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LUXEMBOURG
SPACE RESOURCES
WEEK 2022

Book of Abstracts

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Thursday
May 5TH

Session 1
Research

Chair: Beth Lomax and David Karl

- A Knowledge Sharing Platform for Space Resources
- Beneficiation of Lunar Regolith for Resource Characterisation and Optimisation of Regolith-handling Processes
- Extracting Silica from Lunar and Martian Regolith for Complex Materials and Systems Development
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- Proposal of a Mars Clay House: Material extrusion AM with advanced clay simulants for habitat structures on Mars
- Regolith-based composite manufacturing by Fused Deposition Modelling (FDM)
- Progress in building an additive manufacturing system for printing molten lunar regolith
- Mars in situ oxygen and propellant production by plasmas technology
- Near-Earth Object Resource Utilization

A Knowledge Sharing Platform for Space Resources

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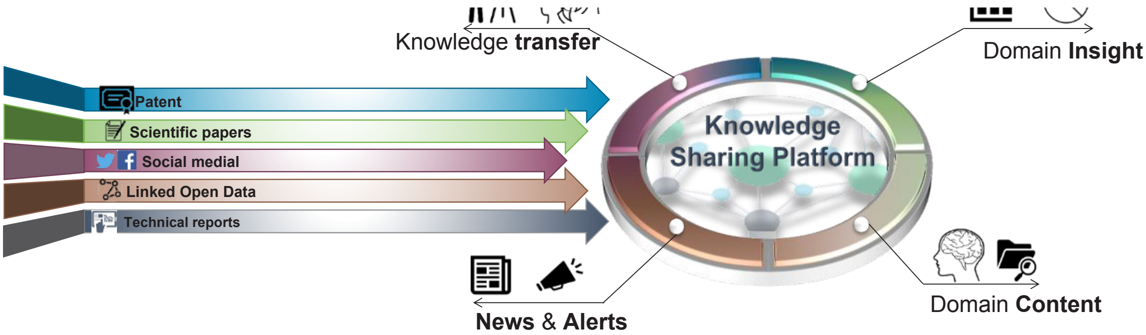
Introduction

The growing interest for space resources generates a vast and dynamic amount of heterogeneous data, information, and knowledge. These are contained in scientific publications, patents, reports, and even news regularly published on the Web. However, the distributed nature of the Web and the velocity of the published documents makes the collection and exploitation of these information difficult for the space resources community which limits the long-term development of activities in the areas of legislation, business, and scientific research.

To overcome this limitation, we have developed a knowledge sharing platform for space resources (see Figure 1).

Figure 1: Knowledge Sharing Platform



The proposed platform, aiming to become the centric point for the community, is designed based on Semantic Web technologies [1] and is able to:

1. Analyse and extract relevant content from documents using natural language processing techniques and a dedicated ontology called SROnto [2] that represents core knowledge of the space resources domain. SROnto has been developed based on existing standard ontologies like BFO [3] in a collaborative manner between domain experts and knowledge engineers and will be regularly updated with new concepts and relationship reflecting the evolution of the space resources domain.
2. Formalize the extracted information into a knowledge graph which is made available to the community via an intuitive user interface and a set of advanced software services able to exploit the properties of the knowledge graph.

We are convinced that this platform will enable the delivery of game-changing business applications and pioneering mission-driven research as well as harnessing private and public synergies.

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Beneficiation of Lunar Regolith for Resource Characterisation and Optimisation of Regolith-handling Processes

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Developing technologies to extract, handle, process and use resources in space presents a unique challenge that integrates many different scientific disciplines and industry sectors. The experience and knowledge of terrestrial and space sectors must be brought together to produce usable commodities reliably, efficiently, and safely from local resources. New technologies, adaptations of existing terrestrial technologies and novel approaches to production flowsheets will be required.

Numerous excavation and reduction processes have been proposed in the literature for metal and oxygen production from lunar regolith. Each process will have different feedstock requirements, although this has not yet been well-defined for any given process. Control of feedstock properties, including particle size and mineral type can be achieved by beneficiation. This intermediate stage of the space resource utilisation (SRU) flowsheet has received relatively little research attention compared to other processes in the lunar oxygen production flowsheet.

The separation of regolith by size and particle type on the Moon presents challenges due to the high fraction of fine particles, the range of different components (glasses, mineral fragments, agglutinates) and the environmental constraints. On Earth, most mineral separations are carried out using water as carrier fluid. A different approach is required for lunar SRU. At Imperial College London, we have focused our efforts on addressing these research and technology gaps, from improving the fundamental understanding of particle contact charging to designing classification and separation techniques suitable for use with lunar regolith.

Electrostatic separation of minerals presents challenges on Earth due to its sensitivity to environmental factors, such as temperature and humidity. On the Moon, however, favourable conditions exist for electrostatic separation of lunar regolith to concentrate specific mineral components such as ilmenite. Our research has focused on understanding and modelling from fundamentals the tribocharging (contact charging) of particles of different size and material type under different environmental conditions. We have used DEM simulations to optimise the design of a tribocharger to control the contact charging of particles in order to improve separation of minerals in a freefall separator, a technology that is suitable for lunar conditions. We have developed simulations of electrostatic conveyance methods (i.e. the electrostatic travelling wave) to assist in the design of novel size classification technologies. In addition to electrostatic size classification, we have worked extensively on vibrational methods for size classification, both on regolith simulants and Apollo 15 samples. Finally, we are developing innovative visualisations of a lunar oxygen production operation, considering different beneficiation scenarios.

In this presentation, we will describe our group's recent work in these fields from particle to system scale. We will demonstrate the criticality of beneficiation for both characterisation and operation, showing the key challenges and research gaps in this field.

Extracting Silica from Lunar and Martian Regolith for Complex Materials and Systems Development

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Moon and Mars are considered to be the first places for extra-terrestrial exploration and establishing human settlements. However, transporting all the materials needed to build-up first outposts on Moon or Mars will be very expensive. Therefore, utilization of materials available on their surface is of high importance. Nowadays, the In-Situ Resource Utilization (ISRU) concept draws much attention as a practical approach to reduce the costs of settling-up Lunar or Martian bases. The ISRU concept bases on utilizing locally available resources in designing functional materials and systems. Most of the current work is focused on using the powdery regolith, which is abundant on Moon and Mars surface, as a component of building materials, like various types of concretes. One of the main mineral ingredients of the regolith is sillicate made of silicon and oxygen elements. In an alkaline environment an amorphous silica can be extracted from this silicate. This extracted silica can be used in the following applications: 1. Aerogels which possess very low mass and high thermal insulation properties; 2. Glass, glass fibers and ceramics; 3. Adsorbents and filters; 4. Reinforced composite materials; 5. Optic fibers for fast information transmission; 6. Agricultural fertilizers reinforcing plant cell walls. Moreover, chemically pure silica is a perfect substrate for elemental silicon that is a main active component of semiconductors used in solar panels and transistors.

This work aims to develop an efficient alkaline extraction technique to produce high purity silica from Lunar and Martian regolith. The silica properties and morphology can be controlled during its precipitation in an aqueous environment. The silica characteristic will be investigated by its specific surface area and surface energy, its purity, particle size distribution and morphology using SEM and TEM. These characterization enables to judge how suitable the produced silica will be for the before mentioned applications which requires different characteristics of the silica.

Acknowledgments

This project is financed by EU Marie Skłodowska Curie Action: Global Fellowship. Grant No. 101025756

Bioinspired Lunar Phosphorus Leaching for Circular Space Crop Growth

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Introduction

With the world population explosion, the demand for phosphorus (P) is increasing due to the high demand for food production. Food-related phosphates account for 50–60% of the total global P supply. The aim of this presentation is to explore the process design of a circular bioprocess [1] for extraterrestrial nutrient supply [2], and to evaluate through experimental results its sustainability and circularity by metrics.

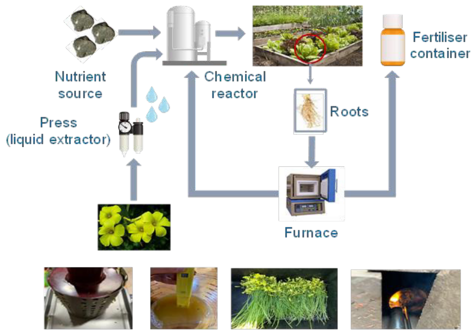

Figure 1: Circular lunar P

Results and Discussion

This presentation will propose a biobased value-chain for a lunar mineral-crop processing symbiosis [3], using moon-crust phosphorus, and the process design is strictly guided by sustainability and circularity [1] We propose a biosink process for phosphate autoaccumulation, in order to overcome the productivity bottleneck of P leaching (Figure 1). Sink methods are known to build up a huge concentration gradient and allow minerals leaching at a high soil-solution ratio. Especially, the Iron oxide impregnated filter paper (Fe-oxide Pi) and Cation and anion exchange membranes (CAEM) have inspired our experiments [1]. Green plants will be taken for this 'silent' accumulation of the phosphorus. Lettuce is the current favorite, as it is known to accumulate high P loads in its roots. The roots will are burned, to take P from the ash (Figure 1).

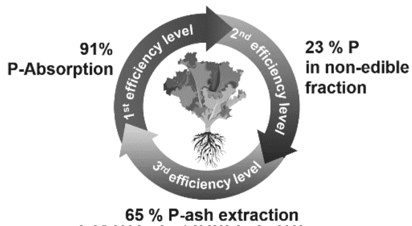

Figure 2: Space P life cycle with three P

The presentation will give a spillover between Earth problem and space solution to stimulate anticipatory technology development. We reviewed 16 different methods of phosphorus leaching, including extraction, reactive extraction and ion-sink extraction, which have their pros and cons [1]. The simplest and most sustainable approaches are Water-, CaCl2- or LiCl Extraction. Yet, we use renewable oxalic acid from sour sobs as green leachant. Our lunar phosphorus production target is: 1 min; solid-solution ratio 1:5; 1000 mg P/kg soil.

Our non-optimized phosphorus uptake efficiencies, experimentally determined (Figure 2), are as follows: 91% as from P-nutrient reservoir to lettuce; 23% P storage in non-edible lettuce roots (rest in edible leaves), 65% microfluidic P-extraction from lettuce roots' potash. With those results, we calculate circularity transition indicators on recycling / recovery, foremost the mass circularity indicator (MCI), recommended by the Ellen MacArthur Foundation, and we compare it to similar bioprocesses that have been postulated as 'Mars biomanufactories' (Table 1).

	Industrial P-mining	Ash-based P-biomining [a]	Comparative space methodologies Anaerobic digestion	 Bioplastic synthesis [c]
Recycling fraction	0.09	0.65	0.16[b]	0.17
Recycling efficiency	0.1	0.46	0.61	0.20
Unrecoverable Waste kg.kg^{-1}	17.7	0.013	6.57	20.6
Waste to landfill kg.kg^{-1}	11.4	0.0065	3.62	0.44
Linear flow index	0.86	0.45	0.46	0.50
Material circular indicator (MCI)	0.22	0.59	0.58	0.55

(a) considering the extractable fraction per kg of ash roots. (b) considering the main biomass fraction is digested. (c) considering only 20% of culture medium is recycled.

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Pyrite from detection to a solar cell – ISRU on the Moon

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Sustainable living on the Moon will require using as many locally available resources as possible. One of the most important issues in establishing a lunar outpost will be the availability of energy sources. Solar panels belong to the most promising options because some areas around the lunar South Pole are constantly illuminated by sunlight. Instead of bringing the solar panels from Earth, it would be more perspective to find a way to produce them *in-situ* on the Moon. The lunar regolith holds several iron-bearing minerals [1] and we have identified pyrite FeS_2 as one possible candidate for a "lunar solar cell" material. Pyrite has all the necessary electrical and optical properties [2] to be a good solar cell material. We propose to use pyrite in microcrystal form in a monograin layer (MGL) solar cell. The MGL solar cell has a superstrate structure: back contact/absorber/buffer/TCO/transparent substrate (Fig. 1). The absorber is a monolayer of semiconductor pyrite crystals of nearly uniform size, with a typical diameter of 50 µm, which are embedded into a layer of epoxy and covered with buffer and window layers.

Other relevant minerals for solar cell fabrication are troilite, which can produce pyrite in combination with sulphur, and ilmenite, which is a source for Fe and TiO_2 that could work as buffer layer in pyrite solar cell. In-orbit spectrometers available today are not sufficient for searching ore mineralization but the aforementioned minerals can be detected by a novel instrument developed in the Polish Academy of Sciences – Multiplanetary far-IR Ore Spectrometer (MIRORES) in cooperation with the space industry (SKA Polska and European Space Foundation), which operates in a wavelength range of 21–30 µm. For example, pyrite could be detected from the orbit in the far-IR range (band centre at 24.3 µm) if its abundance exceeds 10% [4]. Such abundances are common on Earth, where lenses of massive pyrite ores may reach 500 m in length [4]. Therefore, MIRORES can detect orebodies and possibly their stockworks providing valuable information on the allocation of resources for energy production.

