SBIR/STTR

Small Business Innovation Research / Small Business Technology Transfer

NASA SBIR 2021 Phase I Solicitation

Z12.01 Extraction of Oxygen and Water from Lunar Regolith

Lead Center: JSC

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

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 regolith to produce launch/landing 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 lightweight, 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 in temperatures of up to 110 ^{o}C (230 ^{o}F) during sunlit periods and as as low as -170 ^{o}C (-274 ^{o}F) during periods of darkness. Systems must also be able to operate for at least 1 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 I efforts can be demonstrated at any scale; Phase II efforts must be scalable up to 11.1 kW of delivered solar energy, assuming an incoming solar flux of ~1,350 W/m^{2} 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.

- Lightweight mirrors/lenses: Proposals must clearly state the estimated W/kg for the proposed technology. Phase II deliverables must be deployed and supported in Earth 1g (without wind loads) but should include design recommendations for mass reductions for lunar gravity (1/6g) deployment. Proposals should address the following attributes: high reflectivity, low coefficient of thermal expansion, strength, mass, reliability, and cost.
- Efficient transmission of energy for oxygen/metal extraction: 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 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. Proposals responding to this specific technology area must produce and maintain a focal point temperature between 1,000 and 1,100 ^{o}C for the purpose of sintering lunar regolith. Proposals should assume that the focal point can move along the regolith at a speed between 1 and 10 mm/sec.

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:

- Prototype
- Analysis
- Hardware

Desired Deliverables Description:

Phase I deliverables may be a conceptual design with analysis to show feasibility at relevant scales and/or a small demonstration of the concept. Phase II deliverables should be hardware demonstrations at a relevant scale. See Scope Description for additional information on Phase I and Phase II deliverables.

State of the Art and Critical Gaps:

The 2011 paper "Thermal Energy for Lunar In Situ Resource Utilization: Technical Challenges and Technology Opportunities" [Ref. 1] summarized the work performed in this area and recommends future efforts focus on lightweight mirrors (possibly using composite materials) and dust mitigation techniques (dust mitigation is addressed in another subtopic).

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" [Ref. 6].

Relevance / Science Traceability:

NASA Strategic Knowledge Gap (SKG) 1-F, "Determine the likely efficiency of ISRU processes using lunar simulants in relevant environments," as well as NASA SKG 1-G, "Measure the actual efficiency of ISRU processes in the lunar environment," are both important for the development of future ISRU systems. There are multiple ISRU processes that involve the use of solar concentrators, and determining their efficiency through technology development efforts may address NASA SKGs.

References:

1. 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. https://ntrs.nasa.gov/citations/20110023752

2. 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).
3. Mueller, R. P., Sibille, L., Hintze, P. E., Lippitt, T. C., Mantovani, J. G., Nugent, M. W., & Townsend, I. I. (2014). Additive construction using basalt regolith fines. In *Earth and Space 2014* (pp. 394-403). https://ntrs.nasa.gov/citations/20150000305
4. Muscatello, A., & Gustafson, R. B. (2010). The 2010 Field Demonstration of the Solar Carbothermal Reduction of Regolith to Produce Oxygen. https://ntrs.nasa.gov/citations/20110006938
5. Muscatello, T. (2017). Oxygen Extraction from Minerals. https://ntrs.nasa.gov/citations/20170001458
6. 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).

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. The target production rates are 1,000 kg of O_2 per year for a lunar pilot plant, and 10,000 kg of O_2 per year for a lunar full-scale plant. Each of the following specific areas of technology interest may be proposed as individual efforts to support existing oxygen extraction development projects.

- Contaminant Removal: Proposed concepts should be capable of removing 0.36 g of HCl, 0.68 g of HF, and 0.1 g of H_2S per kg of processed regolith from a mixed gas stream of CO, CO_2, and H_2 in a way that minimizes the use of consumables. Phase I efforts should provide an estimated mass/power as a function of contaminant quantities. Phase II efforts should demonstrate the technology using actual gases.
- Regolith Inlet/Outlet Valves: Proposed concepts should be capable of passing abrasive granular material through the valve for at least 1,000 cycles and should be actuated with a type of motor that has flight heritage (e.g., brushless direct current (BLDC) motors or stepper motors). Phase I efforts should provide an estimated mass and power for the concept through analysis and/or demonstration. Phase II efforts should demonstrate the technology using lunar regolith simulant and collect data to predict leak rates for up to 10,000 cycles.
- Contamination-Tolerant Vacuum Pump: Some in situ resource utilization (ISRU)

processes may require a pressurized volume to be evacuated in order to prevent the loss of products and consumables to the vacuum of space when regolith either enters or exits the volume. The pump may be exposed to corrosive substances such as HCl, HF, and H_2S. Proposed concepts should be capable of evacuating a volume of 50 L with an initial pressure of 5 psia down to a pressure of <5 torr at the pump inlet in <2 min while compressing the gases to 1 atm at the pump outlet. Phase I efforts should provide an estimated mass, power, and life for the concept. Phase II efforts should demonstrate the technology using actual gases.

