51st International Conference on Environmental Systems
10-14 July 2022, St. Paul, Minnesota

ICES-2022-338

Architectural Design of a Human-Centered Lunar Geology Lab

Adam Oswald[1]
University of Colorado Boulder, Boulder, Colorado

This paper examines factors driving the design of a human-centered geology laboratory on the Moon. In-situ lunar geological research has not been done by humans since the Apollo era, but will be a cornerstone of future lunar research activities. While the International Space Station is the prevailing model for an operational space science laboratory, both the environment and nature of science investigations differ in significant ways on the lunar surface. The operational environment includes pervasive dust, partial gravity, frequent extravehicular activity field work, and challenging thermal, mass, volume, and power constraints. This study explores current best practices for laboratories in space, on Earth, and in analog environments, while taking into account several decades of experience with astromaterials curation from meteorite recovery and robotic sample return missions. Similarly, this study emphasizes the basic tasks of space architecture: typology investigation, structural and systems integration, and understanding crew comfort and performance as key design drivers. As space habitats become longer-duration, increasingly commercialized, and accommodating of a broader diversity of occupants and science objectives, there is a need for future design work to go beyond traditional human factors engineering and emphasize crew performance, comfort, and well-being. A review of space and space analog laboratory architectures and typologies complements heritage space habitat design for ergonomics and the application of best practices for contemporary labs on Earth to define an integrative approach to a human-centered lunar geology lab.

Nomenclature

ANSMET = *U.S. Antarctic Search for Meteorites Program*
ARIS = *Active Rack Isolation System*
BAS = *British Antarctic Survey*
ConOps = *Concept of Operations*
ECLSS = *Environmental Control and Life Support System*
ESA = *European Space Agency*
EVA = *Extravehicular Activity*
HDU1-PEM = *Habitability Demonstration Unit 1 – Pressurized Excursion Module*
HEPA = *High Efficiency Particulate Air filter*
HLS = *Human Landing System*
ISPR = *International Standard Payload Rack*
ISRU = *In-Situ Resource Utilization*
ISS = *International Space Station*
JAXA = *Japanese Aerospace Exploration Agency*
NASA JSC = *National Aeronautics and Space Administration Johnson Space Center*
PDS = *Passive Damping System*
pLOC = *Probability of Loss of Crew*
pLOM = *Probability of Loss of Mission*
PSE = *Apollo Passive Seismic Experiment*
TRL = *Technology Readiness Level*

---

[1] Bioastronautics Graduate Student, Ann & H.J. Smead Department of Aerospace Engineering Sciences, 3775 Discovery Dr, Boulder, CO 80303

I. Introduction

With a ramping-up of human spaceflight activities, including a number of commercial vehicles, habitats, and even spacesuits coming online, as well as NASA's progress with the Artemis mission, the return of humans to the surface of the Moon seems imminent. But if we are going and "this time to stay," it is worth understanding the precise nature of planned activities, how to conduct them in a way that returns the most value, and how our design work can best support those goals. Some of this definition is ongoing and has been for years, including the Lunar Exploration Analysis Group's Lunar Exploration Roadmap and ESA's plan for a Moon Village, among many others.[1,2,3,4] Similar to other extreme environment habitats, any initial lunar base camp will first and foremost be a laboratory. Geology, as a starting point, offers a means of building on the investigations from the Apollo era and can form a foundation from which to expand into other areas of lunar research.

While a number of different concepts of operations (ConOps) are currently in formulation for the first phase of Artemis landings, it is likely that the Human Landing System (HLS) approach to lunar geology will be similar to that of the Apollo missions: sample acquisition, minimal curation, and return for study in laboratories on Earth. This is a near certainty for the 6.5-day sortie missions defined in the HLS ConOps, and a likely scenario for the longer, 30-day stays in the south polar region.[5] Since the sample return scenario is reasonably well-defined by Apollo, this paper assumes the 30-day mission as a baseline. The research is based on developing science lab needs for long-term lunar habitats where the principal objective is not just sample return, but in-situ geological research. This suggests a design approach that supports in-depth geological investigations and where the permanent nature of the facility justifies more significant capital expenditure and down mass to the lunar surface.

Further, rather than focusing on a minimally-functional habitat as a starting point – establishing a feasible prefabricated and landed habitat architecture, then carving out a reasonable space for science work – this paper starts from the science work itself and builds outward: defining the tasks and idealized work environment that enable the high-performance, comfort, and well-being of the science team, then defining the workspace as a set of parameters for the eventual habitat design. This direction was chosen for the validation approach of helping ensure that future habitat designs will support meaningful science, rather than a verification approach that first assumes a familiar-looking vehicle that some minimal amount of science payload can fit into.

