ISRU Technology Developments at the DLR Institute of Space Systems

P. Zabel[1], L. Kiewiet[2], K. Kulkarni[2], M. Rejón López[3] and S. Fälker[4]
German Aerospace Center (DLR), Institute of Space Systems, 28359 Bremen, Germany.

The Synergetic Material Utilization (SMU) research group was founded in 2021 at the DLR Institute of Space Systems in Bremen with the primary focus on combining Life Support Systems and In-Situ Resource Utilization (ISRU) systems. The group works on a combination of laboratory-scale experimental setups in relevant environments and simulations to contribute to the development of ISRU technologies for Moon and Mars. One research area is regolith beneficiation, which resulted in the development of a laboratory scale model for a multi-stage beneficiation testbed. The testbed achieved a three-fold increase in the ilmenite weight concentration compared to the unprocessed input regolith. The goal is to further develop particle size sorting and magnetic mineral enrichment processes. Another research area is water extraction and purification for in-situ propellant and consumables production. Here, the SMU group has led the EU-funded LUWEX project. Its objective is to extract, capture, and purify water from lunar icy regolith, reaching Technology Readiness Level (TRL) 4/5. Along with validating this water process chain in a relevant lunar simulated environment, the project developed a novel method to produce an icy regolith simulant. As a foundation for LUWEX, an experimental study was performed on the solubility of regolith simulants in water. Additionally, several feasibility studies have been performed on different ISRU topics. One system analysis focused of an ISRU production plant to extract oxygen and metals. Furthermore, a second analysis on the oxygen production costs and logistics on the Moon surface was carried out, leading to the conclusion that the location with the best resources is the main driver in location selection. A third study was conducted on extracting minerals on Mars suitable for plant cultivation. This manuscript gives a comprehensive overview about the results of the different research and development activities carried out since 2021.

Acronyms and Nomenclature

ASTM	=	American Society for Testing and Materials
BLSS	=	Bio-regenerative Life Support Systems
BREMEN	=	Beneficiation of REgolith and Mobile ExcavatioN
DFKI	=	Deutsches Forschungszentrum für künstliche Intelligenz / German Research Center for Artificial Intelligence
DLR	=	Deutsches Zentrum für Luft- und Raumfahrt / German Aerospace Center
ECLSS	=	Environmental Control and Life Support System
ISRU	=	In-Situ Resource Utilization
LCROSS	=	Lunar Crater Obsevation and Sensing Satellite
LUWEX	=	Validation of Lunar Water Extraction and Purification Technologies for In-Situ Propellant and Consumables Production
SMU	=	Synergetic Material Utilization
TRL	=	Technology Readiness Level
WHO	=	World Health Organisation

[1] Head of Synergetic Material Utilization Junior Investigator Group, Institute of Space Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany.
[2] PhD Candidate, Institute of Space Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany.
[3] Research Associate, Institute of Space Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany.
[4] Student Asssistant, Institute of Space Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany.

I. Introduction

REDUCING the amount of material launched from Earth is important to enable sustainable space exploration. Every kilogram of matter brought out of the gravity well of planet Earth is valuable and should be utilized, recycled, and repurposed as much as possible to make up for the energy applied to it when launching it to space. In-situ Resource Utilization (ISRU) can even make the transport of some material (e.g. structural materials for construction and infrastructure, propellant, life support consumables, electronics) from Earth to space obsolete, which would greatly reduce the costs of future exploration of solar system. Environmental Control and Life Support Systems (ECLSS) for human spaceflight already recycle and regenerate as many resources as possible in order to reduce the amount of water, oxygen and other material required for human survival in space to be launched from Earth and will do so even more in future spacecraft.

Human space exploration requires a significant amount of resources such as food, water and oxygen. Waste products such as metabolic waste, polluted water and carbon dioxide are produced by the astronauts. Life support engineers are developing systems and processes to recycle and to regenerate as many resources as possible, also known as 'closing the loops', in order to reduce the material supplied from Earth to enable sustainable human space exploration of the solar system.

Our solar system is full of resources that potentially can be exploited to greatly reduce the material required 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.

Despite the similarities among both fields, ECLSS and ISRU case studies often focus only on one of the fields and forget about integrative solutions. Near-term ISRU mostly relies on robotics and automation without the assistance of humans on-site. Often the presence of humans is rejected with the argument regarding the costs involved of setting up the required ECLSS infrastructure. ECLSS developments for Moon or Mars exploration systems, on the other hand, often overlook the utilization of local resources because of the focus on regeneration and the 'closing the loop' principle, but also by using the cost argument for setting up an ISRU infrastructure. However, in the more recent past this has changed by having more engineers and researchers acknowledging the fact that a holistic approach to resource management involving ECLSS and ISRU is required.

