NATIONAL AERONAUTICS AND SPACE ADMINISTRATION {NASA}

CENTENNIAL CHALLENGES PROGRAM

CO_2 Conversion Challenge Phase 2 Competition Rules

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2.0 DEFINITION OF TERMS

2.1 CO_2 – Carbon Dioxide. A colorless gas with a density about 60% higher than that of dry air. Carbon dioxide consists of a carbon atom covalently double bonded to two oxygen atoms. It occurs naturally in Earth's atmosphere as a trace gas, and makes up the majority of the atmosphere of Mars.

2.2 Centennial Challenges Program – A NASA program that was initiated to use prizes to generate revolutionary and innovative solutions to problems of interest to NASA and the nation. The program seeks innovations from diverse and non-traditional sources and engages the public in the process of advanced technology development.

2.3 Independent Laboratory – A laboratory outside of NASA that will provide independent verification and testing to confirm attainment of the Challenge objectives.

2.4 Judging Panel – A panel of personnel selected from among NASA, academic, and industry researchers and subject matter experts who specialize in the topic area and who will judge Challenge entries but are not competing in the Challenge.

3.0 CHALLENGE BACKGROUND

Future planetary habitats on Mars will require a high degree of self-sufficiency. This requires a concerted effort to both effectively recycle supplies brought from Earth and use local resources such as CO_2, water and regolith to manufacture mission-relevant products. Human life support and habitation systems will treat wastewater to make drinking water, recover oxygen from CO_2, convert solid wastes to useable products, grow food, and develop equipment and packaging to allow reuse in alternate forms. In addition, In Situ Resource Utilization (ISRU) techniques will use available local materials to generate substantial quantities of products to supply life support needs, propellants and building materials, and support other In-Space Manufacturing (ISM) activities.

Many of these required mission products such as food, nutrients, medicines, plastics, fuels, and adhesives are organic and are comprised mostly of carbon, hydrogen, oxygen, and nitrogen molecules. These molecules are readily available within the Martian atmosphere (CO_2, N_2) and surface water (H_2O), and could be used as the feedstock to produce an array of desired products. While some products will be most efficiently made using physicochemical methods or photosynthetic organisms such as plants and algae, many products may best be produced using heterotrophic (organic substrate utilizing) microbial production systems. Terrestrially, commercial heterotrophic bioreactor systems utilize fast growing microbes combined with high concentrations of readily metabolized organic substrates, such as sugars, to enable very rapid rates of bio-product generation.

The type of organic substrate used strongly affects the efficiency of the microbial system. For example, while an organism may be able to use simple organic compounds such as formate (1- carbon) and acetate (2-carbon), these "low-energy" substrates will typically result in poor growth. In order to maximize the rate of growth and reduce system size and mass, organic substrates that are rich in energy and carbon, such as sugars, are needed. Sugars such as D-Glucose, a six-carbon sugar that is used by a wide variety of model heterotrophic microbes, is typically the preferred organic substrate for commercial terrestrial microbial production systems and experimentation. There are a wide range of other compounds, such as less complex sugars and glycerol that could also support relatively rapid rates of growth.

To effectively employ microbial bio-manufacturing platforms on planetary bodies such as Mars carbon substrates must be made on-site using local materials. However, generating complex compounds like glucose on Mars presents an array of challenges. While sugar-based substrates are inexpensively made in bulk on Earth from plant biomass, this approach is currently not feasible in space. Current physicochemical processes such as photo/electrochemical and thermal catalytic systems are able to make smaller organic compounds such as methane, formate, acetate and some alcohols from CO_2; however, these systems have not been developed to make more complex organic molecules, such as sugars, primarily because of the difficult technical challenges and the availability of lower cost alternatives associated with obtaining sugars on Earth. Novel research and development is required to create the physicochemical systems required to directly make more complex molecules from CO_2 in space environments. The advancements in the generation of suitable microbial substrates will enable the making of complex organic compounds from CO_2 that could also serve as feedstock molecules in traditional terrestrial chemical synthesis and manufacturing operations.

The CO_2 Conversion Challenge is devoted to fostering the development of CO_2 conversion systems that can effectively produce singular or multiple molecular compounds identified as desired microbial manufacturing ingredients and/or that provide a significant advancement of physicochemical CO_2 conversion for the production of useful molecules.

