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NASA Centennial Challenges Program: A crowdsourcing tool to advance life support technologies for future NASA missions

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Historically, competitions and prizes such as those executed by the NASA Centennial Challenges (CC) program have created broader avenues through which to spur innovation from unlikely sources. In 2005, Congress amended the National Aeronautics and Space Act of 1958 to authorize NASA to create challenges through which prizes could be awarded to United States citizens or entities that succeeded in meeting the challenge objectives. Over the past 13 years, the CC program has initiated more than 19 challenges in a variety of technology areas, including propulsion, robotics, communications and navigation, human health, science instrumentation, nanotech, materials/structures and aerodynamics. This paper will discuss the status and the accomplishments of the CC program and discuss results of an ideation process designed to identify and formulate topics for a potential Centennial Challenge competition targeting a life support technology gap for future long-term exploration missions. Status of this challenge formulation process with information on how to use crowdsourcing tools will be discussed. An overview of the CC Program's accomplishments, including strategic objectives, past challenges, and current challenge development and execution. This program exemplifies the values that have formed the bedrock of the culture at NASA since the beginning: innovation, imagination, and a passion for exploration.

Nomenclature

ATP	=	Authority to Proceed
CC	=	Centennial Challenges
EPMC	=	Executive Program Management Council
HQ	=	NASA Headquarters
LEO	=	Low Earth Orbit

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STMD	=	Space Technology Mission Directorate
SME	=	Subject Matter Experts
TA	=	Technology Area

I. Introduction

The Centennial Challenges (CC) program, part of NASA's Space Technology Mission Directorate (STMD), bridges the innovation gap between NASA and the nation by catalyzing sources of innovation inside and outside of the traditional aerospace community. As part of an effort to address the sources outside of the traditional aerospace community, NASA began exploring the use of challenge competitions as early as 2003 and, in 2005, with the incentive of congressionally authorized prize purses, the first challenge competition under the CC program was announced to the public. This creative approach to addressing NASA's key technology needs was founded upon the principle that engaging the public at large was a critical component of garnering the true magnitude of grass-roots American innovation and ingenuity.

II. Background

A. Challenge Overview

Historically, competitions and prizes have created broader avenues through which to spur innovation from the most seemingly unlikely and humble sources and/or innovators in tangential industries. For example, after laboring for decades to determine the proper measurement of longitude at sea, the British Parliament passed a bill providing compensation for any citizen who could develop a proven solution. Though attempted by mathematicians, astronomers, and veteran navigators, it was an uneducated clock maker living in poverty named John Harrison who developed the winning solution in 1761 with his invention of the marine chronometer. In the 1920s, an American hotelier with a passion for aviation, Raymond Orteig, established a $25,000 prize for any person who could fly across the Atlantic Ocean. Ultimately, it wasn't a daredevil stunt pilot or WWI fighter ace that won the Orteig Prize, but a humble mail pilot named Charles Lindberg. Utilizing prizes to accelerate research and development (R&D) and spur innovation began a renaissance in the 1990s and have been going strong since many organizations and governments around the world launching prizes to accelerate R&D. Recent prize competitions have ranged from ideas competitions (e.g., ideas on new products or services an organization can offer) to algorithm prizes (e.g., insurance companies updating their actuary tables) to creativity prizes (e.g., new commercials for a consumer product or a new logo for a company) to technology prizes (e.g., creating a new manufacturing technique for existing products or new products) to many more.

With the recent surge in prizes and challenges, a clear set of recommended practices and considerations evolved to help ensure successful outcomes. Some of these best practices include the following:

1. Clearly define a problem and set a clear and measurable target; The criteria needed to solve the problem and metrics for measuring success can be identified, and milestones that serve as additional incremental targets can be identified.

