local resources as enabling capabilities [1]. In this regard, NASA has already proven this capability through MOXIE [2], the instrument onboard Perseverance that converts carbon oxides present in the Martian atmosphere into molecular oxygen. Similar initiatives are planned to be demonstrated on the Moon, to exploit the lunar regolith for different purposes: to produce construction materials for future habitats, breathable air and water, tools, etc. Indeed, at the end of 2023 NASA invited the space community to participate in the Lunar Infrastructure Foundational Technologies (LIFT-1) call [3], with the intent of fostering ISRU technology development finalized to lunar exploration. The access to the lunar surface will be enhanced also by the Commercial Lunar Provider Services (CLPS) missions [4], that will provide opportunities to deliver on regular basis payloads on the Moon to gather scientific data and test technologies in support to the Artemis program.

Regarding the development of ISRU technologies on the Moon, there have been many proposals for those aimed at extracting oxygen from lunar regolith [5], since oxygen represents one of its main constituents [6]. The Italian Space Agency (ASI) is directly involved in the development of the ISRU technological demonstrator, named ORACLE (Oxygen Retrieval Asset by Carbothermal reduction on the Lunar Environment) to be launched to the Moon surface NET 2028. The partner for the in-progress Phase A/B1 is the

Politecnico di Milano (PoliMi), while the Prime Contractor for the next phases, up to the manufacturing and testing of the Flight Model, is under selection. The extraction process is based on a reduction step in a carbothermal reactor (CRB), in which the oxides present in the regolith batch react with CH₄ at 1100 °C to produce CO [7,8,9]. Furthermore, an additional step in the second reactor, called methanator (MET), at 250 °C allows the conversion of CO into H₂O_(g) which is condensed through a dedicated Water Separation Unit (WSU); further details on the process are available in [8,9,10], where a detailed description of each step and regulation parameters is provided. The use of methane a reactant guarantees that the process is agnostic to the regolith used (e.g. extracted from maria or highland), thus the selection of the landing site is not a constraint for the mission. The process has been tested in the laboratories at PoliMi using the lunar simulant NU-LHT-2M [8], obtaining successful results. Additional tests using different simulants [11] are planned to optimize the parameters regulating the extraction process.

In this paper, the development status for ORACLE is described, along with the preliminary scientific requirements identified and the baseline configuration to be developed. Also, a list of preliminary constraints for the interface towards the platform are listed to evaluate the possible providers for the launch and transfer service.

2. Development status

The development of ORACLE follows the roadmap shown in Fig. 1. The project has successfully passed the Preliminary Requirements Review (PRR) and has now entered the phase B1 to be closed in mid-2025. This review has been fundamental to establish the main sets