The concept of Synergetic Material Utilization combines ISRU and ECLSS engineering approaches to lower the material supply required from Earth. Both research and development fields utilize similar resources, technologies and processes. Each field also greatly benefits from the resources provided by the other field. Consequently, there is high potential for synergies between ECLSS and ISRU. In 2021, the young investigator group Synergetic Material Utilization (SMU) was founded at the Institute of Space Systems of the German Aerospace Center (DLR) with internal funds to form a dynamic and innovative team to pursue research in this direction. The long-term vision of the group is to establish a holistic resource management for future space exploration missions incorporating ISRU and ECLSS.

II. Overview of Current Research Topics and Infrastructures

The SMU team primarily focuses its ISRU research and technology development on applications for In-Situ Propellant and Consumables Production as defined in the In-Situ Resource Utilization Gap Assessment Report from 2021[1]. In particular the preparation of resources before processing and the resource processing for mission consumables are of interest for the team. Work is carried out on a theoretical/analytical and experimental level. While several activities are pursued in parallel at low Technology Readiness Level (TRL), specific key technologies are planned to be developed and validated until TRL 5/6.

The three topics on which the SMU group is conducting research are:

1. Regolith Beneficiation and Utilization
2. Water Extraction, Capturing and Purification
3. System Analysis and Feasibility Studies of ISRU Systems

While the first two focus on very concrete technology developments, the third topic focuses on the larger context of ISRU in space exploration and its connection to other space systems and also to mission planning.

The following chapters provide an overview about the research and development work conducted since the foundation of the research group in 2021. Whenever possible, references are provided to provide more detailed information about results and outcomes of the research.

III. Regolith Beneficiation and Utilization

The lunar regolith is a valuable resource for sustainable exploration campaigns as it contains many valuable resources such as oxygen, iron, titanium, aluminium, silicon and many others that can be the primary candidates for in-situ raw material. These materials are however scattered across the lunar surface and are present in different mineral phases and physical forms. Their respective extraction and utilization processes are highly influenced by the composition of the raw material fed into the system. Therefore, a pre-processing step to refine the excavated regolith into the desired feedstock composition is a necessary step in improving system efficiency, performance as well as sustainability. This pre-processing step is called beneficiation and has been carried out in terrestrial mining industry for decades.

A. Regolith Beneficiation Results

Acknowledging the importance of beneficiation, the SMU group has been working on beneficiation for the last four years. Oxygen is a valuable resourse and ilmenite ($FeTiO_3$) is considered as a prime candidate for this process, given its high oxygen yield per unit material processed using hydrogen reduction[2]. Additionally, the production of metals like iron and titanium as by-products of the process adds further to its utilization potential. However, ilmenite is primarily only found in the lunar mare regions with relatively scarce deposits in the lunar highlands making it difficult to utilize its high oxygen yield[3]. Therefore, the focus of the beneficiation research was directed towards ilmenite enrichment of unprocessed lunar mare regolith simulant.

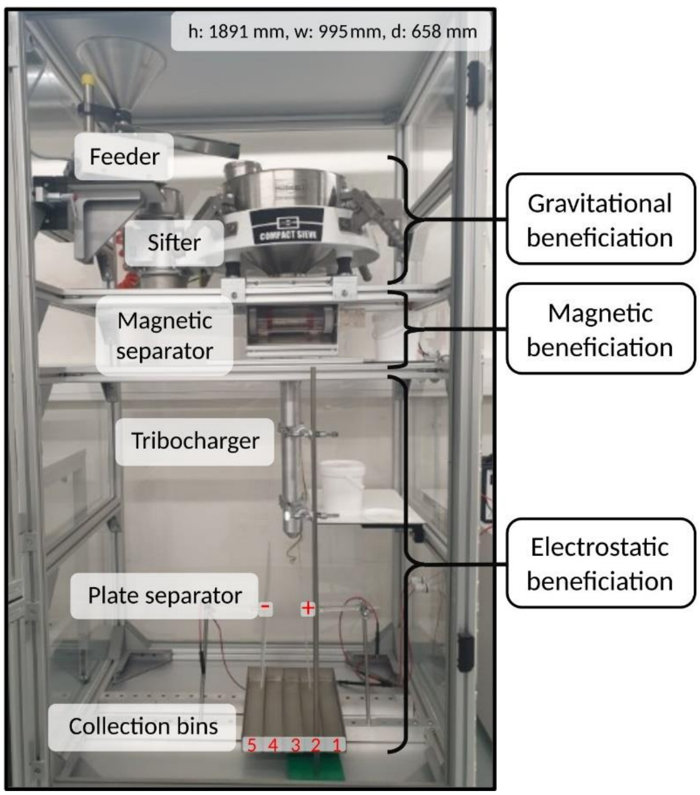

Figure 1: Beneficiation testbed at DLR Bremen.[4]

