MITRE's Response to the OSTP RFI on Sustainability of Microgravity R&D During and Beyond ISS Transition

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Questions Posed in the RFI

1. What should be the United States' vision for the future of microgravity research?

MITRE's recommended vision: *Microgravity research is performed in a collaborative, strategic, and safe manner, thus enabling advancements that benefit all of mankind on Earth and in space.*

While determining activities to meet this vision, it is important to recognize an evolving shift in space presence from government only, to hybrid government/commercial, and finally, to a predominantly commercial footprint in space. With the exponential growth of commercial space, a low earth orbit National Lab may be re-imagined through federal purchasing of microgravity capacity on commercial vehicles across industry vendors. Providers such as Axiom Space,[1] Northrop Grumman,[2] or Blue Origin[3] have all designed their space stations to include research facilities that should benefit from government collaboration. Taking this approach will provide unique flexibility to the U.S. government (USG), indirectly prompt the space-race as commercial carriers compete for government LEO study-capacity grants, and allow flexibility for laboratory attributes across multiple carriers/vehicles/innovation without binding the U.S. government to a physical infrastructure such as the International Space Station (ISS). A public-private partnership is a model that could be successfully implemented to achieve the goals of a national laboratory in LEO after ISS transition.

[1] The world's next breakthrough innovation platform is in orbit. 2022. Axiom Space, https://www.axiomspace.com/axiom-station. Last accessed December 19, 2022.

[2] Commercial Space Station. 2022. Northrop Grumman, https://www.northropgrumman.com/space/commercial-space-station. Last accessed December 19, 2022.

[3] Orbital Reef. 2022. Blue Origin, https://www.orbitalreef.com. Last accessed December 19, 2022.

2. What should be the long-term microgravity research goals for U.S. presence in LEO?

A systems analysis of critical activities reveals five categories that need to be addressed to enable this vision to become reality: health, sustainment, materials science, mining, and infrastructure. Each are further discussed below.

Health

Goal: ensure the safety of a space population with diverse health backgrounds

Health in microgravity is a critical aspect for the future of space missions as commercial activities will involve both more individuals and individuals that aren't as healthy as historical NASA astronauts. Commercial companies are organizing human suborbital flights open to anyone who is at least 18 years old, speaks English, and has a "*passion for humanity and a desire to positively impact the world.*"[4] There are plans to build commercial LEO stations, such as Orbital Reef, for business and fundamental research but also for space tourism, with no accessibility pre-requisites.[5] In addition, NASA's Artemis Plan aims to establish a sustained human presence on the Moon[6] that has a gravity of one-sixth that of the Earth (~1.6 m^2/s); this implies that there will be a new workforce in low gravity conditions, with the need for miners, welders, or construction workers, who will likely not present a health background similar to that of today's astronauts. It is therefore crucial to understand key aspects of this new era, such as how pre-existing conditions can affect life in space, how to respond to emergency situations, or how diversified physical fitness is affected by microgravity.

Existing research on known risks, such as motion sickness or muscle and bone loss, should also continue. Up to 80% of astronauts also experience Space Motion Sickness (SMS) in the first three days of flight,[7] leading to fatigue, nausea, vomiting which can prevent them from performing essential tasks such as flying or docking. Research on potential medications to counteract SMS without significant side effects would be a tremendous advancement in space medicine, but due to drugs reacting differently in microgravity,[8] a LEO laboratory environment is best suited for such research. Other known health issues, such as muscle and bone loss, should be investigated under the assumption that spaceflight will be accessible to people with potential pre-existing conditions (e.g., heart problems, obesity) that would prevent them from exercising adequately (which is currently the preferred method to limit loss). Research into alternate options to limit muscle and bone loss needs to become a priority.

In addition to further understanding current known issues, there is a need to investigate additional risks that will inevitably arise as space becomes more accessible to the general public. There are several topics that are currently unknown and warrant research and development (R&D) initiatives in microgravity, including those listed below:

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[4] The world's first sponsored Citizen Astronaut Program. 2022. Space For Humanity, https://spaceforhumanity.org/apply#selection. Last accessed December 19, 2022.

[5] Orbital Reef.

[6] Artemis Plan - NASA's Lunar Exploration Program Overview. 2020. National Aeronautics and Space Administration.