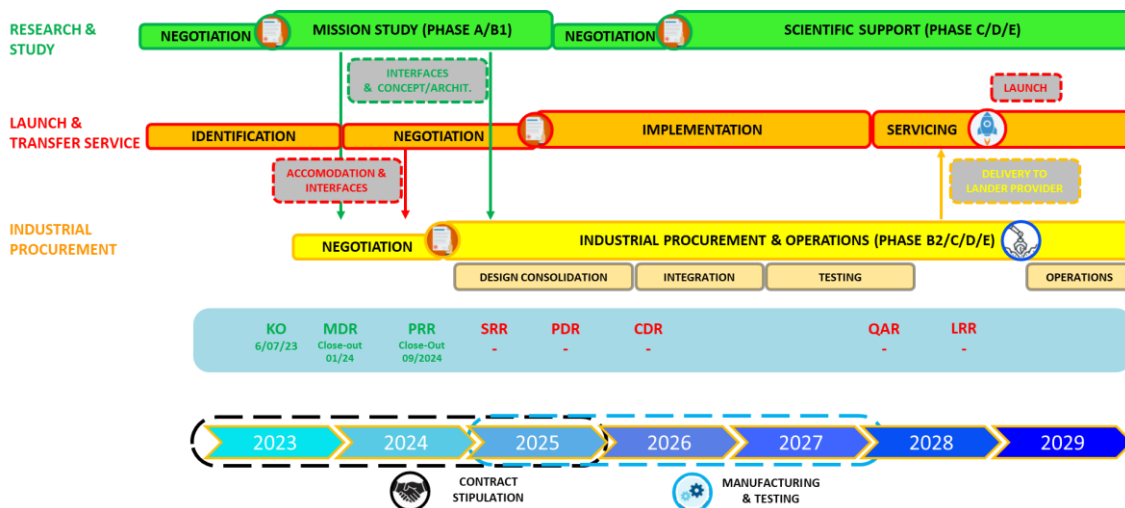


Fig. 1 – ORACLE roadmap development

of preliminary requirements of the payload, as well as highlight the main trade-offs to be discussed in the next phase. Also, the preliminary mass and power budget allowed the identification of constraints towards the platform that will be necessary in the negotiation with the launch and transfer service providers, to identify the most suitable launch opportunity among those available in the timeframe of 2028. In parallel, the selection of the industrial partner is going to be completed; it will take over and proceed from phase B2 until the delivery of the payload for the integration onboard the platform, with a Critical Design Review foreseen by mid-2026, when the final design will be frozen and ORACLE manufacturing will be authorized.

3. PRR main results

The objectives of the PRR [12] have been successfully achieved by identifying the preliminary requirements for the payload and by providing its preliminary configuration and trade-off analysis for the main subsystems. These will be handed over to the industrial partner that will proceed to the finalization of the design and then development of the Flight Model unit.

3.1 Scientific requirements

The list of scientific requirements is reported below:

- S-0001: The payload shall demonstrate the carbothermal reduction process of lunar regolith operating on the Moon surface through the detection of CO after the carbothermal reaction and/or the production of water.
- S-0002 The water recovery yield (water/regolith mass in the reactor) of the carbothermal process shall be >6% (TBC).
- S-0003 The minimum yield of the process should be

obtained for at least 2 (TBC) times in order to demonstrate the repeatability.

- S-0005 The water vapour produced in the methanation reactions shall be separated from the gaseous flow.
- S-0137 The products of the carbothermal reduction shall be converted into water.

The list of scientific requirements highlights the need for ORACLE to be operated on the Moon to extract oxygen from lunar regolith for at least two times to demonstrate the repeatability of the process and its robustness. The amount of oxygen extracted will be quantified either by the CO produced or by the amount of water condensed and collected in the WSU. The current estimate for the yield of extraction of the ORACLE miniaturized plant, according to the preliminary ConOps and the allocated limited time for the process (10 hours), is about 11% of oxygen against the oxygen amount trapped in the feedstock. This estimate, along with the measurement performed throughout the process, will be used to validate the theoretical curve of extraction and evaluate the growth capability if more time were allocated.

3.2 Configurations

The uncertainty related to the launch and transfer provider due to possible mass and volume constraints led ASI to adopt a modular approach for defining ORACLE configuration. Fig. 2 shows the three configurations currently under evaluation. The “Core System” (orange box) is composed by the units whose presence is mandatory to demonstrate the process, thus the extraction phase that takes place in the carbothermal reactor (CRB), where the oxides present in the regolith [5] are converted into carbon oxides [8,10]. This process

