NASA SBIR 2020 Phase I Solicitation

Z12.01 Extraction of Oxygen from Lunar Regolith

Lead Center: JSC

Participating Center(s): GRC, JPL, KSC, MSFC

Technology Area: TA7 Human Exploration Destination Systems

Scope Title

Solar Concentrator Technologies for Oxygen Extraction and In-Situ Construction

Scope Description

Solar concentrators have been used to successfully demonstrate multiple In-Situ Resource Utilization (ISRU) technologies including hydrogen and carbothermal reduction, sintering of surfaces pads, and production of blocks for construction. Terrestrial state of the art solar concentrators are heavy, not designed for easy packaging/shipping and assembly/installation, and can be maintained and cleaned on a periodic basis to maintain performance. For ISRU space applications, NASA is interested in solar concentrators that are able to be packaged into small volumes, are light weight, easily deployed and set up, can autonomously track the sun, and can perform self-cleaning operations to remove accumulated dust. Materials, components, and systems that would be necessary for the proposed technology must be able to operate on the lunar surface: up to 110^{o}C (230^{o}F) during sunlit periods and survive temperatures down to -170oC (-274^{o}F) during periods of darkness. Systems must also be able to operate for at least one year with a goal of 5 years without substantial maintenance in the dusty regolith environment. Proposers should assume that regolith mining operations will be tens of meters away from the solar concentrators, but that regolith processing systems and solar concentrators will be co-located on a single lander. Phase 1 efforts can be demonstrated at any scale, Phase 2 efforts must be scalable up to 11.1 kW of delivered solar energy assuming an incoming solar flux of ~1350 W/m2 while also considering volumetric constraints for launch and landing. Each of the following specific areas of technology interest may be developed as a standalone technology, but proposals that address multiple areas are encouraged.

<u>Lightweight Mirrors/Lenses</u>: Proposals must clearly state the estimated W/kg for the proposed technology. Phase 2 deliverables must be deployed and supported in Earth 1-g (without wind loads) but should include design recommendations for mass reductions for lunar gravity (1/6-g) deployment. Proposals should address the following attributes: high reflectivity, low coefficient of thermal expansion, strength, mass, reliability and cost.

(See Z13.01 - Active and Passive Dust Mitigation Surfacesto propose dust repellent mirror/lens related technologies. This will help to solve issues where dust particles cling to the surface of a mirror or lens and degrade the performance of a solar concentrator.)

<u>Efficient transmission of energy for oxygen/metal extraction</u>: While the solar concentrator will need to move to track the sun, reactors requiring direct thermal energy for oxygen extraction will be in a fixed position and orientation. Concentrated sunlight must be able to be directed to a single or multiple spots to effectively heat or melt the

regolith. Proposals must define the expected transition losses from collection to delivery and should capture any assumptions made regarding the distance from collection to delivery.

Sintering end effector: Solar concentrators have been used to demonstrate the fabrication of 3D printed components using regolith as the only feedstock. However, an end effector designed to melt regolith at 1600^{o}C will not be optimized for selective sintering. Proposals responding to this specific technology area must produce a focal point temperature between 1000^{o}C to 1100^{o}C for the purpose of sintering lunar regolith.

References

Gordon, P. E., Colozza, A. J., Hepp, A. F., Heller, R. S., Gustafson, R., Stern, T., & Nakamura, T. (2011). Thermal energy for lunar in situ resource utilization: technical challenges and technology opportunities.

Nakamura, T., & Smith, B. (2011, January). Solar thermal system for lunar ISRU applications: development and field operation at Mauna Kea, HI. In 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition (p. 433).

Gustafson, R., White, B., Fidler, M., & Muscatello, A. (2010). Demonstrating the solar carbothermal reduction of lunar regolith to produce oxygen. In 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition (p. 1163).

Expected TRL or TRL range at completion of the project: 3 to 4

Desired Deliverables of Phase II

Prototype

Desired Deliverables Description

TRL4 hardware that can be deployed during a field demonstration

State of the Art and Critical Gaps

The 2011 paper *Thermal Energy for Lunar in Situ Resource Utilization: Technical Challenges and Technology Opportunities* summarized the work performed in this area and recommends future efforts focus on lightweight mirrors (possibly using composite materials) and dust mitigation techniques.

The last solar concentrator system developed for ISRU had an overall efficiency of ~33%. The performance of the system is captured in the 2011 Paper *Solar thermal system for lunar ISRU applications: development and field operation at Mauna Kea, HI*

Relevance / Science Traceability

The last time NASA was focused on a lunar destination, solar concentrators were used for multiple ISRU applications.

Scope Title
Novel Oxygen Extraction Concepts

Scope Description

Lunar regolith is approximately 45% oxygen by mass. The majority of the oxygen is bound in silicate minerals. Previous efforts have shown that it is possible to extract oxygen from silicates using various techniques such as carbothermal reduction and molten regolith electrolysis. 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.