This approach is also more reminiscent of the process of designing lab spaces on Earth, where mass, power, and volume are rarely constrained. Instead, the first questions typically asked are of the researchers themselves and what design solutions will best fit their needs. Because these projects are typically only cost- and time-constrained, questions of human performance, comfort, and well-being can quickly become the most important design drivers, as well as the clearest differentiators between architects competing for work. As a result, architectural practitioners have learned to intuitively approach projects – including the design of lab spaces and lab buildings – from this perspective, incorporating lessons learned from past projects, significant development time working directly with researchers to understand needs, and technical integration with building systems to assure the retention of design fidelity as the projects evolve. Adherence to a human-centered design approach will be important for a permanent base camp at the Moon's south pole – what will be the most remote and isolated human outpost ever built.

This paper seeks to define the design problem for a lunar laboratory from two perspectives. First, through an understanding of the impact of the lunar environment on establishing design requirements and parameters. Orbital laboratories from Mir to ISS have delivered decades of experience conducting science in space, but many lessons will not easily translate to a surface habitat on the Moon, a celestial body no human has visited for five decades. Second is through an "inside-out" design approach that starts with the researcher then works outward to establish the physical built environment. This helps ensure that the driving motivation behind design decisions is what is best for the crew, not what makes the engineering close most efficiently. While there are many potential avenues for science investigations on the Moon, this paper will focus on geology and look only opportunistically to science in adjacent fields that can be accomplished without additional equipment, mass, or volume. Beginning with the ISS, this paper will characterize the research lab architecture of different lunar lab analogs with an emphasis on the last decade. It will then explore strategies for designing lab spaces driven by human performance and well-being. Finally it will synthesize relevant design concepts from various lessons learned across the different analog examples into a concise set of design parameters.

II. Existing Work on Space Lab Development

Existing work into laboratory design and development for other planetary surfaces has met with one primary challenge: an absence of crewed missions to the Moon or Mars during the last five decades has prevented a gradual evolution of the way we approach design and operations of surface infrastructure. Instead, every example of lab architecture can only be viewed as an analog for a lunar surface lab with some lessons that can be adapted and others that do not apply. This section will review the design and operation of labs in a variety of development states and with attention to relevance for future lunar geology lab design. These include:

- the International Space Station
- astromaterial sample curation labs
- GeoLab, part of the Desert RATS analog mission
- the Moon and Mars Base Analog (MaMBA)
- the Halley VI Antarctic Research Station

A. The International Space Station

The International Space Station (ISS) has continuously served as a permanent orbital laboratory for the last 20 years and offers many important lessons for constructing and operating a science lab in space. ISS supports a variety of space science investigations in three primary areas: biological, human physiological, and materials science in microgravity.[6] The lab architecture of the ISS is characterized by the modular International Standard Payload Rack (ISPR), which enables standardization for easier payload development on Earth and offers a means of on-orbit reconfiguration, replacement, and expansion.[7] Racks can consist of both science payloads and subsystem equipment, making possible system upgrades without the delivery of a new habitation module.

The ISS interior layout is organized around four axisymmetric structural standoffs, which serve as attachment points, structural load paths, and utility chases (see Fig. 2). The standoffs run the length of the modules and create a square 2.1 m cross section that the crew inhabits.[8] This configuration allows for high volumetric loading of the habitat interior and densely-packed science equipment, while retaining the ability for crew to remove racks for inspection, servicing, repair, and replacement.[6] This density is accomplished, in part, by utilizing all four sides of the habitat interior for equipment loading, which is feasible due to the microgravity environment.

The ISS laboratory configuration is the result of decades of development and architectural evolution, starting with Skylab and continuing to present day. In terms of supporting specific microgravity science investigations in a long-duration, densely-packed orbital environment, the ISS configuration represents the best practices of a lab in space. However, there are also significant differences between ISS and anticipated surface habitats. The key environmental differences for a habitat on the Moon are that it will have to contend with gravity and lunar dust. The introduction of even a partial gravity field has implications for the architectural design of the habitat. Beyond supporting a habitable volume, the crew cabin must also support adequate floor area and ceiling heights – metrics that are difficult to assess in the 1g environment on Earth or the microgravity environment of the ISS. The pervasiveness of lunar dust will be at least a nuisance and at worst a major ongoing issue that may limit the useful life of equipment and habitats and threaten crew safety and well-being.

Additionally, human factors must be reevaluated for a lab in a gravity field. ISS was designed for people generally assuming a neutral body posture in microgravity. Work and reach envelopes for the full range of prospective crew members will need to adjust slightly to accommodate not just a gravity field (well-understood on Earth) but a 1/6 g gravity field (barely-understood). Interfaces can no longer be located underfoot, and the ceiling may be difficult to access. Researchers who would float in microgravity will now be standing at workstations and may need seating provided. Beyond constrained rack loading, every surface can no longer be treated as a wall and the ability to reach elevated equipment, controls, and displays may become an issue. Finally, labs on the Moon and Mars will at least in part emphasize geological investigations. This is an area of study that does not occur on ISS and will require an array of equipment and instruments, many of which may be new to the space environment and could require substantial TRL maturation.