[7] Space Motion Sickness (Space Adaptation). 2016. National Aeronautics and Space Administration.

[8] D. Williams. The biomedical challenges of space flight. 2003. Annual Review of Medicine, https://pubmed.ncbi.nlm.nih.gov/12471177/. Last accessed December 19, 2022.

- How health conditions (e.g., COPD) and/or medical history (i.e, TIA) affect life in space. Moreover, many individuals use prescription medications that have unknown effects in microgravity.
- How supplies and devices operate in space, including the effects of radiation on electronics. For instance, this could mean understanding the consequences of wearing a pacemaker in space or adapting IV fluids delivery to microgravity operations.

Furthermore, with the development of space tourism and the anticipated need for workers, especially in at-risk fields such as mining, space emergency medicine challenges should be addressed. This includes tasks such as testing device efficiency in microgravity but also more complex subjects like developing "space ambulance" designs and testing their efficiency.

Goal: ensure mental health for all travelers

With space becoming accessible to more people, research on mental health in space is even more important than it is with trained astronauts. There have been multiple data points in terms of mental health on MIR and the ISS through analysis of in-flight diaries and data, as well as analog data,[9,10] indicating some level of annoyance, anxiety, and depression. There have been reports of hallucinations or transcendental experiences, including the Overview Effect in which astronauts experience their surroundings "emotionally and viscerally, as with ecstasy" and feel "a sense of total unity and oneness."[11] There is a known absence of olfactory senses stimulation, such as lack of pleasant odors or tasty food that are often the cause of mental health related issues.[12] It is essential to not only fully understand the effect of spaceflight on mental health but also research possible preventive solutions to implement on orbital stations, such as creating a more pleasant space environment, including food. Psychiatric emergencies should also be considered in microgravity R&D in order to implement potential care strategies in space.

Conclusion

Such research could inform several regulations that will need to be adapted to this new era of human spaceflights:

- FAA's medical certificate requirements that are currently limited to crews in orbital and suborbital flights but would need to be extended to passengers and workers as well as space beyond Earth orbits.
- Regulations applied to the spacecraft for safety/protection of passengers, including emergency vehicles and requirements for on-board personal protection equipment.

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[9] Slack, K.J., Williams, T.J., Schneiderman, J.S., Whitmire, A.M., and Picano, J.J. Evidence report: risk of adverse cognitive or behavioral conditions and psychiatric disorders. Houston, TX: NASA Lyndon B. Johnson Space Center, April 11, 2016.

[10] Stuster J (2010) Behavioral Issues Associated with Isolation and Confinement: Review and Analysis of Astronaut Journals. National Aeronautics and Space Administration. NASA/TM-2010-216130 (July).

[11] [2:50 PM] Dr. Valerie Jane Gawron, Accenture Consulting Up, up, and away harnessing opportunity in the stratosphere. Accenture Consulting, 2016.

[12] Vessel EA Russo S (2015) Effects of reduced sensory stimulation and assessment of countermeasures for sensory stimulation augmentation: A Report for NASA Behavioral Health and Performance Research: Sensory Stimulation Augmentation Tools for Long Duration Spaceflight (NASA/TM-2015-218576). NASA-Johnson Space Center, Houston, TX.

Sustainment

Goal: implementation of environmental regulation capabilities and sustainment methods for long duration flight and planetary settlement

As the U.S. is planning sustained presence on the Moon and therefore in space, research on sustainment in microgravity is important. This includes understanding how to grow food in space but also researching solutions for maximizing the nutritional benefits from food grown in microgravity. There are two foreseeable applications to agricultural and sustainment research in space: one is related to planetary settlement and the other to long flights (e.g., to Mars).[13]

Therefore, continued work on crops in space[14] is crucial for long duration spaceflights but needs to be taken a step further, with research into scalable processes for mass production for planetary settlement purposes.

In addition, plants could play a significant role in regulating the spaceship environment. Such experiments should be run in microgravity to understand the ability of crops to play a role in capsule atmosphere regulations while growing in a zero-gravity environment.

