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ORIGINAL PAPER

From lunar regolith to oxygen and structural materials: an integrated conceptual design

Alexandra Radl[1] · Ksenija Milicevic Neumann[2] · Hermann Wotruba[3] · Elisabeth Clausen[1] · Bernd Friedrich[2]

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Abstract
To enable a long-term presence of humans in space, it is essential to use extraterrestrial raw materials to reduce the need for transporting resources or produced materials from Earth. In recent years, a lot of research has been conducted on different ISRU processes, such as regolith excavation, mineral processing and the extraction of oxygen using metallurgical processes. However, it is not sufficient to just focus on a single process but also to focus on how the different processes interact. Therefore, RWTH Aachen's Integrated Conceptual Design presents a novel concept for the production of oxygen and high-quality metal materials. To meet the challenges of mining in space, selective mining is used to provide the best possible blend based on the original material of the deposit. This process is followed by mineral processing to provide a high-quality ilmenite-rich concentrate, the input material for metallurgical processes. Using the novel MOSARI technique, consisting of molten salt electrolysis and metallothermic reduction, oxygen and metal materials can be recovered. Furthermore, this represents a zero-waste approach for the complete utilization of the material.

Keywords Space resources · Mining · Mineral processing · Metallurgy · Regolith · Oxygen

1 Introduction

To enable a long-term human presence in space, the use of extraterrestrial raw materials, which is called In Situ Resource Utilization (ISRU), is essential to reduce the need for transporting those resources or produced materials from Earth.

In this paper, a concept for the efficient production of oxygen and high-quality metal materials is presented taking into account mining, mineral processing and metallurgic processes. The biggest impact on choice of technologies and their feasibility is the lunar environment that has to be considered early on in the decision-making process. In recent years, a lot of research has been conducted on different ISRU processes, such as regolith excavation, mineral processing and the extraction of oxygen using metallurgical processes. Therefore, currently investigated individual technologies and approaches in fields of regolith excavation, mineral processing and oxygen extraction have been evaluated addressing their advantages and disadvantages. However, it is not sufficient to just focus on a single process but also to focus on how the different processes interact. This led to RWTH Aachen's integrated idea for ISRU. Furthermore, the circular economy aspects and sustainability are integrated into this developed concept that has not been done earlier before closing the material cycle and avoiding waste production.

The primary objective in ISRU will be to support vital processes. Therefore, the ice at the lunar poles is of great interest as it can be used for life support. Furthermore, it could be separated into hydrogen that could be used as propellant, and oxygen. [1, 2] Besides the ice at the lunar poles, the regolith is also relevant for ISRU. It is a fine and dusty layer that covers the entire lunar surface and is generally about 4–5 m thick in the mare areas and 10–15 m in the lunar highlands. The regolith is formed by complex processes, in which frequent meteoroid impacts destroy the lunar bedrock and lead to the formation of the dusty layer. Subsequent impacts furthermore lead to mixing of the lunar regolith, which is called lunar gardening Therefore, the regolith is

✉ Alexandra Radl
aradl@amt.rwth-aachen.de

[1] Institute for Advanced Mining Technologies, RWTH Aachen University, Wüllnerstr. 2, Aachen, Germany

[2] IME Process Metallurgy and Metal Recycling, RWTH Aachen University, Intzestr. 3, Aachen, Germany

[3] Unit for Mineral Processing, RWTH Aachen University, Lochnerstr. 4-20, Aachen, Germany

heterogeneous in its composition. It has an ilmenite content that varies from 0 to 11% (e.g., 7–11% in some areas of Mare Australe) [3], it consists of agglutinates with a content from 10 to 17%, it contains 15–25% impact glasses and 3–50% basaltic components. [4] The lunar regolith could be used in its original form as construction or shielding material [5], but research also focuses on the extraction of oxygen from oxygen bearing minerals.

However, the regolith is fine and dusty, electrostatically charged and has adhesive characteristics which for example can cause problems with the visibility of cameras. In addition to this, the particles are abrasive, which complicates all activities in the lunar environment [4, 6].