Through this alliance, we are ready to present almost the full cycle of resource utilization (Fig. 2) from detecting pyrite (FeS_2) or troilite (FeS) from the lunar regolith to MGL solar cell fabrication. This value chain has potential not only for the Moon but also for commercialization and technology transfer to Earth applications.

Fig. 1. MGL solar cell

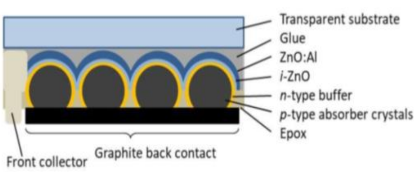
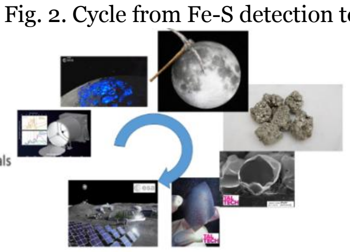


Fig. 2. Cycle from Fe-S detection to solar cell



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Synergetic Material Utilization – ISRU developments at the DLR Institute of Space Systems

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Introduction

Our solar system is full of resources that potentially can be exploited to greatly reduce the material re-quired to be launched from Earth. Among these resources are water ice, hydrates, metals, regolith, rare earths, chemical compounds, volatiles and rare isotopes. Utilizing space resources would enable e.g. propellant production, in-space manufacturing or the construction of large structures which would otherwise be very expensive or not possible at all with material launched from Earth. The 2021-founded research group 'Synergetic Material Utilization' (SMU) at the DLR Institute of Space Systems develops technologies to utilize these resources and also investigates synergies between ISRU and environmental control an life support systems (ECLSS).

Research Activities

Concrete activities of the SMU research group for the next 3-4 years are technology developments for regolith beneficiation, water extraction and purification for in-situ propellant and consumables production. These developments are complemented by a system study for a shared water-hydrogen-oxygen infrastructure with ISRU and ECLSS elements for a future habitat. Table 1 gives an overview of the activities. Focus lies on the development and execution of laboratory experiments. A test setup is already built-up for lunar regolith beneficiation and experiments with regolith simulants are about to start in 2022. The water extraction experiment setup is in an advanced planning stage with manufacturing of first parts already planned. Experiments to develop a lunar raw water simulant, which means water mixed with pollutants expected on the Moon, are ongoing. There the goal is to use this simulant to test water purification techniques to treat water extracted from the lunar surface. Furthermore, a model is in development to simulate a shared H2O-H2-O2 infrastructure for a future habitat, which includes ISRU and ECLSS technologies.

Table 1: Summary of the research activities of DLR's Synergetic Material Utilization research group.

Regolith Beneficiation and Utilization	**In-Situ Propellant and Consumables Production**	**Shared ISRU-ECLSS Infrastructures**
• Focus: separation of regolith constituents for further processing • Method: Development of an experiment setup to enrich ilmenite content in the feedstock • Goal: Increase concentration from ~4-6 % to >50 % to improve efficiency of oxygen extraction	• Focus: water extraction and purification • Method: Development of a test setup for water extraction processes • Method: Combined water treatment for life support and ISRU • Goal: Demonstrate water extraction for propellant and consumables production	• Focus: shared H_2O-H_2-O_2 infrastructure • Method: System analysis and modelling of an infrastructure including water treatment, electrolysis, gas liquefaction, storage • Goal: Conceptualize and simulate a shared ISRU-ECLSS infrastructure

Catalytic Conversion of Resources on Mars

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The exploitation of Martian resources will be necessary for human exploration and colonisation of the planet. Hydrocarbons are potential propellants as well as feedstock chemicals for use on Mars. Specifically, methane can be used as rocket fuel while methanol is an energy resource for fuel cells as well as a building block for secondary products. In this work, we investigate the potential for converting carbon dioxide in the atmosphere into hydrocarbons using Martian surface materials as catalysts. In addition, we will identify the minimum amount of additional resources that need to be transported to the planet. Non-thermal plasma (NTP) CO2 hydrogenation was carried out in a dielectric barrier discharge (DBD) reactor to assess the activity of Mars-abundant materials and understand how conditions might be optimized for the production of fuel in the Martian environment.

Using montmorillonite (MMT) clay, thought to be abundant in regions on the surface of Mars, and silicon oxide and aluminium oxide, common constituents of rock-forming minerals, a series of Ni-based catalysts were prepared using wet impregnation a simple, convenient and conventional method for loading metals onto supports, such as clays and zeolites.[1] The catalyst was packed in the discharge zone of a DBD reactor and treated in situ with pure H_2 at 6 kV and 20.8 kHz to ensure the full reduction of the metal. The gas feed was switched to a mixture of CO2 and H2 (1:4 ratio) and the applied voltage varied between 5.5 - 7 kV keeping the frequency constant at 20.8 kHz. The products were analysed using an on-line gas chromatograph.

To optimise the reaction, the Ni/SiO2 catalyst was tested for CO2 hydrogenation giving a high conversion to carbon monoxide and methane. Furthermore, a series of Ni/MMT catalysts were tested with conversions up to 85% and high selectivity towards methane at the maximum voltage. The early studies of the project have shown that NTP CO_2 hydrogenation is a promising technique for converting CO_2 into methane. Future work will include the use of two Mars-simulant samples (MGS-1 and MGS-1C Clay) and Mars-abundant oxides as supports in the catalyst preparation to further assess the activity of the Martian soil for in-situ resource utilisation.[2]

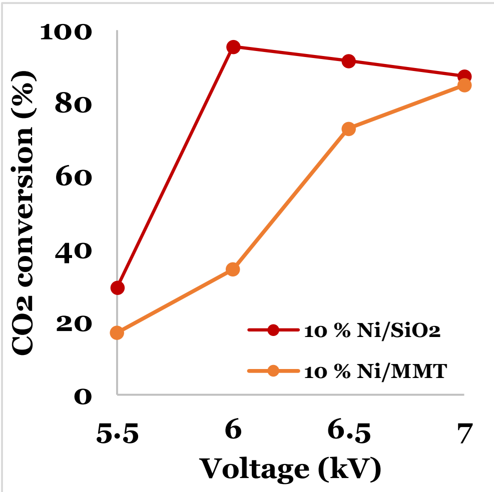

Figure 1: CO_2 conversion (%) as a function of voltage using two Ni-based catalysts.

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Anode technology for the ROXY process – an economical high-purity oxygen and metal production process for lunar ISRU and terrestrial applications

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Introduction

Efficient in situ resource utilization (ISRU) on extra-terrestrial bodies is key to reduce the cost and complexity of prospective explorations of the Solar System. High-purity oxygen and metals, e.g. for construction and radiation shielding, are two of the high priority resources needed for this task. To achieve economic viability, the mass of in situ produced materials must exceed the mass of any consumables and spares used to sustain the production process. The ROXY process (Regolith to Oxygen Conversation), an essential part of the MEFAM campaign (Metal Factory on the Moon), is an innovative fused-salt electrolysis process for the reduction of most oxide constituents of lunar regolith and other extra-terrestrial soils [1]. The design of the process setup enables a compact, simple and robust system that maximizes efficiency and minimizes the need for maintenance and sub-systems. A key element of the ROXY process is the unique, patented anode technology. Featuring a highly selective solid oxide membrane (SOM) and special current collectors, the design allows for direct production of high-purity oxygen without the need for a gas separation sub-system. Another key benefit is the elimination of parasitic electronic currents from the cathode to the anode. Consequently, higher voltages and current densities are possible, increasing the energy efficiency of the process. The ROXY anode design also prevents outgassing of oxygen from the electrolyte, protecting the produced metals, the electrodes and the reaction chamber from corrosion and unwanted side reactions with oxygen. The anode technology can be implemented in a variety of designs, enabling operation at different process temperatures as well as electrode arrays and reactor setups optimized for mass or oxygen production rate. In combination with other key elements of the ROXY process, this permits a high current efficacy and complete regolith reduction, with the metal product being directly suited as starting material for downstream manufacturing processes (e. g. additive manufacturing) or as energy carrier for a metal combustion process. With its design aimed at minimum need for maintenance, maximum robustness and zero emissions, the ROXY process is also of high interest for green and sustainable metal production on earth.

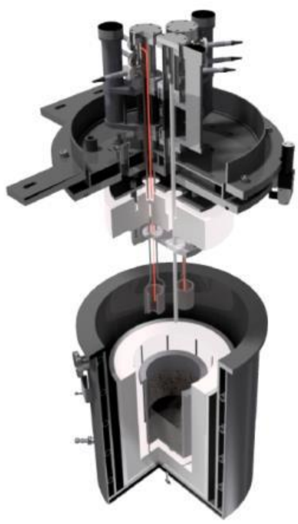

Figure 1: ROXY Lab Model

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Producing oxygen and fertiliser with the Martian atmosphere using microwave plasma

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This work aims to highlight the potential of microwave (MW) plasma technology for in-situ resource utilisation (ISRU) on Mars. In particular, besides CO_2 conversion into CO and O_2 [1], we also show the novel possibility for N_2 fixation [2], the most energy-intensive aspect of fertiliser production and therefore, a key requirement for nourishing any potential future Martian settlers. Plasma conversion in a simulant atmosphere (i.e., 96/2/2 % $CO_2/N_2/Ar$), performed under energy conditions similar to the Mars oxygen in-situ experiment (MOXIE) currently on-board NASA's Perseverance rover, demonstrates that O/O_2 formed through CO_2 dissociation facilitates the fixation of the N_2 fraction via oxidation to NO_x. Promising production rates for O_2, CO and NO_x of 47.0, 76.1 and 1.25 g/h (as shown in **figure 1**), respectively, are recorded with corresponding energy costs of 0.021, 0.013 and 0.79 kWh/g. Notably, the O_2 production rates are considerably higher than those currently demonstrated by MOXIE (~30 times), while the NO_x production rate represents a ~7% fixation of the N_2 fraction present in the Martian atmosphere. MW plasma-based conversion therefore shows great potential as an ISRU technology on Mars, which can simultaneously enable N_2 fixation and O_2 production using the local atmosphere. Future progress will need to capitalise on the promising metrics demonstrated here, by coupling the plasma conversion process with efficient gas separation technologies downstream, in order to generate the purified chemical streams, needed for utilisation as fertiliser, life support and fuel during future robotic, or indeed, human exploration of the red planet.

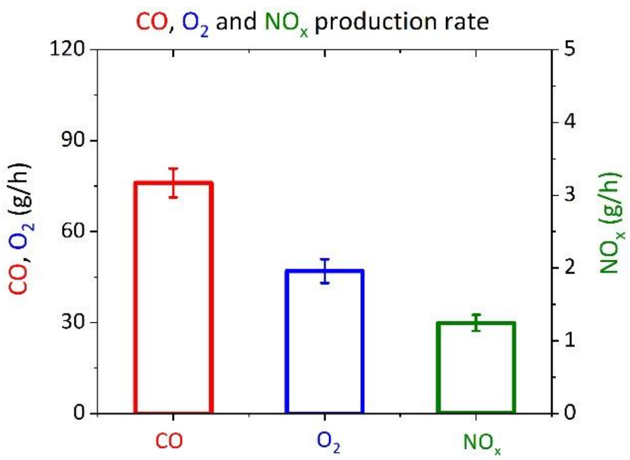

Figure 1: Absolute production rates (g/h) of CO, O_2 and NO_x in a MW plasma using a Martian simulant mixture of $CO_2/N_2/Ar$ (96/2/2 %) at 10 L/min flow rate, 0.34 bar pressure and 1 kW absorbed power. Note: NO_x data is indicated on the right-hand y-axis.

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Progress understanding lunar oxygen extraction using vacuum solar pyrolysis

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Abstract

Technologies for production and utilisation of space resources are still in the early phase of development. The constraints of the space environment in terms of energy available are what greatly tempers ambitions of large-scale resource extraction plans. Oxygen is a particularly interesting resource for both life-support and as propellant. Additionally, construction materials such as metals will be needed for off-Earth construction and manufacturing. The lunar regolith has the potential of providing both resources. Many extraction processes exist and are currently being actively researched and developed [1]. Yet, the vacuum pyrolysis using solar concentration has been understudied compared to other techniques even though it offers a simple physical process with relative low energy consumption as the sun provides requisite thermal energy.

