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An Economically Viable Lunar ISRU Process for Oxygen and Metal Production and Related Benefits for Terrestrial Applications

Achim Seidel and Pierre-Alexis Joumel*†*
** Airbus Defence and Space*
Claude-Dornier-Strasse, 88090 Immenstaad, Germany
Achim.seidel@airbus.com – pierre-alexis.joumel@airbus.com
† Corresponding Author

Abstract

A sustainable exploration of the Solar System will be dependent on the use of local resources, provided that they can be produced very efficiently such that the mass of the locally produced resources exceeds the mass of any needed consumables or spares to sustain the process. Any facility considered for that purpose will therefore need to be as compact and robust as possible, minimize the need for maintenance and spare parts and maximize the efficiency of the process. For the specific case of oxygen and metal production from regolith on the Moon an attractive process would need to have the capability to reduce most constituents of lunar regolith and have a high oxygen yield in order to be largely site-independent. Current trends in process development are reviewed and a new process is proposed that will enable an attractive small, simple, compact and efficient lunar facility design for high-purity oxygen and metals production, and produces a metal product that is well suited for a range of downstream manufacturing processes such as additive manufacturing, and aerosol deposition. With its design for minimum maintenance and mass, maximum compactness and robustness, and zero emissions this process is also very interesting for terrestrial applications in the area of clean metals production, and could be a contribution to lowering the emissions of greenhouse gases associated with metals production.

1. Introduction: From ROXY to Mini-ROXY: The next step towards an efficient method for oxygen extraction from regolith

Space exploration activities are expected to grow significantly over the next decades as evidenced by current trends and numerous roadmaps presented at the national and global levels, beginning with the International Space Station and continuing to the lunar vicinity, the Moon, asteroids and Mars.
Institutional investments in space exploration capabilities and missions serve an important role by advancing technologies, reducing risks and identifying new markets where competition can spur innovation that generates further benefits. Interest from the private sector is creating new opportunities as space agencies look to expand human presence into the Solar System. Growing capability and interest from the private sector indicate a future for collaboration not only among international space agencies, but also with private entities pursuing their own goals and objectives. In particular, the development of commercial launchers is expected to become an enabler for many new applications as the globally available launch capacity increases and the cost per kg to orbit decreases.

Space Exploration is an evolving mega-trend. Indeed:
- Plans include living on the Moon and eventually Mars in the coming decades.
- Space exploration is resource-intensive.
- The costs to transport resources from Earth to the Moon or even Mars are prohibitive
- Need to produce the major resources locally

In order to have a sustainable Moon exploration, we need to be able to use the resources available locally. Therefore, “ISRU” (In-Situ Resource Utilization) is an enabler for Space Exploration
- ISRU will grow exponentially over the next decades
- Commercial demand ~ tens to hundreds of tons O2p.a. by 2030
- Demand for silicon and metals will soon follow

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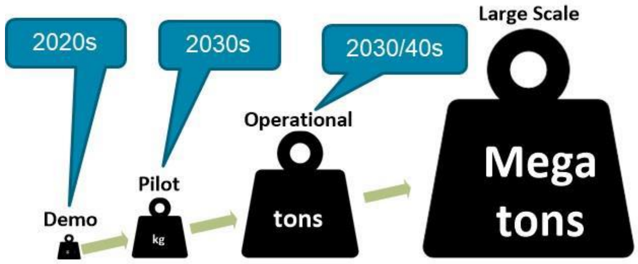

Figure 1: Exponential need of local resources.

Learning how to "live off the land": It is generally understood that sustainable exploration of the Solar System will be dependent on the use of local resources. Human lunar surface scientific exploration will enable further evaluation of the resources on the Moon as potential reserves. The investigations will help determine appropriate methods for resource extraction and processing, and maximizing their use to enhance human exploration capabilities while reducing cost. Those activities could synergistically enable access to lunar samples for science, while scientific investigations of polar ice deposits will also reveal their potential as resources. Learning to use local resources effectively ultimately increases science returns because increased ISRU activities allow crews to spend additional time conducting scientific activities.