The lunar environment differs significantly from the terrestrial environment and therefore has an impact on developing ISRU technologies and implementing processes. With 1.62 m/s^2, the gravity is only about $^1/_6$ of the terrestrial gravity. The lunar atmosphere is thin and therefore is often considered as a vacuum. As it provides only little thermal insulation there are extreme temperatures and temperature changes on the lunar surface. The mean temperature varies between − 153 °C during the lunar night and 107 °C during the lunar day [4]. Furthermore, the temperature changes rapidly which must be considered because of the thermal expansion and contraction of materials. In addition to this, the radiation of the sun is more intense than on Earth and is not only a big danger for humans but can also lead to damage of electronic components [7]. On the moon, the duration of a day cycle is about 29.5 Earth days which means lunar day and lunar night both are about 15 earth days long [8]. Due to the small angle between the spin axis of the moon and the ecliptic plane, there are some locations close to the poles that are permanently illuminated (the so-called "peaks of eternal light") and others that are permanently shadowed [9]. Consequently, the peaks of eternal light would be more favorable for ISRU activities because of easy access to energy supplied from solar power. However, from a resource point of view the permanently shadowed regions (PSR) are also of interest because of water ice, but the energy supply in these regions will be more challenging. [10, 11] Lastly, as the lunar environment is challenging for humans, all processes should at least work tele-operated or even autonomously [12], so humans could, if necessary, control processes from a control room, that might be integrated into a habitat.

2 Review of the ISRU process chain

A number of processes are necessary to convert raw materials into usable products. Basically, these processes are similar for space and terrestrial applications. The first task is prospecting for valuable resources, which is followed by the excavation of the mineral raw material. In the next step, the objective of mineral processing is to prepare the raw material for further subprocesses or usage. This prepared feed could be used either directly for construction purposes or as an input for beneficiation processes, e.g., metallurgical processes for the production of oxygen and structural materials. Finally, the products can be either stored or used.

In addition, a sustainable and responsible use of the raw materials and the lunar environment is essential. For this reason, the highest possible utilization of the excavated material as well as the recycling and reuse of waste or residual streams must also be considered as part of ISRU.

Since the scope of this publication is to present a concept for the production of oxygen and structural materials, excavation, mineral processing and metallurgical processes of the regolith are the focus of this paper. The conventional process chain for mineral concentrate treatment is shown in Fig. 1. Figure 2 shows the simplified ISRU process chain for zero-waste regolith processing. Firstly, the lunar regolith must be excavated. The next step is the mineral processing to get a concentrate for the metallurgical processes. Finally, this concentrate can be used to produce oxygen and structural materials.

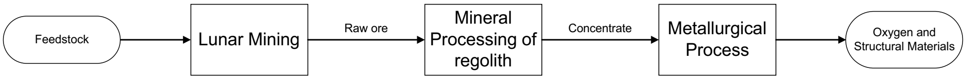
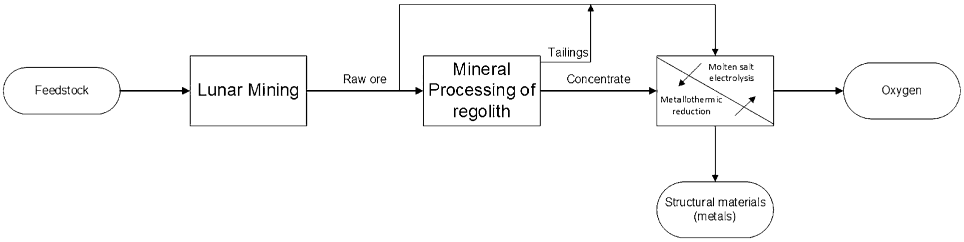


Fig. 1 Conventional process chain for mineral concentrate treatment

Fig. 2 Simplified ISRU process chain for zero-waste regolith processing



2.1 Regolith mining

The excavation of the lunar regolith is the first process in order to make the mineral raw material available. Based on the extensive experience in terrestrial mining, a lot of research has been focused on developing space mining technologies by advancing or adapting terrestrial technologies and concepts [12].

In terrestrial mining, machines must have enough weight to counteract the digging forces which occur during the excavation of the regolith [13]. However, when mining in a low-gravity environment, this would require even heavier machines. Instead, for lunar mining lightweight machines are considered [12], first because of payload constraints [14] and second, big and heavy machines would not be useful because initially significantly lower excavated masses will be required compared to terrestrial mining applications. For this reason, the research focus in recent years mainly has been on how to excavate regolith in low gravity [15] and on how to reduce the excavation forces [14]. Throughout the literature, there are a number of reviews of excavation concepts [13, 15].