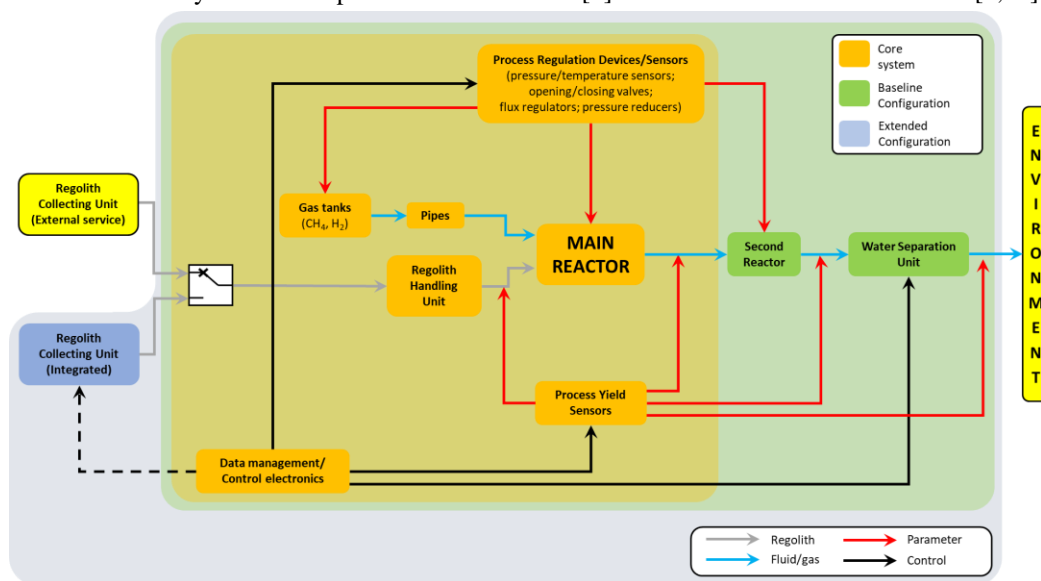


Fig. 2 – ORACLE Configuration

has not been validated in space yet, thus the measurement and quantification of carbon oxides downstream of the CRB represents the minimum success criteria for the mission. The “Baseline Configuration” (green box) comprises the MET and the WSU, through which the carbon oxides are first converted into water vapor and later condensed. This result would be fundamental since liquid water is one of the main supplies needed to make human settlements on the Moon sustainable. Note that for the ORACLE payload the exhaust gases (nominally CH₄ and H₂) will not be stored and recycled but will be released in the environment; the gas recycling subsystem will be studied for the future full-size plant on the Moon. A preliminary baseline configuration for ORACLE is shown in Fig. 3, where it is supposed to be accommodated on a generic lander deck.

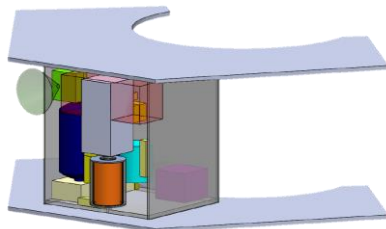


Fig. 3 – ORACLE preliminary baseline configuration accommodated on a generic lander deck

In both the configurations previously described, it is assumed that the Regolith Collecting Unit (REG) is an external service, provided either by the platform itself or shared with other payloads onboard; if this is not the case, the REG would be included in ORACLE. Although the REG does not add any specific scientific value to the process, it is fundamental to collect fresh regolith from the lunar surface and allow the process to take place. For this reason, an “Extended Configuration” (blue box) is considered as back-up.

3.3 ConOps and power budget

As per req. S-0003, the process will take place at least twice (non-consecutive) to demonstrate its repeatability. Each process repetition shall last ≈ 40 hrs divided as in Fig. 4, according to the following sequence of phases:

- ON: ORACLE is activated; the components are checked against nominal values.
- REGC: Regolith is collected from the lunar surface; it could be performed in parallel to ORACLE activation if it were an external service
- LMMI: the collected batch of regolith is loaded to perform mass measurement and visual inspection (LMMI: Load, Mass Measure, Inspection).
- COMM: to check ORACLE parameters and give the GO to the loading into the CRB.

- LOAD: to load and close the CRB.
- CHECK: ORACLE goes back in ON power mode in which the flowmeters, valves and sensors are active to make a pressure sealing check.
- COMM: possible troubleshooting time interval if there are problems with the sealing. The final GO to the process is given.
- HEAT: heating phase. Possible COMM can be requested if the heating ramp cannot be followed.
- PROC: process phase.
- COOL: cooling phase.
- DATA: data collection (images, masses, etc.) and deliver to the platform.
- COMM: the data is sent to Earth for preliminary processing before the next repetition. The time is tuned according to the platform schedule.

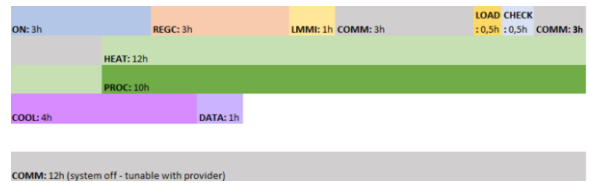


Fig. 4 – ORACLE ConOps

From the preliminary Concept of Operations, it is possible to estimate the power consumption associated with each step, shown in Fig. 5. The most demanding phases are the *heating* (light green) and *process* (dark green), that require overall about 140 W (including contingencies) for about 22 hours. This is due mainly to the power supplied to the CRB to make it reach the necessary temperature and maintain it for the process to take place (1100 °C). This data is fundamental for the selection of the platform since some of them might not guarantee the power supply for such long windows, since it also depends on other payloads’ needs.