A challenge must set a specific goal or target that is easily understood for teams to achieve, and then measure the teams' success based on a set of clear criteria and metrics. Precisely identifying which teams reached the goal (or exceeded it, or reached it first) is critical to any successful challenge. While the goal needs to be clearly set, the ways in which it may be solved are left open. By not presupposing a solution, but defining the parameters, innovation is left open and not hampered.

Depending on the opportunity or goal, the challenge may include milestone targets for teams to achieve. These milestones may be necessary technology steps or iterations along the pathway to a solution, or they may be a way to narrow the number of solvers as the innovation challenge progresses to make judging and operating the challenge more manageable. (They also serve to provide minimal results-based early stage funding to teams, provide teams with validation on their direction that may help them raise additional funds, and serve as a media moment.)

Criteria may range from being the first to accomplish something (how will the judges know it has been accomplished?) to achieving (or exceeding, or being the closest to achieve) specific performance requirements (how will the judges measure performance?). Judges may need to collect both qualitative and quantitative data to assess the solutions' performance.

2. Target a complex opportunity that may require multiple attempts/solutions to address: Incentivize the development of a portfolio of solutions that can address the problem in the marketplace

An innovation challenge is a powerful tool if the problem can be approached from numerous angles, and solutions may come in different forms (or may iterate off each other, or layer upon each other). Additionally, if the problem includes elements of human behavior, different solutions may resonate with different end users, and the challenge may need to incentivize as many solutions as possible that fit the diverse end users' needs.

3. Target an opportunity that is not being solved in the marketplace or by governments (or is not being solved quickly enough) due to the known players being "stuck" or a lack of relevant incentives. The opportunity would benefit from increased focus, R&D, and cross-disciplinary collaboration

The opportunity is one that no one is tackling yet—or people have been working on elements of the opportunity for a long time and have seen little progress (or the progress is slow). New perspectives and incentives may be needed.

4. The means by which the problem or opportunity will be solved are unknown or too speculative for traditional research, contracts, or grants

Innovation challenges are particularly effective tools to use when the desired outcome is known, but the best way to achieve that outcome is unknown. The odds of getting a good solution increase with a broader pool of potential solutions. Innovation challenges can also be used to validate and verify the effectiveness of different types of solutions, through assessment and laboratory or field testing. The data that results from this sort of testing is often highly valuable to both the individual solvers and the industry.

5. Target an opportunity where it is not known who will develop the best solutions or where the best solutions will come from

Innovation challenges open up solution development to new players from unexpected places. A challenge may be open to anyone, from anywhere, for the broadest possible reach. Or a challenge may be limited to specific regions or target audiences. Because innovation challenges are best used when the way to solve a problem is not clear, those that allow for solutions from anyone or anywhere have the greatest likelihood of success. Stakeholders who understand different elements or perspectives of a problem may even be able to collaborate on highly effective solutions. The strength of a challenge comes from the diversity of its potential solvers.

6. Target an opportunity that is not purely regulatory or political; The opportunity may have regulatory or political elements, which the challenge could influence

Problems that are purely regulatory or political are difficult to tackle with innovation challenges, as outside organizations or solvers are likely to be unable to test or implement solutions to these sorts of problems. Most problems do have regulatory or political elements, however, and those can be influenced by innovation challenges. Focusing a community of solvers on a problem and engaging the public around the challenge bring attention to the problem and may encourage regulatory bodies or political figures to align around new solutions. Partnerships with regulatory agencies, or the support (and therefore political will) of elected officials can be beneficial. Agencies may even agree to pilot solutions that result from the innovation challenge. Involve the stakeholders in the process and see how they can help.

7. Engage and inspire the public (and make them aware of the problem so they want to take action and see it solved)

Public awareness is a key element of any innovation challenge, as it educates the public about the issue and helps drive the recruitment of solvers to compete. Inspiration is also a critical element, as it not only spurs individuals to tackle this problem, but advances the narrative that we are all solvers—that everyone can be involved in building a better world.