4.0 CHALLENGE OBJECTIVE

Phase 2 of the NASA CO_2 Conversion Challenge requires the demonstration of a physicochemical system that is able to produce one or more of the target compounds listed in Table 1, with an associated weighting factor between 0 and 100, with D-glucose being the most preferred (the weighting factor will be used in the scoring process as discussed in section 6.3.1 below). Only sugars that are in the "D" form will be acceptable for scoring. Sugars in the "L" form are not acceptable and their mass will be subtracted from the mass of the "D" form of that sugar to calculate a final mass score. The system must use CO_2 as the sole carbon source for the production of these compounds, and may not use any organic compound(s) as a feedstock. Hydrogen molecules may be supplied from either hydrogen gas (H_2) or from water (H_2O). The system must not rely on biological products or processes for any portion of the CO_2 conversion process. While biologically-derived materials may be used for construction of the hardware, such as using plastics for structural components, no biologically-derived products may be employed to perform any aspect of the CO_2 processing. The source CO_2 and hydrogen can be supplied from a commercially available pure gas (i.e., tanked CO_2 and H_2), or verifiably obtained from an alternate source (e.g., H_2 from water electrolysis). To increase the potential for use in space missions, systems that are both low mass/power/volume and scalable are sought. Likewise, the ability to make target compounds at high efficiency and specificity, and with minimal contaminants and/or toxic by-products, is preferred.

Table 1. Challenge target compounds and associated weighting factor.

Challenge Targeted Compounds	**Weighting Factor**
D-Glucose	100
Other 6-carbon sugars (D-hexoses)	80
5-carbon sugars (D-pentoses)	50
4-carbon sugars (D-tetroses)	10
3-carbon sugars (D-trioses)	5
D-Glycerol	5

5.0 CHALLENGE RULES AND REQUIREMENTS

Phase 2 is a Demonstration Phase with a prize purse of up to $750,000. Phase 1 (completed in April 2019) was the Concept Phase that awarded $250,000 equally among the top five scoring teams.

Phase 2 (Demonstration Phase) Rules

5.1 Team Registration – All teams must submit their registration no later than 6:00 p.m. Eastern Time on November 30, 2019, in order to participate in the Challenge. Teams do not need to have competed in Phase 1 in order to register and compete in Phase 2.

5.2 Demonstration Application - All teams must submit their demonstration application no later than June 5, 2020. Competitors' applications are required to provide a description of the physicochemical conversion system they will build to demonstrate the production of selected carbon-based molecular compounds, and will include all of the following:

5.2.1 A description and process diagram which adequately describes the components associated with the system.

5.2.2 A description of the CO_2 conversion process the system uses and its chemistry, including any consumable chemicals, catalysts (including their expected lifetime and stability), waste products, process kinetics, and a flow diagram that depicts the mass flows throughout the operating system.

5.2.3 A list of all compounds and their characteristics (concentration, solid/liquid, whether sugars are D- and/or L- enantiomers, pH and any other applicable information) that the system has produced during testing. The system should be able to make at least one compound in Table 1.

5.2.4 The overall system mass, energy requirements (average and peak), and total system volume.

5.2.5 The demonstrated CO_2-to-product(s) conversion efficiency and production rates. The conversion efficiency can be estimated by comparing the amount of CO_2 supplied against the amount of carbon contained in identified target products.

5.2.6 A description of the ability of the system to be scaled to larger production rates.

5.2.7 A description of the suitability of the system to be utilized in a space environment, taking into consideration the potential effects of reduced gravity conditions.

5.2.8 A description of the expected reliability of the system, including descriptions of anticipated/observed failure modes and maintenance requirements.

5.2.9 A video of the system while in operation that clearly depicts the overall components and operation of the system.

5.3 Trial Application - A trial application indicating readiness for a site visit by a judge. Teams must submit a trial application for a site visit no later than June 5, 2020.

NOTE: The system should be scaled such that, at a minimum, it generates sufficient product within a continuous 7 hour period to allow analytical characterization/verification using conventional analytical methods.

6.0 PHASE 2 EVALUATION OF SUBMISSIONS

6.1 Once received, judges will review the above materials and, upon satisfactory review, schedule a call with the teams to determine if a team has met the requirements for a site visit. A site visit will then be scheduled. A judge will observe and evaluate the system operation at the team's facility, which must be within the United States. The team must perform an on-site demonstration for the judge to verify system performance parameters and collect a product sample for verification by an independent laboratory. Results by the independent laboratory will be the determining factor for scoring the sample's target compound composition and quantity.

