ENABLING HIGH-THROUGHPUT AND HIGH-IMPACT SPACE LIFE SCIENCE RESEARCH ON THE LUNAR SURFACE.

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Introduction: The Artemis program opens the opportunity to conduct biological experiments outside Low Earth Orbit (LEO) and outside of the Van-Allen Belts for the first time in almost 50 years. This is of great importance to the space life sciences community, as environments encountered on the lunar surface can either not be replicated on Earth at all or not for continued long durations typically required for biological studies.

Opportunities: The Moon is unique for its in-situ resources and partial gravity. The resources include both lunar regolith, rich in oxygen, silicon, and iron, as well as potential water ice [1]. While partial gravity experiments are theoretically possible to conduct in microgravity for long durations with the use of centrifuges, practically it is difficult to conduct such experiments continuously, for example, while initiating or terminating the experiment or while performing crew operations such as microscopy or media exchanges. Additionally, the overhead infrastructure required to accommodate rotating machinery in flight hardware is significant. The Moon also provides a hard vacuum, temperature extremes, as well as a deep space radiation environment. While these latter environments are not unique to the Moon, we currently do not have a platform that supports long term deep space radiation studies, as the International Space Station (ISS) is orbiting within the shielding provided by the Van Allen Belts. Care should be taken to not disturb these unique environments on the lunar surface. One example is the shielding of the pressurized volume which could limit the radiation dose to the experiment. If necessary, a pressurized section of the habitat with less shielding should be considered to provide pressurized experiments access to higher dose rates than achievable within the shielded crew section itself.

Challenges and Recommendations: While the lunar surface offers a wide variety of research opportunities, it represents a very hostile environment for conducting space life sciences research at the same time. Three major challenges have been identified and are presented below:

<u>Radiation environment on hardware</u>. Within the pressurized and somewhat shielded modules of the ISS, the typical approach for payload radiation tolerance is to largely ignore it. NASA currently provides no official requirements to ISS internal payload developers to utilize radiation hardened components or design payload systems with sufficient redundancy to continue operating without issue through single event upsets. For ISS, this is indeed a rational and cost-effective approach given the high added cost of radiation-tolerance engineering and the low frequency and consequence of radiation-related payload failures. Further, this approach has enabled the design of payloads incorporating low-cost Commercial Off-The-Shelf (COTS) components designed originally for terrestrial usage. For experiments on the lunar surface, it is important to reassess this approach based on the final radiation exposures expected within the pressurized habitat to ensure that the implicit assumptions that it is dependent upon remain valid. These are, namely, low frequency and low consequence of radiation-related payload failure.

Accordingly, for new hardware and ISS-repurposed hardware, it would perhaps be prudent to provide some basic requirements or guidelines to payload developers to improve radiation tolerance without adding significant cost. For example, incorporating software watch-dogs, using radiation-tolerant (but not hardened) components, and designing failure tolerance into systems. That said, it is crucial not to apply radiation requirements that are too stringent and result in ballooning system cost, complexity, and volume. Unchecked payload requirement creep will decrease the quantity of science that can be feasibly processed on the lunar surface. A 90% experiment success rate with 10 experiments is preferable to a 100% experiment success rate with only 5 experiments.

<u>No continuous crew presence.</u> At least during the initial Artemis program, crewed operation on the lunar surface will only occur intermittently, which is substantially different than the current continuous operations onboard the ISS. While some multigenerational biological studies can certainly be conducted within the multiday surface stays, crew time will foreseeably be very limited to initiate, maintain, and terminate those type of experiments due to the limited surface stay duration. Additionally, a wide variety of studies will require several weeks to months of experiment time to assess the effects of long-term exposure to the lunar surface environment or to capture unique events such as solar radiation flares that might not correlate with crew intervals. This new limitation demands a higher degree of automation than current payload developments. A promising approach is the use

of semi-automation to efficiently conduct a high load of biological experiments. Using the benefits of the adaptable crew to perform the versatile operations to initiate and terminate the experiment while using the benefits of automation to repeatedly maintain and perform continuous measurements can lead to successful long-term experiments. It is worth pointing out that the surface infrastructure should also be capable to provide power, data, and environmental (thermal, pressure) services to payloads while in the uncrewed mission phases.

Limited and infrequent up- and down-mass availability. Compared to the ISS, the Artemis program will feature a lower launch rate (initially one per year) and reduced volume available for science hardware [2]. In that sense, experiments on the lunar surface can be considered "higher-stakes" than ISS experiments due to fewer overall flight opportunities. Due to the increased delta-v requirement to reach the lunar surface compared to LEO as well as the additional infrastructure requirements (e.g. lander and spacesuits) it can be assumed that the available up- and down mass is smaller than available for ISS. In order to efficiently use the available resources, it will be crucial to provide the basic laboratory infrastructure to the diverse scientific experiments. Using the current approach of launching a sample, conducting the active growth phase in space, and then returning the sample in a stabilized state will not only limit the experiment throughput but also delay iterations on experiments based on previous experiment results. Investing in the opportunity to equip the lunar surface infrastructure with modular measurement devices as well as the experiments themselves with active sensors will increase the effectiveness of the performed experiments. General lab hardware that can be used by multiple investigations include for example a scale, DNA/RNA sequencing device, microscope, plate reader, fridge, freezer, carbon dioxide incubator, as well as a glovebox. Heritage hardware used onboard the ISS not just reduces the development costs but also increases the comparability between control experiments onboard the ISS and onboard the lunar surface. Such heritage hardware that can be reused from the ISS includes but is not limited to the Space Automated Bioproduct Lab (SABL), Plate Reader-2, Atmospheric Control Module (ACM), Vegetable Production Unit (VEGGIE), Minus Eighty Degree Laboratory Freezer for ISS (MELFI), Life Sciences Glovebox (LSG), or the Biomolecule Sequencer [3]. Additionally, by providing standard consumables like pipettes, sharp containers, or contingency kits, the mass and volume constraints during transport can be overcome. Giving scientists access to the environmental parameters such as oxygen, carbon dioxide, temperature, pressure, gravity (vibration), radiation measurements also reduces the measurement overhead for each payload.

Conclusion: In order to conduct any meaningful amounts of biological investigations on the lunar surface, experiments have to be performed in-situ without the logistical challenges of time critical transport of heavy, perishable items. Challenges like the increased radiation environment, limited resupply opportunities, as well as non-continuous crew operations have to be addressed by a higher degree of automation and a new approach for radiation hardened hardware qualification. If this high-throughput and high-impact biological life science research can be implemented, the lunar surface can act as a promising testbed for future human exploration missions to Mars and beyond.

References:

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