The first study on equipment for regolith excavation was conducted by Eagle Engineering in 1988. They recommended large front-end loader devices associated with hauling machines but with a higher mass. Therefore, mining in low gravity was not considered to be a problem [13, 16].

In 2005, King et al. [17] evaluated different concepts for regolith excavation and presented the Bucket Wheel Excavator (BWE), a bucket chain overshot loader, as most promising excavation equipment.

In 2009, Clark et al. [18] presented a novel approach for the excavation of regolith. The Bucket Drum Excavator (BDE) is an adaption of a bucket wheel. It has 16 small scoops mounted on the outside of the cylinder. Each scoop collects only small quantities of regolith. Furthermore, the scoops are staggered between rows to reduce the excavation forces. Therefore, the mass of the BDE can be reduced.

In 2011, the NASA developed the Regolith Advanced Surface Operations Robot (RASSOR) that has counter-rotating bucket drums so that the digging forces are neutralized [13]. It has been further developed and the RASSOR 2.0 has a lower system mass with a higher load capacity of regolith at the same time. The next objective is to increase the Technology Readiness Level (TRL) of RASSOR 2.0 from 4 to 5. As soon as the RASSOR 2.0 reaches TRL 6, it will be a possible candidate for future space mining missions [19]. Even though the RASSOR represents an innovative concept for mining in a low-gravity environment, it has a relatively high amount of moving parts, which might be a disadvantage from a maintenance perspective.

Apart from these concepts, there are two different approaches for reducing the digging force. In 2008, Zacny et al. presented a pneumatic excavator that is based on the vacuum jet-lift method and can be used for excavation and particle transfer. It is advantageous because it has a 3000:1 mass lifting efficiency and no moving parts. [20] However, it remains unclear if there is a limitation on the particle size in a way that bigger particles or rocks on the lunar surface could damage the tool and if there is a risk for blockage.

Another approach for reducing the digging forces is to use the percussive excavation method. After a few centimeters, the regolith becomes highly consolidated and, thus, highly dense [4]. This is maybe even more the case for icy regolith at the lunar poles [14]. When using a scope with percussive actuator the regolith is loosened and it is possible to dig deeper and faster. At the same time, this method requires a lower force for excavating the regolith [21, 22].

Furthermore, the NASA started to organize challenges and competitions for extraterrestrial mining since 2007 [13]. Within these challenges, teams, mainly student teams, can develop and test new and innovative excavation concepts [15]. However, there is still no ultimate solution to excavate regolith which is also because of a lack of knowledge about the environment and the whole ISRU process. Therefore, further research must be conducted in future.

2.2 Mineral processing

Moon regolith needs to be processed to prepare it for different applications. These are the production of oxygen, water, metals and various construction materials (e.g., stone wool, printed housing walls, etc.).

While mineral processing on earth is a well-established technology, its application in space needs to be adapted due to low or no gravity and no or reduced atmosphere. Many unit processes (such as crushing, grinding, screening, separating, concentrating) make use either of gravity or of the difference between gravity and other forces like magnetic or electrostatic forces. Other processes, like dry classification, need air or other gases as media. Therefore, the inventory of mineral processing methods has to be evaluated to identify suitable processes for application on the moon with its low gravity and without a technically useable atmosphere [23].

A detailed review of the state of knowledge in mineral processing of lunar regolith is provided by Rasera et al. [24]. Even though many technologies are considered, there is still no established feasible method for mineral processing especially considering the whole process chain toward valuable products—oxygen and structural materials.

2.3 Metallurgical processing

Lunar regolith has been considered, next to water ice, as one of the main sources of oxygen necessary for existential survival of humans in space and as oxidizing agent for propellants. The distribution and difficulties related to water extraction, especially from permanently shadowed regions [25–27] make the easily accessible regolith with high oxygen content more attractive as raw material. Taylor [28] and Schlüter et al. [29] gave an overview of existing in situ technologies for oxygen production considering both named sources indicating the amount of technologies that are under investigation and their requirements. However, in all these mentioned investigations, the researchers were focused on oxygen production without a deep consideration of valuable by-products—metals. The metals and alloys produced in situ will have a significant role in building the habitats enabling the human settlings and opportunity of further exploration developments. Therefore, these technologies will be briefly considered from both aspect—oxygen and metal production and present a view taking into account already a circular economy approach and zero-waste concept.