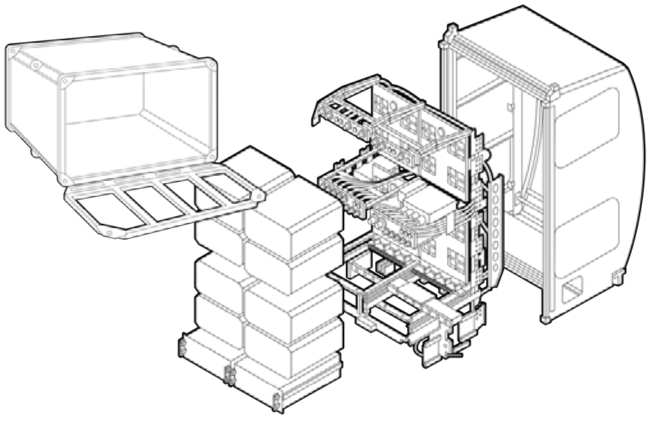

Figure 1. The International Standard Payload Rack (ISPR) standardizes payload and service equipment accommodations on ISS.[9]

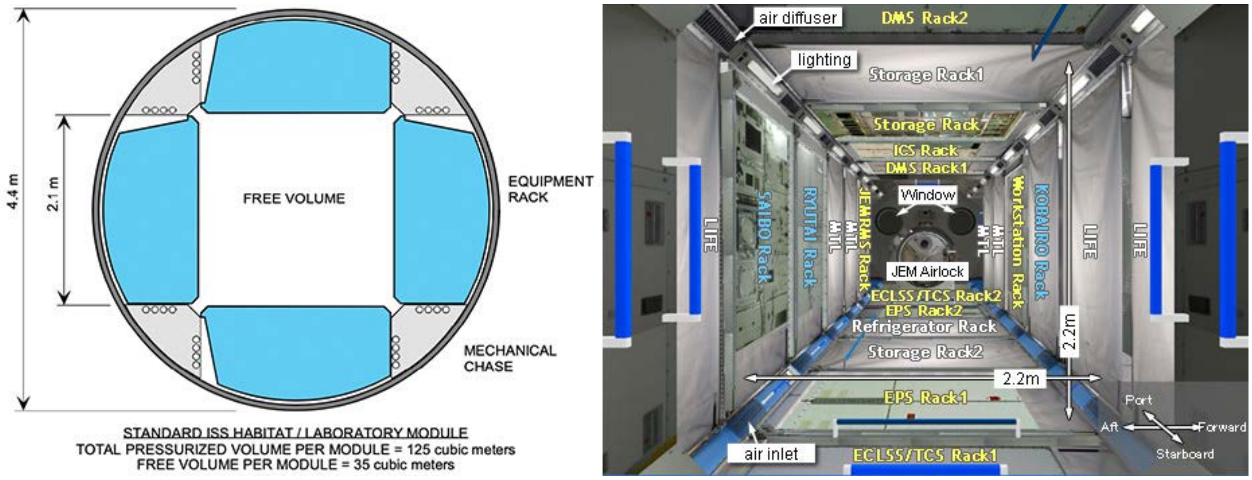

Figure 2. (Left) ISPRs (in blue) define the interior habitable volume in a typical ISS module, leaving room for mechanical chases at the four structural standoffs running the length of the module.[8] (Right) The interior of JAXA's Kibo module with the front faces of the racks and services (diffusers, inlets, and lighting) visible.[10]

Figure 3. Astronauts install a rack in the Kibo module during STS-124 in 2008. In microgravity this is a complex and time-consuming task requiring multiple crew members. In the added partial gravity of the Moon, this is an even less straightforward activity. Removing racks from the floor or ceiling for maintenance or replacement would likely become extremely challenging.[7]

B. Astromaterial Sample Curation

Curation of astromaterials is a planetary science topic that has been given much consideration for several decades, starting with the procedures for the return of lunar materials from Apollo and more recently focusing on robotic sample return with such missions as Hayabusa, OSIRIS-REx, and NASA's planned Mars Sample Return.[11] Additionally, the U.S. Antarctic Search for Meteorites Program (ANSMET) starting in 1976 has recovered more than 20,000 meteorites and has been a major contributor to the ongoing development of astromaterial curation practices.[12]

The primary goal of an Earth-based curation facility is "the isolation of astromaterials from the terrestrial environment."[13] Sample curation generally involves receiving, unpacking, contamination control, and long-term storage and curation, which includes managing samples for scientific research and may take place in a separate facility.[11,13,14] Because most astromaterial curation discourse focuses on robotic sample return, which also accommodates the field work procedures of ANSMET and nominal EVA activities, the characterization of a long-term, in-situ research facility is rarely explored.[11] Instead, EVA sample analysis is limited to "high-grading," or selecting the most interesting samples for return to Earth.[13] However, a lunar lab will essentially be a sample curation facility, just one that is much closer to the samples being acquired. As such, the processes, equipment, and workspaces of astromaterial curation can inform a Moon-based lab in terms of lessons learned, best practices, and requirement definition.

