Fraunhofer IFAM

Request for Ideas

Oxygen and Metals on the Moon

1.1 Background: ISRU – An Enabler for Space Exploration

1.1.1 ISRU (In situ resource utilization)

The exploration of the solar system, and as a first step of the Moon, will heavily depend on the use of local resources at exploration destinations. The build-up of lunar infrastructures and colonies will require the availability of metal-based products for construction and other applications, as well as oxygen.

There is a real and near-term potential for a commercial market for liquid oxygen (LOX) and water sourced from the Moon. It has been estimated that the cumulative ISRU market size will grow to ~1 billion $ by 2030 and further to 63 billion $ by 2040. Oxygen is expected to be the main driver of growth. Estimates for future commercial demand range from tens to hundreds of metric tons a year. Demand for metals and silicon will quickly follow.

1.1.2 ROXY

Electrochemical reduction processes are preferred processes to extract oxygen and metals from regolith. Electrolyzing the regolith powder into oxygen and metals provides two very important materials from an essentially unlimited source. The obtained alloys can be used as structural material for colonies, as feedstock for metallic 3D printers, and more.

The ROXY (Regolith to Oxygen and Metals Conversion) molten salt electrolysis process invented by Airbus meets the requirements for an economically viable process to extract oxygen and metals from regolith without the drawbacks that characterize other solutions. In a larger context, the ROXY process is a core element of the end-to-end product value chain that will eventually produce metal products and oxygen from raw lunar regolith. The advanced Mini-ROXY concept further miniaturizes the electrochemical cell and is thus the next step towards higher resource efficiency.

1.1.3 The Mini-ROXY project

The Mini-ROXY concept is subject to further development by a team involving Fraunhofer IFAM Dresden, TU Bergakademie Freiberg, and Airbus in the frame of a project funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK). Work is focused on two objectives: First, a ground test campaign with a ground model of a Mini-ROXY reactor in preparation of a lunar demonstration mission. Second, the preparation of a design concept and implementation planning of a Mini-ROXY lunar demonstration system and mission as the next step towards larger, scaled-up lunar systems for oxygen and metal product production from lunar regolith.

For more information on the Mini-ROXY project, please consult the presentation from the 2023 ASGSR Meeting.

In Cooperation with

TU Bergakademie Freiberg – TUBAF – Die Ressourcenuniversität. Seit 1765.

INEMET – Institut für Nichteisenmetallurgie und Reinststoffe

AIRBUS

1.2 Goals of the Request for Ideas

1.2.1 Scientific Goals

The project partners work towards the core scientific objective of the Mini-ROXY lunar demonstration mission which is to establish a deep understanding the regolith reduction process, its performance and limitations, and its likely impacts on alternative sites, feedstocks and production scales.

The electrochemical reduction of oxides with molten salt electrolysis and SOM anodes is a wide field. The application of this process to lunar regolith is an exciting new research area which will benefit from scientific collaboration with interested parties with diverse backgrounds. The project partners are therefore looking for complementary and additional ideas and concepts to further enhance the scientific return of the Mini-ROXY lunar demonstration mission. The scientific community is therefore invited to submit ideas for science research activities that can be undertaken in conjunction with this mission.

1.2.2 Industrial Implementation

The current project will provide design concepts and implementation planning for a future Mini-ROXY lunar demonstration facility.

A future implementation project will therefore provide opportunities for interested parties to contribute elements of a Mini-ROXY lunar demonstration facility. This applies in particular to the mechanical-thermal system of a Mini-ROXY lunar demonstrator, which is a candidate element that could be developed by new partners, in particular SME´s. Interested parties are therefore invited to submit ideas and concepts for the mechanical-thermal system of a Mini-ROXY lunar demonstration facility.

1.3 Focus and response deadline

The focus of this Request is both on scientific and engineering aspects of defining, building, and operating ROXY systems of various sizes on the Moon. The Request is therefore subdivided into two parts:

- A Science RFI, and
- An Engineering RFI

The Science RFI is focused on scientific aspects of ROXY missions on two scales:

- A lunar demonstration of the Mini-ROXY Process, either in the frame of a robotic mission, or a man-tended mission
- Scale-up of the ROXY Process towards a Lunar Pilot Plant

The Engineering RFI is focused on the mechanical-thermal design of a Mini-ROXY lunar demonstrator.

The response deadline for both RFIs is **6 January 2024**.