Application of metallurgical processes for regolith processing has been considered already in 1960s during the moon fever. One of the first techniques tested was hydrogen reduction of regolith based on simplicity and knowledge of the process [30]. The product of the reaction is water that can be electrolyzed to oxygen used as oxidizing material for propellant, breathing, and hydrogen that can be returned to the reduction step. Based on the composition of the lunar regolith and its thermochemical properties, only iron oxide can be reduced by hydrogen yielding the iron. These processes were also experimentally confirmed in next decades by NASA and European exploration groups [31–37] giving more details of mechanisms and yield. Drawbacks of this approach remain to be the selectivity of the input material constrained to ilmenite mineral, beneficiation efforts to process and concentrate the iron-bearing ore as well as the availability of hydrogen for the reaction itself.

Carbothermic reduction is also one of the often-considered methods utilizing the pure carbon-graphite [38–41], carbon monoxide [42] and methane [43, 44]. In this reaction, mainly iron is produced but also its alloys and carbides depending on the working temperature. Slag consists of other oxides present in the regolith. Main off-gases coming out of the reaction are CO_2 and CO and if methane is used, additionally H_2 is formed. In this case, similar requirements as in hydrogen reduction are necessary, such as beneficiation of iron rich minerals and carbon source.

Metallothermic reduction has not been so extensively explored as previous ones, mainly because the oxygen is not among the products, but some researchers have explored the possibility to use calcium [45], aluminum [46, 47] and magnesium [48] as reduction agents. The benefit of this technology is that it is an autothermic reaction, self-starting after initial ignition. The products of this reaction are metals/alloys and metal oxides that are re-used for oxygen production and/or for fabrication of ceramic-based products. Depending on which input material and ratio are used, diverse alloys and slags are obtained. The re-supply of reduction metals from Earth and beneficiation efforts are still necessary.

Electrolysis is lately the most followed approach for the high yield oxygen production, applying the electricity to dissociate regolith into oxygen at anode and metals/alloys at cathode. There are different types of electrolysis depending on the material used for the process. Molten oxide electrolysis (MOE) consists of solely regolith without electrolyte that is brought into molten state at high temperatures and electrolyzed. The advantage of this process is that no additional material, except regolith, is necessary which is in vast amount at the surface of the Moon. The disadvantages are high working temperatures increasing the material requirements to withstand these extreme conditions and low conductivity of the melt. The current research has covered not only the modeling and development of reactor [49, 50] but also electrochemical measurements and initial electrolysis trials [49–52]. Since the investigations are focused on oxygen production, the knowledge of exact metallic product composition is not fully addressed. Molten salt electrolysis (MSE) employs typically the halide-based electrolyte in which regolith is either de-oxidized or dissolved at moderate temperatures. Currently, two technologies based on MSE exist in industrial scale on Earth, Fray-Farthing-Chen (FFC) process for titanium production and Hall–Héroult-based cell for aluminum production. The first one—FFC—is done in chloride-based electrolyte and has set itself as an example for regolith processing. The raw material is placed in a crucible that serves as a cathode and applying the electrical current, de-oxidation of regolith occurs leaving behind the metallic powdery mixture of elements contained in regolith whereas the oxygen evolves at inert anode. The oxygen recovery is very high ($\approx$ 100%) and different alloys are determined as a metallic product [53, 54]. Still, the inclusion of electrolyte into metallic powder, incomplete de-oxidation and suitable inert anode material are challenges to overcome. The investigations based on Hall–Héroult process and fluoride-based electrolyte in which the regolith is dissolved and dissociated onto oxygen and metals with the current application have been also considered [46, 55]. The authors have proved the feasibility of the process and have been able to extract oxygen and alloys containing regolith constituents. In all electrolytic case, the suitable inert anode material and long-term process control will be the main challenges to be resolved.

3 RWTH Aachen's integrated conceptual design

For the efficient production of oxygen and high-quality metal materials it is necessary to provide the best possible input materials for each process step. Therefore, it is necessary to follow a holistic approach that takes into account mining, mineral processing and beneficiation. First, selective mining will provide the best possible blend based on the original material of the deposit. Ideally, the excavated material should already have a high concentration of ilmenite which is an oxygen bearing mineral. The excavation of regolith is followed by mineral processing to provide a high-quality ilmenite-rich concentrate which will be the input material for metallurgical processes to recover oxygen and metals. Using the novel MOSARI technique, consisting of molten salt electrolysis and metallothermic reduction, this process will be optimized. Furthermore, this represents a zero-waste approach for the complete utilization of the material. [56].