A result of this work is a multi-stage beneficiation teststand shown in Figure 1. It comprises of a vibratory feeder at the top to control the feed rate of feedstock being transferred into the system. This is followed by a vibratory sifter to filter out coarse regolith fractions and allow the finer fractions to get transferred to the magnetic separator. The separator is a permanent magnet rotating drum separator that removes the stronger magnetic fractions from the sieved fraction into a separate bin while allowing the non-magnetic or weakly magnetic material to fall further into a tribocharger. The tribocharger is equipped with a spiral aluminium surface that creates charge on the regolith particles as a result of the triboelectric effect. These charged particles are allowed to fall through a parallel plate separator that has high voltage electrostatic field across them. Depending on the charge produced on the particles, their trajectories are deflected into the respective collection bins at the bottom. More details on the development of this teststand can be found in a separate publication[5].

An extensive experimental campaign was conducted on the teststand to validate its performance across a wide range of operating parameters details[4]. Every experiment was conducted with a dried regolith simulant sample of 300 g and repeated three times to accommodate experimental deviations. The average of the three trials is considered for experimental analysis. The primary parameters considered for evaluation were the feed rate of the vibratory feeder and the voltage applied across the parallel plate separator. The rotational speed of the magnetic separator was also considered for optimization, however due to some design limitations, this was not achieved during the experimental campaign. The results from this campaign illustrated the increase in ilmenite grade by almost 3 times that of the unprocessed simulant as shown in Figure 2. The Figure 2 shows all output material collected and as shown, there was no material collected in the bins 1, 4 and 5. This is attributed to the distance between the parallel plates that was not considered within the optimization experiments for parameters within this research but it is strongly proposed for future work.

The experiments also highlighted the importance of dust mitigation strategies necessary for regolith handling technologies. The detailed analysis of the experimental campaign and the results can be found in a separate publication.[4] This topic is currently the focus of ongoing doctoral research within the SMU group, which aims to examine the full range of minerals present in lunar regolith across different beneficiation techniques. The study aims to analyze their behavior within a multi-stage beneficiation system and advance the development of a payload-style beneficiation unit, serving as a precursor for future flight missions.