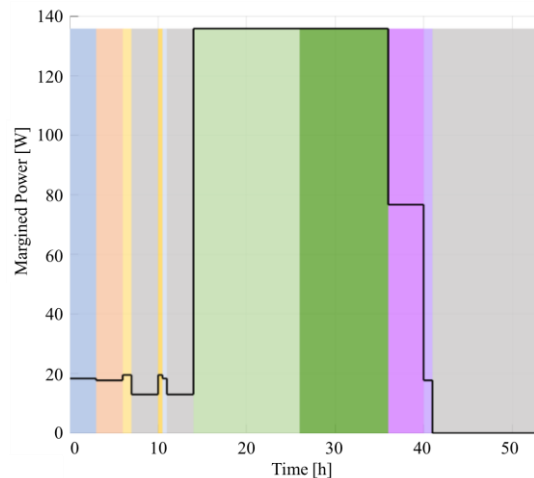


Fig. 5 – Margined power consumption during one repetition

4. Process optimization

The objective of the mission is to demonstrate the capability of extracting oxygen from lunar regolith on the Moon while achieving the highest possible yield of extraction. Currently, the process regulation parameters at each step (operative pressure and temperature, reactant gas flow rates, time alternation between washing and mixture phases, etc.) [8,9,10,13] are set according to preliminary test results and the related yield of extraction is considered as reference. However, minor adjustments on some parameters might be performed to maximize it. For this reason, some studies have already been started, including those that will evaluate how the composition of the regolith batch could affect the yield, to tune the operative conditions (temperature and pressure) in the reactors accordingly.

Among all the parameters, the time allocated to the process is one that affects the yield the most, since the longer the process is, the more oxygen is extracted from the batch. In ORACLE, the flux of methane is alternated to a flux of inert (H_2) to avoid coke deposition and “wash” the batch between two consecutive mixture phases. The current time allocated for the process is about 10 hours (to be discussed with the service provider) thus it is necessary to select the most proper washing/mixture alternation scheme to increase the oxygen extraction. In Fig. 6 the amount of H_2O extracted with different alternation schemes is shown.

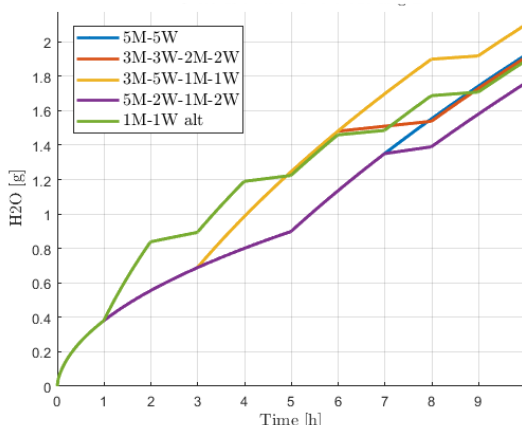


Fig. 6 – Amount of $H_2O_{(g)}$ produced with different mixture/washing alternation schemes.

From the results, it is evident that in the 10 hours frame, the alternation scheme “3M-5W-1M-1W” leads to the higher production of $H_2O_{(g)}$ thus this is currently considered the baseline for the process. Further adjustments could be made depending on the opportunity offered by the service provider.

5. Constraints for the platform

As discussed in previous sections, it is evident that the selection of the Launch and transfer service provider shall be made by evaluating several aspects. The

following lists of “mandatory” and “nice to have” requirements summarize the main constraints for the identification of the most suitable launch opportunity:

Mandatory

- MR 01. The platform shall allow the collection of regolith to be processed by ORACLE.
- MR 02. Proximity to the regolith collecting device if this will be part of the embarking platform or on ground/close to ground if the regolith collecting device will be part of the ORACLE.
- MR 03. The platform shall host ORACLE, whose expected volume envelope is $500 \times 500 \times 500 \text{ mm}^3$ [TBR], with proper clearances.
- MR 04. The platform shall host ORACLE, whose expected target mass is 15 kg
- MR 05. The CRB and WSU shall be accommodated on the embarking platform with a configuration that will prevent its direct exposure to the sun illumination.
- MR 06. ORACLE will discharge H_2 and CH_4 into the environment, thus no other payloads in the proximity can suffer from the presence of those exhaust gases.
- MR 07. The platform shall guarantee maximum the power supply needed to perform the process extraction as in Fig. 4.
- MR 08. ORACLE shall interface with the platform to exchange telemetries, telecommands and data with Earth through the platform. Communication slots shall be available before/after the loading procedure and at the conclusion of each test repetition.

Nice to have

- NTH 01. The service provider shall guarantee the presence of a regolith collecting device (e.g. a robotic arm) on the platform to feed ORACLE; it can be either a device integrated on the platform or a device from another payload onboard it.
- NTH 02. The regolith collecting device shall be equipped with a tool (e.g. sieve) to guarantee that regolith grains larger than 2 mm do not obstruct the reactor inlet.
- NTH 03. The regolith collecting system shall be equipped with a measurement sensor allowing a resolution of 5 grams (TBC)

Among the Mandatory Requirements, it is important to remark that MR 05 and MR 06 will have relevant impact on ORACLE accommodation on the platform: the former to avoid partial/total failure of nearby payloads, the latter to guarantee the operative conditions of the CRB and WSU. Also, MR 02 establishes the need of having the CRB inlet accessible for the regolith.

5.1 Regolith Collecting Unit

One of the main trade-offs to be solved prior to entering in phase B2 is the presence of the Regolith Collecting Unit (NTH 01) as part of ORACLE configuration. As shown in Fig. 6, different scenarios are considered for the accommodation of ORACLE depending on the availability of a robotic arm (or equivalent tool):

1. Regolith Collecting Unit is not part of ORACLE and is an external service as part of
 - a) Lander: it collects regolith in the proximity of landing site (plume impingement effect to be investigated)
 - b) Rover: it collects pristine regolith from different spots far from the landing site and brings it back to feed ORACLE (placed on lander, ground, etc.)
2. Regolith Collecting Unit is shared with other payloads needing the same service or performing complementary tasks (e. g. analysis of granulometry, composition, etc.), also beneficial for ORACLE tasks
3. Regolith Collecting Unit is integrated in ORACLE:
 - a) As a robotic arm developed in parallel to the main payload
 - b) As a drill/h Hoover such that ORACLE would be placed on the ground to collect the regolith.

Cases 1.b) and 2. are preferred: in the former scenario regolith not affected by plume impingement effects would be used, while in the latter preliminary analysis of the regolith batch could be performed to correlate with the extraction yield. Case 1.a) is accepted but some analyses should be performed to investigate how plume impingement effects could affect the extraction yield. Cases 3.a) and 3.b) are not desired since they would imply that a dedicated parallel development for a collecting device should be put in place, thus leading to possible impacts on the mass allocated to other units.

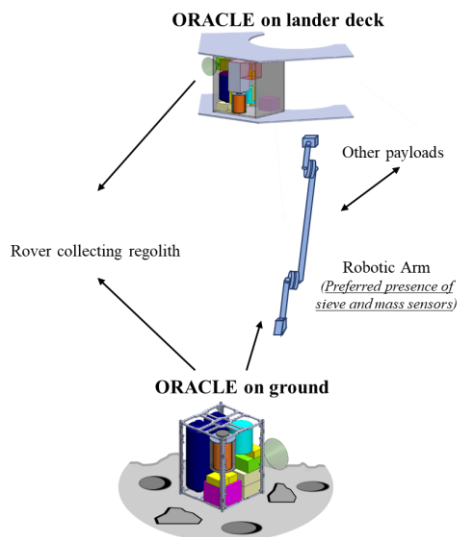


Fig. 6 – ORACLE accommodation

6. Conclusions

ORACLE is a technological demonstrator for ISRU aimed at extracting oxygen from lunar regolith through a carbothermal process. The project officially started in July 2023, with the collaboration between ASI and Politecnico di Milano, while an industrial partner will soon complete the ORACLE team. The demonstration of this ISRU capability on the lunar environment will mark an important achievement for the sustainable human exploration of the Solar System. The local production of water and oxygen without relying on supplies from Earth, could facilitate the long-term human presence on the Moon, as well as the production of propellants for rockets to explore the outer Solar System. The payload is currently foreseen to be ready for launch in 2028, when multiple opportunities should be available among those offered by partnership with other space agencies as well as commercial providers involved in NASA's missions (CLPS, LIFT-1), that are paving the way for the robotic exploration of the Moon in support to the Artemis program.