3.1 Selective mining

Lunar mining machinery and methods must be innovative, for example, to deal with the lower gravity, robust because of the harsh environment and work highly autonomous. Besides, mining machinery must also be small and work efficiently to reduce launch costs and to effectively mine in space. These requirements are partially similar to the requirements for today's terrestrial mining activities, where the increasing awareness of safety and environmental aspects as well as sinking raw material concentrations and more complex deposits have made the excavation of mineral raw materials more challenging [57].

Important elements for meeting these challenges are the increasing automation of processes and the development of innovative mining concepts. Therefore, solutions for space and terrestrial mining can be similar in some aspects.

A concept to meet the requirements of an efficient excavation process is selective mining. While in this context bulk mining means to excavate the entire regolith at a certain site, selective mining means to only excavate the regolith with higher grades of the valuable resources, while the regolith with lower grades of the valuable resource is left in the deposit. Therefore, it is necessary to know the following information.

1. Requirements of the subsequent processes

   For certain applications or processes, defined characteristics of the regolith, for example, a certain mineral composition or certain particle sizes, are required or at least helpful to make the process more efficient. Therefore, the subsequent processes define the valuable resource as well as required mass flows and where and when the raw material has to be provided.
2. Local conditions

   Furthermore, there is a need to know where to find the valuable resources and in which concentrations. Therefore, sensor technologies must be integrated into the mining machinery to characterize the raw material immediately before and during the excavation process.

The formation of regolith by meteorite impacts and subsequent lunar gardening lead to the heterogeneous composition of the regolith. [4] Even though, no great differences in the mineral composition are expected [4], there might be some differences in the concentration of some minerals at certain places. To provide an ilmenite-rich concentrate to metallurgy, it could be helpful to identify areas with a slightly higher concentration of ilmenite and to excavate the regolith only in these areas. Of course, it will never be possible and useful to excavate single particles and, thus, have the "perfect" input material for subsequent processes; even slightly higher concentrations of ilmenite will help to optimize mineral processing. This could be achieved as follows. There is a mine site, like schematically shown as a block diagram in Fig. 3. This mine site is divided into smaller areas for excavation. For each block, a material characterization will be conducted to determine the ilmenite content. In Fig. 3 different shades of gray mean different concentrations of ilmenite. In this first concept, no absolute concentrations of the ilmenite and no dimensions of the blocks are mentioned as the information will highly depend on the excavation site and on the sensitivity of the mining equipment. Now only areas, where a slightly higher concentration of ilmenite is present, will be excavated. Thus, it is possible to reduce the excavated masses and therefore the required machine dimensions. At the same time, an ilmenite-rich regolith can be provided to mineral processing and the whole excavation process will be more efficient.

3.2 Mineral processing

Mineral processing is part of the process chain for mineral resources. It receives the feed material from mining/extraction and delivers processed material to the various consumers and applications. The preferred feed material for the mentioned applications is lunar mare regolith, which consists mainly of pyroxene, basalt, anorthosite,

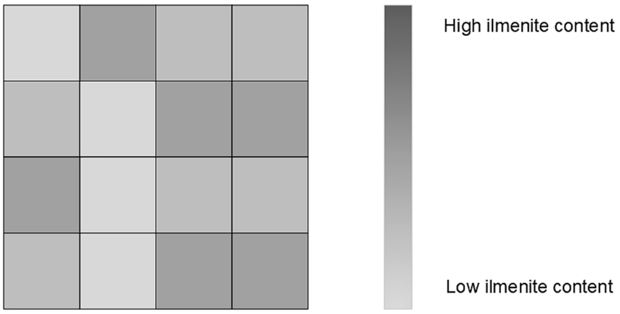


Fig. 3 Schematic block diagram of the mine site

olivine and ilmenite. A typical composition, which is available as LMS-1 Lunar Mare Simulant from exolith labs [58] is given in Table 1.

Critical for mineral processing is the very fine particle size distribution of the lunar mare regolith (Mean Particle Size: 50 µm, Median Particle Size: 45 µm, Particle Size Range < 0.04 µm–300 µm). Typical dry mineral processing methods work in the particle size > 50 µm, so half of the mass of the lunar mare regolith is smaller than this size.

General physical properties of the lunar mare regolith are:

- Loose (no blasting is needed for excavation)
- Fine particle size (< 1 mm), so no crushing/grinding is needed

It is not clear, if coarse material occurs at depth, as the samples on the moon have been taken from the surface. If coarser stones are present in depth, screening to remove them from the fine regolith may be necessary.