NASA JSC Astromaterial Curation Laboratories

The Astromaterials Acquisition and Curation Office at NASA's Johnson Space Center (JSC) has more than 50 years of experience receiving, processing, investigating, protecting, and storing astromaterial samples, as well as distributing them to the scientific community.[13,14] The facility consists of 8 suites of 22 cleanrooms across two interconnected buildings operated by a staff of approximately thirty. Starting with Apollo, the facility has been responsible for curating all of NASA's returned samples. This includes the Apollo lunar samples but also ANSMET meteorites, cosmic dust from NASA aircraft missions, solar wind atoms from the Genesis mission, and comet particles and interstellar dust from the Stardust mission. Lab capabilities have grown since its founding, responding to ongoing science demand and advances in analysis techniques and technologies.[13] The key challenge for astromaterial curation is maintaining the pristine condition of samples, particularly during long-duration storage.[14] The proliferation of samples, especially from meteorites, has challenged the facility's storage capacity, requiring transfer of part of the collection to other locations, including NASA's White Sands Facility in New Mexico and the Smithsonian.[13]

During Apollo 11-14, lunar samples and astronauts returned to a different facility, the Lunar Receiving Laboratory (LRL), where they were quarantined and tested to assess the risk of biological back-contamination from the Moon.[13,14] After Apollo 14, it was established that biological back-contamination from the Moon was not a concern and the facility was disassembled. The LRL continues to serve as a model for sample return where organic material may be involved, as with future Mars sample return, where the purpose is to "receive the returned spacecraft, extract the sealed sample container, open it to access the samples, and then carry out a set of tests under strict containment conditions to determine if the samples are hazardous."[14] For a lunar lab, the hazard is known to be minimal, so several of these steps are not needed.

Gloveboxes

Class III Biological Safety Cabinets, colloquially referred to as gloveboxes, are designed to reduce contamination of both curated samples and laboratory environment.[14,15] They tend to be held at a positive pressure with an atmosphere composed of an unreactive gas, such as nitrogen or argon, and are often located within a cleanroom as an additional layer of containment.[11] Gloveboxes have their own ventilation system with air purifiers, HEPA filters, and a high rate of air changes to maintain the purity of the atmosphere. Gloveboxes are constructed from materials selected to reduce particle shedding and contamination, typically consisting of only stainless steel, Teflon, aluminum, polycarbonate, combusted glass (Pyrex), and neoprene gloves.[13]

The Lunar Processing Cabinet 2.0 is an upgraded version of the Apollo 16 glovebox located in the Lunar Curation Laboratory at NASA JSC.[15] In addition to modern technologies and materials, the glovebox was equipped with a touchscreen interface and 3D scanner. The gloveboxes support interconnection for sequential procedures, maintain a positive-pressure N_2 environment, are located within class 1000 cleanrooms, and are where lunar samples continue to be processed today.[14]

By contrast, the University of Alberta is home to the Subzero Curation Facility for Astromaterials and has a glovebox setup based on the NASA JSC solution, but with some differences.[16] This is a single workstation located in a low-temperature environmental chamber, essentially a walk-in freezer, that maintains a temperature

Figure 4. Glovebox in the Curation Laboratory at NASA JSC.[13]

between -10 and -30 °C. The glovebox atmosphere is controlled and purified, as with JSC, but the gas in this case is Argon, which is inert and assures no interaction with any sample volatiles that may be present, and slows mixing with air in the event of a breach.[16]

Considerations for Lunar EVA Sample Curation

There are generally two challenges with contamination on the Moon: a) lunar dust finding its way into the habitat from a variety of sources, including acquired geological and regolith samples, and b) anthropogenic contamination of geologic samples, whether intended for in-situ analysis or return to Gateway or Earth.

Figure 5. Lunar Processing Cabinet 2.0 at NASA JSC.[15]

Lunar dust is a major source of habitat and equipment contamination that will require constant and robust mitigation strategies.[17] Regolith particles smaller than 45 μm are generally referred to as dust and begin to affect the performance of hardware and crew physiology.[17,18,19] Though "dust" is not a geological classification, the human-facing characterization offers a meaningful conceit for understanding its impact on crew systems. Particles smaller than 10 μm are small enough to be transported into the human body through respiration or direct physical contact and can impact crew health and well-being.[18] Due to its size, the "toxicologically relevant" dust is also the most likely to be transported into the habitat via surfaces, fabrics, mechanisms, and joints, evidenced by respirable particles making up only around 0.5% of lunar regolith but nearly 50% of the dust cleaned from Apollo EVA suits.[18] The dust is also electrostatically charged and tends to stick to everything it touches, making cleaning and contamination control very difficult.[20] This is a challenge not faced by ISS or any Earth-based analog; the best source of first-hand knowledge is from the Apollo missions, which were short-term missions with two crew members who performed only sample collection on a limited number of EVAs. Apollo astronauts reported health effects from lunar dust ranging from skin, eye, throat, and sinus irritation to difficulties breathing akin to an allergic reaction.[21] With longer-duration missions, greater exposure could lead to the development of more serious health consequences.[18]

While general habitat particulate contamination control is an important issue for future surface habitats, it is slightly beyond the scope of this paper. However, the lab itself and the activities needed to engage in the collection, processing, and examination of samples in a way that mitigates dust contamination of the habitat is an important design requirement. Early lunar sample return and the experience with the LRL offers insights into specific approaches for defining and meeting this requirement, and have been applied in studies for a future Mars sample return facility.[14] In these cases, where biological back-contamination is a possibility, facility design adheres to existing cleanroom standards and, at its most extreme, bio-safety laboratory standards used for control of infectious agents.[22,23] This level of containment is unlikely to be feasible or necessary on the Moon since every EVA will introduce regolith dust into the habitat, so protecting the samples from anthropogenic contamination may be the driving curation requirement.

