NASA SBIR 2020 Phase I Solicitation

H3.01 Advancements in Carbon Dioxide Reduction: Critical Subsystems and Solid Carbon Repurposing

Lead Center: MSFC

Participating Center(s): ARC, GRC, JSC, KSC

Technology Area: TA6 Human Health, Life Support and Habitation Systems

Scope Title

Carbon Dioxide Reduction System Components and Unit Processes

Scope Description

NASA has invested in many carbon dioxide reduction technologies over the years to increase the percentage of oxygen recovery from carbon dioxide in human spacecraft for long duration missions. Examples of technologies include, but are not limited to, Series-Bosch, Continuous Bosch, Methane Pyrolysis and Microfluidic Carbon Dioxide Electrolysis. Significant technical challenges still face these process technologies and are impeding progress in technology maturation. Critical technical elements of these technologies have a high degree of technical difficulty. Examples where additional technology development is needed include (this is a partial list):

- High temperature gas purification and/or separation for CO, H_2, and hydrocarbon rich streams.
- Nuisance particulate carbon contamination.
- Solid carbon clogging of frits and filters in recycle gas streams.
- Safe collection, removal and disposal of solid carbon while reactors are in operation.
- Subsystems to recharge reactors with new catalyst and to efficiently use or recycle consumable catalysts.

This subtopic is open to consider novel ideas that address any of the numerous technical challenges that face development of carbon dioxide reduction hardware with particular attention to those listed above. Specifics on two of these challenges are provided below.

<u>Gas Purification and/or Separation for Carbon Monoxide, Hydrogen and Hydrocarbon Rich Streams</u>

Many process technologies currently under development have challenging multi-component streams which could benefit from improved gas separation technology. High purity, high yield and continuous supply of separated gases are all desirable features of a proposed technology. The targeted process streams that may benefit from improved gas separations are the following:

- Producing a high-purity hydrogen product from a hydrogen-rich gas stream containing acetylene (as high as 6.4 mole %), trace amounts of other hydrocarbons (ethylene, ethane, benzene), unreacted methane,

- carbon monoxide, carbon dioxide and water vapor. It is imperative that the proposed separation technologies do not hydrogenate hydrocarbons, such as acetylene. This separation is directed at methane pyrolysis technologies including the Plasma Pyrolysis Assembly (PPA).
- Hydrogen separation from an ethylene-rich stream. This separation is directed at the effluent stream from a Microfluidic Electrochemical Reactor which consists of ethylene, hydrogen, methane, carbon monoxide, carbon dioxide and water vapor.
- Recovery of unreacted carbon dioxide and hydrogen from a carbon monoxide-rich stream. This separation is needed for a Bosch/Reverse Water Gas Shift (RWGS) Reactor.

Technology solutions could include, but not be limited to, filtration, mechanical separation or novel sorbents. If novel sorbents are developed the proposed technology solution should also address issues with scale-up to kg quantities (difficult for some novel sorbents). Technology solutions proposed in this subtopic could potentially be leveraged for In-Situ Resource Utilization (ISRU) applications.

Separation of Particulate Carbon and Hydrocarbons from Process Gas Streams

Oxygen recovery technology options, including carbon formation reactors and methane pyrolysis reactors almost universally result in particulates in the form of solid carbon or solid hydrocarbons. Mitigation for these particulates will be essential to the success and maintainability of these systems during long duration missions. Techniques and methods leading to compact, regenerable devices for removing, managing and disposing of residual particulate matter within ECLSS process equipment are sought. Separation performance approaching HEPA rating is desired for ultrafine particulate matter with minimal pressure drop. The separator should be capable of operating for hours at high particle loading rates and then employ techniques and methods to restore its capacity back to nearly 100% of its original clean state through in-place and autonomous regeneration or self-cleaning operations using minimal or no consumables (including media-free hydrodynamic separators). The device must minimize crew exposure to accumulated particulate matter and enable easy particulate matter disposal or chemical repurposing.

State of the Art and Critical Gaps

Future long duration human exploration missions may benefit from further closure of the Atmosphere Revitalization System (ARS). The state-of-the-art Sabatier system, which has flown on the International Space Station as the Carbon Dioxide Reduction Assembly (CRA), only recovers about half of the oxygen from metabolic carbon dioxide. This is because there is insufficient hydrogen to react all available carbon dioxide. The Sabatier reacts hydrogen with carbon dioxide to produce methane and water. The methane is vented overboard as a waste product causing a net loss of hydrogen. Mars missions target >75% oxygen recovery from carbon dioxide, with a goal to approach 100% recovery. NASA is developing several alternate technologies that have the potential to increase the percentage of oxygen recovery from carbon dioxide, toward fully closing the ARS loop. Methane pyrolysis recovers hydrogen from methane, making additional hydrogen available to react with carbon dioxide. Other technologies under investigation process carbon dioxide, recovering a higher percentage of oxygen than the Sabatier. All of these alternative systems, however, need additional technology investment to reach a level of maturity necessary for consideration for use in a flight environmental control and life support system (ECLSS).