Arrhenius et al. [59] describe the electrostatic condition of the regolith due to radiation. The material is electrostatically charged, so fine particles attract each other and form agglomerates, which can cause problems during classification/screening or influence electrostatic separation. Surface charge decreases with increasing particle size.

Also there is no available information about the electrostatic condition and its influence on mineral processing of the regolith due to solar wind. If the material is electrostatically charged, agglomeration of fine particles may occur, which can cause problems during separation or influence electrostatic separation.

Physical properties which can be used to separate/upgrade the regolith, e.g., to produce an ilmenite concentrate or material suitable for other purposes like laser-printing or stone wool are:

- Particle size (if certain minerals are enriched in certain particle size classes).
- Magnetic properties (differences in magnetic susceptibility).
- Conductive properties (conductor–semi-conductor–non-conductor).

Table 1 Mineral composition of LMS-1

Component	Wt.%
Pyroxene	32.8 Wt.%
Glass-rich basalt	32.0 Wt.%
Anorthosite	19.8 Wt.%
Olivine	11.1 Wt.%
Ilmenite	4.3 Wt.%

For example, ilmenite is a paramagnetic mineral while anorthosite is a diamagnetic mineral. Ilmenite can therefore be separated from anorthosite by high-intensity magnetic separation. Magnetic concentration of ilmenite is widely used on earth, e.g., for beach sand deposits. However, the magnetic properties of ilmenite as the main target mineral are in a similar range as other iron-bearing minerals of the regolith like pyroxene and olivine.

Ilmenite is also conductor, while anorthosite is a non-conductor. They may be separated by electrostatic separation. As well as magnetic separation, electrostatic separation of (heated) ilmenite is used for ilmenite production on earth.

If screening is needed to remove coarse particles/stones, vibrating or centrifugal screens may be used.

For the separation/concentration of magnetic particles, low- and high-intensity drum or belt separators as well as crossbelt- or disc separators are appropriate. For electrostatic separation/concentration, corona drum separators or slide separators may be used.

Another possible feed material for mineral processing is material from lunar polar regions, where water ice is present (and ice is the target). This material is most probably hard (frozen), so crushing/grinding, e.g., by jaw or roll crushers may be needed. From crushed rock, water may be then separated by evaporation/condensation.

There are a number of issues regarding mineral processing on the moon or other planets, like:

- Presence of naturally enriched feed material (e.g., with higher ilmenite content than average regolith, only detectable by prospection/exploration).
- Processing properties/composition of the different feed materials.
- Transferability of test-work made on earth.
- Dust handling and de-dusting during excavation, transport and processing.
- Sensitivity of mineral processing methods to strong changes in temperature.
- Influence of solar wind on processing properties.

3.3 MOSARI technique

All named processes for metallurgical regolith processing are focused on oxygen production and the characterization including application of obtained metallic product is considered only surficial. Considering the metallurgical technologies for regolith processing keeping in mind that oxygen production is still vital but also taking advantage of simultaneous metal and alloys production and utilization importance, the MOSARI concept has been developed consisting of molten salt electrolysis and metallothermic reduction.

Hydrogen and carbothermic reduction processes have low oxygen yield requiring mainly beneficiated input material and reduction agents that are not available on lunar surface. Also, the obtained products from both reactions need to be post-processed to yield the desired oxygen. On the other hand, electrolysis is semi-continuous with capability to process both non- and beneficiated regolith. In that sense, electrolysis also offers a high oxygen yield. Knowing the challenges that follow molten oxide electrolysis (MOE) (high working temperatures, physical properties of the melt, etc.), our choice led to molten salt electrolysis (MSE). Further consideration of electrolyte constituents has revealed some advantages of fluoride-based salts in comparison to chlorides such as lower vapor pressure [60] leading to reduced evaporation rates. Also clean separation of metal from electrolyte following Hall–Héroult approach in comparison to FFC in chlorides is advantageous. Furthermore, our long experience in research and process automatization [61–63] and the named reasons above led to decision that MOSARI concept employs molten salt electrolysis in fluoride-based electrolyte.

In this step, the oxygen will be produced at inert anode and all metals from input material deposited at the cathode.