Since most astromaterial sample curation is chiefly concerned with protecting samples from environmental contamination, relevant lessons can be learned from this experience. This is especially the case with ANSMET procedures and specific meteorite recovery cases, such as the cold curation of the Tagish Lake meteorite.[16] Utilizing EVA astronauts to conduct sample collection has direct precedent in the Apollo missions and more recent experience with the ANSMET program. Apollo astronauts worked with Earth-based geologists to visually survey and select samples for return, then double-bagged samples prior to return to the lander. Some samples were then permanently stored in vacuum-sealed stainless steel containers, some of which remain unopened today.[11,13] ANSMET procedures similarly include double bagging meteorites with Teflon bags and aluminum identification tags, then leaving the samples frozen (outside in Antarctica; in freezers during transit) and unopened until arriving at the curation facility.[12]

One challenge with learning from the experience with Apollo is lunar geology consisted of entirely sample return to Earth, with effectively no in-situ investigation. While Earth sample return will undoubtedly remain a key aspect of lunar science, long-term surface missions will benefit from research activities in-situ as well.

Figure 6. (Left) The GeoLab bay layout from the Desert RATS analog mission in 2011 showing the sample glovebox, multiple touchscreen displays, a microscope (above), other cameras and instruments, and control box below. (Right) Crew members at the workstation, including strained body posture for the glovebox operator. The addition of a seat (left) likely helps with glovebox ergonomics, but may increase the look angles to the monitors.[24]

C. GeoLab

GeoLab was a prototype geology lab designed and built in 2010 for NASA's Habitat Demonstration Unit 1, Pressurized Excursion Module (HDU1-PEM), as part of the Desert Research and Technology Studies (Desert RATS) analog mission.[25,26] The prototype habitat was based on a lunar surface mission scenario from the Constellation program intended to support early, long-duration surface missions. The initial analog mission supported two weeks of operations in northern Arizona with two pressurized, crewed rovers.

GeoLab was integrated into HDU1-PEM following Johnson Space Center's Astromaterials Acquisition & Curation Office's best practices for sample handling. The lab and sample handling setup was intended for preliminary investigation of samples prior to return to Earth-based labs. The layout was organized around a custom-built trapezoidal glovebox that was attached directly to the habitat structure and enabled a positive-pressure environment in which to conduct physical analysis (see Fig. 6). The glovebox was accessible from the habitat exterior through three small dedicated airlocks by which samples could be delivered without exposing them to the habitat environment.[26] Designed to support multiple instrument configurations, the glovebox was initially outfitted with a stereomicroscope, high-definition video cameras, a hand-held X-ray fluorescence spectrometer, a mass balance and scale, and a variety of sampling and manipulating instruments. The instrument setup also supported remote observation and monitoring by ground-based experts.

The GeoLab experience is one of the most relevant prototyping exercises conducted in support of likely lunar surface operations and lab design needs. While the Artemis mission architecture has changed significantly in the 12 years since the Constellation-style pressurized rover scenario, the emphasis on high-cadence EVA, geological sample collection, and laboratory operational needs still provide a good baseline for determining design parameters and constraints. In particular, the Desert RATS team generated a number of lessons learned about different aspects of the GeoLab design and operations, including:

- Affixing the glovebox to the habitat structure restricted adjustments and negatively impacted ergonomics
- Glovebox airlock door location and operation (swing direction) was a challenge
- Cleaning the glovebox was difficult and could have benefitted from additional design interventions
- Touchscreens were difficult to use and to adjust
- Imaging and microscopy requires better vibration isolation
- Sample collection and preparation need to be considered in lab design
- Computer and software interfaces were sometimes barriers, including the useability of some instruments[18]

While these are specific responses to GeoLab design concerns, many of these lessons continue to be relevant and can be adapted to serve future lab designs in a more general way. Some version of the glovebox will likely remain at the center of physical sample examination, introducing challenges with ergonomics, workspace layout, cleaning, exterior access, and vibration control. Sample examination equipment will grow in complexity and diversity, particularly as mission duration and expected returns from in-situ study increase. The glovebox airlock system will need improvements through design iterations and further mock-up testing. Results write-up is difficult on a touch screen, and when sharing a workspace with the glovebox. These and other insights from GeoLab make it an invaluable contribution to future lab designs.