Please send responses to the following e-mail address:

georg.poehle@ifam-dd.fraunhofer.de

1.4 Who Can Apply

- **Universities**
- **Non-University Research Institutions**
- **Companies (especially SME's)**

1.5 Incentives

- Access to experts at Fraunhofer IFAM Dresden, TU Bergakademie Freiberg and Airbus Defense and Space
- Possibility to pitch to the Evaluation Team of Fraunhofer IFAM Dresden, TU Bergakademie Freiberg and Airbus Defense and Space, as well as DLR (Deutsches Zentrum für Luft- und Raumfahrt) in the case of the Science RFI
- Preparation of joint publications
- Development of proposals (with the aim of a joint application for public funding)[1]

1.6 Evaluation Criteria

1.6.1 Science RFI

Science RFI responses will be assessed using the following criteria:

- Scientific content and significance to the Mini-ROXY lunar demonstration objectives
- Research approach
- Background and experience

1.6.2 Engineering RFI

Engineering RFI responses will be assessed using the following criteria:

- Technical content and significance to the Mini-ROXY lunar demonstration objectives
- Contribution to mass and power reduction, and simplification goals
- Technical feasibility and compatibility with lunar environment
- Background and experience

[1] Please note that no commitment to future public funding has been made by DLR or any other agency or public body at this stage.

1.7 References

1.7.1 Publications

Publications listed below provide information that may be useful for preparation of RFI responses, including context information on ISRU and space exploration, and descriptions of the ROXY process and the Mini-ROXY configuration.

1 – Global Exploration Roadmap:

https://www.globalspaceexploration.org/wordpress/wp-content/isecg/GER_2018_small_mobile.pdf

2 - PWC study on lunar ISRU market:

https://www.pwc.com.au/industry/space-industry/lunar-market-assessment-2021.pdf

3 – Article on the ROXY process, ICES 2022:

https://ttu-ir.tdl.org/server/api/core/bitstreams/bd80313e-3708-4f89-8df2-aced23933928/content

4 – Mini-ROXY presentation, 2023 ASGSR meeting

PDF provided at https://www.aviation-space.fraunhofer.de/en/projects.html

1.7.2 Mini-ROXY Lunar Demonstrator System Technical Requirements

The following data and high-level system requirements shall be assumed for the preparation of the RFI responses:

Mini-ROXY lunar demonstrator system requirements

- Minimization of overall mass and power consumption are high-level design goals
- Reception of regolith batches from an external system, batch size: up to ~ 1 kg
- Tolerance to overfilling, i.e., no spilling of excess regolith in the environment is allowed
- Preparation of samples and sample transfer to the cartridges
- Heat lower part of cartridge to processing temperature for the duration of the process
- Controlled heat-up and cool-down
- Cartridge extraction after process is not required
- Determine the mass of regolith in the cartridge before heating up the cartridge
- Optionally, determine the mass of regolith in the cartridge during and after the process
- Minimization of salt loss to the lunar environment during processing, i.e., containment of (most of) the salt vapor that is produced during processing, inside the cartridge volume

Regolith transfer and samples preparation

- Reception of regolith from external system by Mini-ROXY System.
- Preparation of samples for processing by Mini-ROXY System
- Sample size: 3-5 grams of regolith
- Processing of 1-3 regolith samples, 1 sample per cartridge

Mini-ROXY cartridge technical data

- Mass 1-1.5 kg, tbc.
- Outer diameter 64 mm, tbc.
- Height 150 mm, tbc.
- Regolith loading from top through a 30 mm diameter loading port

Processing parameters

- Cartridges are single-use
- 3 cartridges are processed sequentially
- Processing temperature 850 °C to be established in lower part (60 mm) of cartridge
- Processing duration 10 hours, plus time for controlled heat-up and cool-down at 1 K/min.

Salt Electrolyte

- During the process the salt is heated to the processing temperature.
- Equilibrium vapor pressure of the salt at the processing temperature: $3x10^{-2}$ mbar
- Salt evaporation rate at the processing temperature: 200 $\mu g/cm^2 \cdot s$

1.8 Requested Information

The information requested for both RFIs is defined in the sections below. Partial responses are welcome. The topics of interest for each RFI and the requested ideas are specified below.

The authors are open to further questions.

1.8.1 Science RFI

The science RFI is related to 3 topics of interest, as follows and as detailed in the subsections:

- Mini-ROXY Lunar Demo Mission (Robotic)
- Mini-ROXY Lunar Demo Mission (Man-Tended, with Sample Return)
- Scale-Up to Pilot Plant Size

Instructions: Include science objectives, hypotheses, and clear science justification and relevance for Mini-ROXY objectives. Describe the activity framework, technical methods and requirements, design implementation, and operational concepts. Provide information on relevant team expertise, background and prior achievements. Maximum 3000 words plus figures. Supplementary information, including bibliographic data may be provided if needed, limited to 4 A4 pages.

Mini-ROXY Lunar Demo Mission (Robotic)

In a robotic mission, the Mini-ROXY system will be accommodated on a lander for lunar surface operations and will be provided with resources by the lander. The Mini-ROXY system will operate largely autonomously with support from ground control. There will be no astronauts available. The Mini-ROXY system will process samples in three cartridges sequentially. After processing, samples and cartridges will remain in the Mini-ROXY system. Sample return is not part of the mission.

Ideas are requested for:

1. The preparation of the lunar demonstration mission, including activities such as lab experiments and process modelling to address specific questions.