Material science

Goal: understanding new material properties and manufacturing for long-duration flight, planetary settlement, and Earth-bound applications

Material science is becoming an increasingly important challenge to address. Understanding new material properties and manufacturing in microgravity will help with Earth-bound applications and planetary settlement.[15] MITRE recommends that the research that is currently performed on the ISS National Laboratory continues, such as microgravity-enabled material production capabilities, advanced manufacturing, additive manufacturing, material testing, etc.[16] Such research should also be extended to lunar applications, such as 3-D printing using regolith simulants.[17] Microgravity in LEO laboratories are also a great opportunity to research and test levels of protection to radiations for various materials.

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[13] Human Needs: Sustaining Life During Exploration. 2007. National Aeronautics and Space Administration, https://www.nasa.gov/vision/earth/everydaylife/jamestown-needs-fs.html. Last accessed December 23, 2022.

[14] Growing Plants in Space. 2021. National Aeronautics and Space Administration, https://www.nasa.gov/content/growing-plants-in-space. Last accessed December 23, 2022.

[15] Outside the Box – The Materials Science in Space Workshop. 2019. National Aeronautics and Space Administration, https://science.nasa.gov/news-article/outside-the-box-the-materials-science-in-space-workshop-july-2019. Last accessed December 19, 2022.

[16] Spaceflight R&D Spans Many Disciplines. 2022. ISS National Laboratory Center for the Advancement of Science in Space, https://www.issnationallab.org/research-on-the-iss/areas-of-research/physical-sciences/. Last accessed December 19, 2022.

[17] Outside the Box – The Materials Science in Space Workshop.

Mining

Goal: test mining methods for Artemis mission plans

With the Artemis Accords, NASA anticipates the needs for mining processes.[18] While many solutions to the challenges of extracting regolith and ore from materials are currently being addressed (e.g., thermal mining, Radiant Gas Dynamic mining, and bulk excavation)[19], most do not get tested in a microgravity environment. A LEO Laboratory equipped with adequate capabilities would present a great opportunity to test such methods before sending them to the Moon. This could also be used to test alternative ore extraction methods (e.g., the newly developed flash heating)[20] in microgravity, as has been done with biomining of rare earth elements onboard the ISS.[21]

Goal: informed planning of planetary vehicles trajectories and interaction with planetary surfaces

Soil properties and geotechnical tests should be explored in microgravity in anticipation of multiple missions to the Moon (manned and robotics) and Mars. Key intrinsic properties such as cohesion and angle of internal friction can help retrieve bearing capacity, soil failure point, and in general, understand planetary terrains in order to inform path assessment and planning for autonomous robotics missions.[22] The lack of knowledge of geotechnical properties of soils has led to several incidents on multiple robotics missions,[23] one famous example being the loss of the rover Spirit in 2010.[24] On Earth, such parameters can be found via direct methods involving samples subjected to stresses and confining pressures (triaxial test)[25] or indirect methods using instruments such as cone penetrometers and shear vanes. These indirect methods have been suggested as candidates for astronauts and rovers to run geotechnical experiments, and some were tested on the Moon with limited success,[26] but further research is needed to develop more robust techniques or adapt existing ones to microgravity conditions.

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[18] Artemis Plan - NASA's Lunar Exploration Program Overview

[19] C. Dryer. Mining Lunar Polar Ice for LO2/LH2. 2021. American Institute of Aeronautics and Astronautics, https://arc.aiaa.org/doi/10.2514/6.2021-4235. Last accessed December 19, 2022.

[20] B. Deng. Rare Earth Elements from Waste. 2022. Science Advances, https://www.science.org/doi/10.1126/sciadv.abm3132. Last accessed December 19, 2022.

[21] C. Cockell, et al. Space Station Biomining Experiment Demonstrates Rare Earth Element Extraction in Microgravity and Mars Gravity. 2020. Nature Communications, https://www.nature.com/articles/s41467-020-19276-w. Last accessed December 19, 2022.

[22] G. Hedrick, et al. In-situ Terrain Analysis for Planetary Rovers. 2021. Proceedings of the ISTVS International Conference.

[23] C. Zacny, et al. Robotic Lunar Geotechnical Tool. 2010. ASCE Earth and Space, https://ascelibrary.org/doi/abs/10.1061/41096%28366%2919. Last accessed December 19, 2022.

[24] J. Johnson, et al. Discrete element method simulations of mars exploration rover wheel performance. 2015. Journal of Terramechanics, https://www.sciencedirect.com/science/article/pii/S0022489815000154. Last accessed December 19, 2022.

