Microwave heating **A**pparatus of lunar **R**egolith for **V**ariant **E**xperiments of **L**unar ISRU missions (**MARVEL**)

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Executive Summary

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Introduction

Humans require habitation with substantial protection from space radiation and micrometeorites for an extended stay on the Moon. The lunar regolith is a readily available resource in-situ, which can be thermally treated to build lunar habitats/infrastructure and extract oxygen/water. Due to the volumetric heating characteristic intrinsic to microwave heating, it is a more energy-efficient process than solar or laser sintering for large-scale manufacturing and construction. Our proof-of-concept experiments have demonstrated that microwaves can readily heat lunar simulants above their melting temperature. Nevertheless, more information on microwave heating of lunar regolith is required, including the influence of nanophase iron, the contribution from electrostatic effects, and the importance of irregular particle shapes under the natural lunar environment.

The final goal of the MARVEL project is to develop the flight hardware of a Microwave Heating Demonstrator (MHD) payload for future ESA lunar ISRU missions to demonstrate the potential of microwave heating for construction and the extraction of volatiles such as water and oxygen. The MHD payload will (i) collect six samples (50g each), (ii) heat them with 250 W of input power for up to 60 minutes and cool them down to match the heating time, and (iii) measure the temperature and the released volatile profile during the experiment. We hope to mature the technology to be space certified in the mid-to-late 2020s and launch the developed technology to build lunar habitats/infrastructure and extract resources in the early 2030s.

The outcomes of this project will be used for developing a microwave-based 3D printing technique and its mobile printing platform as part of an ISRU-derived lunar construction process (building lunar habitats and infrastructure) and resource extraction (e.g., oxygen, water and iron) from lunar regolith. Ultimately, the MARVEL project will help us to fulfil the goal of lunar construction-related research; consequently support the ESA's scientific utilisation and ISRU-derived lunar surface exploration. The expected market of the developed technology would be (i) international space agencies and governmental bodies supporting future lunar exploration and deep space gateway roadmap in the early stage, and (ii) Space construction and mining industries.

State of the Art / Background

The current global interest in Space Odyssey and visiting other planetary bodies in and beyond our solar system has been one of humanity's oldest dreams from time immemorial. Such curiosity has led people to consider how best we might provide habitats in unfamiliar and potentially hazardous extra-terrestrial environments. Emergent research and practices in the Space Architecture domain attempt to eliminate technical barriers to making dreams come true. With various efforts to apply the 3D Printing technology to the Earth construction process, those involved in the Space Architecture field believe that robotised 3D Printing technologies could become a key technology for In-Situ Resource Utilisation (ISRU) derived extra-terrestrial construction process to build human habitat and infrastructure on other planetary bodies.

Microwave heating-based 3D Printing

As a 3D printing fabrication method, researchers have considered the relative merits of solar concentration, laser, and microwave sintering technologies. Microwave heating in a volumetric manner for applications including palaeontological experiments, volatiles extraction, and nano-phase iron (np-Fe^0) production has significant advantages over conventional heating, such as a furnace using fossil fuel. It promises substantial energy savings of up to 90%. It has been suggested that microwave power is suitable for fabricating construction components, e.g., bricks, pavement and spacecraft launch and landing pads, using lunar regolith.

Various researchers conducted an extensive experiment on microwave sintering with various lunar regolith simulants to demonstrate the practicality of selected 3D printing technologies on the Moon.

Preliminary results suggested that (i) the absence of nano-phase iron (np-Fe^0) in lunar simulants do not affect the sintering process, and (ii) additional ilmenite and infrared preheating of the material enhanced the reliability and controllability of the sintering process. They concluded that microwave heating is one of the most attractive fabrication methods for a lunar construction process considering the lunar regolith's composition and dielectric characteristics.

Until now, however, most experiments have been conducted using simulant materials under environments which cannot replicate those conditions that are difficult to simulate, e.g., low gravity for more than 20 seconds, abrasiveness, dryness and nano-phase iron in the lunar regolith. The cohesion of lunar regolith when rapidly heated in low gravity is also unknown, mainly if it contains volatile materials which become vaporised on heating. In addition, most experiments have used a microwave frequency of 2.45 GHz, which has high efficiency in heating liquid water but may not necessarily be optimal for heating lunar regolith. Thus, while addressing the challenges at 2.45 GHz, it is equally important to examine the behaviour of lunar soil at other frequencies in the microwave range, as the penetration depth of lunar regolith depends on microwave frequencies.