The evaporated amount of electrolyte will be captured in the off-gas chamber as it is practiced by aluminum industry, and re-circulated to the cell. The possible separation methods of evolved oxygen from potentially remained salt vapors is already investigated and described by Schlüter et al. [64]. Since the oxygen evolution occurs at the inert anode a sufficient distance is to be maintained to the cathode to prevent the re-oxidation of the deposited metallic material. The corrosion of the cell body and components by hot oxygen will be minimized using ceramic insulations. The deposited solid alloy can be stripped from the cathode sheets/rods, which then will be re-used in the process.

So obtained alloy can be further utilized in metallothermic reduction as reducing agent. It selectively reduces the nobler metallic components from regolith concentrate without any energy consumption. The advantage of the concept is that electrolysis can be run under autogeneous oxygen environment and that metallothermic reduction benefits from lunar vacuum. Remaining slag (oxides) can be used either for 3D printing [65], construction materials or be returned into electrolysis cell and electrolyzed again to oxygen and metals. The typically used cell for molten salt electrolysis and reactor for metallothermic reduction at IME Process Metallurgy and Metal Recycling institute are presented at Fig. 4.

The re-utilization of products closing the material circle is a good starting point for establishment of zero-waste and circular economy activities in lunar environment, reducing the necessity of re-supply from Earth. Specifically, in our initial RWTH integrated concept the alloy obtained from electrolysis of regolith rich in metals like Ca, Mg, Al and Si will be used as reduction agent for beneficiated ilmenite concentrate to get Fe-rich alloy, which can be used as construction material for human habitats. Since the metallothermic reduction does not require any energy input except ignition start, it is an economically viable route to obtain functional material on the Lunar surface. This approach can be applied also for other beneficiated minerals leading to different products. Since the surface of the Mars is also covered by regolith this concept can be transferred to this planet as well. The schematic depiction of MOSARI concept is presented at Fig. 5. In general, this concept should contribute

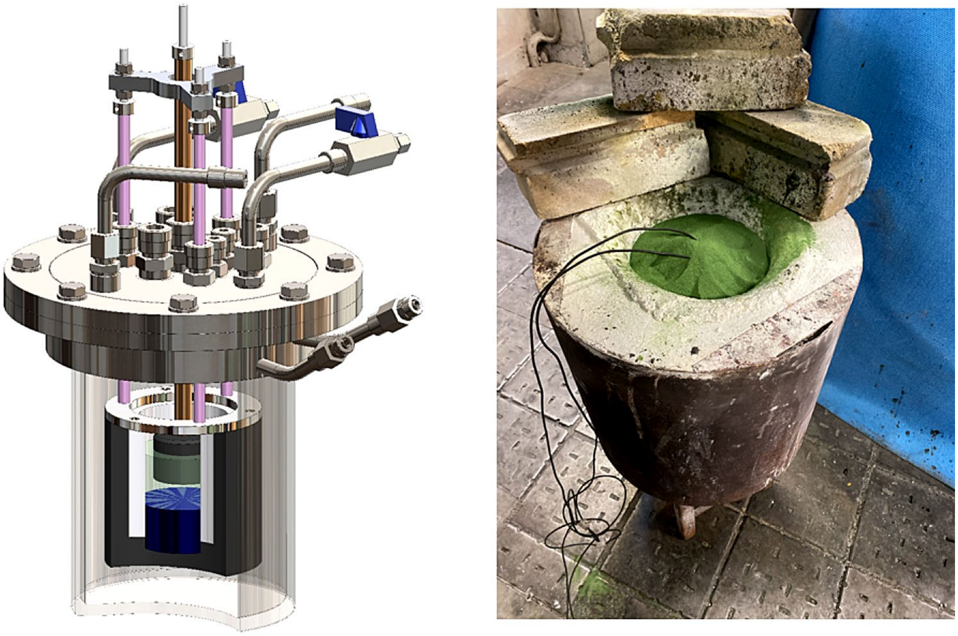


Fig. 4 (Left) Cross section of typical cell used for molten salt electrolysis process; (right) Typically used reactor for metallothermic reduction at IME institute

to the oxygen production and higher product quality with increased efficiency in comparison to so far investigated methods named in this manuscript. Since the metallothermic reduction is integrated, the energy consumption of the concept is expected to be lower than other methods for subsequent upgrade of obtained master alloy from electrolysis process. The experiments for MOSARI concept, i.e., molten salt electrolysis and metallothermic reduction are ongoing.