D. Mars and Moon Base Analog (MaMBA)

MaMBA is a surface base analog designed to be modular and emphasize habitability, defined as a combination of the "three pillars" of life support, behavioral health, and safety.[27,28] The habitat is intended to be a "first arrival" solution without reliance on bioregenerative systems or in-situ resource utilization (ISRU) structures, but does assume the support of a small "village" of seven other modules that supply various functions and services. The initial module mock-up was constructed at the Center of Applied Space Technology and Microgravity in Bremen, Germany to test the architectural design and perform human operations simulations. Future work is planned to expand the prototype module and create a fully-functioning analog habitat.[29]

Figure 7. MaMBA science lab mockup with modular racks to support different science configurations.[27]

Like GeoLab, the MaMBA science lab conforms to a cylindrical module similar in size to typical ISS modules. But because it dispenses with the ISPR architecture, it supports considerably more occupiable floor area across two levels that are 2.3 m in height. It also presents a prototypical redesign of science racks with three smaller modules – bench-size for work areas, tall for storage, and hanging racks for additional overhead storage – that are more reminiscent of the casework found in labs on Earth than the densely-packed ISPRs.[27] The lab benches can be used only while standing, though the capability for pull-out tables is a planned addition and would allow for seated work. Three lab use cases are defined: (1) experiments utilizing the lunar environment, (2) analyzing rocks and regolith, and (3) preparing samples for return to Earth.[27,29]

MaMBA is designed with the intent of supporting both technical functionality and human well-being. As such, the design makes moves to control and insulate intramodule sound, uses adaptive lighting to help manage fatigue and stabilize circadian rhythm, and employs moveable interior partitions to create additional privacy.[27]

E. Halley VI Antarctic Research Station

One of the closest terrestrial analogs to the environment encountered by a lunar research facility is Earth's polar research bases.[30] Much like space habitat design, "traditional" polar facilities have been characterized by pragmatic design and an emphasis on engineering response to the extreme and remote environmental conditions.[31] Only after the turn of the century did the architecture begin to consider human comfort as a design parameter nearly on par with the engineering, science requirements, logistics, constructability, and environmental factors. Contemporary facilities, such as the Halley VI outpost designed by Hugh Broughton Architects and AECOM, has as a key requirement to support people in a "safe, comfortable, and stimulating environment" during the summer and winter months.[31]

Operated by the British Antarctic Survey (BAS), the Halley research bases were first established in 1956 and have engaged with scientific investigations ranging from glaciology and seismology to meteorology and radio astronomy.[32] Halley VI takes a modular approach to serving different crew functions with standardized modules dedicated to science activities, living, sleeping, operations, and energy production (see Fig. 8). The entire structure is elevated on skis to respond to the 1 m/year snow accumulation and to enable relocation due to ice shelf drift that moves the station toward the sea at a rate of 400 m/year.[32] Raising the structure on stilts also delivers several psychological benefits to the inhabitants, including better access to the surrounding views and natural light during the summer, and views of the Aurora Australis in the winter.

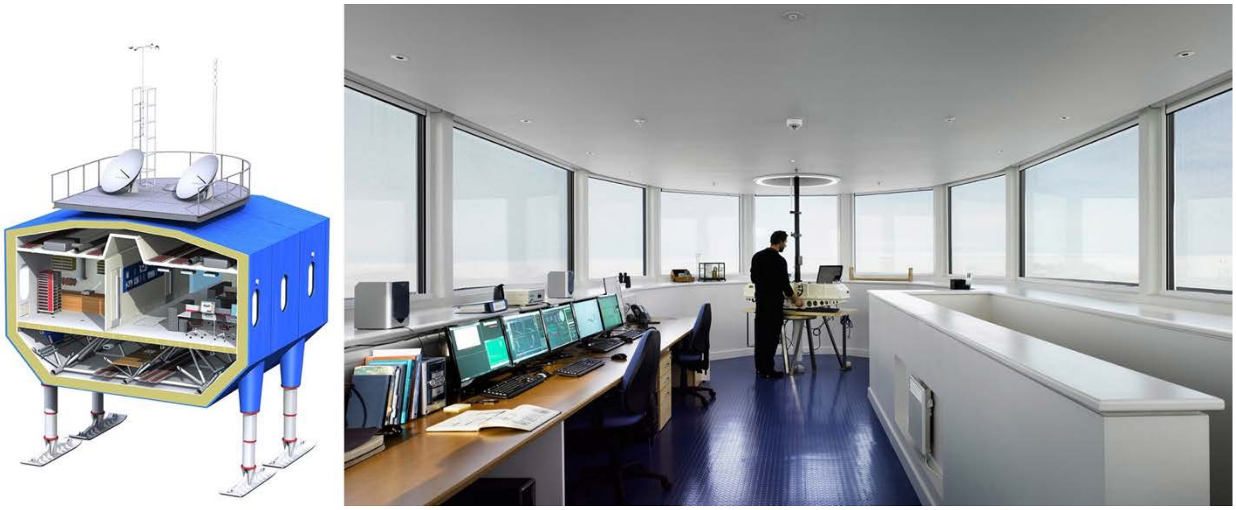

Figure 8. (Left) Cross-sectional cutaway view of a Halley VI standardized module showing internal structure, the habitable area, and the stilts and skis used for relocation. (Right) The meteorological observation deck offers panoramic views and daylight.[31]