2. The design of the process and process diagnostics, such as key elements of the cell (solid oxide membrane, anode, cathode, salt), process diagnostics with Electrochemical Impedance Spectroscopy and/or other means, oxygen diagnostics, complementary or alternative to the approaches developed in the ongoing project..

3. Near-real time and post-flight data analysis

Mini-ROXY Lunar Demo Mission (Man-Tended, with Sample Return)

In a man-tended mission, the Mini-ROXY system will be accommodated on a lander for lunar surface operations and will be provided with resources by the lander. The Mini-ROXY system will operate largely autonomously with support from ground control. Astronauts will be available to perform limited activities during EVA´s on the lunar surface. Such activities could include survey of the terrain, acquisition of regolith, analysis of regolith, beneficiation of regolith, transfer of regolith to the Mini-ROXY system. After processing, processed cartridges could be extracted from the Mini-ROXY system by the astronauts and returned to Earth for post-processing and analysis.

Ideas are requested for:

1. same as above
2. same as above
3. same as above
4. Regolith acquisition and diagnostics by astronauts

- Simple, robust, and low-mass concepts, e.g. hand-held devices.
- Minimum resource concepts (EVA time, mass, power)
- Approach to survey terrain and select acquisition site
- Regolith acquisition
- Regolith diagnostics
- Sample storage and transfer to beneficiation equipment or Mini-ROXY system

5. Regolith beneficiation and diagnostics

- Simple, robust, and low-mass concepts, e.g. hand-held devices.
- Minimum resource concepts (EVA time, mass, power)
- Beneficiation type (chemical, mineralogical, physical, other)
- Beneficiation principle
- Beneficiation equipment
- Diagnostics of beneficiated regolith
- Sample reception from upstream process (regolith acquisition and diagnostics)
- Sample storage and transfer to downstream equipment, e.g. Mini-ROXY system

6. Post-flight processing of reduced regolith

- Recovery of reduced regolith from cathode & salt
- Metal extraction and refinement
- Additive manufacturing trials with material from extracted metal samples

Scale-Up to Pilot Plant Size

The target capacity of the planned future pilot facility is 500 kg of oxygen and 500 kg of metal per year, corresponding to 3 grams per minute, with an assumed duty cycle of ~ 1/3 to account for the lunar night and other downtimes.

The pilot facility shall be optimized for low mass and low power consumption, high yield (mass of oxygen and metal produced per unit mass of regolith feedstock), and high ratio of product mass per unit time (oxygen and metals) and consumables mass per unit time (replacement of life limited items, materials needed to sustain the process, e.g. fluids, etc.)

The pilot facility shall be operated robotically with limited involvement from ground control. A high degree of autonomy is needed, the involvement of astronauts in routine operations such as exchange of anodes, cathodes, regolith, reduced regolith is not foreseen.

Ideas are requested for:

- Configuration of scaled-up cells: ROXY-type (both anode and cathode in reactor), Mini-ROXY-type (cathode in anode), alternative arrangements of the ROXY-type key components, or other
- Design of the process, e.g. addressing choice of salt, process temperature, cell potential and current, anode setup, cathode setup, process diagnostics, limitation of salt evaporation
- Identification of intermediate development steps such as lab demonstrators
- Repeated introduction and removal of the cathodes
- Repeated introduction and removal of regolith into/out of the cathodes
- Repeated introduction and removal of the anodes, e.g. at end of their lifetime
- Mass and power estimates of pilot plant
- Autonomous operations concept of pilot plant
- Techno-economic modelling of a lunar pilot plant, taking into account economic conditions in lunar environment, in particular transportation cost from Earth

1.8.2 Engineering RFI

Subject of this RFI is the mechanical-thermal concept of a Mini-ROXY lunar demonstrator

Ideas are requested for:

- Mechanical-thermal system concept of the Mini-ROXY system
- (Design details of the cartridges are not in scope of this RFI)
- Reception of regolith batches from an external system
- Distribution of regolith, preparation of samples, and sample transfer to the cartridges
- Tolerance to regolith overfilling, avoidance of regolith spilling
- Mechanism concept for drives, etc.
- Thermal concept to heat lower part of cartridges and minimize overall heat loss to the environment
- Limitation of salt loss due to evaporation during processing
- Structural concept
- Mass and power estimates

Instructions: Include key assumptions, design drivers, design concept and technical description, resource estimates, interfaces and operational requirements.

Maximum 3000 words plus figures. Supplementary information, including bibliographic data may be provided if needed, limited to 4 A4 pages.

Contact

Dr.-Ing. Georg Pöhle
Cellular Metallic Materials and Components
Phone +49 351 2537 421
Mobile +49 0172 2716942
georg.poehle@ifam-dd.fraunhofer.de

Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM
Branch Lab Dresden
Winterbergstrasse 28
01277 Dresden I Germany
www.ifam-dd.fraunhofer.de