8. Provide incentives that will make it worthwhile for teams to spend their own time and money to compete (e.g., incentives they could not get on their own or would be difficult or expensive for them to get on their own)

Innovation challenges ask solvers to dedicate their own resources—both time and money—to solve the problem or meet the target. They invest their resources on the chance (not the certainty) that they will meet the goal and receive whatever award is offered. Identifying the cash prize purse (or other award) that will be provided to the winners is one important element of innovation challenge incentives—but not the only element. Potential solvers respond to a variety of incentives, and well-designed innovation challenges offer multiple incentives that will motivate and encourage teams to compete.

Before joining a challenge, teams generally balance the costs of competing and the potential benefits of competing. The costs of competing include: (1) the time and effort they must put forth to compete, (2) the opportunity costs of not undertaking other activities, (3) the capital outlay they must make to develop their solutions, and (4) how much intellectual property (IP), if any, they will need to relinquish to the sponsor. In some cases, these costs are in the millions of dollars per team.

When assessing the potential benefits of competing in a challenge, teams know that only one or two or three of them will win the prize—so a well-designed innovation challenge offers numerous benefits to teams beyond just the prize purse. Other operational incentives should be offered to encourage the maximum number of qualified teams to compete—all with the goal of having the greatest possible positive impact.

These operational incentives can be broken down into two categories: (1) hard incentives and (2) soft incentives. Hard incentives are those resources or benefits that if teams have unlimited time and money, they could go out into the marketplace and purchase themselves—but it is cheaper and easier to provide within the challenge. Soft incentives are those resources or benefits that, even if teams have unlimited time and money, they could not go out to the marketplace to purchase themselves—but that the challenge has the unique ability to provide. The hard and soft incentives include resources or benefits such as access to experts, potential funders, policy makers, and regulators; education, including business plan and fundraising training and market studies; media exposure, including brand promotion; partnership opportunities; and access to testing facilities and third-party verified data about their solutions. Hard operational incentives are shown in Figure 1, and soft operational incentives are shown in Figure 2.

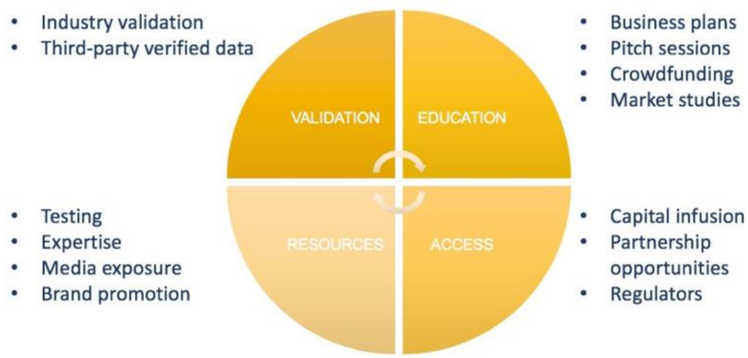

Figure 1. Hard Operational Incentives. *Those resources or benefits that if teams have unlimited time and money, they could go out into the marketplace and purchase themselves—but it is cheaper and easier to provide within the challenge.*

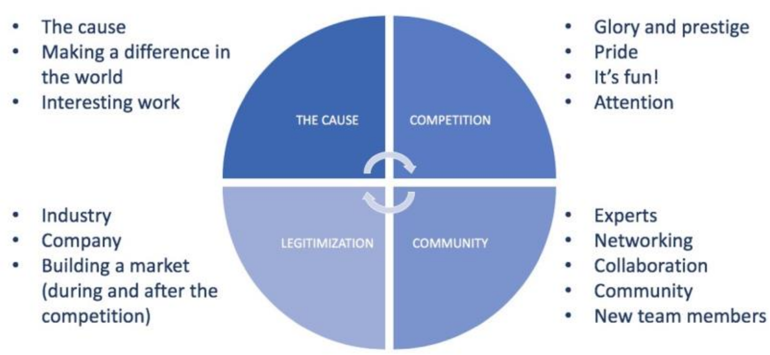

Figure 2. Soft Operational Incentives. *Those resources or benefits that, even if teams have unlimited time and money, they could not go out to the marketplace to purchase themselves—but that the challenge has the unique ability to provide.*