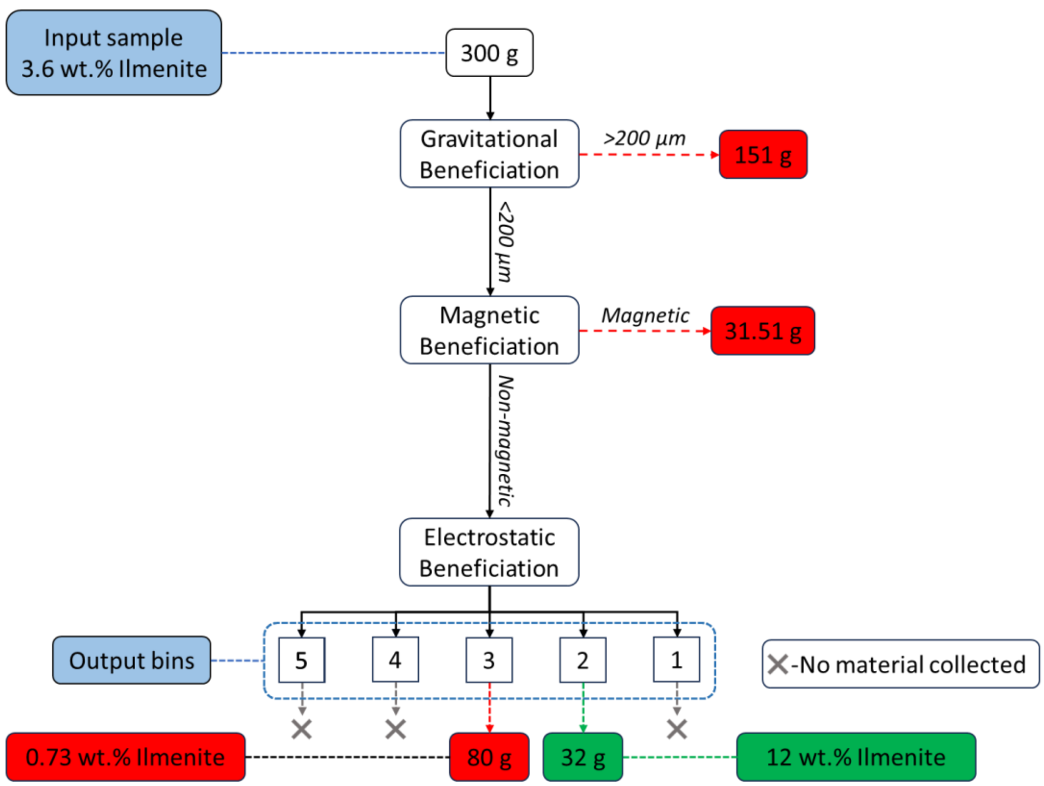

Figure 2: Beneficiation experiment results for ilmenite enrichment.[6]

B. Combining Beneficiation and Excavation

The SMU team is also working on integrating beneficiation into an ISRU process chain by combining it with excavation. This allows research interactions and develops interfaces between beneficiation and excavation, but also dust handling during the transfer and transporation of regolith. Concrete work in this direction is currently ongoing in collaboration with the German Research Center for Artificial Intelligence (DFKI). DLR and DFKI have teamed up to participate in the Space Resources Challenge 2024/25 - Collection and Beneficiation of Lunar Regolith (https://src.esa.int/).

The devised architecture is composed of two primary components: a mobile rover for regolith collection and transport, and a stationary processing system for size sorting. The mobile platform (a teleoperated four-wheeled rover) shall carry an excavation and handling system, and a delivery system to transfer the regolith to the processing unit. The material is fed into the stationary processing payload via an inlet funnel that acts as the interface between both processes and regulates regolith flow into the beneficiation subsystem. After size sorting, the processed regolith is transferred into different collection boxes depending on size distribution and ensuring minimal dust dispersion.

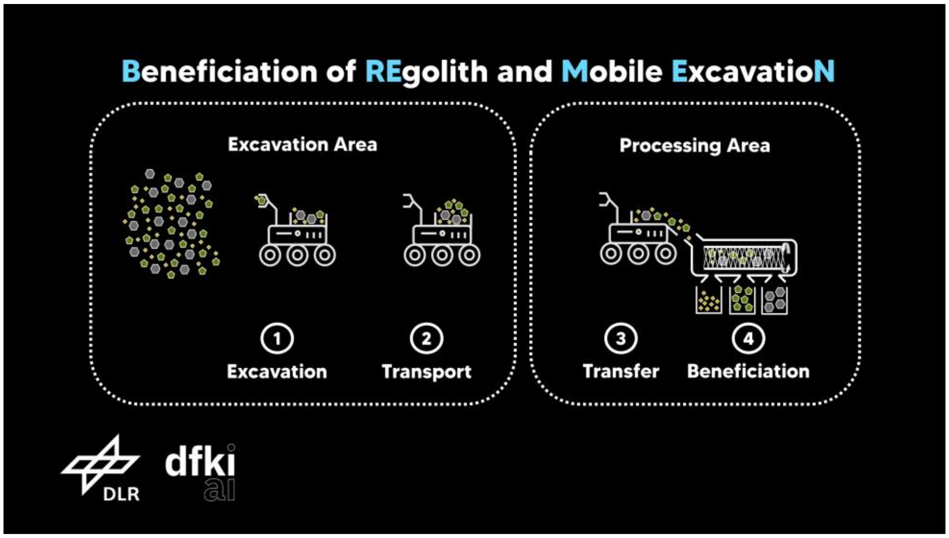

Figure 3: BREMEN (Beneficiation of REgolith and Mobile ExcavatioN) system architecture.

As represented in Figure 3, the team aims to operate in tandem the mobile rover that shall navigate a lunar analogue terrain, excavate the raw material and deliver it to the processing payload, where it shall be treated to produce the optimum feedstock for oxygen production on the Moon. Several collection and delivery operations of the rover are necessary to collect all the required regolith, while in parallel the stationary processing unit sorts the regolith. This approach optimizes the use of energy and time. The field test of the challenge takes place in October 2025 in the LUNA Analog Facility (https://luna-analog-facility.de/), which is jointly operated by ESA and DLR in Cologne, Germany. According to the challenge requirements and team objectives, the system aims to excavate 15 kg or more and deliver at least 5 kg of regolith with grain sizes between 100 µm and 500 µm. The available time to achieve the target mass is limited to 2.5 hours. The requirements of the challenge include the total weight of all systems being limited to 60 kg and the available energy being limited to 300 Wh.