If on-site judging is prohibited due to circumstances related to COVID-19, each team will be judged virtually instead of through an on-site visit.If this happens, each team will be contacted by a judge who will develop a "Virtual Judging Protocol" for each team that meets the delivery requirements outlined in 6.0 of the Rules Document.

6.2 After samples from all participating teams have been collected and analyzed by an independent laboratory, the team will be provided an official score based on the results and scoring criteria described below.

6.3 The judging panel's evaluation of the submissions will be based on the following scoring criteria:

6.3.1 Factor 1.) Product Quality Assessment (100 points): Each team will receive one opportunity for on-site production of the sample designated for later analytical characterization.

This process will be conducted with a Challenge judge present during the entire production period. The system must be started from a non-operating condition and produce the sample within 7 hours of starting the system. Pauses in system operations are permitted but after 7 continuous hours have elaspsed since initial system start, no additional product will be accepted.

The sample must be in the form of a liquid or solid for verification analysis. The team must provide the analytical methodology used to identify and quantify the target compounds. The quantity of sample produced for confirmatory analysis must be (at least) the same amount that was used by the team to identify and quantify conversion products to allow replication of the team's results by an independent laboratory. The amount of sample required will be confirmed in consultation with judges prior to the on-site testing.

In addition to providing the sample, the team must indicate the predicted compound(s) in the sample, indicate if a racemic mixture of sugars is expected and approximate concentrations. The sample must contain one or more challenge target compounds listed in Table 1. The sample will be collected by the judge, sealed in a provided container, and shipped to an independent laboratory for verification. Note, the sample will only be evaluated for up to five (5) target compounds identified by the team. Beyond these five compounds, any additional target compounds will not be considered in the judging. Any preliminary analysis during system development/assessment is the responsibility of the team.

Scoring –The team's product will be examined using an independent chemical analysis to determine if any of the targeted compounds in Table 1 are present. If enantiomers of the targeted compounds are present, the mass of each will be measured. The total score will be calculated by taking the mass of the most desired enantiomer "D" form minus the mass of the undesired "L" form. For example, if equal amounts of "D" and "L" glucose are found, then no points will be given for that compound.

- Each target compound will be assigned a score by multiplying the mass fraction of the target compound in the sample by the corresponding weighting factor from Table 1.
- The assigned scores for each target compound will then be added to produce a cumulative score for each team.
- The cumulative score for each team will be normalized against the highest cumulative score such that the team with the highest cumulative score will receive a reference value of 1.0 and the other teams will receive a reference value in proportion to the ratio of their cumulative score to the highest cumulative score (i.e., a reference value less than 1.0).
- Finally, the reference value for each team will be multiplied by 100 points to provide the overall score for product quality.

An additional 10 points will be added to a team's score for providing a Mid-point Progress Update as described in Section 6.4. These points are optional and are not subtracted if an update is not provided. With these points, the maximum possible score for this challenge is 110.

6.4 Optional Challenge Mid-point Progress Update

Teams are encouraged to provide a Mid-point Progress Update that reflects the current status of their project. This report will be due anytime between March 1st, 2020 and March 31st, 2020. If a team completes their system and submits a report within the aforementioned timeframe, describing the elements listed below, they will automatically receive these 10 points:

(i) An overall status report of system development efforts indicating progress on the design, building and testing of the team's system.
(ii) Preliminary CO_2 conversion results, predicted and/or produced
(iii) Photographs/diagrams of existing system components.

Reports that contain this information will have a full 10 points added to the team's final score. Reports that do not provide all three of the elements listed above will not receive any additional points.