The definition of crew well-being that drove much of the station's interior design goes beyond human factors design for optimizing crew productivity and begins to explore a human comfort design space. Some of this work has been characterized with respect to space habitat design, which explores the trade space of designing habitats that keep the crew "alive, healthy, happy, and productive."[33] This model defines "alive and healthy" as the realm of ECLSS, biomedical countermeasures, and human factors design, while "happy and productive" is enabled by crew accommodations, psychological support, and operational efficiency measures. While quantifying good human-centered design in a simple, encompassing way comparable to engineering metrics for safety (e.g. pLOC, pLOM) or productivity (e.g. Cooper-Harper rating) remains elusive, this has not stopped generations of architects, including those who designed Halley VI, from engaging in a collective trial-and-error approach over many thousands of design iterations, resulting in a "survival of the fittest" distillation of design work that successfully satisfies these criteria.

Broughton's design for the Halley VI research base builds on lessons learned from previous polar research bases, including previous Halley bases, and incorporates architectural design principles that take the facility into the well-being design space. The modularity of the design increases the overall flexibility of science investigations, enhances fire protection, and improves acoustic performance. The interiors are reconfigurable to adapt to changing science needs and are customizable for individuals to personalize their space. A warm color palette and lighting were carefully designed to assist sleep patterns in winter and summer and to combat the isolation and contrast the bleak arctic environment. Bedrooms were explicitly designed to "support the crew through the long, dark winters" and wood paneling was used as a multi-sensory design element.[31] The science accommodations were a driving functional requirement and support an array of changing science investigations within the standardized habitat module through flexibility, customization, and reconfigurability.

With scientific investigations centered on geospace studies, radio astronomy, and meteorology, Halley VI is not a geology lab and does not engage in the kind of sample acquisition and study expected from a lunar geological expedition.[32] However the approach to interior design and human comfort considerations, which go beyond the human factors design needed to keep the crew healthy and bring in architectural design best practices, are highly relevant to the development of a laboratory space on the Moon. The design moves meant to combat sensory deprivation and suppressed circadian rhythm in Antarctica will also be needed to support psychological well-being on extended-duration lunar missions, especially those at the proposed Artemis Base Camp at the lunar south pole that will not even have summer and winter seasons to mark the passage of time.

In the hierarchical model of "alive, healthy, happy, and productive," it is difficult to achieve the higher-level performance aspects with deficiencies in the lower ones. This framework offers a key step in designing a space where crew are expected to be, at least, productive and happy and at most inhabiting a built environment designed around their well-being.

III. Design Concepts and Parameters

To define design parameters for a long-term lunar geology laboratory, it is useful to consider the scope of presently defined mission scenarios. The current NASA HLS ConOps calls for 30-day stays for a crew of 4 in a pre-placed, permanent habitat.[5] Little is known about the physiological or psychological effects of living and working on the lunar surface for this amount of time, which is an order of magnitude longer than the longest Apollo mission surface stay. While no single space-based or Earth-based laboratory offers a perfect analog for a lunar laboratory, synthesizing previous work leads to a number of insights that can drive future laboratory design efforts.

A. Support significant in-situ investigations, without substantial need for Earth sample return

Desert RATS utilized a Constellation-style habitat and was focused on a shorter-term mission, which the Artemis HLS ConOps classifies as sorties.[5,25] The science capabilities of GeoLab were scaled accordingly and focused on preliminary sample curation. A longer-term lunar research station would ideally have greatly improved capabilities and not rely on Earth sample return for in-depth science. This implies a significantly expanded workspace with greater flexibility to accommodate different investigations, many of which have yet to be identified.

Astromaterial sample curation has experienced a continuous growth path since the return of the first lunar samples. Though sample return had a 32-year hiatus between the end of Apollo and the 2004 Genesis mission that returned solar wind atoms, the return and curation of ANSMET meteorites and ongoing curation of the Apollo lunar samples has built up a wealth of experience, procedures, equipment, and facilities. The return of samples to Earth-based science labs represents the mainstay of astromaterial science, but does not consider the potential advantages of developing an in-situ, crewed lab on the Moon.

EVA sample return has not occurred since Apollo and in-depth, in-situ analysis of samples by humans has effectively never occurred. However, the gains accrued by significantly reducing sample up mass from the Moon at the cost of a slight increase in equipment down mass may turn out to be a preferred scenario for a permanent habitat. Beyond limiting sample mass returns to Earth, this would increase the cadence of primary science, reduce the complexity of sample curation, and substantially mitigate contamination risk.