For several decades, the use of local resources at exploration destinations has been studied as a way to limit the cost and complexity of bringing all the needed supplies from Earth. Water and oxygen are high priority resources, as they can be used for life support consumables and the production of rocket propellant. Other resources, including bulk regolith for construction and radiation shielding, solar-wind implanted gases, and the many chemicals and minerals that make up the surface materials on the Moon, Mars and asteroids may also be valuable for sustained long-term human presence

The promise of ISRU is to establish affordable extraterrestrial exploration and minimize transportation needs. The prerequisites:
–High efficiency
–Mass of products > facility mass
–Mass of products > consumables
–Near emission-& waste-free processes
ISRU processes are also very interesting on Earth due to their low resource consumption and emission-free characteristics

1.1 ISRU processes for oxygen and metals extraction

Many processes for reduction of lunar regolith to produce oxygen have been proposed:

• Hydrogen reduction and Carbo-thermal (methane) reduction:

–Chemical reduction of lunar regolith using hydrogen is a comparably simple means of extracting the oxygen from the mineral phase, mainly FeO, SiO2, and TiO2. The reduction with hydrogen occurs at temperatures in the range of 700-1000°C, with an optimum towards the higher temperature boundary. It has been reported that the oxygen yield is directly proportional to the FeO content of the regolith. In a subsequent reaction step, the produced water can be electrolyzed to derive oxygen and hydrogen. The latter can be recycled and fed back to the initial reaction. The initial amount of hydrogen must be provided by transport from Earth.

–Carbo-thermal reduction of regolith can be utilized to extract oxygen from the mineral phase with methane as a reagent. Minerals susceptible to this reduction include iron oxides and silicon oxides. In the first process step carbon monoxide/dioxide is produced. Water is produced in a second reaction step, where the carbon monoxide/dioxide reacts with hydrogen. This reaction step is referred to as Sabatier reaction or methanation. Besides water, methane is produced, which can be fed back to the initial reaction step. As in the reduction with hydrogen process from above, the product water can be split by electrolysis to produce oxygen and hydrogen.

•Molten regolith electrolysis:

–With Molten Oxide Electrolysis (MOE) the regolith is electrolyzed directly. This process requires the oxides to be molten and thus operates at significantly high temperatures (>1500°C, depending on oxide

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composition and metal to be reduced), which comes with significant technological challenges related to containment and anode deterioration.

•Ionic liquid electrolysis:

–Regolith reduction with ionic liquids provides a pathway for electrochemical production of metals and oxygen on the Moon and Mars without permanent restocking raw materials from Earth. Metals are extracted via chemical dissolution of regolith and subsequent electrochemical deposition of pure metals in ionic liquids in a closed system, whereas oxygen is produced at the anode. The process is based on the use of so-called Ionic Liquids (IL), which are transported once from the earth. IL serve as solvents for the partial or complete chemical dissolution of the metal oxides. In addition, they are also the electrolyte for the electrochemical production of metal and oxygen. Ionic liquids are salts that are present in liquid form at room temperature or slightly higher temperatures and are very stable electrochemically. In addition, they have a very low vapor pressure and therefore, they work under the vacuum conditions on the moon without any protection measures. Since ionic liquids do not participate directly in the electrochemical reaction, they are not consumed. A well-known Ionic Liquid for the electrodeposition of aluminum is 1-Ethyl-3-methylimidazolium chloride. This process allows lowering the electrolysis operating temperature to less than 100°C, making it attractive in terms of energy consumption and materials handling, and is therefore very interesting for lunar applications. Challenges exist due to the high stability of the oxides which can make the dissolution of minerals, e.g. olivines, anorthites difficult. Another advantage is the possibility of separating different metals from complex mixtures, such as those obtained in the reduction of regolith or from recycling material. Due to the possibility of producing pure metals, the potential uses are expanded and the products that can be manufactured are more sophisticated