B. Centennial Challenges Overview

Centennial Challenges is an embodiment of NASA's continuing commitment to technological advancement and innovation through non-traditional programs. The challenges create opportunity for collaborative, technological advancement within the framework of a competition, while simultaneously enabling contestants to expand their business models and customer base. The Centennial Challenges program is dedicated to encouraging innovation and imagination through its organic approach to utilizing the great talents this nation has to offer, while also capturing the public imagination, engaging communities, fostering collaboration, and attracting greater public attention to these endeavors.

Since 2005, eighty-eight prizes totaling more than $8.3 million – ranging from $5,000 dollars to $1.35 million – have been awarded by the CC program, and several new companies have been born in the private sector using those technology advancements. While the program evolved over the last two years resulting in many measurable positive outcomes like the significant increase in participation in the challenge competitions and increase in prize purse awards, the program continues to look for ways to increase the benefits to the Agency and participants. By increasing collaboration with other government agencies and academia and the public understanding of the program, NASA expects to continue to refine the Centennial Challenges program and looks forward to great outcomes that will continue to be of benefit to Agency and the Nation.

International teams can participate in the CC competitions granted that the country's request to participate is accepted by the program and with the understanding that, because of the program legal authority, they are not eligible to win prize money. Despite this, the program has accepted registrations from more than eight countries, and five teams (Japan, Singapore, Spain, European Space Agency/Germany and South Korea) have won top honors in two challenges (3D-Printed Habitat and Space Robotics). After the challenges completed, participants were offered information and guidance on opportunities to continue the development of their respective innovations and suggestions on transitions into a NASA program, increasing the overall benefit to both NASA and the teams themselves. Finally, the Centennial Challenges program is taking great strides towards enhancing its understanding of non-challenge activities that are still essential to continued success, such as fostering greater media attention and cultivating new business ventures.

Challenges selected by the CC program are thoroughly researched, evaluated, and deliberated through broad collaborations with subject matter experts (SMEs), both inside and outside the federal government. To serve as an example of our inclusive design methodology, the following sections explain the steps taken to assess opportunities for the potential life support related challenge competition that in this paper will be referred to as the StarHab Challenge. The initial name of this potential Challenge is meant to symbolize a habitat in space – not limited to one location, like the Moon or Mars; but one that could exist anywhere among the stars. If the competition is approved by NASA for development and execution, the name might be changed to reflect a specific topic area.

III. Challenge Formulation

The Challenge formulation process began with an assessment of the current state-of-the-art technology. This assessment was informed by interviews with the CC program team, the plant research team at NASA Kennedy Space Center, and 17 other experts, plus a review of the relevant literature and internal NASA documents. The assessment did not seek to identify all opportunities for technology development, but rather to identify opportunities for a potential challenge that would incentivize industry, academia, non-governmental organizations, and the general public to develop solutions that would benefit NASA and the world.

NASA has plans to go the Moon in the next decade in a way it has never gone before - with innovative new technologies and systems to explore more locations across the surface than was ever thought possible. This time, when NASA goes to the Moon, the goal is to stay, and use what is tested and learned on the Moon to take the next giant leap of sending astronauts to Mars. The success of these long-term exploration missions will ultimately rely upon life support systems for crew that are Earth-independent, and that will meet all of the crew's needs without relying upon frequent (or any) resupply missions. Much innovation needs to occur to meet these lofty goals and innovation challenges can play a part. Two such areas include food and water where opportunities exist for a Centennial Challenge to help fill existing technology gaps. And with the re-energized efforts to return to the Moon in the very near-term, using the Lunar surface as a potential "testbed" to develop and test new technologies and systems is a fast-approaching reality.