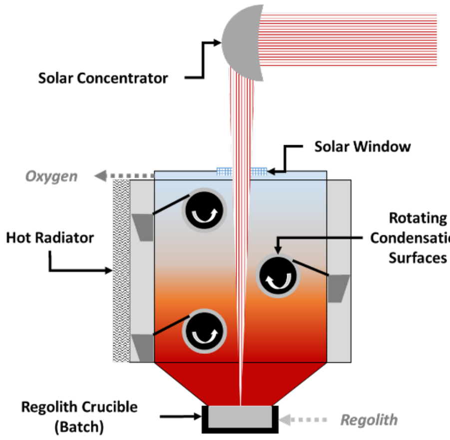

Figure 1: Vacuum Pyrolysis System Design

The vacuum pyrolysis process is relatively straight-forward. At high-temperature, even metal oxides evaporate and dissociate into suboxides, metal and oxygen. The separation of oxygen from the solid or liquid phase happens in the gas phase by immediate condensation on a cooled surface after evaporation to prevent exothermal recombination of oxygen. The oxygen gas is then collected for storage and the slag is left on the condensation plates. A number of designs have been studied [2].

In practice, there are significant challenges and knowledge gaps that need to be solved before this technology can be used [3]. Unlike other extraction processes, vacuum pressure allows for lower processing temperatures compared to other extraction techniques. But dealing with regolith vapor poses additional constraints regarding concentrated heat, condensation on walls and solar window. In this presentation we provide an update on the ongoing research into the vacuum pyrolysis process at CNES and EAC, both on the system design (Fig. 1) and on the process conditions.

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Electrochemical extraction of resources on the Moon using molten salts

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Molten salt electrolysis (also known as the FFC or the Metalysis process) is a promising method for extracting oxygen and useful metals from lunar regolith at any location on the lunar surface. Among other things, the composition of the regolith material and lunar environment are unique to this application. While we can learn a lot from the terrestrial processing of oxides to extract metals, research is required to better understand how processes behave with complex and heterogenous powdered regolith and in altered gravity environments.

Research ongoing at the European Space Research and Technology Centre (ESTEC) aims to better understand how the rate of regolith reduction via molten salt electrolysis changes over time, and to improve the overall efficiency. While a certain level of reduction may be the most efficient in terms of oxygen output, other factors also need to be considered.

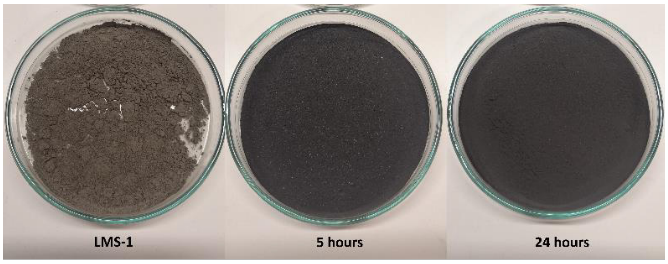

Figure 1: Regolith simulant before and after 5 and 24 hours of reduction using molten salt electrolysis.

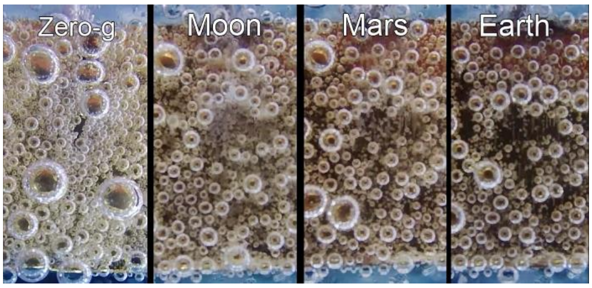

Figure 2: Electrolytic bubble behaviour under different gravity levels.

On the Moon the gravity is $1/6^{th}$ of the gravity on Earth. Gravity impacts many physio-chemical processes, including the gas-solid-liquid interactions of bubbles on an electrode surface. This presentation will also briefly outline the fundamental impact gravity has on bubble behaviour and electrolysis efficiency [1], the potential impact this may have on resource extraction on the lunar surface, and how systems can be designed and tested with this in mind.

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Chemical extraction of oxygen from lunar simulants using microwaves

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Introduction

Oxygen has been extracted from molten lunar simulants using laser energy (simulating solar radiation) [1]. Microwave energy has been proposed as a heat source to sinter or melt lunar regolith for use in additive manufacturing because microwaves couple efficiently with lunar regolith [2]. Here we describe preliminary experiments to extract oxygen using hydrogen reduction and carbothermal reactions [3] from the molten lunar regolith using microwave energy.

Method

50 g samples of JSC-1A were loaded into alumina crucibles and dried in a vacuum oven at 230 °C for at least 48 hours. Ilmenite was then mixed with the sample before placing in the cavity of a Microwave Heating Unit (MHU). The MHU can supply 1 kW 2.45 GHz microwaves to the cavity which can be evacuated to a pressure below 1 x 10^{-5} mbar. The cavity was then filled with 100 mbar of the reactant gas and the MHU switched on at 1kW power until the sample was observed to melt. Throughout the experiment, the pressure was monitored, and the mass spectrometer measured the gas composition, scanning from 2 to 99 u at a rate of 0.5 u/s.

Hydrogen reduction

Samples were doped with from 0 to 8.0 g of ilmenite. Mass spectrometer profiles of hydrogen and water for a typical experiment are shown in Figure 1a. Initially the pressure of hydrogen increases as the gas is heated, then suddenly decreases in several steps. The water concentration was observed to increase during the reduction, but the amount was not quantifiable because of the high background pressure and water condenses on cold regions of the vacuum manifold. Up to 0.27 g of oxygen was extracted, calculated from the loss of hydrogen.

Carbothermal reactions

Ilmenite was not added to the sample. Mass spectrometer profiles of methane, hydrogen and carbon monoxide for the experiment are shown in Figure 1b. The pressure increased rapidly just before the sample melted as the methane was converted to carbon monoxide and hydrogen. 0.3 g of oxygen was liberated from the sample, limited by the depletion of methane.

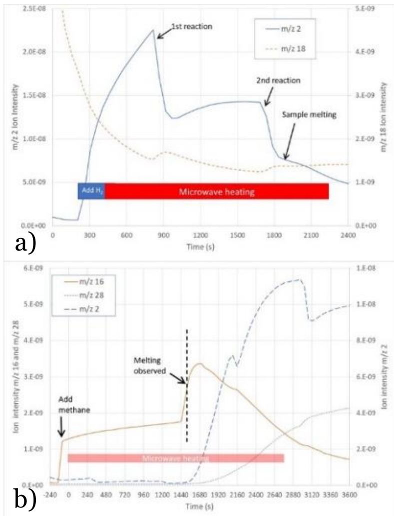

Figure 1: Mass spectrometer profiles a) m/z 2 and m/z 3 during hydrogen reduction of 50 g JSC-1A sample doped with 4 g of ilmenite. b) m/z 2, 16 and 28 during carbothermal reaction of 50 g JSC-1A

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Increasing Oxygen Extraction from Lunar Regolith via the Metalysis FFC Process

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Introduction

This program of work has built on the initial proof of concept study conducted by B. Lomax et al. in 2019, where the authors demonstrated the ability of the process to extract both oxygen and mixed metal alloys from lunar regolith simulant. The activity has further progressed and optimised the technology by testing several key parameters and their effects on the process, significantly increasing oxygen production output.

The main areas of development included a rigorous redesign of the reactor system itself, followed by investigations into: the form and type of regolith introduced into the reactor, temperature, power type, anodic current density and CaO concentration in the salt.

Careful materials selection and reactor design has enabled capture of previously lost product oxygen reported by Lomax et al. via reaction with materials of construction, meaning higher oxygen rates and yields were measured via mass spectrometer in this activity. Fine-tuning of the electrolysis parameters have also increased the benchmark oxygen production rates and total oxygen liberated. The plots to the right show the previous oxygen removal baseline (B. Lomax et al 2019 utilising 30g feedstock regolith), and the new baselines set within this activity, for both 24g and 48g of regolith feedstock. Under the conditions tested in 2019, oxygen rate peaked at **~0.15g/hr** and total yield at **~36% (Fig. 1)**. For this activity utilising 24g feedstock, these values peaked at ~**0.45g/hr** and **60% (Fig. 2)**, and for **48g** feedstock, these peaked at **~0.9g/hr** and **~90% (Fig. 3)** respectively.

This activity has led to a deeper understanding of the process using regolith as the feedstock material, enabling significant increases in oxygen production rate and yield. It has also highlighted the capability and flexibility of the process under different operating conditions as well as the associated challenges that must be overcome if this is to be taken to the lunar surface.

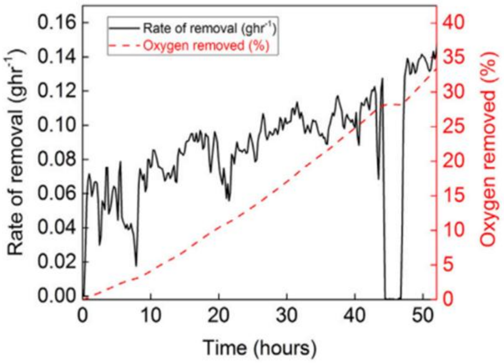

Figure 1 - Previous baseline – 30g regolith (B. Lomax et al 2019)

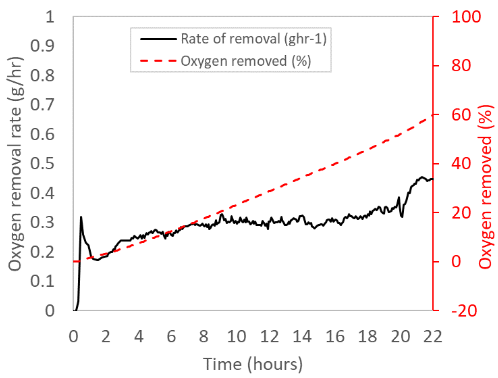

Figure 2 - New baseline – 24g regolith (2021)

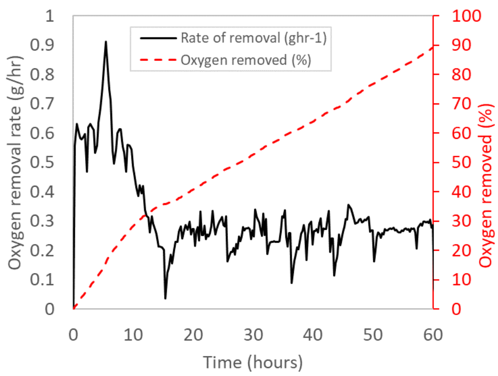

Figure 1 - New baseline - 48g regolith (2021)

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Lunar Oxygen Production with a Fluidized Bed Powered by Concentrated Solar Radiation

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Lunar Oxygen

The in-situ production of resources on the Moon could significantly reduce the amount of mass needed to be launched from Earth. The most needed and abundant resource on the Moon is oxygen. One problem is that oxygen release requires high temperatures due to the strong chemical bonds in the minerals. The process with the most benign operating conditions is hydrogen reduction of ilmenite (1) and subsequent water electrolysis (2):

(1): $FeTiO_3 + H_2 \Rightarrow Fe + TiO_2 + H_2O$

(2): $H_2O \Rightarrow H_2 + \frac{1}{2}O_2$

Fluidized Bed

A chemical reactor for reaction (1) must work in continuous mode, be able to heat and process large amounts of lunar regolith, and offer the solids a long residence time and a good mixture with the gaseous reactant. All these conditions can be satisfied by a low expansion fluidized bed reactor. Fluidization is the operation by which solid particles are transformed into a fluid like state through suspension in a gas.

Solar Thermal Reactor

The Plataforma Solar de Almería (PSA) is a public research center for concentrated solar power in Spain. A fluidized bed reactor powered by concentrated solar radiation was developed, assembled and tested for the hydrogen reduction of ilmenite. The goal was to build a full scale reactor to carry out tests on Earth, coming up with as many solutions as possible for the challenges it could face on the Moon.

The center-piece of the reactor is a fluidized bed with capacity for 22kg of lunar regolith. Feeding and removal of the solids is done in continuous mode by auxiliary fluidized pipes. The concentrated solar power enters the reactor vertically through a quartz window on the top, directly heating the particles. Special attention was given to the off-gas treatment. This includes cooling, hot gas cleaning from remaining fines, and efficient separation of the desired product water from the gas stream.