Scope Title

Solid Carbon Repurposing

Scope Description

Solid carbon is produced as a major by-product from many candidate oxygen recovery technologies under consideration for long-duration missions, including Bosch, Series Bosch, Methane Pyrolysis by Carbon Vapor Deposition, and technologies containing carbon formation reactors. Based on metabolic CO_2 production for a crew of 4, 1.135 kg of solid carbon, with a volume as high as 2.8 liters, may be produced each day by oxygen recovery technologies, which then must be disposed of or repurposed. Repurposing of this carbon reduces logistical challenges associated with its disposal and may ultimately result in materials or processes advantageous for long-duration missions. The produced solid carbon may include nanofibers, microfibers and amorphous material with varying particle size, with the smallest in the micrometer range (10-50 µm). It may contain quantities of metals including, but not limited to, iron, nickel and cobalt. The solid carbon may be in the form of a loose powder or a densified cake with densities ranging from 0.4 to 1.8 g/cc and will vary by technology. Venting or disposal of this carbon to space will present considerable logistical challenges and will result in large volumes of space debris. Disposal of this carbon on a planetary surface may result in concerns for planetary protection or planetary science. NASA is seeking technologies and/or processes that repurpose solid carbon and its contaminants resulting in useful products for transit, deep space or planetary surface missions. The technology and/or process must limit crew exposure to the raw carbon.

References for All Scopes

"Hydrogen Recovery by Methane Pyrolysis to Elemental Carbon" (49th International Conference on Environmental Systems, ICES-2019-103)

"Evolving Maturation of the Series-Bosch System" (47th International Conference on Environmental Systems, ICES-2017-219)

"State of NASA Oxygen Recovery" (48th International Conference on Environmental Systems, ICES-2018-48)

"Particulate Filtration from Emissions of a Plasma Pyrolysis Assembly Reactor Using Regenerable Porous Metal Filters" (47th International Conference on Environmental Systems, ICES-2017-174)

"Methane Post-Processing and Hydrogen Separation for Spacecraft Oxygen Loop Closure" (47th International Conference on Environmental Systems, ICES-2017-182)

“Trading Advanced Oxygen Recovery Architectures and Technologies” (48th International Conference on Environmental Systems, ICES-2018-321)

NASA-STD-3001, VOLUME 2, REVISION A, Section 6.4.4.1 “For missions longer than 14 days, the system shall limit the concentration in the cabin atmosphere of particulate matter ranging from 0.5 ?m to 10 ?m (respirable fraction) in aerodynamic diameter to <1 mg/m3 and 10 ?m to 100 ?m to <3 mg/m3.” https://www.nasa.gov/sites/default/files/atoms/files/nasa-std-3001-vol-2a.pdf.

Expected TRL or TRL range at completion of the project for Phase I: 3

Expected TRL or TRL range at completion of the project for Phase II for All Scopes: 4 to 5

Desired Deliverables of Phase II for All Scopes

Prototype, Analysis, Hardware, Research

Desired Deliverables Description for All Scopes

Phase I Deliverables - Reports demonstrating proof of concept, test data from proof of concept studies, concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II. Conceptual solution in Phase I should look ahead to satisfying the requirement of limiting crew exposure to the raw carbon dust.

Phase II Deliverables - Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, test data and analysis. Prototypes must be full scale unless physical verification in 1-g is not possible. Robustness must be demonstrated with long term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

State of the Art and Critical Gaps

No existing operational technology exists in this focused technical area. A crew of 6 during a 540 day Mars surface mission could potentially generate 920 kg of solid carbon - this will be a significant storage or disposal issue and may be a considerable raw product resource for potential utilization. Very limited research and development have been performed in this area. Some studies added carbon to plastic trash which subsequently was processed by a heat melt compactor to make "tiles", which encapsulated the carbon. Although these tiles are a safe way to get rid of trash waste, they were also studied for potential benefit for use as spacecraft radiation shielding. Other work included adding binders to make rudimentary bricks for structural use.

Relevance / Science Traceability

These technologies would be essential and enabling to long duration human exploration missions, in cases where closure of the atmosphere revitalization loop will trade over alternate ECLSS architectures. The atmosphere revitalization loop on the ISS is only about 50% closed when the Sabatier is operational. These technologies may be applicable to Gateway, Lunar surface, and Mars, including surface and transit. This technology could be proven on the ISS.

This subtopic is directed at needs identified by the Life Support Systems Capability Leadership Team (CLT) in areas of water recovery and environmental monitoring, functional areas of Environmental Control and Life Support Systems (ECLSS).

The Life Support Systems (LSS) Project, under the Advanced Exploration Systems (AES) Program, within the Human Exploration and Operations Mission Directorate (HEOMD), is the expected customer. The LSS Project would be in position to sponsor Phase III and technology infusion.