Topical: A Dedicated Lunar Laboratory for Transformational Biological and Physical Sciences Investigations

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Executive Summary

To fully support a successful Biological and Physical Sciences (BPS) scientific portfolio in NASA's Artemis program, full consideration should be given in this decadal survey to the development of the laboratory facilities to support BPS experiments on the surface of the Moon. This paper supports the development of a lunar surface laboratory dedicated specifically to transformative biological and physical sciences investigations specifically enabled by returning to the lunar environment.

1.0 Introduction

The Biological and Physical Sciences 2023-2032 decadal survey (BPS2023) calls for community suggestions of "transformative science at the frontiers of biological and physical sciences research in space." The scientific community will no doubt provide a wide range of compelling research topics for the BPS2023 committee to consider, many that will include details about experimental science that would benefit from being done on or within the vicinity of the Moon. One of the biggest lessons we have learned from operating a science program on the International Space Station (ISS) over the past twenty years is that "first-ever" science requires appropriate laboratory facilities dedicated to a wide range of disciplines. A strong lunar science program will require the same. The lunar utilization community has so far developed an initial set of constraints to work within a conceptual framework of how an Artemis base camp would operate. This community has developed use cases for the types of science, sample collection, storage, and analysis, and is integrating these use cases within internal requirements documents. This white paper reflects these current requirements. Due to resource constraints of building the Artemis Base camp, most use cases call for returning samples to Earth for analyses, and none of these requirements currently calls for a dedicated BPS research laboratory on the lunar surface.

2.0 Types of BPS Science and Cornerstone Capabilities

In 2020, a team of experts, internal and external to NASA, developed an Artemis III Science Definition Team Report [1] to prioritize science activities based on the seven overarching science objectives from the Artemis Plan. Artemis III is expected to be the first mission planned for human activities on the lunar surface, and it will be a firm foundation for future discovery that will also enable the continuous evolution of BPS research plans. Conducting experimental science in the lunar environment and investigating and mitigating exploration risks were among the top seven scientific goals listed in the report.

The types of BPS tasks that may be conducted include, but are not limited to, incubation of biological specimens; specimen processing; in-situ analyses; human physiology and lunar adaptation; physical sciences studies; and, microbial ecosystems and survivability sample collection. These activities will require both common-use and unique instruments, facilities, resources (consumables and non-consumables), and science experiment hardware. Support capabilities including standardized systems and interfaces, rack systems, stowage for instruments and consumables, power, multi-use facilities like gloveboxes, and access to gases and heat rejection represent the baseline science utilization capabilities necessary for conducting BPS experiments on the Moon. Although many of these laboratory capabilities could be used as part of an integrated instrumentation strategy for the broader lunar science plans beyond only BPS, a BPS lunar laboratory should have dedicated facilities, ranging from autonomous to crew-tended, and include at least basic BPS capabilities such as:

- *Contamination Control:* sample collection (e.g., baseline samples), stowage, and transport requirements for sterility, particulate cleanliness, organic contamination, contamination knowledge, etc., will need to be defined and balanced between the various sample types. Safety considerations for the samples will also need to be defined and addressed, such as for samples in preservatives or that could release volatiles.
- *Power:* While some instruments may not have any power needs (e.g., retroreflectors, passive collection devices), most instruments could be either self-contained (i.e., they carry their own power supply) or require power from other Artemis assets. Long-lived experiments, which would address many high-priority utilization objectives, would require operations over time periods longer than the surface missions themselves.
- *Conditioned Stowage:* Typical utilization will require conditioned stowage spanning +4°C refrigeration to freezer use (-20°C to -80°C or lower) and cryogenic temperatures.
- *Automated Environmental Monitors:* Data collected from automated monitors of habitable volumes will enable utilization analyses, so wherever possible, the Artemis program should leverage operational capabilities such as radiation monitors, CO_2, O_2, temperature, humidity, and other sensors that address the utilization goals of stakeholders.
- *Multi-use standard lab capabilities:* Cameras, centrifuges, microscopes, gloveboxes, storage racks, and vibration characterization.

2.1 Unique Capabilities: Biological Sciences

The biological science that could be accomplished on the Moon under a long-duration mission will be part of the consideration of the BPS2023. Suggestions range from understanding the fundamental biological and physiological effects of the lunar environment on human health to understanding the consequences of long-duration exposure to lunar gravity alone or in combination with space radiation on biological systems, including those of model organisms and crop plants. NASA is currently defining the types of samples that will be collected from biological science experiments and include samples of microorganisms and complex organisms (e.g., plants, frozen rodent parts, or live animals) to support investigations of how various organisms adapt to, and are affected by, the lunar environment. These samples take the form of cultures, bacterial, fungal, and environmental samples, and science payloads (e.g., tissue-on-a-chip) that must be returned to Earth for detailed laboratory analysis. Such samples have a long history of collection and return on prior human spaceflight missions; however, recent advances in biological investigations and analytical capabilities make it possible to do unprecedented biological science in deep space environments. Therefore, we should make room in our facility plans for advancements in biotechnology that can reduce the need for constrained sample return. Examples of capabilities unique to biological science experiments include microbial, cell, and tissue culture systems; animal habitats; incubators; sample handling and fixation systems; plate readers; and, DNA processing and analysis systems.

2.2 Unique Capabilities: Physical Sciences

Physical science research that could be accomplished on the lunar surface includes biophysics, combustion science, complex fluids fluid physics, fundamental physics, and materials science. The 2011 Life and Physical Sciences Decadal recommended studies in combustion; multiphase flow models; interfacial flow; granular media behavior; supercritical water experiments; materials stability and flammability; pool and flow boiling; propellant storage; lunar resource recovery of important elements; production of concrete from regolith; and, production of oxygen from lunar regolith. Many of these potential investigations could be fully automated but would require unique experimental facilities that need volume in a pressurized habitat and analytical tools and equipment, such as those found in the Fluids and Combustion facility aboard the ISS.