System Testing

All goals were successfully achieved: Identification of the gas flow demand of the main fluidized bed in the reactor as a function of temperature, reactor operation at 800-1000 °C solely heated with concentrated solar power, and demonstration of water production from the reaction of ilmenite with hydrogen. Further goals like the demonstration and control of the continuous particle feed/removal from the reactor, or the off-gas treatment, were also accomplished.

Presentation

The presentation will provide an overview of the system's design and the testing results with a special emphasis on details that could be of interest for regolith processing beyond hydrogen reduction, like concentrated solar power, particles handling, and chemistry.

Adaptive Density Minimal Surfaces: New Method for Multi-functional Load-bearing Radiation Shielding for 3D-printed Moon/Mars Habitats.

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About Adaptive Density Minimal Surfaces (ADMS)

ADMS are an infinite family of freely configurable, aperiodic Minimal Surfaces discovered by the authors, and subsequently implemented as to allow for the autonomous design of versatile additively manufactured components. Any configured ADMS fulfills a multitude of requirements while providing maximal strenght at minimal material usage and the fastest, most energy-efficient printing. Support-free, no post-processing.

Fig. 1: ADMS with density gradient.

Properties of ADMS include: adaptability to any enveloping geometry and to multi-physics boundary conditions (fig. 1), efficient diffusion of stress (fig. 2), avoidance of stress concentrations, controllabe elasticity, no catastrophic failure modes, containment of local failure, support-free printing in any AM process, print paths without self-intersections. ADMS consist of two interleaved, continuous labyrinths (no enclosed spaces), have excellent heat exchanger characteristics, and can be made open-pored or closed (in order to store one substance or two).

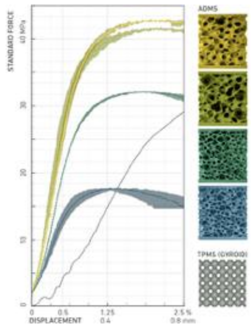

Fig. 2: stress/strain correlation of mass-equiv. Gyroid and ADMS structures.

Subjects currently studied include a lightweight aluminium satellite interface bracket (ESA OSIP Study), internally cooled injection moulds, structural heat exchangers, bioresorbable ceramic medical implants, lightweight iron casts, and high-performance large-scale plastic parts.

Moon and Mars Habitats

In this paper we argue that ADMS provide the ideal geometry for the design, straight-forward and both material as well as energy-efficient priniting of Moon and Mars habitats using regolith/binder extrusion (fig. 3). Such ADMS structures are not only maximally robust using minimal material, but also double as containers to be filled with loose regolith material (or water), to provide radiation shielding while functioning as an insulating or heat-exchanging, load-bearing and possibly pressurized structure.

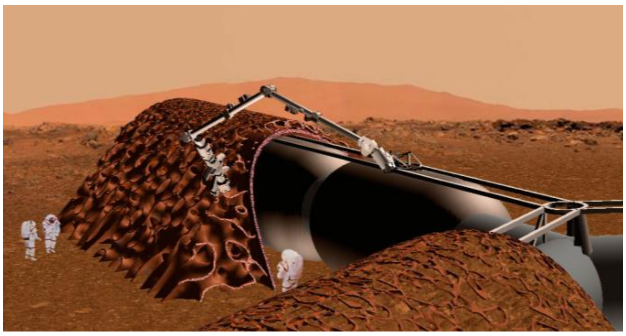

Fig. 3: Pioneer habitat (exemplary design). Interplanetary transfer repurposed to serve as pressurized core. Outer struc-

The inherent characteristics of ADMS — smooth, printer-friendly extruder paths without self-intersections, no need for build supports, no internal atmosphere pockets — make such designs ideally suited to be robotically printed.

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Proposal of a Mars Clay House: Material extrusion AM with advanced clay simulants for habitat structures on Mars

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Introduction

A human mission to Mars could provide answers to the fundamental questions of how, when, and where life on Earth began. In the past decades, scientists searching for life on Mars have focused their remote efforts on Martian clay mineralogy in an approach called *follow the water*. This concept assumes the most promising location to search for signs of life is in regions with clay deposits. Here we discuss possible locations for human Mars missions and propose to use the prevalent clay minerals and their geological deposition context for habitat building directly at the site of scientific inquiry.

Structure concept of the Mars Clay House

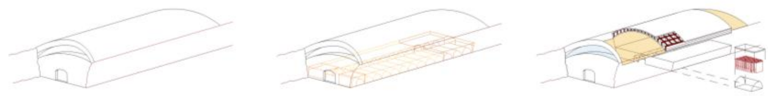

Figure 1: Mars Clay House concept: An AM manufactured Nubian vault made of clay minerals spans a pre-existing geological feature creating a Mars habitat.

Using geological features as shelters is a well-known concept on Earth, which also has been proposed for habitats on Moon and Mars, such as lava tubes. Along those lines, the Mars Clay House Architecture concept employs widely available depressions and graben as foundations/sidewalls and creates a closed habitat structure by extruding a self-supporting Nubian vault structure of clay minerals spanning the top. The concept uses the fact that at the end of the Martian surface water epoch, depressions and graben accumulated phyllosilicates (and salts) when weathering products were deposited in lower surface features [1]. Here, a detailed architecture concept is proposed, including AM of Nubian vaults spanning up to 30 meters and the use of the same vault concept in a reduced size to create interior sublevels.

Clay wet-processing additive manufacturing material concept

Fusion drying of clays has been (and still is) an essential construction technology for all major civilizations on Earth. In the past, some of us have shown that clay-based material systems for unfired clay structures (adobe) on Mars can be formed using all common shaping processes, with adobe from clay slurries/pastes showing a compressive strength of 5 to 30 MPa, similar to common terrestrial concretes [2]. Here, we introduce a new clay simulant approach based on mixing MGS-1 Martian simulant with highly specialized clays from the Source Clays Repository, including nontronite and saponite (the dominant smectites on Mars) [3]. Nine different clay mineral species were wet-processed using material extrusion AM, and the clay species' influence on rheology was examined. Moreover, selected clays were extruded using simulated brine water, which can be expected to be liquid at the current surface conditions on Mars. Non-brine and brine AM wet-processing of smectites produced adobe geometries with compressive strength typically > 10 MPa, which can be considered more than twice the strength of traditional adobe bricks used on Earth to build clay architectures [4], such as Nubian vaults.

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Regolith-based composite manufacturing by Fused Deposition Modelling (FDM)

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Key words: Additive Manufacturing / Composite Manufacturing / Out of Earth Manufacturing / Regolith / Lunar Exploration / Materials Obsolescence

Setting up a permanent base on the lunar surface will imperatively require in-situ resource utilization, considering the scarcity of the raw materials. Blending regolith (lunar soil) with thermoplastics enables a significant decrease in demand for Earth-manufactured materials, as well as an improvement of the mechanical properties compared to the pure polymers. Combining regolith-based composites with additive manufacturing appears then as a promising technique for future astronauts for rapid prototyping, for the production of a broad range of custom-made objects and for the replacement of varied parts and tools.

Two processes that have been investigated for the composite synthesis, based on the EAC-1A regolith simulant developed by European Space Agency (ESA). The first process is a simple melt-compounding, where polymer and regolith powders are melted together and extruded to produce a filament suitable for FDM technology. The second process, called "slurry formulation", employs polymer pellets instead of polymer powder. The pellets are dissolved in a solvent, enabling a homogeneous blend with the regolith powder. After the solvent is removed, the obtained composite is pelletized and fed into the extruder. The extrusion step is critical for both processes, as the filament properties largely determine the ones of the final printed object. Several proportions of regolith have been tested – a concentration of up to 70 wt.% in the final parts has been achieved. The use of additives to improve the manufacturability and the printability of the regolith-based material have also been investigated.

FDM of the composite is demonstrated with commercial 3D-printers that have not encountered any major hardware modification. The printing parameters must have been optimized to ensure the highest homogeneity of the object produced. Various objects, from spare parts to different tools that could be used by future astronauts in their everyday life, have been manufactured with this process, and successfully responded to their specifications. The limited number of resources available on the Moon also led to consider the recyclability of the filaments already extruded and of the objects already printed. The whole life cycle of the composite material has been characterized with a focus on the mechanical properties.

Regolith-based composite manufactured by FDM have thus revealed encouraging results regarding their applicability in future lunar exploration.

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Progress in building an additive manufacturing system for printing molten lunar regolith

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Introduction

The thermal processing of lunar regolith enables the creation of a wide range of material properties. While sintered lunar regolith has already been studied several times, glasses made of lunar regolith are still rather unexplored. The EDAM-R project at TU Berlin is investigating the additive manufacturing of molten lunar regolith without the use of additives. The aim of the project is to melt lunar regolith in a high vacuum, deposit it in a controlled manner and then evaluate the material properties of the resulting glass. For the printing trials TUBS-M regolith simulant will be used [1].

Klein et al [2] showed that additive manufacturing of soda-lime glass is possible and that a solid structure can be produced by cooling the melt. Melting and cooling glass on the Moon is even more complicated, among other things because of the high temperature fluctuations and the highly varying chemical composition of the regolith. As part of the EDAM-R project, the system for additive manufacturing will be set up in a vacuum. While the system is still under construction, various regolith simulants are already being tested for their high-temperature properties. The viscosities of various lunar regolith simulants at temperatures up to 1550°C were measured and compared with common viscosity models to evaluate the usability of these models on the Moon. Further investigations, such as the wetting properties of molten lunar regolith on different substrate materials and DSC/TGA measurements are currently being carried out.

Figure 1: Layered regolith melt in liquid (top) and solidified state (bottom)

Figure 2: Recently produced Regolith glass

Acknowledgement:

This work is supported (support code 50WM2057) by the Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag.

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

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Mars in situ oxygen and propellant production by plasmas technology

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Introduction

Space exploration has fascinated mankind for decades, stimulating the interest in science and engineering, while contributing to the advancement of new and exciting technologies. In this context, Mars is commonly viewed as the next step towards the voyage of humanity into the Universe. Indeed, after the lunar landing, the achievement of a manned mission to Mars will mark the next frontier of discovery and the dawn of a new age in planetary exploration. Among the many scientific and technical challenges required to make this journey a reality (protection against radiation, adaptation to reduced gravity, etc.), the harvesting of local resources at the site of exploration is of special and mandatory importance. This approach is known as in situ resource utilisation (ISRU) and it has the potential to enable humans to thrive beyond Earth, for extended periods of time, in a self-sufficient way. ISRU becomes particularly interesting when considering the possibility of oxygen production directly from the CO_2-enriched Martian atmosphere. Local production of oxygen would reduce the logistics and costs of manned missions to Mars, while providing a breathable environment for future human outposts and a source of rocket propellant. Moreover, exploring such technology would equally promote the development of new methods targeted at CO2 recycling on Earth, which is one of the great challenges for the 21st century.

In this work we will demonstrate the feasibility and interest of using plasma technology for in-situ resource utilisation applications in space exploration, namely to produce 02 and CO from CO2 decomposition under Martian conditions. We will present experimental and modelling results related to plasma-based oxygen production under Martian conditions. To analyse and interpret experimental results, we have developed a detailed self-consistent kinetic model for CO2 plasmas, describing the coupled electron and heavy-particle kinetics. It is shown that the pressure and temperature ranges in the ~ 96% CO2 Martian atmosphere favour the vibrational excitation and subsequent up-pumping of the asymmetric stretching mode, which is believed to be a key factor for an efficient plasma dissociation, at the expense of the excitation of the other modes. Moreover, we will further discuss recent progress dedicated to the installation of a new lightweight and compact microwave plasma source in the laboratory, dedicated to oxygen production under Martian conditions. This last point will address the development of an experimental framework on which the physical mechanisms of Martian plasmas can be explored in detail.

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Acknowledgements

This work was supported by the Portuguese FCT - Fundação para a Ciência e a Tecnologia, under the projects UIDB/50010/2020, UIDP/50010/2020, the individual grant of Scientific Employment Stimulus (CEECIND/00010/2018) and the exploratory project EXPL/FIS-PLA/0076/2021

Near-Earth Object Resource Utilization

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Introduction

The population of Near-Earth objects (NEOs) mainly consists of asteroids scattered from the asteroid main belt into low-perihelion (<1.3 AU) orbits. These asteroids are comparably easy to reach with low Δv requirements from and into cis-lunar space. Spacecrafts have visited the NEOs 25143 Itokawa (Hayabusa, JAXA), 162173 Ryugu (Hayabus2, JAXA) and 101955 Bennu (OSIRIS-REx, NASA) and have returned samples to terrestrial laboratories or are on the way to do so. Scientific milestones of these missions are the first firmly established links between asteroid spectral classes and known meteorite groups. This provides the opportunity to develop SRU schemes based on asteroid population taxonomies and laboratory utilization studies using meteorites and other analogue materials. These missions also provide ground truth on asteroid characteristics not readily deducible from meteorites, such as pristine mechanical and mineralogical properties and the influences of space weathering on the spectral fingerprints of asteroid regoliths.