Microwave heating-based volatile extraction

Solar wind hydrogen at concentrations of about 300 ppm is released at temperatures between 200 and 400 °C, and water from recombinant OH is released at temperatures of around 400 to 600 °C. The ESA PROSPECT instrument on the Luna27 mission aims to measure the concentration of volatiles released by heating lunar regolith at high lunar latitudes where there may also be deposits of trapped water ice. A proof-of-concept experiment has demonstrated that microwave energy can extract frozen water from JSC-1A lunar simulant doped with 1% water.

In addition, it may be possible to extract oxygen from the regolith by either hydrogen reduction or carbothermal reactions. Most attention has concentrated on the hydrogen reduction of iron-bearing minerals, most notably ilmenite, as this occurs at a moderate temperature of around 900 °C. Reaction rates increase with temperature; however, they are limited to about 1,100 °C to prevent sintering and melting of the lunar regolith, which causes problems in removing the processed material from the reactor. The oxygen yield increases with Fe_2^+ concentration; however, at best is only 10% for pure ilmenite ($FeTiO_3$), a common lunar mineral concentrated in mare regions up to around 10 wt.%. The process has been demonstrated in field trials to TRL 5, achieving about 1-2% yields. Yields of about 5% oxygen have been achieved using pure ilmenite in a solar-heated fluidised bed.

Carbothermal reactions, where methane is the reactant gas, can extract oxygen from SiO_2 in lunar minerals at temperatures above 1,500 °C and give oxygen yields of 20% at temperatures of 1,500 °C. The oxygen yield is less constrained by feedstock material, so the carbothermal process is less restrictive in the actual lunar environment. However, the methane reactant gas must be transported from Earth, so to be a viable process, the methane needs to be efficiently recycled through the Sabatier process. The technical challenges of higher temperatures have limited the development of carbothermal reactions, the need to handle molten regolith, and the need to recover the methane post efficiently. The carbothermal process has been demonstrated using lasers to melt globules of lunar simulant, achieving yields of 9.6 wt % in field trials.

Aim/objectives for this project

The MHD payload would fill the knowledge gaps in Space Science and Engineering aspects by (i) revealing the physicochemical characteristics of microwave-heated lunar regolith under the natural lunar environment and (ii) providing vital information and potential for extracting oxygen and iron from lunar regolith. The development objectives of this project are as follows with the expectation to increase the TRL from 2/3 to 4:

(i) Develop the experiment scenario on the lunar surface and define the components of MHD.

(ii) Develop an optimal design of the MHD payload.
(iii) Conduct simulations using an early design of the microwave generator and chamber;
(iv) Build an in-house breadboard of the MHD payload and detailed experiment plans based on the payload requirement of the possible mission landers we have identified, e.g., ESA European Large Logistic Lander (EL3), Astrobotics Griffin lander, and Intuitive Machines lander Nova-C and Nova-D; and
(v) Prepare a follow-up proposal to build a prototype and flight unit of the MHD payload.

Technical benefits

The innovative aspect of the project lies in developing critical scientific understanding and closing the knowledge gap in space engineering. The particular technical benefits derived from the developments of this project would be to (i) generate vital information for fabricating construction components and (ii) identify potential extraction of oxygen and iron from lunar regolith. More details on these technical benefits from the MHD experiment are as below:

- The atmosphere could affect the particle properties significantly as particles will absorb atmospheric water, which will change the bulk behaviour of regolith such as cohesion and electrostatic. However, there is no valid data on microwave heating of lunar regolith, which includes nanophase iron and highly electrostatic and irregular particle shapes, under the natural lunar environment yet, i.e., vacuum and microgravity. Thus, understanding changes in physicochemical characteristics of lunar regolith under microwave heating relevant to ISRU applications will provide helpful insight into the material properties on the Moon.
- It is only in the last decade that the presence of water/hydroxyl on the surface and in the permanently shadowed craters of the Moon has been confirmed. However, the exact quantities, distribution and speciation of water and other associated volatiles are virtually unknown. The proposed MHD experiment will provide one of the fundamental pieces of information vital for understanding the sources and origin of lunar water, which also feeds into ISRU considerations.
- The MHD payload will also allow us to (i) observe any deleterious effects of dust on system operation and fabrication and other risks, which will lead us to develop appropriate mitigation methods, and (ii) conduct conventional and destructive measurements for measuring the mechanical properties of the heated (possibly sintered/melted) specimens in terrestrial laboratories if the sintered/melted specimens can be returned for further study.