6.5 Bonus Prize - System Effectiveness for Space Mission Applications: The information provided in the Demonstration Application (Section 5.2) as well as information gathered during the on-site judging event will be used by the judging panel to assess the overall system effectiveness for future application in space missions. A total of $100,000 will be available for bonus prizes in amounts determined by the judges for up to 3 teams. Teams do not need to win one of the contest prizes to be awarded a Bonus Prize. The top score will receive $50K and the next two highest scores will receive $25K. A minimum score of 65 points is required to be eligible for a bonus prize. The scoring matrix will consist of a total of 100 points divided into the following three categories:

System Efficiency (40 Points) – Operating CO_2 conversion systems in space will benefit substantially by operating at high levels of efficiency with respect to consumable useage, waste production and power requirements. Therefore, systems will be assessed with respect to power requirements, consumables needed, and wastes produced as compared to the amount of products produced. Increased levels of efficiency results in increased scores. Points will be allocated based on the efficiency of:

- power used (15 points)
- consumables used (15 points)
- waste production levels (10 points)

System Scalability (30 Points) – Application of CO_2 conversion systems to support space biomanufacturing operations may need to operate from small to large scales. Therefore, systems will be assessed based on their ability to increase and decrease in scale in terms of system volume, mass, power and consumable useage as compared to the tested configuration. Greater capability for effective scaling results in increased scores. Points will be allocated based on the scaling capability of:

- volume (10 points)
- mass (10 points)
- power (5 points)
- consumable useage (5 points)

System Robustness and Reliability (30 points) – Systems in space are required to reliably operate for long periods of time with minimal or complex maintenance. Therefore, systems will be assessed regarding their ability to handle off-nominal events, stops and restarts, general reliability of component parts and catalysts, and anticipated maintenance. Scoring will be based on the information provided in the

Demonstration Application and information obtained during the on-site demsontration. Factors include demonstrated and theoretical evidence of resilience to system starts and stops, perturbations, and failures, as well as projected maintenance procedures. Greater robustness and reliability results in increased scores.

- resilence to perturbations, failures and stops/restarts (15 points)
- expected maintenance (15 points)

7.0 ELIGIBILITY WIN PRIZE MONEY

NASA welcomes applications from individuals, teams, and other entities that have a recognized legal existence and structure under applicable law (State or Federal) and that are in good standing in the jurisdiction under which they are organized with the following restrictions:

(i) **Individuals <u>must be</u>** U.S. citizens or permanent residents of the United States and **<u>must be</u>**18 years of age or older.
(ii) **An entity <u>must be</u>** incorporated in and maintaining a primary place of business in the United States.
(iii) **Teams <u>must be</u>** comprised of otherwise eligible individuals or entities, and led by an otherwise eligible individual or entity.

As stated in Section 6.1, **teams <u>must</u>** conduct their demonstration work in facilities based in the United States, to include Alaska, Hawaii, and U.S. territories and possessions.

U.S. Government employees may enter the competition, or be members of prize-eligible teams, so long as they are not acting within the scope of their employment, and they rely on no facilities, access, personnel, knowledge or other resources that are available to them as a result of their employment except for those facilities, access, personnel, knowledge or other resources available to all other participants on an equal basis.

U.S. Government employees participating as individuals, or who submit applications on behalf of an otherwise eligible entity, will be responsible for ensuring that their participation in the competition is permitted by the rules and regulations relevant to their position and that they have obtained any authorization that may be required by virtue of their Government position. Failure to do so may result in the disqualification of them individually or of the entity which they represent or in which they are involved.

Foreign citizens <u>may only participate</u> through an eligible U.S. entity as:

(i) An employee of such entity
(ii) A full-time student of such entity, if the entity is a university or other accredited institution of higher learning,
(iii) An owner of such entity, so long as foreign citizens own less than 50% of the interests in the entity, **OR**
(iv) A contractor under written contract to such entity.

No Team Member shall be a citizen of a country on the NASA Export Control Program list of designated countries in Category II, which are countries determined by the Department of State to support terrorism. The current list of designated countries can be found at http://oiir.hq.nasa.gov/nasaecp/. Please check the link for latest updates. In the case of dual citizenship, U.S. citizenship will be accepted over citizenship of a designated country for eligibility.

A team-designated team lead shall be responsible for the actions of and compliance with the rules, including prize eligibility rules, by all members of his or her team.

8.0 AWARDS

The three highest scoring teams will be awarded the following prizes:

1st Place - $350,000
2nd Place - $200,000
3rd Place - $100,000

In the event of a tie score between two or more teams, the corresponding award(s) will be divided evenly among the teams. For example, a tie for first place will result in both teams receiving ($350,000 + $200,000)/2 = $275,000.

Additional details can be found on the official challenge site at www.co2conversionchallenge.org