•**FFC Molten salt electrolysis:**

–Another electrolytic process is based on molten salt electrolysis which has been used in terrestrial applications to produce metallic titanium, molybdenum, and tungsten from oxides. This FFC (Fray, Farthing, Chen)-Cambridge process involves the solid-state electrochemical reduction of metal oxides to metals in molten salt (CaCl2) at temperatures of around 900°C. This process can theoretically reduce all lunar minerals and oxides, which removes any constraints on regolith composition (and therefore it is suitable for oxygen extraction on the Moon). This FFC process has been demonstrated at industrial levels for production of titanium. In contrast with the previous processes discussed above, the main reaction of the FFC-Cambridge process results in the direct production of oxygen, i.e. a separate electrolysis step is not required to produce oxygen. In terms of the desirable characteristics mentioned above the FFC process has therefore large advantages over the other reduction processes: it should produce large amounts of oxygen; that is, it should reduce the majority of the mineral constituents of lunar regolith, and has a very high oxygen yield, defined here as the fraction of the oxygen content in lunar soil which is recovered, of up to 100%

1.2 ROXY

The ROXY (Regolith to Oxygen Conversion) process has been developed by Airbus with the intention to mitigate or eliminate most issues that limit the attractiveness of the current terrestrial FFC process for lunar applications, and to establish a reactor and system design that meets the requirements for an economically viable lunar oxygen production facility.

The ROXY concept is based on a combination of key technologies and features into a novel and integrated solution, in particular a molten salt reactor, an oxygen ion pump anode, a porous metal cathode cup, salt removal/recovery from cathode cup by evaporation, and recovery of the reacted regolith from the cathode cup. The implementation of the concept will lead to a drastic simplification of the reactor and the downstream gas management system, and will further lead to a robust, small, low-mass, simple and compact overall system design, with very little need for maintenance and/or the re-supply of consumables.
–ROXY meets all of the ISRU viability criteria
–ROXY has been specifically conceived for oxygen and metal extraction from lunar regolith
–Operation in vacuum, no process gas, direct production of hi-purity oxygen, production of metal powder
–Invented by Airbus, based on a long heritage of the SOM process developed by Boston University

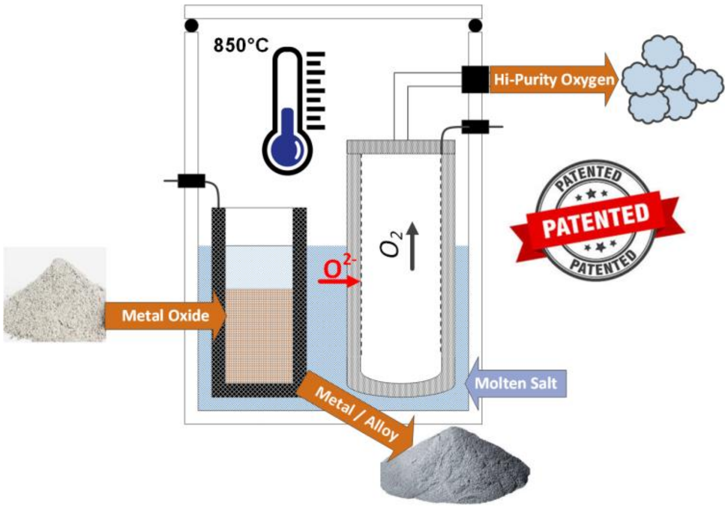

Figure 2: ROXY working principles. The reactor with the porous metal cup cathode that contains the regolith powder in contact with the molten salt, and the zirconia oxygen ion pump that recovers high-purity oxygen from the molten salt are shown on the left. Elements needed to handle the harvested oxygen are limited to a gas tank, and are shown on the right. The porous metal cup can be heated to evaporate any remaining salt after the reaction and to evaporate volatiles from raw regolith when placed outside of the reactor. Not shown are the regolith insertion/removal mechanism, and ancillary equipment

A key element of the ROXY process is the oxygen ion pump, which is a tube made of yttria-stabilized zirconia with an anode and current collector on its inner side, and a flange mounted on its upper end which provides the connection to a downstream oxygen management system. The oxygen ions generated at the cathode pass through the molten salt, then through the oxygen ion pump to the anode, where high-purity oxygen is produced. Various high-performance and robust current collector designs have been developed by the team, for example a solution based on liquid silver.