Through the outcomes of the payload experiment, our project MARVEL will provide helpful insight into the material properties of the Moon and other airless bodies with near-vacuum atmospheres, e.g., Martian moons and asteroids, which are of interest to exploration communities worldwide. Therefore, MARVEL will lead us to realise lunar construction and ISRU mission activities.

Business benefits

The main aim of the project at this stage is to reduce the risk of the technology required to perform 3D printing on the moon in a safe, effective and costly manner. The mid-term objective is to develop the full ISRU payload, including a multi-purpose gantry foldable cable robot (PRO-ACT: https://www.h2020-pro-act.eu/), proposed by AVS that might play an essential role within the broader plans for future exploration missions, including lunar habitat construction. The ultimate long-term objective will be to target lunar ISRU demonstrator missions in the mid-to-late 2020s.

The current project includes an assessment of the payload's potential for future commercial product development and exploitation. This will provide the preliminary work necessary to formulate a business case and a technology roadmap review in collaboration with ESA and exploration stakeholders. Our proposal includes two UK Space hardware SMEs that will benefit from this development: AVS and VIPER RF, positioning them at the forefront of ISRU technology and creating new jobs and opportunities in developing Space mechanisms and mechanical and microwave systems.

Project Work Packages (WP)

The conducted tasks are categorised below with the sequential Work Packages (WP) following the objectives above. Note that WP1 and 2 were conducted during Phase A, while the rest were completed during Phase B incorporating the results from Phase A.

WP1: Lab experiments to refine the experiment scenario on the lunar surface (Lead: OU)

Work Package 1 (WP1) is led by OU, and the planned tasks have been conducted using the bespoke microwave heating equipment at OU. The primary purpose of WP1 is to redefine the main functions and experiment scenario of the MHD payload, which were initially defined based on OU's preliminary study under atmospheric conditions with support from the UK Space Agency between January to March 2020. Four tasks have been designed and conducted below to achieve the above purpose. Note that all tasks have been conducted under low-pressure conditions.

Task 1: Microwave heating experiment of four lunar simulants

To further optimise the input power and heating time for various lunar regolith, four lunar simulants have been tested under the following settings. However, the highland and mare regolith simulants are our primary focus of the experiment. During Phase B, the microstructure of the selected JSC-1A and OPRH3N samples will be further analysed using the new machine. The chosen samples' mechanical properties (hardness and true density) will also be measured for a comparative analysis with the microwaved samples under atmospheric conditions. Nevertheless, the current results from the Task 1 experiments have reassured that **lunar mare and highland regolith would be coupled with microwave energy and heat to be sintered/melted under a vacuum. However, a specific microwave cavity design that satisfies the resonant frequency of each material is crucial.** Thus, we have updated the microwave cavity accordingly in WP2 and WP4 to satisfy both resonant frequencies of lunar mare and highland regolith and maximise the electric field to improve the heating performance of the microwave cavity.

Task 2: Measuring the effect of doping lunar simulant sample with water

This experiment aims to measure the efficiency of water extraction from various lunar regolith simulants. Thus, the samples were doped with 5 and 10 wt % water, and the experiments were done under low pressure (≈$10e^1$ mbar) with 250W input power. Despite the current cavity setting being optimal for the JSC-1A's resonant frequency, all the experiment outputs demonstrate that most water contents were released in each sample. **The result indicates that a microwave heating method can vaporise water in lunar regolith with low energy in any lunar regolith. Thus, we plan to add a water collection function (using a cold finger, for example) to the existing mass spectrometer subsystem in the MHD payload in the next update to investigate whether this method could also be applied under the lunar surface condition.**

Task 3: Oxygen extraction using reactants

This task was planned to identify the potential reactant gases that could maximise oxygen extraction and produce water from the lunar regolith. Two experiments were conducted, i.e., hydrogen reduction and carbothermal reaction.