At the time of writing, the team is finalizing the designs and entering the testing campaign prior to the challenge field test at the LUNA facility in Cologne.

IV. Water Extraction, Capturing and Purification

Water as a resource in space is one of the most versatile and important resources. It can allow a sustainable presence of humans by providing drinking water, oxygen, and even radiation shielding. For a more sustainable exploration of the solar system, the water can also be turned into rocket propellant, potentially lowering the launch costs from Earth. Many national space agencies and companies have an interest in the poles of the Moon, where large quantities of ice are believed to be[7], to set up a lunar economy.

At SMU, research is conducted by researchers, PhD candidates, and university students on the topic of extracting, capturing, and purifying water obtained from icy lunar regolith simulant. It started with investigating different methods to extract water on the lunar surface, and a trade-off on these methods using simulations[8,9]. Also, efforts in hybrid systems combining volatile extraction with oxygen and metal extraction were investigated[10]. The EU-funded LUWEX (Validation of Lunar Water Extraction and Purification Technologies for In-Situ Propellant and Consumables Production) project is the latest achievement in this research topic. During the LUWEX project, a method to reliably extract and purify water from (contaminated) icy lunar regolith simulant was developed and tested in a simulated lunar permanently shaded region environment.

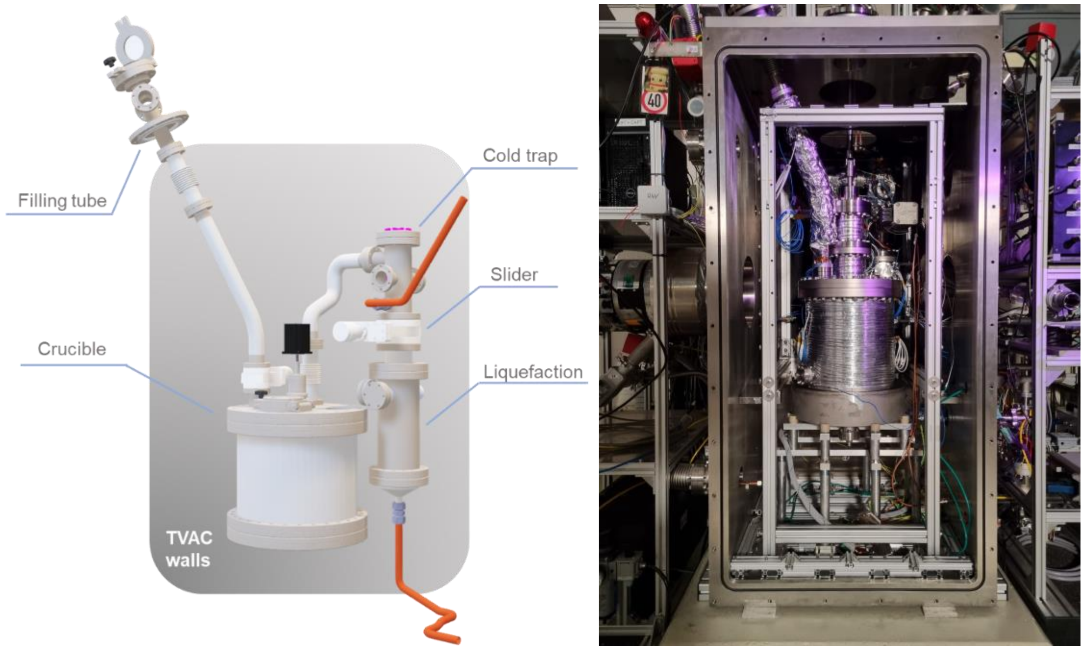

Figure 4: A 3D schematic of the LUWEX water extraction and capturing system, and a photo of the actual hardware inside in the dusty TVAC at the TU Braunschweig.