Another key element of the ROXY process is the porous metal cathode cup, which is made from cellular metallic materials. In order to manufacture materials with manifold structure parameters and properties numerous technologies have been introduced during the past 20 years. Materials with interconnecting structures and pore sizes in the range of 20 µm up to several mm have been developed.

1.3 The ROXY Benefits

The ROXY process has a number of benefits both for the electrochemical process, the design of an overall system based on this concept, and for the development of a lunar payload:

Process benefits:
In current terrestrial FFC concepts the anode must conduct electrons at high temperature in a pure oxygen and molten salt environment, which is very challenging from a materials compatibility point of view. The innovative Oxygen Control System between the salt and anode removes this problem.

Since the anode is “behind” the zirconia membrane the oxygen is separated from the molten salt. The oxygen ion pump therefore prevents the pure oxygen gas from reaction with the reactor vessel or the reduced regolith, i.e. no oxygen is lost to corrosion with the reactor vessel and the quality of the reduced regolith is improved. Contamination of the produced oxygen with inert gas from the reactor or molten salt is eliminated due to the high selectivity of the oxygen ion pump for oxygen.

As another key benefit parasitic currents, e.g. due to electronic conduction are eliminated since the electronic conduction path from the cathode to the anode is essentially cut by the oxygen ion pump. Consequently, higher voltages and current densities are possible and the energy efficiency of the reaction increases while all the advantages of the FFC Cambridge process are maintained. To the best of our knowledge, no other anode technology can achieve these

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results because all other anodes produce gases in the electrolyte that react with the metals produced and the electrodes, or corrode the reaction chamber.

Even though the main focus of the lunar demonstrator mission is on oxygen production, it should be noted that the ROXY process will also be ideally suited to provide reduced regolith in powdered or sintered form as a high-quality raw material for the manufacturing of a wide range of products "Made on the Moon" using techniques such as additive manufacturing, aerosol deposition, etc.

System Benefits:
Benefits on the level of an overall ROXY-based system arise from the much simpler architecture and lower complexity of a ROXY-based reactor compared to a classical terrestrial FFC set-up:

- The need for a gas system to manage/recirculate the inert gas, including gas storage, compressors, instrumentation and piping, etc. is eliminated
- The leak rate requirements for the reactor cover are drastically reduced, since the process will operate in vacuum, and the function of the cover seal is limited to the containment of the molten salt. Also, less pressure differential will have benefits with respect to container material selection and wall thickness, and therefore system mass.
- Due to its low volatility the evaporation of the specific ROXY salt electrolyte mixture will be very limited and the evaporated salt electrolyte will be contained by the reactor. Salt loss due to evaporation which could be a major concern is therefore not an issue.
- Since the presence of molecular oxygen in the salt bath is essentially eliminated unwanted oxidation reactions and corrosion will be drastically reduced.
- In addition, the reactor design provides for individual control of the temperature at the reactor body, bottom, and cover, and thus enables a thermal management to e.g. condense the salt vapor at the reactor cover, if desired.
- A dedicated system to separate the inert gas from the produced oxygen, and a salt particle filter are not needed as the OCS already performs this function
- A dedicated system to analyze the composition of the produced oxygen, such as a mass spectrometer is not needed, since the OCS is highly selective, and high-purity oxygen is directly produced. Note that YSZ-based oxygen ion pumps are considered for medical applications
- Due to the elimination of electronic conduction in the salt bath the efficiency of the reaction is increased and the power required by the reactor is reduced
- Due to the compact reactor design, the mass, accommodation and thermal control requirements are reduced
- Few active elements such as sensors and actuators are needed to monitor and control the reactor leading to lower requirements for the control electronics.