For the test with hydrogen, different masses of ilmenite were added to 50 g of JSC-1A to see if ilmenite could contribute to the hydrogen reduction process. The hydrogen reduces the ilmenite to iron and titanium dioxide to produce water. The reaction rate is affected by several parameters not well constrained within the microwave chamber. In our experiments, the gas in the microwave chamber is sampled by a capillary inlet into the mass spectrometer as the gas is heated by the sample, the pressure increases, which also increases the gas flow rate into the mass spectrometer. The results show that the hydrogen is reacting with ilmenite, producing some water. However, water is condensing on the cold walls of the vacuum system between the microwave cavity and the mass spectrometer, so the water yield cannot be determined from the mass spectrometer m/z 18 signal.

On the other hand, carbothermal reactions using methane have the advantage over hydrogen reduction as oxygen can be liberated from a greater range of minerals. The methane signal decreases as the hydrogen and carbon monoxide increase. By the end of the microwave heating, the total gas pressure had increased to 390 mbar. From these results, we conclude that carbothermal reactions occurred when the sample melted. The initial quantity of methane was 0.0225 mol, while the final quantity of methane was 0.0045 mol. The percentage of methane reacted was 80%, and oxygen liberated (as CO) mass was 0.288 g. Overall, 1.4% of oxygen was liberated from the sample. This was limited by the amount of methane present in these preliminary experiments. **Despite the small number of experiments, the results have already shown complex findings, which indicate the potential of a microwave heating method for oxygen and water extraction from lunar regolith. Thus, this project will plan and conduct more experiments with a microstructure analysis of the heated sample during Phase B.**

Task 4: Re-identifying the experiments scenario

Task 1 was conducted to reassess the MHD payload's experiment scenario. This was necessary because the scenario was planned based on the previous microwave heating experiment under atmospheric conditions. Task 1 using the microwave heating equipment at OU have confirmed that lunar mare and highland regoliths can be sintered/melted within 15 minutes (1,000 W) and 60 minutes (250 W) if the microwave cavity matches the resonant frequency of the material.

The initial scenario was developed based on the microwave heating experiment using JSC-1A under atmospheric conditions where a 50 g sample could be melted in 3,600 seconds with 250 W input power. Although the more intensive optimisation of the cavity design and simulation with a comparative analysis between the lab experiment and simulation results will be conducted in WP3 in Phase B, **the current result indicates that the initial scenario's planned heating time could be reduced from 3,600 seconds to 1,500 seconds.** Furthermore, with the update of the storage rack design for multiple crucibles, which replaced the original design of the crucible holder, i.e., carousel tray-type, the MHD payload could hold up to five crucibles. Thus, **the total experiment number using the MHD payload would be increased from three to six.**

WP2: Develop an optimal design of the MHD payload (Lead: AVS, Participants: OU)

We have conducted the following optimisation for a few subsystems of the MHD payload.

Microwave Cavity Design & Optimisation:

COMSOL Multiphysics software has been used to simulate the Electric Field within the Microwave Cavity. It performs temperature studies to determine the proportion of regolith, sintered/molten. All simulations run at 250 W input power fixed at the port boundary.

Cavity Launching Methods: The method of cavity launching has been explored in three forms, (i) the traditional Coaxial to Waveguide transition, (ii) the "In-line" Coaxial to Waveguide transition, and (iii) the Direct waveguide feed explored for the simplicity of future packaging in a flight-like payload.

Coaxial port, Traditional: This is the version taken as the starting point for the resonance chamber in this project. It features a waveguide-like design; thus, the standardised WR340 Waveguide is selected as the preliminary geometry.

Coaxial port, Inline: On one end of the chamber, the coaxial antenna protrudes roughly ¼ wavelength into the cavity, which is shorted and thermally shunted down to the chamber floor. This thermal shunt provides a heat dissipation path away from the antenna, improving (i) the system's thermal management, (ii) power handling compared with having the coaxial port below the chamber, (iii) the packaging within a payload envelope, and (iv) the lossy transitional components between the generator and the cavity.

Waveguide: The waveguide was simulated by an enforced TE10 mode boundary condition on the end wall where the antenna was located in the previous model. The subsequent optimisation process results in the cavity dimensions moving away from the standardised WR340 profile. As such, either a non-standard PSU would be required with high-cost implications or a transitional tapering waveguide that would negate any associated packaging benefits.

Optimisation for Mare Low-Ti Regolith: The cavity resonates with a centre frequency of 2.447 GHz and an FWHM (Full Width Half Max) of 36 MHz, ensuring the cavity is not overly sensitive to a frequency that small drifts in supply frequency result in off-resonance behaviour. The cavity has been optimised for Mare Low-Ti rather than Highlands due to the expected landing location of a future mission in the Mare Regions. However, the cavity still resonates strongly with highlands regolith at a slightly higher frequency of 2.479 GHz but within the expected generator frequency band.