A. Water Extraction and Capturing

Extracting water from icy lunar regolith can be achieved by thermal extraction. The icy regolith is heated until the ice inside sublimates and outgasses so that the resulting water vapour can be captured. In general, a distinction can be made between two high-level methods to do this, the in-situ extraction, and the excavated extraction. For in-situ extraction, the water is extracted directly from the surface, without excavation. Excavated extraction means that the ice-bearing regolith is excavated and placed in an (enclosed) system. For LUWEX, an excavated extraction method was chosen after a design trade-off. The tests conducted are to date the largest experiments done in a relevant environment, with the system being designed to hold up to 15 kg of icy lunar regolith, and able to repeatedly capture the ice.[11,12] In Figure 4, a 3D image and a photo of the extraction and capturing hardware is presented. The relevant environment was provided by a Thermal-Vacuum Chamber at the Technische Universität Braunschweig, which was originally build to conduct research on comet physics.[13]

Figure 5: Icy regolith simulant after finishing the mixing of dried regolith simulant with ice particles.

The icy regolith simulant is a carefully crafted mixture of discrete micrometer-sized ice particles[14] and lunar regolith simulant (see Figure 5). The lunar regolith simulant used in the experiments is a mixture of 75% LX-T100 and 25% LX-M100 with a maximum particle size of 1 mm[15]. This special simulant was specifically developed for the LUWEX project. Different methods of mixing a regolith simulant with ice particles have been tested and also the thermal conductivity of the resulting mixtures was measured[16]. For each experiment, a sample of this icy regolith simulant was heated and simultaneously stirred inside the crucible. The resulting water vapour travels towards the cold trap, where it is deposited as ice on the cold fingers. Once the cold fingers collect enough ice, they are heated so the ice delaminates and falls into the liquefaction chamber, which is closed by a slider so that enough pressure can be built for the ice to melt. The main goal is to prove that a single system is able to extract, capture, and liquefy the water present in regolith. Additionally, the influence of adding methanol in accordance with the results from the LCROSS (Lunar Crater Obsevation and Sensing Satellite) mission[17], was tested to see the impact of this contaminant. Early results show that the capturing process is greatly influenced by the presence of methanol, since it can condense on the cold trap surface and prohibit water-ice from forming. Investigations of the benefit of stirring the sample are currently being conducted to see whether the increase in complexity is worth the potentially increased efficiency and extraction rate.

After the water is liquefied, it is delivered to the Water Purification and Storage Subsystem, which is described in detail in a separate publication[18]. The preliminary results indicate that the LUWEX system was able to recover water from icy regolith simulant with an energy efficiency of roughly 50 g/kWh. After fine-tuning the concept of operations, the recovery efficiency was above 70 %. The best-capturing efficiency obtained was roughly 90 %, meaning that around 10 % was lost to the simulated lunar environment. The remaining mass was left in the sample and has likely never sublimated. As can be seen in Figure 6, a lot of contamination found its way into the liquid water, highlighting the need for proper purification techniques.

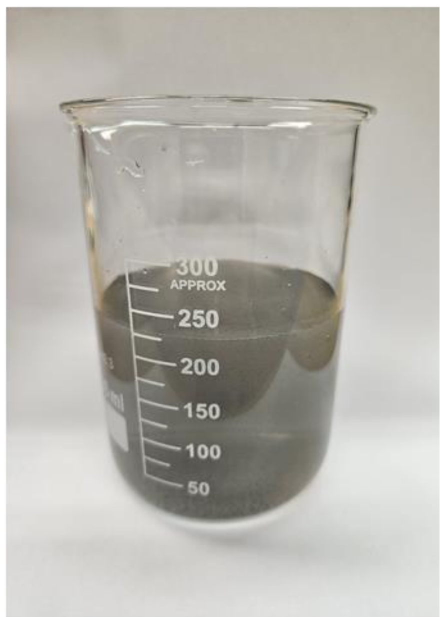

Figure 6: The first successfully extracted, captured and liquefied water from LUWEX experiments (before purification).

B. Water purification

All systems located and utilised on the Lunar and Martian surface will be exposed to lunar dust. This also applies for the process chain of in-situ water extraction, capturing, transport and usage. Due to the adhesive properties and the very fine particle sizes of lunar regolith, which covers the entire surface of the Moon, contact between liquid water and lunar dust will be unavoidable. The resulting contamination negatively affects the quality of the water, making it unusable for drinking or electrolysis without proper treatment, and imposes the risk of clogging pipes, valves and other essential instruments. At SMU, an experimental study was conducted to analyze and characterize water contaminated by lunar dust. A lunar water simulant with known composition and contaminants was developed and provided for water purification systems, such as used in the LUWEX project, acting as basis for the determination of the functionality and quality of the purification process. In addition, a lab-sized water purification system was developed and put into operation.