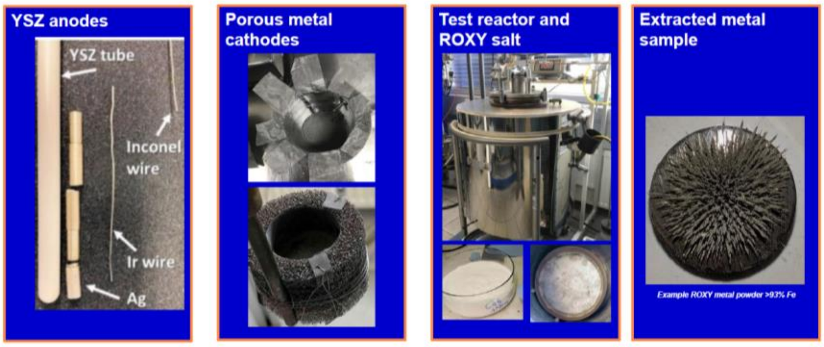

Image credit: Fraunhofer IFAM

Figure 3: ROXY lab test pictures.

1.4 ROXY Lunar Demonstrator

An ISRU Pilot Plant represents a key milestone in the overall exploration strategy to enable a sustainable human presence on the lunar surface. Ultimately, Airbus aims at demonstrate the process on the Moon:

• 50-100 g of oxygen in 1 lunar day

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- Advanced process diagnostics with Electrochemical Impedance Spectroscopy
- Very low mass and power demands

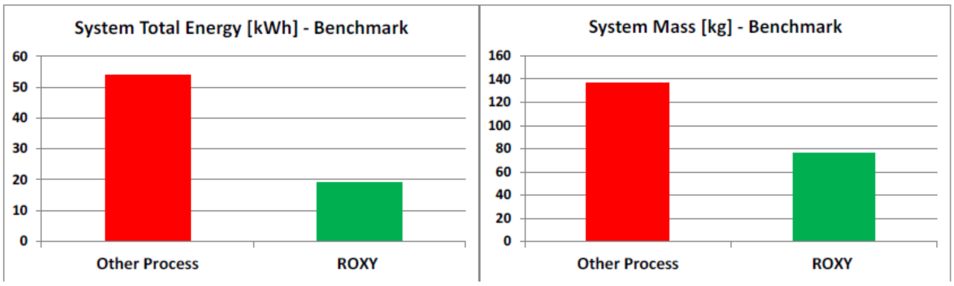

Figure 4: ROXY energy and mass benefits.

ROXY: The path to scalability
The scalability of the design proposed herein to this scenario will be assessed for all major aspects of the operation from excavation to production. Scale up principle inherited from reference facilities includes an increasing number of anodes and cathodes. An attractive scaled-up lunar ROXY system can be implemented with existing technology, and will operate near the thermodynamic efficiency of the reaction.

- ROXY is scalable to pilot and operational scales
- Scalability principle: large number of anodes & cathodes
- Energy efficiency increases with increasing reactor size
- A large ROXY plant will produce excess heat
- Combination with lunar heat storage facility would be very attractive and a novel solution for lunar energy storage

2. Mini-ROXY: The next step towards resource efficiency

In order to adapt ROXY to a lunar demonstration, the concept of Mini-RXY has been established. The principle consists of the elimination of the reactor vessel and the use of the YSZ tube as crucible, as follow:

Features:
–Much smaller form factor
–Further mass reduction
–Flexible power needs via thermal insulation