Heating Performance: The Heating performance of the Cavity has been characterised by the Mare Low-Ti regolith. The sample heats as expected for the initial 60s before the maximum temperature dramatically rises around 75s into the simulation. The root cause of this is a thermal runaway effect observed in the experiments conducted at the Open University. This change in electrical conductivity drastically shifts the electric field profile and decreases the efficiency of the heating.

Payload CAD

A few subsystems of the MHD payload through the project have also been updated.

Microwave Cavity: A rotating door shutter-like mechanism is proposed initially, with a Metal C type Seal providing the cavity seal. The temperature of the regolith is monitored by a Pyrometer centred on the regolith sample. Combining the loading mechanism with the seal may be preferable through a mechanism that seals by applying vertical pressure on a resettable knife-edge seal. The cavity should seal the crucible volume from the remaining cavity volume to avoid a plasma discharge when exposed to the high electric field strength.

Regolith Sampling: The sweeping mechanism has been maintained from the initial payload concept. However, instead of a single collection attempt with a regolith storage location which must then distribute to each sample container, it is proposed to modify the concept such that the sample containers are sequentially loaded into the sweeping mechanism and directly filled, removing the requirement for the intermediary steps and distribution mechanism(s). This concept is based on AVS's existing Sampling Brush Mechanism (SBM), successfully demonstrated on a microgravity flight designed for sampling from low gravity bodies. The sampler consists of 2 electronically commutated (EC) motor-actuated brushes that sweep regolith when the bristles touch the regolith surface. The regolith particles are lifted and driven into the sample container above the bristles.

Crucible Storage: Compared to the previous Iteration of the proposed payload design, we have eliminated the rotatable wheel in favour of a fixed location for storing up to 6 sample containers, as opposed to three, which were accommodated by the sample wheel. The design of the storage and handling components of the payload are unusually linked to the performance of the cavity through the crucible geometry, which directly impacts the cavity's resonant properties. This was considered in detail in the next phase of the project. The chamfered faces of the crucibles and the rack provide the alignment within the rack, while the rack lid provides the downward force to secure the crucibles. Post-heating crucibles will be placed back in the storage rack.

WP3: Computational simulations using the developed chamber design (Lead: OU)

Work Package 3 (WP3) is led by OU, and the first task – computational simulation – has been conducted using the numerical model of the microwave heating of lunar regolith. The primary purpose of WP3 is to conduct a complementary experiment to support the validity of the lab-based microwave heating experiment of lunar simulants. To further validate the results from the WP1 experiments and understand the effect of the initial sample temperature on the microwave heating performance, we have conducted concise simulations of two lunar regoliths, mainly focusing on the correlation between the EF peak and hotspot/thermal runaway.

Three Electric fields (EF) and three temperature curves in the samples have been simulated. All simulations under different conditions show a similar phenomenon: the temperature curves flatten towards the end of their heating cycles. This indicates a lower efficiency of microwave heating, possibly caused by the decrease of the EF in the sample. The maximum EF in the sample fluctuates with temperature increase, i.e., it dramatically decreases when the sample is heated (after 150 seconds), spikes with thermal runaway (after 350 seconds), and decreases again up to a certain level (around 800 seconds). However, it was observed that the EF spike only occurs in a small area on the bottom of the sample; thus, it does not contribute to the overall heating performance.

The difference between the three temperature curves indicates that the hotspot by thermal runaway is relatively small as the high-EF could not be sustained for an extended period, which means that the hotspot heat couldn't penetrate the entire sample, resulting in much lower temperature areas. This is why the gaps between the maximum and minimum EF & temperature curves are significant, e.g., the hotspot temperature reaches 1,600 °C. In contrast, some sample surface temperatures are lower than – 100 °C*.* This is because (i) the hotspot size is relatively small, (ii) the high electric field couldn't sustain a more extended period, and (iii) the thermal conductivity of lunar regolith is very low, decreasing the heat transfer from the hotspot to the sample surface. The decrease of the *EF* in the sample is related to the change of material properties by temperature increase; however, the exact cause needs to be investigated further.