- Phase 1 demonstrations can be at any scale, but eventually the technology must be able to demonstrate an average rate of 1.85 kg O_2/hr (10 metric tons of Oxygen in 225 days).
- Phase 2 demonstrations can be subscale, but must define the number of subscale units necessary to achieve an average extraction rate of 1.85 kg O_2/hr.
- Demonstrations do not need to produce actual oxygen gas, but can end at a reaction product that has successfully removed oxygen atoms from the silicate mineral.
- Proposers need to define any Earth supplied reagents or hardware that might be consumed or need to be recycled and should estimate replenishment or loss rates expected.
- Proposals should state expected energy requirements (both electrical and thermal) as well as temperatures at which the proposed process will operate.
- Proposers should estimate Wh/kg 0_2 for concepts and/or provide a plan to determine that value as part of the effort.
- Proposers should address how concepts can be shutdown and restarted.
- Proposers should address the ability of a concept to be able to operate for at least one year with a goal of 5 years without substantial maintenance.

References

1. Gustafson, R., White, B., & Fidler, M. (2011, January). 2010 field demonstration of the solar carbothermal regolith reduction process to produce oxygen. In *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition* (p. 434).
2. Sirk, A. H., Sadoway, D. R., & Sibille, L. (2010). Direct electrolysis of molten lunar regolith for the production of oxygen and metals on the moon. *ECS Transactions*, *28*(6), 367-373.

Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

TRL 4-6 hardware that can demonstrate a scalable oxygen extraction process in a manner that accommodates the movement of material through the extraction zone.

State of the Art and Critical Gaps

The carbothermal reduction process was demonstrated at a relevant scale using an automated reactor in 2010. The approach was successful but used many moving parts and was never life tested for the types of durations that will be required on the lunar surface. Molten Regolith Electrolysis has been demonstrated at the bench scale, but current designs lack a means to move regolith in and out of the oxygen extraction zone. Both 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 know if it would offer a better return on energy investment than oxygen extracted from the regolith. A lunar water prospecting mission is required to properly assess the utilization potential of water on the lunar surface. Until water prospecting data becomes available, NASA recognizes the need to make progress on the technology needed to extract oxygen from dry lunar regolith.

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 (PSR), where temperatures are low enough to keep water in a solid form despite the lack of atmospheric pressure. One challenge with extracting the water is that desorption and sublimation can occur at temperatures as low as 150 Kelvin. The inverse challenge exists with water collection. Unless the water vapor is under pressure, extremely cold temperatures will be necessary to capture it. NASA is seeking methods to acquire lunar water ice from permanently shadowed regions. Proposals must describe a method for extracting and/or collecting lunar water ice that exists at temperatures between 40 to 100 Kelvin and 10-9 torr vacuum.

- Phase 1 demonstrations can be at any scale, but eventually the technology must be able to demonstrate an average rate of 2.78 kg H_2O/hr (15 metric tons of water in 225 days).
- Phase 2 demonstrations can be subscale, but must define the number of subscale units necessary to achieve an average extraction rate of 2.78 kg H_2O/hr.
- Proposals should state expected energy requirements (both electrical and thermal).
- Proposers should assume a mobile platform is considered to be available, but should not be necessary for technology demonstration.
- Proposers should state their assumptions about water ice concentration.
- Proposals should describe a tolerance for a trace amount of organics or volatiles that may accumulate on collection surfaces.
- Proposers should estimate Wh/kg H_20 for concepts and/or provide a plan to determine that value as part of the effort.
- Proposers should address the ability of a concept to be able to operate for at least one year with a goal of 5 years without substantial maintenance.

Estimates for mass and volume of the final expected hardware should be specified.

References

Colaprete, A., Schultz, P., Heldmann, J., Wooden, D., Shirley, M., Ennico, K., & Goldstein, D. (2010). Detection of water in the LCROSS ejecta plume. *Science*, *330*(6003), 463-468.

Hibbitts, C. A., Grieves, G. A., Poston, M. J., Dyar, M. D., Alexandrov, A. B., Johnson, M. A., & Orlando, T. M. (2011). Thermal stability of water and hydroxyl on the surface of the Moon from temperature-programmed desorption measurements of lunar analog materials. *Icarus*, *213*(1), 64-72.

Poston, M. J., Grieves, G. A., Aleksandrov, A. B., Hibbitts, C. A., Darby Dyar, M., & Orlando, T. M. (2013). Water interactions with micronized lunar surrogates JSCâ€1A and albite under ultraâ€high vacuum with application to lunar observations. *Journal of Geophysical Research: Planets*, *118*(1), 105-115.

Andreas, E. L. (2007). New estimates for the sublimation rate for ice on the Moon. *Icarus*, *186*(1), 24-30.

Expected TRL or TRL range at completion of the project 4 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

TRL 4-5 hardware that can demonstrate scalable water ice extraction technology in a relevant environment

State of the Art and Critical Gaps

Scoops and bucket-wheel excavators have been demonstrated for the collection of unconsolidated material but may not be effective at excavating consolidated regolith-ice composites. The Planetary Volatiles Extractor (PVEx) developed by Honeybee Robotics is the state of the art for heated core drills, but life testing is required to determine the rate of wear due to repeated excavation. Multiple groups have investigated the use of thermal mining methods to separate water from regolith, but the depth of water removed is relatively shallow. Very little work has been performed on the ability to capture water in a lunar environment after it has been released from the surface.

Relevance / Science Traceability

The current NASA Administrator has referenced water ice as one of the reasons we have chosen the lunar poles as the location to establish a sustained human presence. STMD has identified the need for water extraction from permanently shadowed regions. Multiple mission directorates over the past several years have provided funding for a water prospecting mission so that we can gain the information required to establish an ice mining architecture.