4 Conclusion and outlook

A new concept for the production of oxygen and high-quality metal materials was presented. RWTH Aachen's integrated conceptual design follows a holistic approach taking into account mining, mineral processing and metallurgical processes instead of focusing on a single process.

Through selective mining, it is possible to provide the best possible blend based on the original material of the deposit. Thus, the excavated mass flows can be reduced, and the excavated material already has a slightly higher concentration of ilmenite as an oxygen bearing ore. However, as this is a new approach for space mining applications, new subprocesses such as the material characterization within the excavation process need to be investigated.

The excavation of regolith is followed by mineral processing to provide a high-quality ilmenite-rich concentrate which will be the input material for metallurgical processes to recover oxygen and metals. There are a number of issues regarding mineral processing on celestial bodies, such as dust handling or the influence of solar wind on processing properties, that need to be considered in future research.

Finally, the MOSARI concept, consisting of molten salt electrolysis and metallothermic reduction, does not only focus on the production of oxygen but also takes advantage of the simultaneous metal and alloys production and utilization. The concept is developed considering the current trend and assumed capabilities of lunar mining and mineral processing but also robust enough to process untreated regolith. Further advancements and optimizations are still to be done to make these processes suitable and functional in lunar harsh environment. The combination of two metallurgical process closing the material loop is of outmost importance toward circularity bringing the lunar and terrestrial benefits.

In further studies, relevant investigations including hardware development and testing will be conducted in order to specify the requirements for the presented processes and, thus, specify the presented concept. The investigations will initially be carried out separately for the individual subprocesses, but always taking into account the entire process chain. Once these have been successfully carried out and

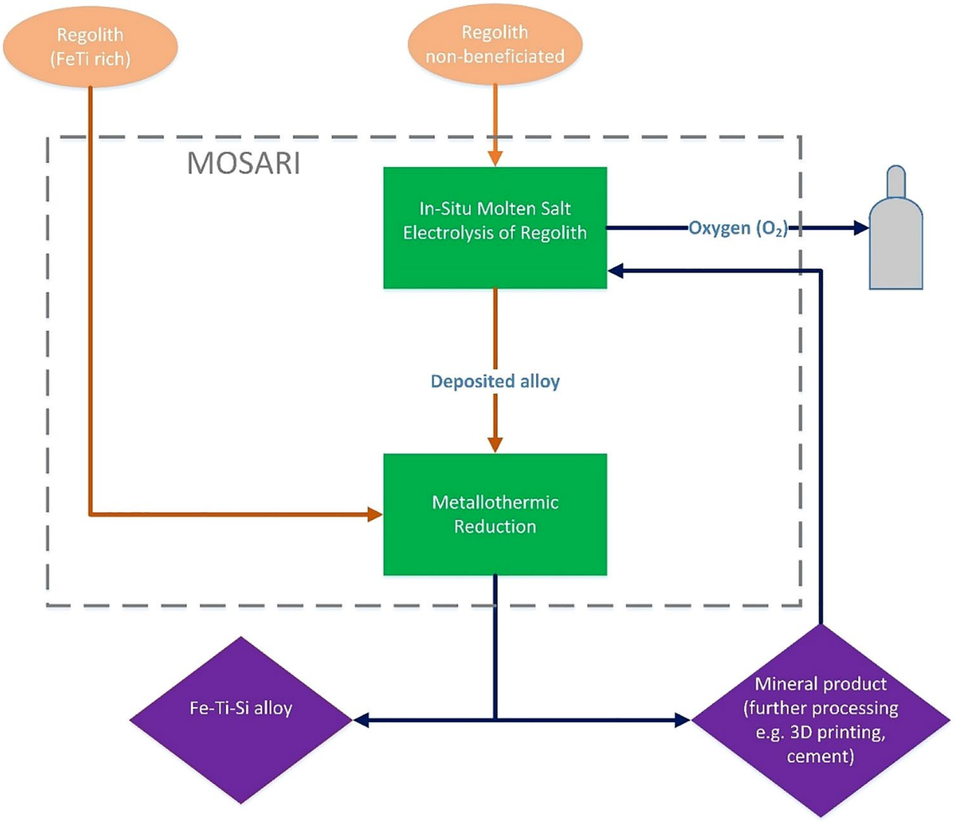


Fig. 5 Schematic presentation of MOSARI concept for oxygen and structural material production from regolith on the Moon and Mars

concepts expanded and optimized, testing of the entire process chain is possible in the future.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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