Taking this vision into consideration, the first step in assessing the current state of the technology began with NASA's expanded Technology Roadmaps (originally developed in 2010, and updated in 2015), which detail its anticipated mission capabilities and associated technology development needs through 2035.[6] Within those roadmaps, Technology Area (TA) 6 focuses on human health, life support, and habitation systems. The overarching focus area of TA 6 is described as follows:

> *"For future crewed missions beyond low-Earth orbit (LEO) and into the solar system, regular resupply of consumables and emergency or quick-return options will not be feasible, and spacecraft will experience a more challenging radiation environment in deep space than in LEO. Therefore, TA 6 focuses on developing technologies that enable long-duration, deep-space human exploration with minimal resupply consumables and increased independence from Earth, within permissible space radiation exposure limits."*[7]

Julia Robinson, chief scientist for the ISS, in an article for The Atlantic described NASA's efforts in providing food for the astronauts as something they've spent years perfecting. "But even though the meals are meant to last, they wouldn't survive the long journey to Mars"[8]. Crews on ISS currently get frequent fresh food supplements in their diet when cargo missions resupply them. However, a lunar mission will not be able to provide this frequent resupply, mainly because the cost is not sustainable. The current method of using stored foods will also not sustain a long-term mission because the nutrients in the food degrade over time, and do not provide the enjoyable and desirable experience that is critical for the crew's physical and mental health. There are efforts in the area of existing life support systems currently used to supply food crops and nutrients for short-term missions on the International Space Station (ISS), but those will not be sufficient for long-term deep space exploration or habitation. ISS payloads are small scale, and science focused, and growing food crops in space has had mixed success. Although predecessors of future extraterrestrial farms beyond Earth,[9] the process is not yet reliable or predictable enough to have earned a place as a critical system in the spacecraft. While many elements of these existing subsystems are likely to be used as-is or modified for future missions on varying length, new technologies will need to be developed to enable long-term, Earth-independent missions, and to address issues such as the volume and water needs of food production. Investing in food and human systems is one of the best ways to demonstrate that we are working on sustainable, permanent presence on the moon, not just an Apollo redo. All the technology that will be needed to support a sustainable food production system on the Moon will have direct application to a planetary mission- in fact it will help increase the reliability of this system and decrease the risks for long duration missions to Mars and beyond.

While NASA has small teams with key expertise in food systems and plants in space, it does not hold the nation's expertise in horticulture - the development and modification of plants. The use of a Centennial Challenge to address the technology gaps in space would leverage private industry and open-source innovations in areas where NASA does not need or want to own the expertise, but rather would partner with said sources to identify and continue to develop technologies. With the population continuing to increase, and the demands for clean water, food and energy rise[10], these technologies would not only benefit future NASA missions, but would also have Earth applications and benefits. When examining the current research, it became evident that the technology is advancing quickly, and in several directions. Examples such as Samson Ogbole growing "plants in the air" without soil in Nigeria[11], and China's recent

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[1] Office of the Chief Technologist, "*2015 NASA Space Technology Roadmaps*" [online database], URL: https://www.nasa.gov/offices/oct/home/roadmaps/index.html [cited July 2015].

[2] "TA 6: Human Health, Life Support, and Habitation Systems," *2015 NASA Technology Roadmaps* [online report], URL: https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_6_human_health_life_support_habitation_final.pdf [cited July 2015].

[3] Marina Koren, "How Do Plants Grow in Space?", The Atlantic [online article]; URL: https://www.theatlantic.com/science/archive/2019/01/plants-flowers-international-space-station-moon-mars/581491/ [cited 30 January 2019].

[4] Marina Koren, "How Do Plants Grow in Space?", The Atlantic [online article]; URL: https://www.theatlantic.com/science/archive/2019/01/plants-flowers-international-space-station-moon-mars/581491/ [cited 30 January 2019].