NEO Resources

Samples returned from Ryugu and on the way from Bennu are the first from dark, carbonaceous C-group NEOs. Their spectral signatures indicate the presence of hydrous phyllosilicates analogous to C-type chondritic meteorites. Ryugu was recently confirmed to bear material similar to the CI meteorite group [1]. This group and its C-type siblings bear serpentines, smectites and other hydrous minerals accounting for up to ~10 wt% H_2O chemically bound as hydroxyl groups. Several wt% of carbon occur as carbonates, such as calcite, dolomite and magnesite, as well as in the form of soluble and macromolecular organic matter that also contains considerable amounts of nitrogen. Water, carbon and nitrogen are critical resources for extended lunar presence and chemical manufacturing of propellants in cis-lunar space. Carbon and nitrogen are especially scarce on the lunar surface, and retrieval of these resources from NEOs might become a long-term option for sustained space economy.

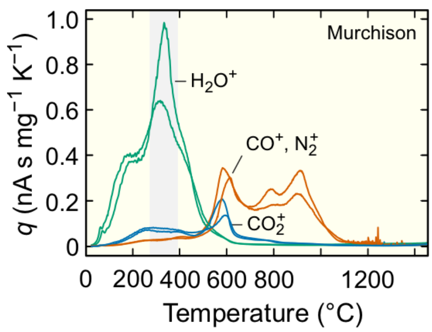

Figure 1: Volatile species detected by quadrupole mass spectrometry during controlled high-vacuum heating of the Murchison CM2 chondrites at 10 K/min.

Exploratory heating experiments of C-type chondritic meteorites using high-vacuum extraction and mass-spectrometric detection of released volatiles indicated complex release patterns of H_2O, CO_2, CO and nitrogen compounds. Thermodynamically valuable CO appears to be a major species and likely the result of redox reactions involving the carbonates, organic matter and magnetite. Extractions yields, energy requirements, and catalytic chemical conversion of this potential feedstock into further products, such as fuels and oxidizers, are some of the to-be-studied process constraints for NEO-based SRU.

References

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Thursday
May 5TH

Session 2
Simulants supporting Research

Chair: Beth Lomax and David Karl

- JHU-APL LSII Analysis of Lunar Regolith Simulants
- European Space Agency (ESA) Sample Analogue Curation Facility (SACF)

JHU-APL LSII Analysis of Lunar Regolith Simulants

K.R. STOCKSTILL-CAHILL[1], A.C. MARTIN and C.M. WAGONER, [1]JHU Applied Physics Laboratory (Karen.Stockstill-Cahill@jhuapl.edu)

Introduction

NASA's Artemis program will return humans to the surface of the Moon and establish the first long-term presence on the lunar surface. These missions will require development of innovative technologies in areas such as construction of habitats, mobility, *in situ* resource utilization, generating power, and beyond. A critical aspect of this development and maturation of technology is testing under relevant lunar surface conditions, including in the presence of and using lunar regolith simulants. Simulants are approximations of lunar regolith that do not reproduce all of the characteristics that the regolith exhibits *in situ* on the Moon. Simulants used for testing of lunar surface technologies need to be verified and validated to ensure that the impact of the differences between the simulants and the lunar regolith is understood, and the impact on the testing of the lunar technologies can be evaluated. As such, one of the roles of the Lunar Surface Innovation Initiative (LSII) at the JHU Applied Physics Laboratory (JHU-APL) is to work with the NASA simulant team to characterize and assess simulants and their components. We evaluated eight commercially-available lunar regolith simulants in terms of composition (mineralogy and bulk chemistry), particle size and shape, and availability and supply chain reliability. The simulants were compared to lunar regolith samples returned by the Apollo missions. The results of the evaluation were published as a document [1] (Figure 1) and made publicly available through the Lunar Surface Innovation Consortium (LSIC) website and confluence pages. The information gathered is also available through a portal located on the LSIC confluence site, which can be accessed by all LSIC members. We will present results of this assessment.

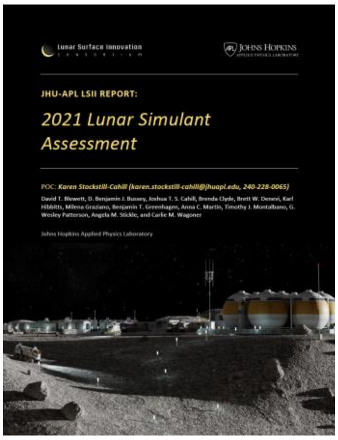

Fig. 1: 2021 Lunar Simulants Assessment document.

References

[1] Stockstill-Cahill *et al.* (2021) JHU-APL LSII Report: 2021 Lunar Simulants Assessment, 43 *pp*.

European Space Agency (ESA) Sample Analogue Curation Facility (SACF)

K.MANICK[1] and X.ZHANG

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Introduction

ESA's SACF is a geological repository and analytical laboratory focused on the curation and characterisation of analogue rock and soil samples. It is located on the Harwell Campus in the UK and is affiliated with ESA's ECSAT site. The SACF is part of ESA's Human and Robotic Exploration (HRE) Directorate and is operated by a multidisciplinary, onsite team.

The SACF was originally created by the Natural History Museum in London, UK [1]. It was transferred to ECSAT in November 2018 and since then, has been under development and initial operations. It is currently in the recommissioning phase post-Covid and expected to reach steady-state operations in 2023.

The overarching aim of the SACF is to provide expert support on analogue sample topics to research and technology development projects (focused on space exploration and planetary science applications) within ESA, its member states, and the rest of Europe. The nature of that support includes:

- Provision of analogue samples (either direct from the SACF and/or from an associated provider).
- Support with analogue sample requirements definition.
- Identification and recommendation of analogue sample options.
- Characterisation of analogue sample properties (either within the SACF and/or at an associated laboratory).

Key Activities

The SACF recently released an 'Analogue Sample User Survey'. The survey was part of a mapping exercise to understand user requirements and identify any gaps or issues with user access to analogue samples.

The results of the survey are currently under review by the SACF and will inform discussions at a simulant workshop in late April 2022. The workshop will bring together several key European simulant creators and suppliers from various institutions and industry to understand the existing/potential capabilities for filling any gaps regarding user access to analogue samples.

Alongside the scoping exercise, the SACF is planning research and development (R&D) activities across the following themes:

- Research on new analogue samples for present and future missions
  - Design and creation of new simulants for ISRU purposes
  - Simulated agglutinates to improve new/existing lunar simulants
  - High fidelity mechanical simulants for terrain/traversability applications
- Development of sample-receiving facility technologies
  - Robotic arm test programme for sample handling and manipulation
  - Automated curation
  - Remote/micro-scale sample processing and preparation

References

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Thursday
May 5TH

Session 3
Enabling infrastructure

Chair: Advenit Makaya, Aidan Cowley and Alexandre Meurisse

- The Commercial Lunar Surface Access Service (LSAS) - Service for Innovating Future Lunar Exploration
- Regenerative fuel cell systems for energy storage on the Moon
- Robust fuel cells and electrolysers for lunar energy systems
- The problem of ISRU reactor chamber sealing in lunar environments: an approach to the solution and how to test it
- MEFAM - The Metals Factory on the Moon
- Mission Data Systems for Lunar Surface Operations
- A feasibility study of a multi-purpose vehicle for commodity transportation to lunar settlements
- Enabling Autonomous Surface Prospecting and Mining with Lunar Rovers
- Robotic Filament Winding Lightweight Technology for Sustainable Space Exploration
- The Electronic FieldBook Tool Suite: field science and prospecting decision support tools for structured information collection and distribution for astronaut training and human planetary exploration
- Applicability of MIRORES FIR spectrometer for detection of lunar sulfides and oxides

The Commercial Lunar Surface Access Service (LSAS) – Service for Innovating Future Lunar Exploration

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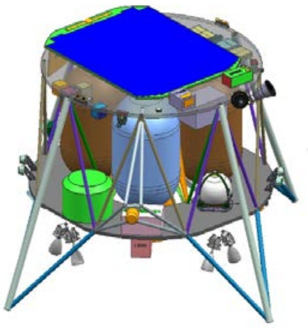
Introduction

The Lunar Surface Access Service (LSAS) is a commercial service proposed by OHB System that offers institutional and private customers a first flight opportunity to the lunar surface already three years from now.

It is the only planned service worldwide with actual flight heritage because it is a design evolution of the Israeli Beresheet lunar lander that flew in 2019 as the first ever privately funded lunar orbital and landing mission.



Innovative Figure 1. LSAS current model with a payload capacity of 85kg.l

OHB and IAI signed an industrial teaming agreement in 2019 and since then have been working on the delta design of the lander to accommodate up to 85kg payload capacity and introducing specific capabilities such as precision landing. In addition, in 2020, OHB and ESA signed a MoU to start working on a Pilot Phase towards establishing a commercial partnership.

LSAS has its first flight planned for 2025 with two more flights intended within this decade. The first mission, LSAS-1, will be targeting one of the so-called "highly illuminated sites" mapped close to the lunar South Pole, where darkness durations during a lunar rotation cycle only measure 2-4 Earth days. The S/C design is such that the LSAS-1 mission will survive these darkness periods repeatedly, without the need of unusual heat sources, thus achieving a long-lived surface mission. Supported by an international consortium with a LSAS-1 Germany-Israel core team, the subcontractor's pool concentrates already in the first mission for more than 65% within the member states. LSAS can accommodate payloads from a variety of customers, and mostly important the main goal of LSAS is to support ESA as a de-risk and pilot management process for the EL3-Mission and services.

In this paper we give an overview of the LSAS-1 preparation efforts: from the delta engineering approach, selection of the landing site, lander capabilities and overview of the business plan.

References

References should be listed in the order of appearance in the abstract, following the brief numbered style (e.g. [1], [2], etc…). The list should then appear at the end of the abstract under the "References" section. The following format must be used:

[1] C. Bergemann, L. Richter, A. Jaime Albalat, S. Jacquet, D. Paltera, T. Stuffler., The European Commercial Lunar Surface Access Service (LSAS) (2021), *NASA Exploration Science Forum & European Lunar Symposium*

[2] C. Bergemann, S. Jacquet, T. Stuffler, The European Lunar Infrastructure Service- A Reality for your Technology on the Moon (2021), *Space Tech Expo Europe*

Regenerative fuel cell systems for energy storage on the Moon

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[1]Air Liquide Advanced Technologies, France

[2]Clara Venture Labs AS, Norway

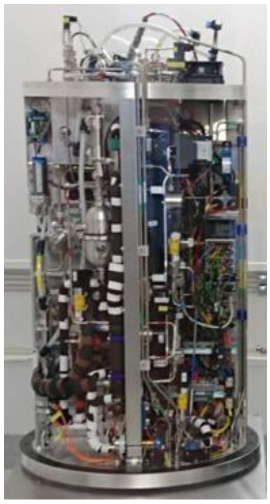
Introduction

Before 2030 the Moon should see a return of humans on its soil. This time the aim will be to stay on our closest satellite and prepare humans for longer missions towards Mars. Thus, the Moon will become an exciting playground for testing technologies and assessing permanent human life in space.

However, a lot of technological gaps need to be addressed before a sustainable activity on the Moon is a reality. This is especially the case for space transportation (reliable lunar landers and rovers), habitat and human health (to provide efficient shelters for preserving human health) or ISRU (capability to use resources present on the Moon). A common point of all these different fields is the energy storage challenge. Indeed, the Moon's environment is known to be harsh with long periods of darkness and cold (many days to permanently). During these lunar nights, the sun cannot provide power anymore but most of the equipment must be maintained at ambient temperature (or even “On”) requiring electrical (or thermal) power. Thus, energy must be stored during lunar days to be provided during the nights.

Development of Regenerative Fuel Cell Systems (RFCS)

Most common energy storage systems today rely on mature battery technology. However, when energy for a long Lunar night is to be stored, the presently low energy density of batteries (around 200 Wh/Kg) becomes unattractive: to store enough energy for one rover (3 kW over 14+ days) gives at least 5 tons of batteries).



Thus, a higher energy density system must be developed which is the case of RFCS (Regenerative Fuel Cell Systems). The principle is very simple. It consists of splitting the water molecule into H2 and O2 gases when energy from the sun is available and storing them. Then using the H2 and O2 in a Fuel Cell to produce electrical power during the night. An RFCS can reach energy density in a wide range, from 200-300 up to 1000 Wh/kg (low power, very high energy stored). Therefore, the total mass of the energy storage system can be drastically reduced.