2.4 Important enabling ISRU Research

Initial ISRU research requirements are currently being documented within NASA as limited to three types of sample processing: 1) pre- and post-processed regolith, 2) intermediate and final gas, liquid, and/or solid products from physical science experiments and ISRU processing, and 3) coupons or hardware associated with physical science experiments, ISRU processing, and exposed materials. However, for sustained lunar human presence, larger-scale ISRU research should be done in appropriate dedicated laboratory facilities. For example, of critical importance is research that would enable humans to grow crop plants to support long-term sustainable human exploration there, with real lessons learned for Mars planning. Plants also play an important role in life-support systems because they recycle water and oxygen and filter out CO_2 while generating food [2]. Humans will need both closed and open systems. Initial attempts to grow plants and other photosynthetic organisms on the Moon will require dedicated lab space where pressure, gas composition, temperature, and relative humidity can be controlled. Furthermore, studies of the use of lunar regolith will be critical to maximize *in situ* resources. The lunar regolith has fewer of the essential elements for plants than Mars [see tables from [3]. Nitrogen is the most notable element, and the number 1 element for plants on a molar basis, with potassium a close second. Some potassium is in the lunar rock, but all of these elements would need to be broken down from their native minerals and then become available in the soil solution. The lunar regolith could be a source of some essential elements but studies will need to be done to determine what kind of fertilizer what would be needed for any kind of plant growth. This could include studies of using the regolith as a type of bioreactor, for example, incorporating organic matter (e.g., from processed waste biomass or other sources) into the regolith to allow the minerals to oxidize and weather, and enable a healthy microbiota to establish to become a good "soil." [Wheeler, personal communication 2021]. Additionally, studies would need to be done to determine the appropriate particle size in the lunar gravitational environment. Very fine particles would have drainage issues in reduced gravity, so studies of various soil depths or regolith sieve processing for appropriate size for drainage would need to be conducted in a dedicated lab space.

Facilities dedicated to synthetic biology research would also allow biological organisms to be optimized for human use by using biological intermediates to create fundamental necessities utilizing *in situ* resources. For example, studies examining the use of trapped lunar volatiles in the regolith could be important target areas of propellant, food, biopolymers, and pharmaceuticals with the introduction of biological intermediates, similar to research being done relevant to Martian applications [4].

3.0 Type of Lunar Labs

The ISS was constrained by volume, but the lunar surface will not have the same constraints and should be able to accommodate dedicated lab space as needed. However, with only one week per year of humans on the surface of the Moon in the early Artemis missions, and around 30 days for longer missions, there will be far less crew time available for Artemis missions than has been for ISS missions. Therefore, potential lab concepts should consider a few different options: a lab that would be placed inside the habitat to maximize activities in smallest volume, a lab as its own stand-alone pressurized space separate from the habitat, and a completely separate stand-alone, unpressurized space. Additionally, with such limited crew time on Artemis missions, fully crew-tended, partially-tended, or fully automated science activities should be carefully evaluated. A fully-dedicated pressurized lab space separate from the habitat living space would be ideal for the most transformative science, and would allow the science community to focus their resources on their own investment priorities while benefitting from combining laboratory capabilities for planetary science and biological and physical sciences. This laboratory space could be a mix of automated and crew-tended activities. For example, though the specialized instruments in fundamental physics investigations require pressurized volume and unique facilities, these are experiments that could be performed untended. Physical sciences experiments around combustion and materials research and manufacturing are also potential candidates for full automation. Possible biological science examples include microbiology experiments that do not require end-to-end sample processing and analysis, and cell science that would have facilities sophisticated enough to provide cell nutrition and waste removal and the appropriate environmental conditions for survival. A crewed laboratory would consist of instruments for data collection and monitoring of crew health and performance, as well capabilities for in-lab sample analysis, and more complex biological and physical science experiments in deep space that could untangle effects of partial gravity and radiation stress on systems.

An unpressurized space detached from the habitat and exposed to elements of the lunar environment would be a low-cost option, with mostly automated activities where the crew may stop in while on their way to or from an EVA activity to perform minimal maintenance activities. Because these would be fully automated, this would limit the research capabilities to likely investigations that would not have the highest transformative scientific value.

Discussions on the benefits and constraints of the different types of lunar labs, along with trades associated with crew time availability and costs within NASA are forthcoming. Cost estimates for a BPS lunar lab concept will range from the most rudimentary, untended facility to the most complex crew-tended facility and will be managed with contributions and collaborations from international and commercial partners.

4.0 Conclusions

The scientific community should boldly advocate for the dedicated BPS laboratory facilities to enable the most transformative research that will enable humans to advance basic discovery, learn to live for extended periods on the lunar surface, and perform the experiments necessary to successfully explore Mars. Therefore, the new decadal survey must consider recommending a fully dedicated BPS laboratory for the lunar surface outfitted with the appropriate capabilities and technologies to support these goals. Because of the magnitude of the research efforts and the inevitable advancements of scientific capabilities on Earth that could be applied to lunar BPS research, multi-year funding will be needed. This decadal survey should strongly support and recommend funding new programmatic elements designed to develop these important capabilities and to greatly encourage BPS to pursue all programmatic options with other organizations, space agencies, and the commercial sector that will lead to supporting the research that will come from this unprecedented opportunity of long-duration lunar BPS science.

References

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