[5] The National Academies of Sciences, Engineering and Medicine, *"Environmental Engineering for the 21st Century Addressing Grand Challenges"*[online report]; URL: http://nas-sites.org/dels/files/2018/12/Env_Eng_Briefing-12_4_final-for-POSTING.pdf [cited 6 December 2018].

[6] Brandon Clements and Aanu Adeoye, "Meet the wizard farmer who grows crops in the air", CNN report [online article], URL: https://www.cnn.com/2018/12/14/africa/nigerian-farmer-grows-crops-in-air-africa-intl/index.html [cited 14 December 2018].

success sprouting cotton seeds on the dark side of the moon[12], reinforce the need for a broad-sweeping effort, like a collaborative public challenge. As the world continues to move towards an increase of investments in these types of technology areas, a challenge could potentially be of interest to a wide range of potential participants.

It was these types of findings from the initial opportunity assessment that were then refined and used to help frame further discussions with a broader range of experts. Thirty-five experts from NASA, industry and academia came together to validate and prioritize the findings from the assessment. The following eight key opportunity areas were identified, and are shown in Table 1.

Table 1. Key Opportunity Areas for a Potential StarHab Challenge.

Food Production Efficiency	○ Cost effective ○ Energy efficient ○ Optimization of height/volume/density, water, nutrients, light
Growing method and medium	○ Regolith to soil ○ Hydroponics ○ Alternatives
Systems integration modeling	○ Modeling ECLSS and air/water/plant integration ○ Big data analysis ○ Develop models and applications for remote operations
Plant modification	○ Effectiveness, efficiency ○ Engineer plants to fit a given environment ○ Plant sensing ○ Molecular farming
Organic waste management	○ Recover nutrients, carbon, and water from inedible biomass
Food safety	○ Make plants safe for consumption without damaging taste, smell, or appearance ○ Ease, scale, effectiveness
Automation of horticultural processes	
Water systems	○ Potential integration with plant food production systems ○ Water storage and safety

The outcomes of these discussions were then used to formulate three potential StarHab challenges based on researched, vetted, and validated topic areas.

IV. Options for the StarHab Challenge

The three potential challenge concepts were designed to offer different levels of flexibility for both NASA and the challenge participants. The goals in offering three options is to provide NASA with maximum flexibility in determining what works best for the Agency's needs, and provide different on-ramps and off-rams for teams. It is not expected that all three concepts will be launched as a Centennial Challenge; rather it is proposed that one of the concepts will be further researched, vetted, refined, and, potentially launched as a Centennial Challenge. Each option described in the subsequent sections is not final, and is not guaranteed to be launched as a Centennial Challenge in the future. The options are all subject to change upon further development and consideration.

A. Challenge Option One

Challenge Option One is designed in two phases, with the first phase laying the groundwork for the full development of the teams' solutions in the second phase. Once launched the same teams would continue throughout the entire competition and NASA would commit to launching the entire competition.

The Challenge is designed to address a suite of opportunities necessary to efficiently provide eighty-five percent or more of the crew's diet for long-term planetary missions in an integrated way. Diet is defined as all of the calories and macro/micro nutrients the crew needs for optimal health. The winning team(s) will develop the best

[7] Jessica Stewart, "China Sprouts the First Ever Seeds on the Far Side of the Moon", My Modern Met [online article]; URL: https://mymodernmet.com/plants-sprout-moon-change-4/ [cited 17 January 2019].

comprehensive food production system that provides eighty-five percent or more of the diet for the crew of future long-term planetary missions, given a specific set of constraints.

In Phase One (System Models), teams will develop comprehensive, integrated models of future food production systems, given a specific set of constraints, that integrate food/nutrition, water, air, and waste management to the extent necessary to efficiently produce eighty-five percent or more of the crew's diet. Production of essential outputs will be assessed, as well as factors such as food/nutrient palatability and diet variety. In Phase Two (System Prototyping), teams will develop prototypes of their food production systems, including all processes needed to get food from production to plate, including food safety and waste management, and operate those prototypes over a given number of production cycles. At the end of Phase Two, teams that have developed the most effective, efficient comprehensive systems will win.