Despite the temperature difference, the overall heating performance of both samples was similar. Thus, assuming the simulation represent the correct heating trend of lunar regolith, we believe that:

- Lunar mare and highland regolith would take well coupled with microwave energy and heat to be sintered/melted under a vacuum, even if the initial sample temperature is very different.
- The total energy for this simulation (375 kJ) was ≈42% of the initially targeted energy (900 kJ).
- This indicates that we may not prepare different scenarios of microwave heating experiments depending on the mission site.
- However, the simulation also reveals there is room to improve the heating performance as the strength of the electric field does not reach a maximum (or optimal) stage, resulting in a smaller hotspot size than anticipated.

WP4: Breadboard/Detailed design of the MHD payload (Lead: AVS, Participants: OU)

The updated design of the MHD payload was further analysed and detailed as follows.

Payload CAD design: The conceptual design of the payload has been refined with the following details. Some of the payload interfaces and budgets are: (i) lander power requirements – 500 W, (ii) thermal heat rejection to lander – 150 W, (iii) dimension – 1480mm (W) x 420mm (L) x 250mm (H), (iv) peak power – 450 W, and (v) total mass – 9.44 kg. Feasible mechanisms have now been implemented for the cavity's vertical loading and transport and storage of each crucible. The Microwave cavity developed in WP2 has also been integrated into the payload concept.

Crucible Transport Carousel: The carousel system moves sample containers between different stations within the payload. The carousel is raised above most other structures, is free to rotate a full 360 degrees when not holding a crucible, and is restricted to ~180-degree motion while transporting a crucible. The carousel provides the actuation for otherwise passive mechanisms such as the crucible storage wheel. The carousel arm has two semi-circular cut-outs along its length. The outermost is for holding the crucible, while the innermost allows the arm to wrap around the cavity loading mechanism without interference. The arm passively grips onto the side of each crucible with the spring-loaded ball detents, while a small ring groove provides the vertical alignment.

Crucible Storage Wheel: During the Launch, transit and landing phases of the mission, crucibles are stored within the crucible storage wheel. Each crucible is secured by a single-use hold-down release mechanism which is actuated at the beginning of the operational mission phase. The wheel's rotation is locked to prevent rotation by an additional hold-down release mechanism. The carousel is designed on a ratchet-based system with 6 discrete rotational positions 60 degrees apart, corresponding to the 6 crucibles which are stored. A clockwise rotation of the transport carousel will collect a crucible and move it to either the dosing station or the microwave cavity for heating. Rotating the transport carousel counterclockwise allows the crucible to be placed back on the storage wheel.

Dosing Station: The proposed sample collection mechanism remains unchanged from the previous iteration of the payload design, A brushing-type mechanism in which samples lose regolith from the lunar surface. Each crucible is transported underneath the transfer interface by the transport carousel to the position referred to as the dosing station. A controlled quantity of regolith is deposited into each crucible by opening a ball valve. A small voice coil mounted on the crucible transport arm provides micro-vibrations to promote a level surface to the regolith. An optical sensor determines the fill capacity and ensures consistency between the crucibles.

Microwave Cavity: In order to improve the loading/sealing mechanism, a new design update has been conducted, as shown in Figure 1. Now, the cavity comprises four main components that connect seamlessly to preserve the internal surface uniformity - preventing RF-leakage. The structure and external function have had some modifications. The loading orientation has been modified to make the crucible bottom loaded. In this configuration we could introduce a static sealing cap allowing a fixed interface for the gas lines and the pyrometer. The back panel, while internally featureless, has an external feature allowing the integration of the lead screw's fixed support, whose close proximity to the load force reduces motor torque requirements and the system's footprint. The cavity loading mechanism consists of a single stepper motor and a planetary gearbox coupled to a lead screw that will raise and lower the crucible via the elevator pad.