Acknowledgements

This work is developed in the framework of the Agreement between ASI and Politecnico di Milano "ASI-PoliMi n. 2023-11-HH.0".

References

List of references

- [1] "In-Situ Resource Utilization Gap Assessment Report", [Online]. Available : <https://www.globalspaceexploration.org/wordpress/wp-content/uploads/2021/04/ISECG-ISRU-Technology-Gap-Assessment-Report-Apr-2021.pdf>
- [2] M. Hecht, J. Hoffman, D. Rapp, J. McClean, J. SooHoo, R. Schaefer, A. Aboobaker, J. Mellstrom, J. Hartvigsen, F. Meyen, E. Hinterman, G. Voecks, A. Liu, M. Nasr, J. Lewis, J. Johnson, C. Guernsey, J. Swoboda, C. Eckert, C. Alcalde, M. Poirier, P. Khopkar, S. Elangovan, M. Madsen, P. Smith, C. Graves, G. Sanders, K. Araghi, M. de la Torre Juarez, D. Larsen, J. Agui, A. Burns, K. Lackner, R. Nielsen, T. Pike, B. Tata, K. Wilson, T. Brown, T. Disarro, R. Morris, R. Schaefer, R. Steinkraus, R. Surampudi, T. Werne, and A. Ponce. "Mars Oxygen ISRU Experiment (MOXIE)", Space Sci. Rev., 217:1–76, 2 2021
- [3] "Lunar Infrastructure Foundational Technologies", [Online] Available : <https://www.nasa.gov/general/stmd-lift-1-industry-day/>

- [4] “Commercial Lunar Payload Services Overview”, [Online] Available: <https://www.nasa.gov/commercial-lunar-payload-services-overview>.
- [5] L. Schlüter e A. Cowley, “Review of techniques for In-Situ oxygen extraction on the moon”, Planetary and Space Science, 2020.
- [6] I. A. Crawford, “Lunar Resources: A Review”, Progress in Physical Geography, pp. 137-167, 2015.
- [7] I. Troisi, P. Lunghi e M. Lavagna, “Oxygen extraction from lunar dry regolith: Thermodynamic numerical characterization of the carbothermal reduction”, Acta Astronautica, pp. 113-124, 2022.
- [8] J. Prinetto, A. Colagrossi, A. Dottori, I. Troisi e M. Lavagna, “Terrestrial demonstrator for a low-temperature carbothermal reduction process on lunar regolith simulant: Design and AIV activities” Planetary and Space Science, 2023.
- [9] A. Dottori, I. Troisi, M. R. Lavagna, S. Pirrotta e F. Latini, “Lunar pilot plant payload design toward in situ demonstration of oxygen extraction by carbothermal reduction”, in Aerospace Europe Conference2023 - 10th EUCASS - 9th CEAS, Lausanne, Switzerland, 2023.
- [10] F. Latini, S. Pirrotta, R. Mugnuolo, M. R. Lavagna, A. Dottori, I. Troisi, “The ORACLE ISRU Demonstrator Payload for Oxygen Extraction on the Moon”, in IAC, 74th International Astronautical Congress, Baku, Azerbaijan, 2-6 October 2023.
- [11] L. A. Taylor, C. M. Pieters e D. Britt, “Evaluation of luna regolith simulants” Planetary and Space Science, vol. 126, 2016.
- [12] ECSS-M-ST-10C_Rev.1(6March2009)
- [13] I. Troisi, A. Dottori, M. R. Lavagna, F. Latini, S. Pirrotta, R. Mugnuolo, “Advancements in Lunar Resources Utilization for Oxygen Extraction: Analysis and Design of the ORACLE Payload” in IAC, 75th International Astronautical Congress, Milan, Italy, 14-18 October 2024.