A variety of dissolution experiments was conducted to understand the concentration of ions that are released from selected lunar regolith simulant samples into the water[19]. In detail, the concentrations of Al, Ca, Fe, K, Mg, Mn, S, Si and Ti as well as pH and turbidity were measured and documented. Furthermore, the influences of pH, regolith simulant to aqueous solution ratio, dissolved oxygen, simulant particle size and exposure time on the results of the dissolution experiments were investigated. The results were compared to the NASA and WHO (World Health Organisation) requirements for drinking water and the ASTM (American Society for Testing and Materials) requirements for Type I and Type II electrolyses water for further evaluation.

The insights gained from the dissolution experiments was used to define and produce a representative simulant for lunar water[20] contaminated with lunar dust and volatiles. It is composed of ultrapure water with a contamination of the lunar regolith simulant LHS-1 in a simulant to water ratio of 1:100 and represents the worst-case scenario. This raw water simulant shall serve as input solution, allowing to test water purification systems without the urge to develop an associated extraction system. The results of the purification tests can be compared to the parameters of the input water simulant to assess the functionality and quality of the purification process chain in a comparable and reproducable manner, which is inevitable for the ongoing development of water purification systems for future lunar habitats.

In this context, a trade-off of purification technologies was conducted and a lab-scale water purification system was developed, see Figure 7. The system consists of a dust-removal subsystem via sedimentation and filtration, an ion removal subsystem via distillation, a measuring subsystem with selected instruments for pH, EC, fluid level and temperature, and the control subsystem executed through a LabView program. It is designed to operate fully automatic and purify water to Type I water for electrolyses according to ASTM[21].

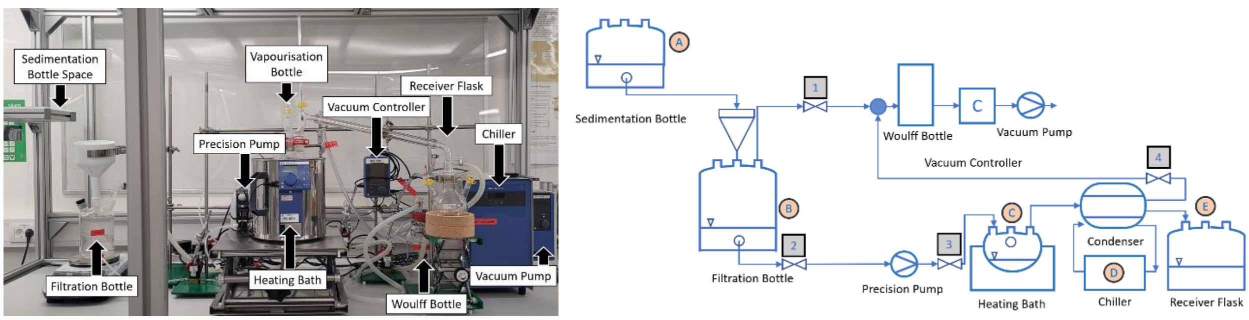

Figure 7: Photo and schematic of the water purification laboratory setup at DLR Bremen.

V. System Analysis and Feasibility of ISRU Systems

A number of system analysis and feasibility studies of ISRU systems are conducted by the SMU team. The topics cover a broad range of ISRU applications on Moon and Mars and the interactions with other systems and mission planning.

A. ISRU production plant designs

One study analyzes and compares three different ISRU production plants designed to extract metals and oxygen from lunar regolith, particularly at the Moon's South Pole. These ISRU processes are hydrogen reduction of ilmenite combined with carbonylation producing low-carbon steel and oxygen, molten regolith electrolysis producing ferrosilicon alloys and oxygen, and molten salt electrolysis (FFC-Cambridge process) combined with vacuum distillation producing aluminum–silicon alloys and oxygen. Each process was assessed based on mass and power requirements, effectiveness, and scalability. Based on this analysis the best option is molten regolith electrolysis, requiring 6776 kg of hardware to produce 25 t of ferrosilicon alloys annually, along with 23.9 t of oxygen. The mass payback ratio was 0.14 kg of hardware per kg of product per year, the best among the three methods. Hydrogen reduction of ilmenite with carbonylation highly depends on the ilmenite concentration in regolith. For low iron-content lunar regolith, this process was inefficient, requiring 4.65 kg of hardware per kg of product per year. In high-Ti Mare regolith regions this method becomes more competitive. Molten salt electrolysis with vacuum distillation is capable of extracting aluminum-silicon alloys, but the process was heavily penalized by the mass of electrolyte salts required (85% of the total plant mass). The study emphasized the need to reduce the salt ratio significantly to improve efficiency.[22,23]