[25] A. Bishop, et al. The measurement of soil properties in the triaxial test. 1962. Edward Arnold Publishers Limited.

[26] C. Cockell, et al.

Infrastructure

Goal: ensure adequate facilities are available to conduct research

Developing the adequate infrastructure to promote microgravity R&D is essential. There needs to be dedicated space facilities for each area of research, such as a clinic for health studies, a soil laboratory for mining and geotechnical research, or a material science module with the necessary equipment. Such infrastructure will require maintenance, which could be achieved via a public-private partnership.

Goal: provide adequate infrastructure to test artificial gravity in anticipation of long-duration flights to the Moon, Mars, and beyond

It is important to further investigate how to reproduce various levels of gravity in space in order to 1) test the effects of prolonged exposure to lunar and Martian gravity, as well as gravity greater than that of Earth; 2) provide adequate testing conditions for various planetary experiments; and 3) promote research into artificial terrestrial gravity for long duration missions in outer space.

Such efforts would not only inform mission-related decisions but also safety-related requirements such as implementation of an insurance policy for space workers with a full understanding of the related risks.

3. What are the top critical research, development, or operational needs required to ensure a smooth transition between the International Space Station and future commercial LEO microgravity platforms and realize the ideal future of microgravity research?

To ensure a smooth transition from a national laboratory to government to a more public-private collaborative model, it is crucial to implement an adequate strategy that will prioritizes the safety of travelers. There are no regulations outlining who can be on the space stations put together by industry, and granting access to anyone without proper understanding and handling of health conditions would be detrimental for sustaining LEO stations. The top critical R&D effort should therefore evolve around space health and pharmaceutical manufacturing, as mentioned in response to question #1, to ensure safety of people going to space.

There will also be a need to develop new training programs in partnership with commercial vendors ahead of the retirement of the ISS to ensure a smooth transition. The programs will need to reflect the various populations that will potentially board the stations and could be implemented in levels depending on each person's role in space (very similar to levels of medical certificates for pilots). And finally, it will be necessary to establish new requirements and regulations for conducting research in commercial space stations, including safety requirements pertaining to individual modules/laboratory.

4. What would be the most effective role of the U.S. government to ensure sustained LEO microgravity R&D following the retirement of the ISS?

As previously stated, the space sector is becoming predominantly commercial. Therefore, the USG needs to ensure a domestic commercial market for sustained microgravity research to ensure U.S. competitive advance in science and technology. For example, the USG can incentivize U.S. commercial interests directly through purchasing power, policy, legislation, tax benefits, and other aspects. It can also incentivize commercial interests in space indirectly, by defending a U.S. presence in space.

Additionally, to ensure sustained LEO microgravity R&D following the retirement of the ISS, the USG needs to fortify, if not build, coordination and collaboration on two fronts:

- The U.S. government should continue to foster collaboration with spacefaring nations (Europe, Japan) post-ISS to promote efficient microgravity research. This implies encouraging information sharing between countries at a government level on microgravity R&D. It also includes understanding international space laws and policies in this new space era, which could have implications at a national level, such as the extension of National Institute for Occupational Safety & Health and Occupational Safety and Health Administration plans to include a space component.
- The U.S. government should also foster collaboration between industry and government to ensure safety of crews, passengers, and workers in space. With the aforementioned shift towards industry predominance in the space sector, the USG should promote safe exchange of information between companies and industry/government. This could help understand health conditions, new designs, advanced materials, etc. similar to the role the Aviation Safety Information and Analysis and Sharing (ASIAS) system plays in the aviation sector.[27]

5. Should the U.S. government continue to sponsor a national lab in LEO after ISS transition? If so, what would be the best model(s) for a LEO national lab?

MITRE recommends performing a full analysis of alternatives on the following three options:

1. Retaining the ISS beyond 2030 and descoping the mission to just microgravity research. The government could continue to benefit from this highly capable platform if it chooses to continue to fund sustainment of the ISS infrastructure.
2. Incentivizing industry to provide the orbital platform for microgravity research and to fund sustainment.
3. A public-private partnership in which private industry and the government share costs and achieve mutual benefits from an orbiting laboratory.

[27] FAA Aviation Safety Information Analysis and Sharing (ASIAS) System. 2022. Federal Aviation Administration, https://www.asias.faa.gov/apex/f?p=100:1. Last accessed December 19, 2022.