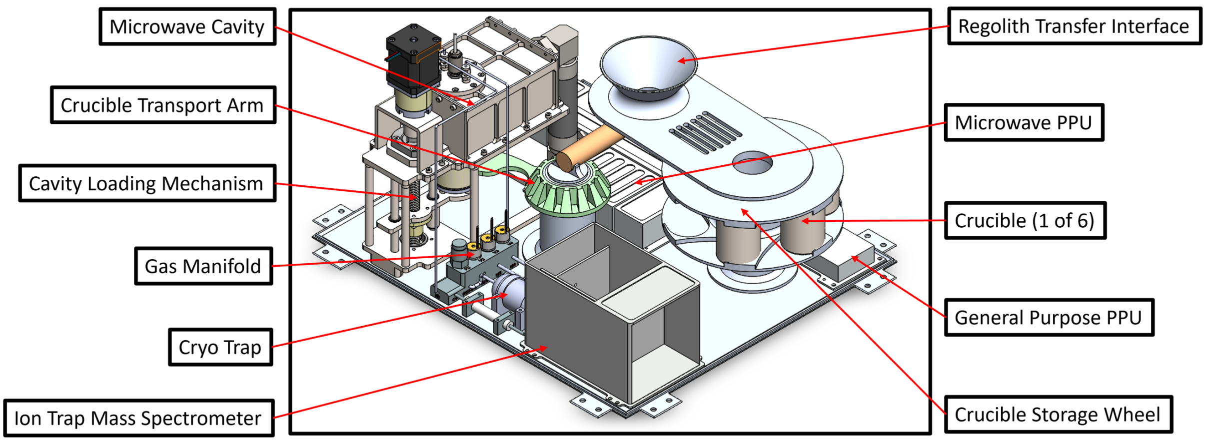

Figure 1: MHD Payload Concept

WP5: Follow-on proposal to build a prototype and flight unit of the MHD payload (Lead: OU, Participants: AVS, VIPER)

In addition to this project, we developed a preliminary design of a 250 W S-band Microwave Generator that will be used for the MHD payload with support from UKSA's research grants (PF3-090 and

UKSAG21_0088). **Thus, we have submitted a follow-on proposal to the UK Space Agency's Enabling Space Exploration 2022 funding, successfully secured the grant (ESE17, £200k), and started the project on 1st December 2022.** As we need to increase the TRL of the MHD payload further, this proposal's main objectives are as follows.

(i) Conduct extensive microwave heating of lunar simulants and oxygen extraction experiments using the newly developed subsystem during the current project. Three simulants (e.g., JSC-1A, NU-LHT-4M, ESA-1A) will be used for microwave heating and oxygen extraction with two methods – hydrogen reduction and carbothermal reaction (OU),

(ii) Manufacture and test a prototype hardware unit for a 250W S-band Microwave Generator (MWG), demonstrating state-of-the-art efficiency (>50%), implemented through solid-state integrated building blocks and customised amplification stages (VIPER RF), and

(iii) Manufacture the microwave cavity and carry out an extended test campaign at OU using regolith simulants; Advance some of the critical mechanisms and mechanical subsystems with a detailed trade-off analysis of the preliminary mechanisms of the MHD payloads; Generate a fully detailed TRL map of the MHD payload component development (AVS).

Outcomes and the deliverables (MS1, MS2, MS3)

Through the project duration (April 2021 to December 2022), we have submitted three deliverables below and published 3 journals and 6 conference papers as follows:

Publications

- Journals: Nature Scientific Report (1), Acta Astronautica (1), Advances in Space Research (1)
- Conferences: European Lunar Symposium (3), Space Resources Week (3)
- Under review: Nature Scientific Report (1), Acta Astronautica (1)
- Manuscript preparation: Advances in Space Research (1, preparation)

Deliverables

(1) First deliverables: Outcomes from WP1 and WP2, including the preliminary design of the MHD payload and the lab experiments on microwave heating of lunar simulants.

(2) Second deliverables: Outcomes of WP3 and WP4, including computational simulations of the microwave heating behaviour of the new microwave cavity design and the operation sequence of the MHD payload.

(3) Third deliverables: The compulsory deliverables (final report, executive summary, five minutes video of the outcome summary, illustration of the activity in one self-standing image), WP4-Task3 report, microwave cavity hardware CAD drawing, and three microwaved (1,000W, 600W, 250W) samples. A 3D printed MHD payload model (1:2 scale) will be posted to ESA in January 2023, and the manufactured microwave cavity will be handed over to The Open University in January 2023.

Conclusion & future work

With ESA's tremendous support, we developed the preliminary design of the Microwave Heating Demonstrator (MHD) payload concept through this project. As we aim to build a flight-ready payload and to be selected as one of the lunar ISRU-derived technology demonstration missions, we will continue to increase the TRL of the payload subsystems while seeking additional scientific/technical experiments to be added to the payload. For example, we have recently established a research network with Universitat Politecnica de Catalunya (UPC), which plans to investigate the potential of lunar soil as an energy storage medium. Thus, we plan to add a function to the payload to measure the thermal conductivity of the microwaved samples for further analysis.