In long term vision, H2O value chain can be developed on the Moon and therefore RFCS can constitute a cornerstone for all the future infrastructures

Based on these highly interesting advantages, ESA decided to mature this technology by developing a TRL 4 prototype. Clara (formerly Prototech), Airbus and Air Liquide were selected by ESA to design and test this breadboard. Clara stands for design, production and testing of the breadboard; Airbus provides input and requirements for the system, while Air Liquide develops the modeling software tool, helps assess the way forward and provides its commercial PEM fuel cell stack for the breadboard test This paper will present the overall design and main test results as well as current and future challenges.

Robust fuel cells and electrolysers for lunar energy systems

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Introduction

The space proven fuel cell and electrolyser technology will likely play a crucial role in the infrastructure of a remote lunar outpost. Excess energy can be stored by splitting water, which is potentially derived from ISRU processes, while formed hydrogen and oxygen can be turned back to electricity on demand. However, this technology needs to be optimized to cope with the harmful constituents found in ISRU derived water. According to a publication by Colaprete et. al [1], large amounts of sulfides and ammonia, as well as smaller quantities of hydrocarbons were spectroscopically detected alongside water in an ejecta plume of a permanently shadowed crater. These compounds are well known impurities causing reversible but also irreversible damage to the platinum catalyst and other components of the membrane electrode assembly [2]. Commercially available proton exchange membrane (PEM) fuel cells, on the other hand, require highly purified fuels with acceptable contamination levels of only a few ppb. To avoid damages caused by these impurities, energy intense multi-step purification processes are required before water and the fuel gases are in a useable condition – a process that might be too costly in the extreme environment of a lunar outpost. Hence, this work aims to study and improve electrolyser and fuel cell resilience against ISRU derived impurities. This will be attempted by incorporating catalysts with a protective polyaniline coating into a nanofiber electrode layer that is fabricated with electrospinning, a method which has recently been employed to produce high performance and durable electrodes. Optimized fuel cells will be compared to conventional fuel cells under accelerated stress tests with conventional but also heavy lunar conditions, where the feed gases are contaminated with said impurities. The outcome of this study aims to support the exploration community in developing robust energy systems on the moon by investigating ISRU process output interactions with PEM fuel cell and electrolyser technology.

References

[1] Colaprete A, et al., Detection of Water in the LCROSS Ejecta Plume (2010), *Science*, 330, 463-468

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The problem of ISRU reactor chamber sealing in lunar environments: an approach to the solution and how to test it

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Introduction

Lunar dust represents one of the main challenges to be solved for future exploration and use of Moon's resources. Among all the technologies impacted by the lunar dust, sealing is one of the most critical ones with regard to ISRU, as it is required in reaction chambers for obtention of oxygen. Apollo's experience already shown that common sealing technologies extensively used on Earth are not valid for lunar environment, particularly due to dust presence [1] . Additionally, applications such as ISRU chambers impose other challenging constraints, like extreme process temperatures, as high as 1000ºC, and presence of chemicals [2].

Problem definition and solution

AVS leads an ESA activity to design, manufacture and test on representative conditions a reusable seal compatible with high temperatures and dust presence, in collaboration with Open University and Airbus. Three ISRU oxygen production processes were analysed to derive the seal requirements: Iron oxide reduction by hydrogen, Carbothermal reaction (high and low temperature) and FCC-Metalysis process. The analysis was used to define the constraints in temperature and chemical resistance for the seal. The same analysis also provided information on the acceptable leak rate for each process, identified as the main driver in the design of the seal, since the quantity of reactant lost in each cycle is one of the key aspects to evaluate the sustainability of ISRU processes. Sealing concepts and materials compatible with the process requirements have been investigated, and three concepts have been proposed for manufacturing and testing. All of the concepts are based on the renovation of the seal surface so as to minimise dust particles impact on sealing capability. Sealing technologies like the ones proposed as solution for the ISRU chamber could be also adapted to other potential uses, such as sealing of regolith for ISRU to protect volatiles from evaporation between collection and process, and the sealing of sample containers for prospection.

Testing

The test campaign is particularly critical in this project, as the performance of the seal mechanism must be verified in a relevant environment, including representative temperature ranges, vacuum, and lunar dust presence. A dedicated vacuum chamber has been set up for the test. For the dust presence verification, a dedicated Dust Deposition Device has been developed to guarantee a repeatable and measurable deposition of very low dust quantities (capable of representing natural depositions due to exposition to lunar environment), one of the key parameters of the testing campaign. Test are ongoing at the present moment and are expected to be finished by the time of the conference.

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MEFAM - The Metals Factory on the Moon

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H. Wotruba, Unit of Mineral Processing, RWTH Aachen, Germany

K. Milicevic, B. Friedrich, Process Metallurgy & Metal Recycling, RWTH Aachen, Germany

C. Drebenstedt, J. Grigoleit, Technical University Freiberg, Germany

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Abstract

The exploration of the solar system, and as a first step the Moon, will heavily depend on the use of local resources at exploration destinations. The build-up of lunar infrastructures and colonies will require the availability of metal-based products for construction and other applications, as well as oxygen. Lunar regolith is almost universally available in vast quantities, easy to acquire, and can be used to produce oxygen and metal products for all kinds of lunar applications, and is therefore particularly useful. The production of metal-based products on the Moon will require appropriate technologies for the main process steps along the end-to-end metal product value chain, including excavation and mobility, beneficiation, electrochemical reduction, metals extraction and refinement, and manufacturing. The selection of appropriate technologies will be mainly driven by viability criteria under lunar conditions, such as low mass and low power consumption, high efficiency, and in particular near waste-free processes that minimize or eliminate the need for consumables. The build-up of capabilities will likely be a staged process starting from initially very limited capabilities both in terms of production capacity and output product quality. The MEFAM collaboration addresses these issues systematically, by developing a roadmap for the development of lunar metal products production capabilities along the scenarios described in the Global Exploration Roadmap. This is based on an assessment of use cases, technology evaluations and tests, the preparation of design concepts for lunar equipment and related engineering budgets, in particular mass and power. Repeatability, scaling and optimization potentials, and synergies between process steps are covered as well.

Mission Data Systems for Lunar Surface Operations

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Introduction

ESA's European Space Operations Centre (ESOC) is supporting a wide range of activities to prepare ESA, its partners, and European Industry for future robotic missions on the Lunar surface and beyond. These activities consisted so far of Lunar analogues, experiments utilizing the International Space Station (ISS)[1] and simulation campaigns in virtual environments.

As part of these initiatives, we are continuously learning and improving on the Mission Data Systems that are required to support operators in the tasks to control future robotic assets on the Lunar surface in near-real-time. Through experience from over a decade of experiments and analogues with rising complexity, as well as continuous innovation in mission data systems for operations have matured and addressed needs covering monitoring and control of assets as well as auxiliary tools to enable these analogues, facilitate the work of the operators and to increase mission success [2].

Key capabilities include but are not only limited to:

- Service based, distributed monitoring and control systems to support operations for assets of multiple, collaborating actors.
- Extension of simulation infrastructures to enable near-real time robotic surface operations simulations within a full mission context of orbiters and relays.
- Utilization of Augmented and Virtual reality to support planning, simulation and awareness of operators.
- Real-time identification of objects in rover video feeds and training of algorithms through Artificial Intelligence.
- "Space Internet" and next generation protocol stacks for communication with and between future lunar assets.
- Planning systems ingesting orbital or local terrain maps to plan optimal traversal paths within given mission parameters.

Figure 1: Virtual environments supporting Lunar operations preparation

This paper provides a full overview of the ESOC mission data systems infrastructure to enable preparatory and future activities for asset control in Lunar exploration and utilization scenarios.

References

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A feasibility study of a multi-purpose vehicle for commodity transportation to lunar settlements.

M.CHAILLET [1], T.WEBER [2], E.SOLIS [3], A.DIAZ [4], F.NITSCHKE [5], and B.BAHOV [6]

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Moon exploration has experienced a revival of interest in recent years and both public institution budgets and private initiatives have emerged to exploit lunar resources. Water ice has been discovered in craters at the poles and its utilisation is a common idea in many of these projects, from essential life resources to fuel for launchers. The Connecting Ridge region, near the south pole, is particularly in the interest of this paper as NASA, CNSA and Roscosmos have declared their intentions to deploy lunar bases to welcome astronauts by the end of this decade.

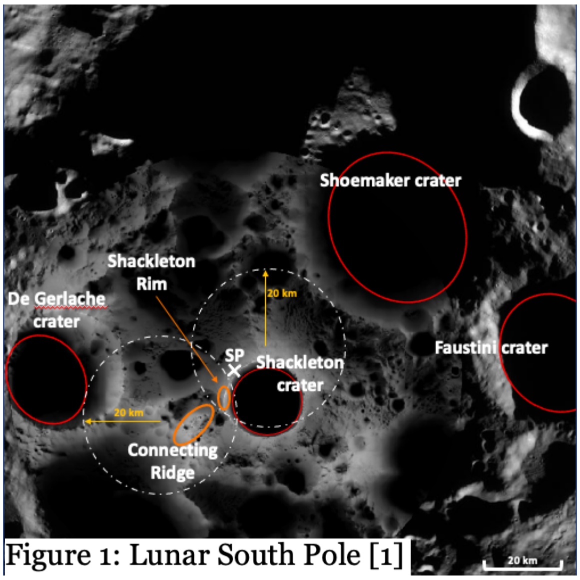

Figure 1: Lunar South Pole [1]

However, assuming extraction is completed and resources stored on the surface - available and ready to use - the transport to the consumer - i.e a lunar base or launch pad - needs to be assessed. This work details the preliminary design of an autonomous vehicle able to refuel a spacecraft, a launcher, or to provide essential commodities to astronauts. Limitations are also discussed: GNC capabilities can be high and power or processing capabilities could limit the feasibility of the design. It is assumed that a practicable and clear path is available between every user. It is also considered that there will be a need to transport the commodities by the time of the mission. These hypothesis are in line with recent public institutions declarations, which have started the development of such infrastructures. A scenario of a fleet of cargo vehicles travelling at reasonable speed to refuel a HLS (Human Landing System developed by SpaceX : Moon version of the Starship) in 2 lunar days is presented. Details on different subsystems are discussed as well in this paper, including locomotion, power, payload, GNC, and communications. Based on a stakeholder analysis and the study of the lunar south pole topography and environment, the feasibility of the mission can be demonstrated.

References

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Enabling Autonomous Surface Prospecting and Mining with Lunar Rovers

K. Raimalwala, M. Cross, M. Battler, and M. Faragalli; Mission Control Space Services Inc.; kaizad@missioncontrolspaceservices.com

The Need for Autonomous Surface Mobility

The rise of commercial missions and activities on the Moon necessitates the shift to increasingly self-reliant system architectures to support a growing lunar economy, using on-site computing to enable real-time autonomous robotics with AI applications just as we will increasingly rely upon in-situ resources. This is critical to mitigate Earth-Moon delays, expected or unforeseen network dropouts, and data transfer constraints. Therefore, vehicles and other systems must operate to a high degree of supervised autonomy. Mission Control is developing a suite of flight software applications to allow lunar rovers to autonomously and intelligently understand the lunar surface environment and make key decisions in support of ISRU-relevant activities such as resource prospecting, excavation, and construction.

Enabling Autonomy in Understanding Environment and Making Decisions

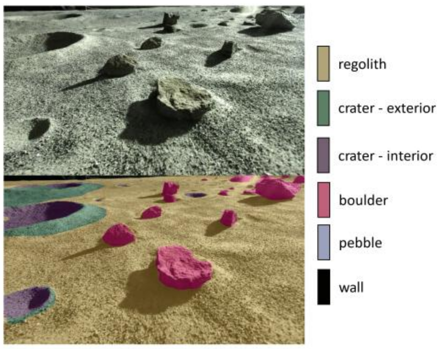

Fig 1: Mission Control's AI-based lunar terrain classification

Mission Control's technologies allow a rover to visually identify lunar surface features for navigation and payload support, build a data-driven model to predict rover behaviour such as wheel slip and energy consumption, and stitch a map to aggregate data from multiple sources in real-time to support navigation and payload operation. Figure 1 shows an example of using Deep Learning to identify surface features like rocks and craters. This will be demonstrated as an edge-computing payload on the ispace mission M1 launching in 2022 and directly supporting the Rashid micro-rover as part of the Emirates Lunar Mission [1].

