Scope Title
Oxygen from Regolith

Scope Description
Lunar regolith is approximately 45% oxygen by mass. Most of the oxygen is bound in silicate minerals. Previous efforts have shown that it is possible to extract oxygen from regolith using various techniques. NASA is interested in developing novel oxygen extraction systems that can be proven to handle large amounts of lunar regolith throughput while minimizing consumables, mass, and energy. NASA is also interested in developing the supporting technologies that may enable or enhance the ability to extract oxygen from lunar regolith. Each of the following specific areas of technology interest may be proposed as individual efforts or combined.

- Novel Silicate Reduction Methods: Proposed concepts should describe a reduction method for highland anorthosite that avoids reduction of the regolith in the molten liquid state (i.e., gas/granular, liquid/granular, or vacuum/granular material processing). If reactants are utilized in the reduction process, and multiple reaction products are generated, all steps in regenerating the reactants and separating the products need to be considered. Proposed concepts must include a method to move regolith through the reaction zone (e.g., regolith inlet/outlet valves capable of passing abrasive granular material through the valve for hundreds of cycles). The target production rate for a pilot plant system is 1,000 kg of oxygen per year. The target production rate for a full-scale system is 10,000 kg of oxygen per year. Since access to continuous power is not initially planned, proposers will need to consider how to stop and restart their reduction method periodically throughout the year.
- Noncontact High-Temperature Measurement: Proposed concepts should be capable of determining temperatures up to 2,000 °C without contacting the material being measured (e.g., pyrometer). Compatibility with multiple oxygen extraction methods is desired. Instruments must be capable of operating inside of a vacuum chamber.
- Regolith Feed/Removal Systems and Mineral Measurement for Oxygen Removal: For oxygen extraction from regolith systems, it is anticipated that hardware will be required to transfer regolith from excavators to the reduction reactor and to transfer processed regolith from the reduction reactor to a holding hopper or the lunar surface. To better understand and control oxygen/metal extraction processes, NASA would like to examine the regolith material before and after the reduction process. Proposed concepts should describe a regolith feed/removal system that includes instrumentation to determine the amount of oxygen in the regolith upstream and downstream of an oxygen extraction zone. Measurements should be taken at a frequency that accounts for the regolith feed rate. The target regolith feed rate for a pilot plant system is 2.5 kg/hr. The target regolith feed rate for a full-scale system is 25 kg/hr. Compatibility with multiple oxygen
extraction methods is desired. Instruments must be capable of operating inside of a vacuum chamber.

Expected TRL or TRL Range at completion of the Project

4 to 5

Primary Technology Taxonomy

Level 1

TX 07 Exploration Destination Systems

Level 2

TX 07.1 In-Situ Resource Utilization

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description

Phase I efforts should provide a feasibility study and/or proof of concept. Phase II efforts should demonstrate the technology using lunar regolith simulant where applicable. Phase II efforts should be demonstrated no less than 1/10 of the pilot plant production rate where applicable and should describe how the process can be applied at the full-scale production rate.

State of the Art and Critical Gaps

Some oxygen-from-regolith methods have been demonstrated at relevant scales and are progressing toward TRL 6. Many other methods have been demonstrated at the bench scale, but current designs lack a means to move regolith in and out of the oxygen extraction zone. Many of these processes are used terrestrially, but industrial designs do not provide a means to keep gases from escaping to the vacuum of space.

Relevance / Science Traceability

STMD (Space Technology Mission Directorate) has identified the need for oxygen extraction from regolith. The alternative path, oxygen from lunar water, currently has much more visibility. However, we currently do not know enough about the concentration and accessibility of lunar water to begin mining it at a useful scale. Lunar water prospecting missions are required to properly assess the utilization potential of water on the lunar surface. Until more water prospecting data becomes available, NASA recognizes the need to make progress on the technology required to extract oxygen from dry lunar regolith.

References

Physics. [https://ntrs.nasa.gov/citations/20070014929](https://ntrs.nasa.gov/citations/20070014929)

- Gustafson, R. J., White, B. C., Fidler, M. J., & Muscatello, A. C. (2010). The 2010 field demonstration of the solar carbothermal reduction of regolith to produce oxygen. [https://ntrs.nasa.gov/citations/20110005526](https://ntrs.nasa.gov/citations/20110005526)
- Muscatello, T. (2017). Oxygen extraction from minerals. [https://ntrs.nasa.gov/citations/20170001458](https://ntrs.nasa.gov/citations/20170001458)

**Scope Title**

Lunar Ice Mining

**Scope Description**

We now know that water ice exists on the poles of the Moon from data obtained from missions like the Lunar Prospector, Chandrayaan-1, Lunar Reconnaissance Orbiter (LRO), and the Lunar Crater Observation and Sensing Satellite (LCROSS). We know that water is present in permanently shadowed regions (PSRs), where temperatures are low enough to keep water in a solid form despite the lack of atmospheric pressure. Many efforts are now underway to develop technologies needed to extract and capture lunar water ice. However, many other volatiles may be co-located with the water ice that may have additional in situ resource utilization (ISRU) applications. NASA is interested in developing technologies to capture and utilize other volatiles that may be located in PSRs. NASA is also interested in developing the supporting technologies that may enhance efforts to excavate water ice. Each of the following specific areas of technology interest may be proposed as individual efforts or combined.