The proposed timeline for the entirety of Challenge Option One is three years.

Table 2. Option One Summary.

Problem statement(s) / opportunities	Address of suite of opportunities necessary to efficiently provide 85 percent or more of the crew's diet for long-term planetary missions in an integrated way. Diet is defined as all of the calories and macro/micro nutrients the crew needs for optimal health.
The winning team will...	The winning team(s) will develop the best comprehensive food production system that provides 85 percent or more of the diet for the crew of future long-term planetary missions, given a specific set of constraints.
Challenge structure	Comprehensive Challenge Structure. This challenge is designed in two phases, with the first phase laying the groundwork for the development of prototypes of the solution in the second phase. Phase 1: System Models—Teams will develop comprehensive, integrated models of future food production systems, given a specific set of constraints, that integrate food/nutrition, water, air, and waste management to the extent necessary to efficiently produce 85 percent or more of the crew's diet. Production of essential outputs will be assessed, as well as factors such as food/nutrient palatability and diet variety. Phase 2: System Prototyping—Teams will develop prototypes of their food production systems, including all processes needed to get food from production to plate, including food safety and waste management, and operate those prototypes over a given number of production cycles.
Challenge timeline	3 years
Intended impacts	The development of a comprehensive system that addresses the suite of opportunities necessary to provide 85 percent or more of the crew's diet for long-term planetary missions that has been modeled and prototyped.

B. Challenge Option Two

Challenge Option Two is designed as a large-scale, staged competition with phases. Each of the phases builds upon the previous phase. This challenge structure could be launched through just the first Phase, through the first and second Phases, or through all three Phases, depending on the appetite of NASA and its allied organizations (however, the first Phase must be launched before the second Phase, etc.). These stages are designed to build upon each other to eventually reach an audacious outcome. Teams can choose to participate in all Phases that are launched or exit or enter at any Phase.

The goal of this Challenge is to address a single, primary need for future long-term missions: essential nutrients for the crew that are produced in real-time, reducing the need for stored foods that lose their nutrients over time.

There are three proposed phases throughout this challenge: Phase One winning team(s) will develop robust, validated models of plant production systems for future long-term missions that maximize nutrient production while minimizing inputs (including energy, payload weight, water, and crew time) and waste; Phase Two winning team(s) will develop and test those systems for two plant production cycles; and Phase Three winning team(s) will prove reliability and replicability of the systems for four plant production cycles.

Teams that participate in Phase One could continue on through Phases Two and Three as they are launched, building upon their previous work. New teams would also be permitted to join at each Phase, and could build upon the work done by teams in the previous Phases. The challenge could be designed so that teams could have access to the work of other teams in the previous Phases in a variety of ways, ranging from requiring teams' solutions to be open sourced to crafting specific licensing agreements that allow each team's solution to be used by other teams in the challenge.

Significant value is derived from the challenge whether it ends at Phase One, or at Phase Two, or is completed all the way through Phase Three. At each Phase—systems models, production proof of concept, and proof of reliability and replicability—teams will produce advancements that NASA deems high-priority and necessary for future long-term missions, and upon which NASA can then build further advancements.

The proposed timeline for the entirety of Challenge Option Two is two-to-three years.

Table 3. Option Two Summary.