B. Nutrient extraction from Martian regolith

A student work investigates the feasibility of extracting nutrients from Martian regolith to support bio-regenerative life support systems (BLSS) for future crewed Mars missions. It focuses on higher plants, green algae, and cyanobacteria, which are critical for oxygen production and food supply in extraterrestrial habitats. Essential macronutrients (potassium, calcium, magnesium, sulfur, sodium, silicon) and micronutrients (iron) are present in Martian minerals. Martian regolith composition, based on global mineral data, shows potential for in-situ nutrient extraction. Different extraction methods are evaluated. One option is leaching and chemical extraction using various acids, salts, and heat treatments. A second option is the direct use of minerals as fertilizers. The third option is microbial treatment utilizing microbes to enhance nutrient availability. The study confirms that Martian regolith contains sufficient nutrients to support plant and algae growth, but effective extraction methods must be optimized for Martian conditions. Future work should focus on refining nutrient extraction techniques and integrating them into sustainable BLSSs for Mars missions.[24]

C. Location dependent flight cost for ISRU-refueling

Another study examines the impact of location-dependent flight costs on ISRU site selection and determines whether these costs significantly alter the optimal placement of resource extraction facilities. To assess the viability of different ISRU locations, the study evaluates two primary cost components. First: ISRU Efficiency – This factor is influenced by the concentration of ilmenite (a key oxygen-bearing mineral), availability of solar energy, and the complexity of regolith processing. A higher ilmenite concentration translates to more efficient oxygen production with less required infrastructure. Second: Transport Efficiency – The cost of launching oxygen from the lunar surface to an orbital fuel depot depends on the energy required for the transfer. This study utilizes delta-v (Δv) maps to calculate the fuel expenditure necessary for different locations, taking into account factors such as launch site elevation, lunar rotation, and direct transfer trajectories to the Lunar Gateway. The research models a scenario where an ISRU plant extracts oxygen from lunar regolith through hydrogen reduction of ilmenite, a well-established process that involves breaking down ilmenite ($FeTiO3$) using hydrogen to release oxygen. The produced oxygen is then transported to an orbital fuel depot using a single-stage launcher that refuels its hydrogen at the Lunar Gateway. The study finds that flight costs have a minimal impact on ISRU location selection compared to ISRU efficiency. Ilmenite concentration is the dominant factor in choosing an ISRU location. Since its distribution varies significantly across the Moon's surface, the infrastructure and operational requirements differ considerably based on location. Flight costs are secondary to ISRU efficiency. Even in a scenario where direct launch transfers are used (rather than more fuel-efficient orbital maneuvers), the differences in spent fuel per payload remain small compared to the total ISRU costs. Long-duration transfer orbits eliminate flight cost concerns. If oxygen transport utilizes low-energy transfer orbits that take more than 100 days, the cost differences between different launch sites become negligible. The best ISRU sites remain consistent regardless of whether transport costs are included in the selection criteria. This suggests that planners can prioritize locations based on resource availability rather than being overly constrained by launch cost considerations.[25]

VI. Summary and Future Plans

This manuscript describes research and development activities of DLR's SMU team in the field of ISRU. Results and outcomes of analytical and theoretical work achieved in three specific areas of ISRU since 2021 are presented. Furthermore, ongoing activities in the areas of regolith beneficiation and utilization, and water extraction, capturing and purification are summarized.

In the field of regolith beneficiation, technologies for particle size sorting and mineral enrichment will be further investigated using laboratory experiments in order to provide a pre-defined feedstock for oxygen and metal extraction from regolith. The long-term goal is to design, build and test an efficient and compact multi-stage beneficiation system, which could be tested during a technology demonstration mission to the lunar surface.

In the coming years the SMU team will further develop the water extraction and capturing technologies of the LUWEX project in order to validate these up to TRL 6 preparing for a future technology demonstration mission on the lunar surface. Purification of in-situ raw water will be further advanced together with the corresponding partner from the LUWEX project.

While the current focus of the technology development is primarily on the application on the lunar surface, the team will also investigate which adaptations are necessary to also apply the same techniques for Mars ISRU. Additionally, the SMU team will conduct more system analysis and feasibility studies for ISRU systems whenever an interesting research question arises. The field of Regolith Based Agriculture[26] is also of high interest for future activities as it is a research area which directly relates to the original idea of SMU to combine ECLSS and ISRU in a holistic resource management approach.

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