- Nonwater Volatile Capture: Proposed concepts should define a target volatile (e.g., H₂S, NH₃, SO₂, C₂H₄, CO₂, CH₂OH, CH₄) to be captured from lunar regolith and describe how it may be utilized in a way that reduces the cost of landing consumables on the lunar surface. Concepts need to operate in PSRs of the lunar poles (<100K), and collected products will be removed from the PSR and processed in a near-permanently lit location nearby. Concepts to minimize electrical power usage are highly encouraged.
- Regolith/Ice Crushing: Proposed concepts should be able to crush frozen regolith simulant with a water ice content of 90% by mass while minimizing temperature increase in the material. The target production rate for a pilot-plant-scale ice-crushing system is 10 kg of regolith per hour. The target production rate for a full-scale system is 100 kg of regolith per hour. Concepts should consider how volatiles released during crushing may be minimized or captured if a significant fraction are lost.

**Expected TRL or TRL Range at completion of the Project**

4 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 07 Exploration Destination Systems

**Level 2**

TX 07.1 In-Situ Resource Utilization
Desired Deliverables of Phase I and Phase II

- Prototype
- Analysis
- Hardware

Desired Deliverables Description

Phase I efforts should provide a feasibility study and/or proof of concept. Phase II efforts should demonstrate the technology using lunar regolith simulant where applicable. Phase II efforts should be demonstrated no less than 1/10 of the pilot plant production rate where applicable and should describe how the process can be applied at the full-scale production rate.

State of the Art and Critical Gaps

Multiple efforts are now underway to extract, purify, and capture lunar water ice. However, little work has been performed on developing technologies to capture and utilize other useful volatiles that may be co-located within a PSR. Ice-crushing technology was developed at a small scale to support the Regolith and Environment Science and Oxygen and Lunar Volatiles Extraction (RESOLVE) project, but little work has been performed for larger scale applications.

Relevance / Science Traceability

NASA has referenced water ice as one of the reasons we have chosen the lunar poles as the location to establish a sustained human presence. The Space Technology Mission Directorate (STMD) has identified the need for water extraction technologies. The Science Mission Directorate (SMD) is currently funding the Volatiles Investigating Polar Exploration Rover (VIPER) mission to investigate lunar water ice.

References:

- Environment Science and Oxygen and Lunar Volatiles Extraction (RESOLVE), [https://ntrs.nasa.gov/citations/20150022136](https://ntrs.nasa.gov/citations/20150022136)
- Volatiles Investigating Polar Exploration Rover (VIPER), [https://www.nasa.gov/viper](https://www.nasa.gov/viper)

Scope Title

Size Sorting, Beneficiation, and Metal Production

Scope Description

Size sorting and beneficiation can be applied to ice mining and to oxygen extraction from regolith. Size sorting is a necessary step in any in situ resource utilization (ISRU) process involving regolith to ensure that the regolith delivered to an ISRU plant does not include objects large enough to cause mechanical failures within the system. Beneficiation allows for improved efficiency of ISRU processes that involve heating regolith in order to acquire a...
specific resource. NASA is also interested in processes where the primary product is metal—specifically metals other than iron, since iron extraction from regolith is a fairly advanced technology. Each of the following specific areas of technology interest may be proposed as individual efforts or combined.

- **Size Sorting:** Proposed concepts should demonstrate a means to remove particles larger than 1 mm from a feedstock of lunar regolith simulant. The target production rate for a pilot-plant-scale system is 10 kg of regolith per hour. The target production rate for a full-scale system is 100 kg of regolith per hour.
- **Beneficiation of Water Ice:** Proposed concepts should describe a method for separating water ice from bulk regolith without causing the water ice to change phase. The described method should address how sublimation losses can be minimized. The target production rate for a pilot-plant-scale system is 10 kg of regolith per hour. The target production rate for a full-scale system is 100 kg of regolith per hour.
- **Mineral Beneficiation:** Proposed concepts should define a target mineral to be concentrated from lunar regolith feedstock and describe how it will be utilized in a way that reduces the cost of landing consumables on the lunar surface.
- **Metal Production:** Proposed concepts should define a target metal (e.g., aluminum) to be extracted from lunar regolith and describe how it will be utilized in a way that reduces the cost of landing consumables on the lunar surface. Proposed concepts must include a method to move regolith through the reaction zone (e.g., regolith inlet/outlet valves capable of passing abrasive granular material through the valve for hundreds of cycles.) Near-pure metals or metal alloys are acceptable. Properties of metals extracted for manufacturing should be considered and provided.

**Expected TRL or TRL Range at completion of the Project**

3 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 07 Exploration Destination Systems

**Level 2**

TX 07.1 In-Situ Resource Utilization

**Desired Deliverables of Phase I and Phase II**

- Analysis
- Prototype
- Hardware

**Desired Deliverables Description**

Phase I efforts should provide a feasibility study and/or proof of concept. Phase II efforts should demonstrate the technology using lunar regolith simulant where applicable. Phase II efforts should be demonstrated at no less than 1/10 of the pilot plant production rate where applicable and should describe how the process can be applied at the full-scale production rate.

**State of the Art and Critical Gaps**

The Moon to Mars Oxygen and Steel Technology (MMOST) SBIR Phase II sequential project is currently implementing size sorting and beneficiation of minerals containing iron at a relevant scale and is also producing iron as the main product. There has been little advancement toward the production of other metals such as aluminum. The Aqua Factorem project funded through the NASA Innovative Advanced Concepts (NIAC) program represents the state of the art for ice beneficiation.
Relevance / Science Traceability

NASA has referenced water ice as one of the reasons we have chosen the lunar poles as the location to establish a sustained human presence. The Space Technology Mission Directorate (STMD) has identified the need for water extraction technologies. The Science Mission Directorate (SMD) is currently funding the Volatiles Investigating Polar Exploration Rover (VIPER) mission to investigate lunar water ice.

References

- Volatiles Investigating Polar Exploration Rover (VIPER). [https://www.nasa.gov/viper](https://www.nasa.gov/viper)