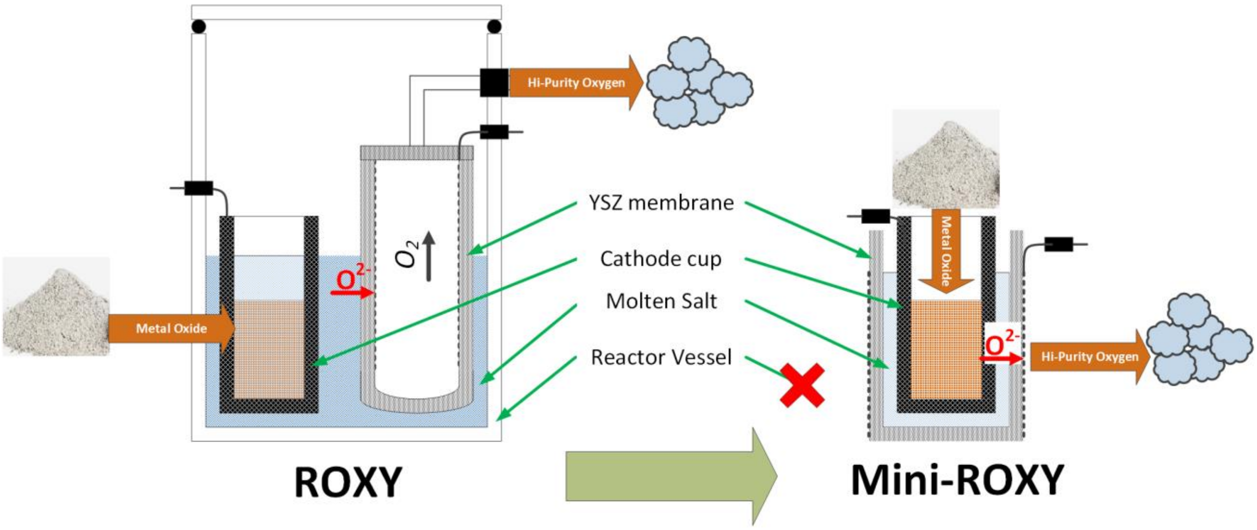

Figure 5: Mini-ROXY concept.

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2.1 Mini-ROXY Benefits

A smaller lunar demonstrator brings the following benefits:
- Low resource requirements (<10kg, <50W)
- Demonstration and characterization of oxygen production on the Moon
- Flexible accommodation on landers and rovers
- Rapid development cycle
- Basis for scale-up

Currently, the team is focusing on regolith reduction on oxygen production and metals extraction. This will lead to the next steps of a ground test campaign and a lunar demonstration preparation such as:

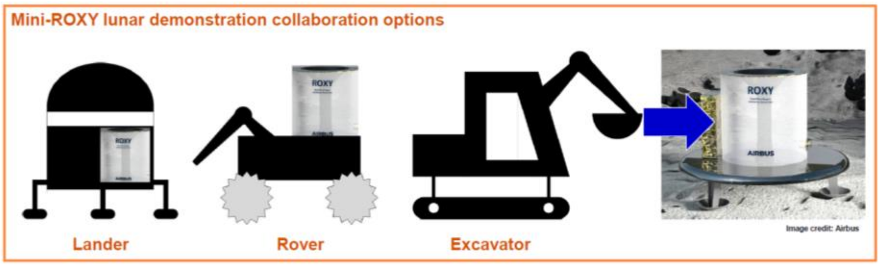

Figure 5: Ground demonstration envisaged.

3. Conclusion

ROXY is an innovative process to extract oxygen and metals from lunar regolith that meets the viability criteria for ISRU. The proposed Airbus ROXY process will mitigate or eliminate several issues that limit the attractiveness of the current terrestrial FFC process for lunar applications, and will thus enable an attractive, small, simple, compact and efficient ISRU lunar payload design.
A space-grade solution for the core element, the oxygen ion pump is available; substantial heritage in terrestrial applications shows that no principle issues related to the development of a lunar payload based on this concept exists. A convincing proof of principle has been achieved in a series of tests, such that the way towards an operational system is now clear. ROXY is therefore uniquely suited for a variety of extraterrestrial and terrestrial applications.

Lunar ROXY facilities will be very attractive due to their compactness, low mass, low power consumption, and high efficiency. The advanced Mini-ROXY is the next step towards resource efficiency and is the basis for upscaling towards larger lunar facilities. Mini-ROXY will allow a low-cost lunar demonstration of the ROXY process, with short development time, and flexible accommodation options on a variety of landers or rovers