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:

See Scope Description for definitions of Phase I and II deliverables for each technology.

State of the Art and Critical Gaps:

The carbothermal reduction process was demonstrated at a relevant scale using an automated reactor in 2010. Multiple efforts are underway to bring carbothermal reduction technology to TRL6. Other techniques that use ionic liquids, molten salts, and molten regolith electrolysis 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:

The Space Technology Mission Directorate (STMD) 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. 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.

References:

1. Fox, E. T. (2019). Ionic Liquid and In Situ Resource Utilization. https://ntrs.nasa.gov/citations/20190027398
2. Gustafson, R. J., White, B. C., & Fidler, M. J. (2009). Oxygen production via carbothermal reduction of lunar regolith. *SAE International Journal of Aerospace*, *4*(2009-01-2442), 311-316.
3. 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

4. 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).
5. Muscatello, A., & Gustafson, R. B. (2010). The 2010 Field Demonstration of the Solar Carbothermal Reduction of Regolith to Produce Oxygen. https://ntrs.nasa.gov/citations/20110006938
6. Muscatello, T. (2017). Oxygen Extraction from Minerals. https://ntrs.nasa.gov/citations/20170001458
7. Paley, M. S., Karr, L. J., & Curreri, P. (2009). Oxygen Production from Lunar Regolith using Ionic Liquids. https://ntrs.nasa.gov/citations/20090017882
8. Sibille, L., Sadoway, D. R., Sirk, A., Tripathy, P., Melendez, O., Standish, E., ... & Poizeau, S. (2009). Production of Oxygen from Lunar Regolith using Molten Oxide Electrolysis. https://ntrs.nasa.gov/citations/20090018064

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. One challenge with extracting the water is that desorption and sublimation can occur at temperatures as low as 150 K. 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 PSRs. Proposals must describe a method for extracting and/or collecting lunar water ice that exists at temperatures between 40 and 100 K and 10-9 torr vacuum.

- Phase I 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 II 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 1 year, with a goal of 5 years without substantial maintenance.

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

In addition, each of the following specific areas of technology interest may be proposed to support existing efforts related to lunar ice mining.

- Regolith/Ice Excavation: Proposed concepts should be able to excavate frozen regolith simulant with a water ice content of at least 5% by mass while minimizing a temperature increase in the excavated material. Phase I efforts should provide an estimated mass/power for the excavation concept as well as an estimate for any temperature increase in the frozen regolith caused by the excavation technique. Phase II efforts should demonstrate the technique with lunar simulant at a target production rate of 0.28 kg H_20/hr and collect data to predict the estimated wear over time.
- Regolith/Ice Crushing: Proposed concepts should be able to crush frozen regolith simulant with a water ice content of at least 5% by mass while minimizing a temperature increase in the excavated material. Phase I efforts should provide an estimated mass/power for the crusher concept as well as an estimate for any temperature increase in the frozen regolith caused by the crushing technique. Phase II efforts should demonstrate the technique with lunar simulant mixed with ice having an initial unconfined compressive strength of 10 MPa at a target production rate of 0.28 kg H_20/hr and collect data to predict the estimated wear over time.
- Subsurface Volatile Extraction: Proposed concepts should be able to release volatiles at a depth of 50 cm below the surface with a water ice content of at least 5% by mass. Phase I efforts should provide an estimated mass/power for the concept. Phase II efforts should demonstrate the technique with lunar simulant at a target production rate of 0.28 kg H_20/hr and collect data to predict the estimated wear over time if applicable.

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:

See Scope Description for definitions of Phase I and II deliverables for each technology.

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 technologies. The Science Mission Directorate (SMD) is currently funding the Volatiles Investigating Polar Exploration Rover (VIPER) mission to investigate lunar water ice.

References:

1. 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.
2. 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.
3. 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 JSC?1A and albite under ultra?high vacuum with application to lunar observations. *Journal of Geophysical Research: Planets*, *118*(1), 105-115.
4. Andreas, E. L. (2007). New estimates for the sublimation rate for ice on the Moon. *Icarus*, *186*(1), 24-30.