Mission Control's technologies also enable intelligent onboard decision-making that leverage these data products. For rover navigation, this includes planning and executing safe and efficient trajectories that also maximize key objectives in prospecting and mining scenarios. Based on an understanding of lunar surface features, the rover can also make intelligent decisions to target payloads to collect high-priority data, and rank and prioritize data for immediate downlink to support operator decision cycles. Targeted actuation such as scooping, drilling, and robotic arm operations can also be achieved autonomously using the same methodology. Mission Control can integrate this comprehensive flight software suite on a high-performance and compact processor to enable lunar rovers to autonomously conduct critical activities for resource prospecting, mining, and more.

In this presentation, Mission Control will also provide an overview of participation in the ESA-ESRIC Space Resources Challenge.

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Robotic Filament Winding Lightweight Technology for Sustainable Space Exploration

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Abstract

In our exploration journey as humans, it is necessary to consider the highest end technologies which can not only persist the harsh environment of space, but can also bring more efficiency, reliability, and even replicability. GRADEL lightweight technology brings all of these elements together to present a state-of-the-art solution to tackle the very challenging space resources activities. The idea is to minimize the building materials and maximize the load cases at the same time in order to manufacture the lightest possible structure of its kind. The result then would be decreasing the material usage, i.e. structural weight, between 20-70 percentage. This will bring capacity to implement more payload, to make radiation shields more stronger, and/or to decrease the launch costs [1]. On the other hand, considering the challenges of power management in space, applying lightweight structures will improve the energy efficiency during mobility which is around 3.5 J/m/kg for lunar transportation [2]. Decreasing mobility energy consumption then by itself can lead to lighter power sub-system. Considering the specific power of solar arrays and specific energy of batteries -which for now is around 50 W/kg and 200 Whr/kg- the effect of lightweight technology on the power sub-system would be considerable [3]. Finally, regarding the fully digital manufacturing process and also the option to apply nature-based minerals such as Basalt as building material, the technology would be a differentiator actor for in-situ space manufacturing. This specially can enforce our sustainable presence on the Moon due to the composition of lunar regolith and the possibility to design an in-situ space manufacturing station. The advantages of the technology can be summarized as:

- Potential to manufacture lightest structure of its kind
- Possibility to use Moon-based minerals such as Basalt as raw material
- Full digital manufacturing process

GRADEL has already realized a lightweight lunar rover for LunaLab at University of Luxembourg in which its conceptual and final design is shown in Figure 1.

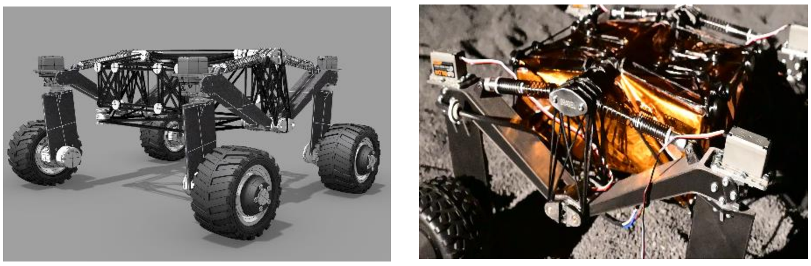

Figure 1: Lightweight rover developed for LunaLab at University of Luxembourg

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The Electronic FieldBook Tool Suite: field science and prospecting decision support tools for structured information collection and distribution for astronaut training and human planetary exploration

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Scientific exploration will form an important part of future human missions to the Moon. To enhance the scientific return of these missions, it is important to accurately record, index and store all the scientific information collected during exploration, and then rapidly distribute it in a structured way amongst the relevant mission support personnel. Such capabilities will be essential for the ground-based science teams supporting these future missions for maintaining situational awareness, enabling them to provide useful and timely feedback to the astronauts and thereby enhance the scientific expertise present on the lunar surface. The Electronic FieldBook (EFB) Tool Suite is a deployable and modular set of tools being developed to address these requirements. The EFB [1] is designed to support field mission operations, scientific data gathering and direct interaction with support teams through the automatic exchange of information. The system provides near realtime situational awareness to mission support teams during scientific traverses. It achieves this through several methods. The system provides a structured way to collect data. Users can document a sampling procedure, retrieve information from several sensors or analytical tools, look up reference information, and take notes. All the information gathered is automatically geo-located and tagged to ensure it is associated to specific sites or samples along a traverse. The suite of tools includes also imaging devices, such as 360-degree cameras, wide high-resolution cameras, panoramic bifocal cameras and microscopes. Further analysis can then be carried out using analytical tools directly controlled by the EFB. The system can analyse the data produced using embedded machine learning modules [2][3] to characterise the mineralogy of samples and inform on their scientific value. The EFB ensures disruption tolerant information exchange, allowing users to continue working regardless of temporary or extended loss of connection. Provided connectivity is present, any user of the system will receive information gathered in near real time, enabling them to direct or support the operations, and provide relevant and informed scientific advice where required. EFB has been the key supporting tool for ESA's PANGAEA/PANGAEA-X 2018, 2019 and 2021 field campaigns (Fig.1), which offer planetary geology training integrated with operations and technology testing. These campaigns bring together geology, high-tech survey equipment and space exploration. Astronauts, scientists, operations experts and instrumentation engineers work side-by-side to advance European know-how of integrated human and robotics mission operations. Within this context, the EFB has co-evolved to support both ESA training and testing activities, and provides a solution to the data integration challenges presented by future human scientific exploration in space. Collaborations with European industry and research institutes is actively ongoing for further research and development on the various tools of the suite.

Fig.1 [left] NASA astronaut Kathleen Rubins performing detailed analyses with the EFB-associated microscope. [right] ESA astronaut Matthias Maurer using EFB during sampling operations in PANGAEA-X 2018. Credits: ESA–A. Romeo, ESA–V. Crobu.

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Applicability of MIRORES FIR spectrometer for detection of lunar sulfides and oxides

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Lunar sulfides and oxides are major sources of noble (Au, Ag, Pt, etc.) and base (Cu, Pb, Zn, Sn, Co, Ni, Cr, Ti, Mn, etc.) metals and will, therefore, be vital for the self-sustainment of future human colonies. Sulfide detection finds application in new solar panel production methods [1], while ilmenite, besides being the main iron and titanium ore on the Moon, can provide helium-3 isotope for nuclear fusion, as well as oxygen. Capability of ilmenite detection finds a counterpart in the works over processing this resource, performed under an ESA contract [2]. Finding optimum concentrations of ore minerals is crucial for ISRU mission planning. The most important ore minerals have prominent absorption peaks in a narrow far-IR (FIR) wavelength range of 22–28 µm. Their spectral features in the FIR range are much stronger than the spectral features of any of the common terrestrial planet minerals including major silicates (olivines, clinopyroxenes, orthopyroxenes, plagioclase), sulfates, and carbonates. Our simulations based on linear mixing of pyrite with the aforementioned silicates indicated that fields containing 10–20% pyrite could be detected from the orbit in the far-IR range. However, ore deposits including massive pyrite on Earth are relatively small reaching maximally up to hundreds of meters by hundreds of meters [3]. Therefore, active FIR space spectrometers with spatial resolutions down to ~3 km, respectively, are not sufficient to search for ore mineralization. Thus, we have designed a new instrument suitable for sulfides identification in the FIR range called the Multiplanetary far-IR Ore Spectrometer (MIRORES). The field view of 16.5 x 19.9 m enables detection of areas covered by 33–66 m² of pyrite on a surface of ~330 m² creating possibilities for detecting large and moderate-size orebodies and probably also their stockworks. This has the potential to be achieved by the use of the Cassegrain optical system. MIRORES will measure radiation in six narrow bands (0.3–0.4 µm in width) that can include up to three bands centered on the ore minerals absorption lines, for example, 22.7, 23.8, and 24.3 µm for ilmenite, troilite, and pyrite, respectively. The instrument size is 32 x 32 x 42 cm and the mass is <10 kg, which fits the common microsatellite requirements. MIRORES project is currently applying for ESA Business Applications, to find feasible business models for commercial development of the future lunar services. Finding new use cases as well, as funding and commercialization models for the ISRU is one of the important elements of the activity. It includes technology transfer to Earth applications such as the production of renewable energy, and ore prospecting in areas with low humidity (with a dedicated UAV-compatible MIRORES version).

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Thursday
May 5TH

Session 4
Capability demonstration

Chair: Advenit Makaya, Aidan Cowley and Alexandre Meurisse

- ISRU and moon building: the role of sintering processes
- Microwave Heating Demonstrator (MHD) payload â€" Design progress
- Puli Lunar Water Snooper - A neutron spectrometer payload for rovers to map lunar water deposits
- Development of the MOONRISE FM payload for demonstration of Regolith laser melting on the lunar surface
- Air Liquide technologies for gas management on the moon to unlock ISRU capabilities
- SpaceLand Mars Habitat
- Competing to map the Moon – an update on the Space Resources Challenge

ISRU and moon building: the role of sintering processes

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Introduction: Scientific Background and Objectives

In situ resource utilization (ISRU) refers to the in-situ generation of consumables for activities autonomous or human activities from raw materials found on the Moon or other planetary bodies. The use of ISRU on the Moon can provide a means to reduce the cost and risk of human exploration of the Moon and beyond, and a boost for commercial contributions to lunar exploration. Future astronauts will require the ability to harvest space resources and turn them into breathable air, drinking water, rocket propellants, materials construction materials and more.

The development of a method of using in situ resources to build space habitats and infrastructure on the lunar surface is necessary to support sustainable space exploration. In this regard, lunar can be an appropriate construction material and the solidification process is essential to produce building materials using lunar regolith. Microwave sintering may be an appropriate ISRU method to produce construction materials on the lunar surface.

Nanoracks Europe is directly involved in an ESA-funded project that aims to develop a technique for the sintering of regolith simulants using microwave technology with the aim of being able to produce two types of products: compact bricks, mechanically stable potentially suitable for structural purposes and others that have a certain density, a higher porosity, but equally mechanically stable, potentially usable as electrodes in electrolysis processes, such as for example oxygen extraction.

The current activity is the realization of a terrestrial technology demonstrator capable of exploiting the radiation localized microwave heating (LMH) to achieve the sintering process of samples of lunar regolith simulant DNA-1 (Made in Italy). The delineation of a roadmap allows to identify the necessary steps to achieve a payload operating on lunar soil.

Microwave heating is considered a more suitable fabrication method for lunar applications compared to other methods such as the solar sintering [1] since this technique does not depend on the availability of the sunlight. In addition, LMH, due to the significant concentration of energy, can be implemented at relatively low powers (on the order of ~0.1 kW) and through the use of solid-state generators [2]. This solid-state technology opens to new possibilities for the realization of compact LMH devices.

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Microwave Heating Demonstrator (MHD) payload – Design progress

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Introduction

MARVEL (**M**icrowave heating **A**pparatus for **R**egolith **V**ariant **E**xperiments for **L**unar ISRU) is a collaborative project between the Open University, Added Value Solutions UK Ltd. and VIPER RF. The team has been developing the **M**icrowave **H**eating **D**emonstrator (**MHD**) payload [1,2] since 2019 with the ambition to perform pre-defined experiments on the Moon, which explore the potential of microwave heating-based 3D printing for developing a lunar construction process and *in-situ* resource extraction, available for selection on future NASA/ESA missions to the Moon. The final goal of the MARVEL project is to support ESA's Terrae Novae 2030+ strategy roadmap for the Moon, particularly for the large surface habitat and ISRU pilot plant & excavation missions. The initial concept development of the MHD payload was completed with support from UKSA's NSTP GEI (GEI2-037), Pathfinder (PF3-090), Space Exploration Technology (UKSAG21_0088), and ESA's Off-Earth Manufacturing and Construction Campaign (4000133998/21/NL/GLC) (Figure 1 [3]).

In this presentation, we will report the current progress of the MHD development conducted through the ESA's Off-Earth Manufacturing and Construction Campaign as part of the Open Space Innovation Platform (OSIP), focusing on the challenges with optimising the heating performance of the MHD cavity design.