Problem statement(s) / opportunities	Address a single, primary need for future long-term missions: essential nutrients for the crew that are produced in real-time, reducing the need for stored foods that lose their nutrients over time.
The winning team will...	There will be multiple phases throughout this challenge: ● Phase 1: The winning team(s) will develop robust, validated models of plant production systems for future long-term missions that maximize nutrient production while minimizing inputs (including energy, payload weight, water, and crew time) and waste ● Phase 2: The winning team(s) will develop and test those systems for two plant production cycles ● Phase 3: The winning team(s) will prove reliability and replicability of the systems for four plant production cycles
Challenge structure	Staged Challenge Structure. This challenge is designed as a large-scale, staged competition with Phases. This challenge could be launched through just the first Phase, through the first and second Phases, or through all three Phases, depending on the appetite of NASA and its allied organizations. Phase 1: Systems Models—Teams will develop valid, robust models of plant production systems for future long-term missions that maximize nutrient production while minimizing inputs (including energy, payload weight, water, and crew time) and waste, and predicts that they will have a system that meets success criteria. Phase 2: Production Proof of Concept—Teams will develop and test their systems for two plant production cycles, returning the entire system to its starting state at the completion of each cycle. Phase 3: Reliability and Replicability—Teams will prove reliability and replicability of their systems over four plant production cycles.
Challenge timeline	2-3 years
Intended impacts	Maximize nutrition production while minimizing inputs and waste.

C. Challenge Option Three

Challenge Option Three is designed as multiple separate challenges that can run simultaneously or one at a time. Although they are designed to be independent of each other (and therefore can be launched in parallel or sequentially and any can be launched with or without the others), they are also designed to complement each other. In this manner, if more than one is launched, the aggregate value will exceed the value of the individual challenges. NASA could decide to launch one or more challenges, and it will not negatively impact the outcome if NASA decides not to launch them all. In addition, teams can choose to participate for one or more challenges.

For the first challenge, the winning team(s) will develop the most comprehensive validated models for future integrated life support systems. For the second and third challenges, the wining team(s) will optimize the required outputs while minimizing inputs and waste. All three challenges will result in technology advancements that are valuable as stand-alone advancements, but which can also be integrated into future long-term mission systems.

The challenges are designed to be quick challenges that will be run in “sprints”, and will accelerate the technology innovation in each area. The proposed timeline for the entirety of the Challenge Option Three is eighteen months to two years.

Table 4. Option Three Summary.

Problem statement(s) / opportunities	Address a number of opportunities that exist for future long-term planetary missions, including: (1) optimization of plant production for food/nutrients through systems design and/or plant modification, (2) resource recovery (e.g. water, nutrients, carbon) from plant production systems and inedible biomass, and (3) data analysis and modeling of future biological/hybrid life support systems.
The winning team(s) will...	This challenge is designed as three separate challenges that can run simultaneously or one at a time. For the first two challenges described below, the winning team(s) will optimize the required outputs while minimizing inputs and waste. For the third challenge, the winning team(s) will develop the most comprehensive validated models for future integrated life support systems.
Challenge structure	Building Blocks Challenge Structure. This challenge is designed as three separate challenges that can run simultaneously or one at a time. These three challenges will result in technology advancements that are valuable stand-alone advancements, but which can also be integrated into future long-term mission systems. The three challenge targets are: 1. Challenge 1: Optimize plant production for food/nutrients through systems design and/or plant modification 2. Challenge 2: Recover water, nutrients, and carbon from plant production systems and inedible biomass 3. Challenge 3: Analyze big data and model future life support systems that include plant production
Challenge timeline	18 months - 2 years (depending on number and staggering of individual challenges)
Intended impacts	Technology advancements in three high-priority areas: plant production optimization; resource recovery; and data analysis and modeling. Each of these are valuable advancements on their own, and are likely to be integrated or implemented synergistically for future long-term missions.

V. Conclusion

The next step in moving the potential StarHab Challenge from formulation and into the formal development process, will be for the Centennial Challenges Team to pull the landscape analysis, research results, and potential Challenge topics and structures into a more detailed written report and charts for consideration by NASA’s Executive Program Management Council (EPMC) at NASA Headquarters (HQ) in Washington, D.C.. This Council will ultimately give the Authority to Proceed (ATP) to the Centennial Challenges program to further develop the the topic and the actual structure of the competition tasks and requirements. As the formulation and development process continues, more information and updates will be provided in future papers if appropriate.

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