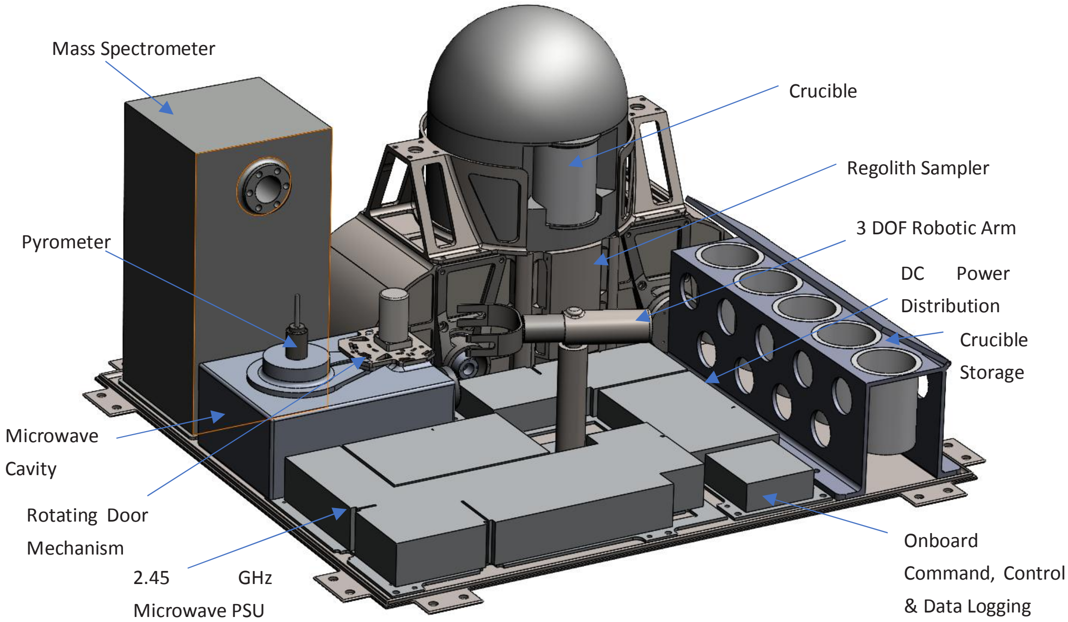

Figure 1: 3D CAD model of the MHD payload (dimensions 400 x 400 x 250 mm) [3]

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Puli Lunar Water Snooper – A neutron spectrometer payload for rovers to map lunar water deposits

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The Puli Lunar Water Snooper (PLWS) is a small neutron spectrometer payload instrument developed by Puli Space Technologies and funded by NASA for a year after winning two NASA challenges with the payload concept [1].

PLWS can in-situ identify and measure the local subsurface water equivalent hydrogen concentration of the lunar regolith by detecting albedo neutrons. Due to cosmic rays, albedo neutrons are produced inside and leaving the lunar regolith with a neutron energy spectrum characteristic to the local soil composition. PLWS detects thermal and epithermal neutrons separately using modified commercial off-the-shelf CMOS image sensors as neutron detectors.

With these capabilities, PLWS addresses essential needs of the Space Resources community, and scientific goals of the NASA Artemis program [2]. Moreover, it is extremely lightweight (382 g), small-sized (10×10×3.4 cm) and low-cost (COTS-based), making it suitable especially for small lunar rovers.

Successful neutron tests have been performed at CERN, demonstrating the capability to monitor both thermal, epithermal and fast neutron count rates in parallel in various neutron environments over wide ranges and long durations.

PLWS prototypes at TRL 6 have been already manufactured and delivered to NASA JPL in February 2022 for further testing in preparation for a potential lunar flight opportunity in 2024. In collaboration with CERN, the first terrestrial spin-off application of PLWS is being prepared as well, using it as a radiation monitor in high-energy particle accelerator environments.

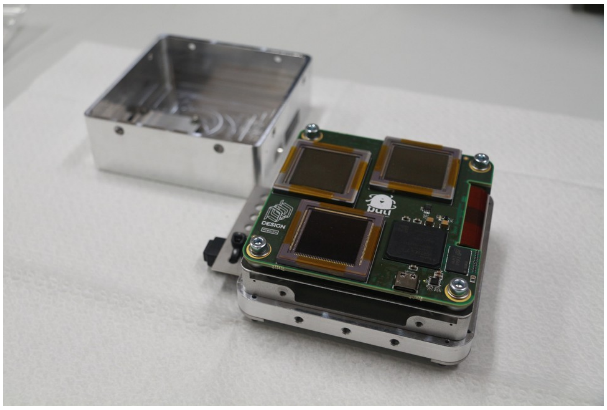

Figure 1: The Puli Lunar Water Snooper (PLWS) payload with its cover removed

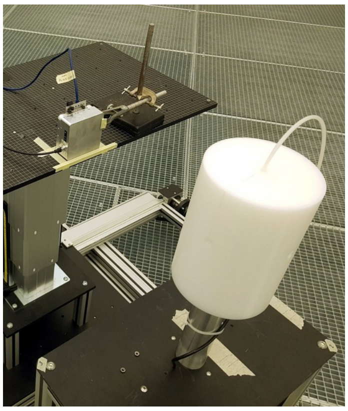

Figure 2: Neutron testing of PLWS at CERN

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Development of the MOONRISE FM payload for demonstration of Regolith laser melting on the lunar surface

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Introduction

In-Situ Resource Utilization (ISRU) technologies pave the way for a sustainable colony on the Moon. Above all, the construction of structures using only the available resources is an important factor in reducing costs and logistical effort. The MOONRISE technology aims to melt lunar regolith using lasers on mobile platforms for the Additive Manufacturing of structures [1,2]. This process is called Mobile Selective Laser Melting (M-SLM) and has the advantage that only electrical energy and a moving system are required.

After extensive testing with the Engineering Model (EM) of the MOONRISE payload (Fig. 1), construction of the Flight Model (FM) of this experiment began. In the period of 2024/25 regolith melting tests on the lunar surface should be carried out by this FM. In preparation for the flight to the moon, an extensive sample testing program was carried out with different regolith simulants [3] and varying gravity [4] (Fig. 2). In addition, the material properties that can be realized with the M-SLM process were determined. Tests are currently being carried out to enable the production of 2D and 3D components (Fig. 3). Main results of this work and current status of hardware development will be presented within the Space Resource Week.

Figure 1: MOONRISE EM

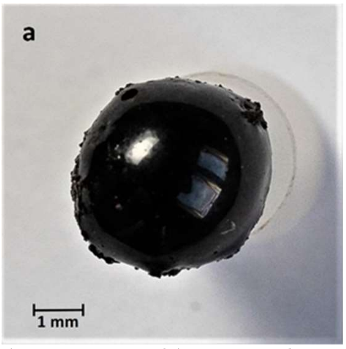

Figure 2: Melting sample as expected on the moon

Figure 3: MOONRISE EM during the production of a 2D element

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Air Liquide technologies for gas management on the moon to unlock ISRU capabilities

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Before 2030 the moon should see a return of humans on its soil. This time the aim will be to stay on our closest satellite and prepare humans for longer missions towards Mars. Thus, the moon will become an exciting playground for testing technologies and assessing permanent human life in space.

Among all the challenges raised by this future ambition, management of gases will be critical. Indeed, extending human presence in space with a permanent life on the moon requires developing a sustainable approach for all the future operations. As extracting from earth gravity is highly demanding in terms of energy (with propellants) we need to optimize materials, systems and molecules brought from earth. It is especially the case with the development of ISRU technologies that could limit the need from H_2, O_2 and H_2O coming from earth. Based on this observation and on the long history of Air Liquide in gas management on earth (storage, separation, purification, liquefaction, ...) we think that we can bring a sound contribution in developing sustainability on the moon.
These wide competencies have been translated into a strategic ambition on ISRU and Life Support technologies. Indeed, Air Liquide is used to manage many different gases on earth from their separation to their supply by way of purification and liquefaction. Indeed, Air Liquide has a strong experience in gas management, which includes production, purification, storage but also supply. These functions involve specific processes already commercialized by Air Liquide, such as liquefaction or physical separation.

In this paper Air Liquide will present its main strategy with regard to gas management on the moon as well as the technologies and systems that could be developed for improving sustainability in space.

SpaceLand Mars Habitat

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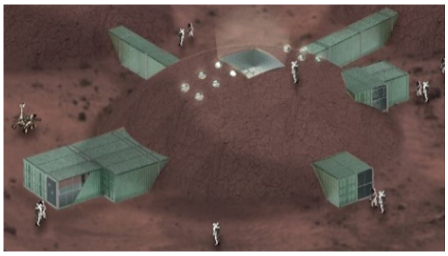
B. Celeste PETRAROLI[2], SpaceLand Managing Architect - engineering@SpaceLand.it

Abstract

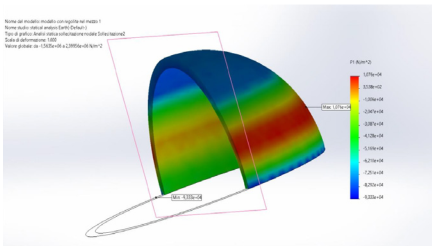
The Swiss-Italian group SpaceLand has incorporated SpaceLand Africa as an African spin-off for projects to support humankind's exploration of Mars, while at the same time spinning-in new habitation building methods for populations with low-income in developing Countries.

Within such a mandate, a dome-shaped habitat has been preliminarily designed to be prototyped for hand-on demonstration of newly conceived ISRU (In Situ Resources Utilization) materials, based on local soil resembling Mars-regolith, as well as novel mixed-technology construction systems conceived to reach a two-fold objective, addressing Mars and our planet:



a) support humans' first steps on the Red Planet thanks to safe, easy and saluber NZEB (Near-Zero-Energy-Building) solutions for radiation-proof and thermally insulated habitats;
b) provide disruptive construction methods for novel NZEB dwellings, catering for the needs of people living in extreme poverty in remote or harsh environments on our planet.
The hereby presented construction concept is being structurally and functionally tested with the support of well-known Engineering Universities in Italy and SpaceLand subcontractors; it employs breakthrough proprietary tools to enable astronauts to structure-rigidize a shelter by working as much as possible in a shirt-sleeved environment on Mars, right after landing, using local-soil-based reinforced concrete. The method hinges about an ad-hoc developed multi-chambered foldable form-work to be on-site pressurized to create the needed volume and then binder-jetted through proprietary construction procedures and tools.

Such a cost & time-effective method allows minimum upload and maximum use of local soil. It enables astronauts to comfortably construct their martian habitat from inside, safely and effectively, reducing exposure to the Mars environment. Moreover, it also minimizes those hazards and risks potentially impacting the crew's health which tall structures, being designed by others, might generate (e.g. radiations, dust devils, structural instabilities, multi-floor configurations in Mars-gravity affecting human energy and everyday's living and working-related comfort).



We deem that such cutting-edge technology and material solutions can revolutionize not only planetary exploration programs, by providing easily buildable, radiation-proof, structurally stable habitats for astronauts, but also the housing construction industry on our planet: by adapting the chemistry for the ISRU-based conglomerate used for the hereby proposed construction method, to best match with our portable form-work concept and building procedure, this project can prove to be transformative both for humankind's future on Mars and for novel, cheap but saluber and quickly erected homes utilizing local soil especially to benefit people currently living in unhealthy metallic-plastic slums world-wide.

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Competing to map the Moon – an update on the Space Resources Challenge

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Introduction

In 2019, Luxembourg and ESA signed a memorandum of co-operation [1] to foster collaboration between the agencies, out of which the Space Resources Challenge was born. ESA & ESRIC recognise the value of the European ISRU market as innovation driver and decided to tap into this strength to solve pressing ISRU challenges. European companies were invited to participate in ESA's Space Resources Challenge (SRC), which aims to harness the power of outcome driven innovation [2]. The SRC aims to engage space and non-space industry actors with ISRU activities, as well as showcase the state of ISRU capabilities of European space businesses, specifically in resource prospecting to the wider ISRU community.

ESA & ESRIC designed a challenge aiming to harness the expertise, ingenuity, and resilience of European companies to solve a specific issue facing current ISRU work: the geo-locating of precious resources on the Moon and subsequent generation of geological maps [3]. The participating companies were invited to the Netherlands, where they were tasked with traversing and mapping a lunar analogue landscape spanning 2500m^2, with a focus on locating and identifying a range of samples strategically placed. Teams also encountered terrain features, like ramps and obstacles that they had to map and traverse. To increase the fidelity of the analogue, the area was kept hidden from participants and could only be explored using their technology of choice. Additionally, a 5 second time delay and periodic signal outages simulated the challenges of navigating on the Moon while encouraging autonomy. Participating teams showcased wide range of approaches, involving multiple rover systems, some of which worked in conjunction with drones.

Competing teams had their performance evaluated by a panel of experts, which gave scores based on the quality of their map, scientific analysis, autonomy, and traversal of the area. Additionally, teams had to submit a work-plan showing how they would incorporate their prize money into future work. 5 teams were chosen to receive 75.000€ each as well as an invitation to join for phase 2 of the Space Resources Challenge in Luxembourg in 2022. Here teams can showcase their improved technologies on a more challenging stage, with the winning team receiving up to 375.000€ in prize money in the form of an ESA-ESRIC development contract.

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