B. Capable of workspace modular expansion

For the reasons outlined above, an ISPR-style equipment module is unlikely to make sense on the lunar surface. But to support crew flexibility, growing or changing science needs, and fabrication and interface standardization across different stakeholders, a version of a lab equipment module will add many of these benefits to a lunar lab. The scale of modularity across various analogs – from casework to habitat modules – and what best suits a lunar lab remains a question. ISS habitat modules have been constrained by launch vehicles but are otherwise bespoke design solutions. ISPRs offer a standardized framework, but are far from repeatable constructs. MaMBA and Halley VI utilize modularity at the habitat scale and MaMBA's modular racks offer flexibility for interior lab layout but do not easily support habitat equipment and services or crew ergonomic workspace customization. The gloveboxes in GeoLab and JSC's Curation Lab are designed to function as individual units, but can also be interconnected to support different investigations.

Until mass-produced lunar habitat modules become the norm, it may best suit early labs to remain bespoke and highly customized to the specific required tasks. This is a much more prevalent architectural approach to modularity, where the module tends to be more akin to the brick or steel stud. Because a lunar geology lab is such a unique design problem, an approach focused on functionality and user needs may be preferred over a design that emphasizes future expansion. The challenge with this approach is incorporating sufficient flexibility such that the lab can support investigations that are both geology-adjacent and those that are yet unknown, as well as consistently controlling interfaces for a variety of international and interdisciplinary partners.

C. Provide workspace flexibility for different science investigations, working styles, and anthropometry

Flexibility is important for this workspace, both in terms of the variability in anthropometry of the crew members and the science investigations that need to be accommodated, some of which may be unknowable in advance. A single-size and configuration workspace that accommodates a variety of users is reasonable in a microgravity lab, with the availability of minor adjustments such as repositioning a foothold or laptop orientation. In a surface lab, a wider range of customizations are necessary to support crew members subject to gravity. Due to the existing constraints inherent to human spaceflight, this lab space is unlikely to be either dedicated exclusively to lunar geology or large enough to support an idealized science investigation workflow. To address this, the lab workspace should use an idealized scenario as a baseline, but offer the flexibility to accommodate a variety of crew members – both size and work styles – and a variety of science investigations, including an expansion or contraction of planned geological investigations.

Equipment Needs

Heinicke et al. provide a thorough outline of recommended equipment for a lunar geology lab in relation to the MaMBA analog.[29] Their work covers a more comprehensive lab that supports investigations into geology, materials science, astrochemistry, astrobiology, astronomy, and medicine, and seeks to understand overlaps and synergies between the respective equipment specifications. A geology lab with a more focused equipment complement can support limited adjacent science, such as characterizing the material properties of regolith to support future in-situ resource utilization (ISRU) and chemically analyzing the volatile compounds present. However, these investigations would only be opportunistic, if made possible by the existing geology lab space and equipment. Table 1 is a summary of equipment and tools suggested by the MaMBA team,[29] by the GeoLab team,[26] by Beaty et al,[14] and by me. Note that sample collection is closely and critically tied to EVA, but that those tools are not covered here.

Table 1. Lunar lab equipment summary

Activity	Tools & Equipment
Direct physical inspection hand tools	hammers, chisels, core drillers, pocket lens, scale
Physical Investigation environment	glovebox with airlock(s) and antechamber(s), environment sensors, cold & inert atmosphere
Sample collection & curation	Teflon-lined bags, containers, storage
Mineral Separation	sieves, crushers, density separators, magnetic separators
Magnetic characterization	susceptometer
Visual inspection & microscopy	binocular magnifier, translucence microscope, reflection microscope, fluorescence microscope, scanning electron microscope with energy dispersive x-ray (SEM-EDX), x-ray fluorescence spectrometer, x-ray tomography
Remote inspection	high-definition video and still cameras with uplink capability, radiation-resistant data storage
Thin section production	rock cutter and polisher
Volatiles	ion mass spectrometer
Control & Visualization	Displays and/or touchscreen
Personal Protection and Consumables	Lab gloves, safety goggles, masks, lab coats, chemical solvents and applicators, cleaning supplies

D. Workspace designed for crew comfort and well-being

Contemporary labs on Earth are designed to support different working modes and degrees of collaboration, offering researchers a flexible range of possibilities for science and work styles (see Fig. 9).[34] The realities of spaceflight tend to result in an overprescribed work environment that preferences engineering metrics (mass, power, volume) over human comfort and well-being. This is not unreasonable for a 3-day Apollo surface mission or even a 6.5-day HLS sortie. For a longer stay, starting with the HLS 30-day mission as a baseline but looking ahead to a potential ISS-style cadence of expeditions in 3-month increments for up to a year, the physiological and psychological constraints of living and working in the most isolated habitat ever occupied by humans will take a more significant toll on the crew and should be addressed in the design. Halley VI takes a much more architectural approach to the design of the research station than that of other examples and is a good starting point for designing with the crew in mind.

One aspect of crew comfort is workspace seating. With the exception of vehicle cockpits, space habitats generally do not include chairs; they make little sense in microgravity and were famously removed from the Apollo descent module to save mass. But in the partial-gravity workspaces of a surface habitat, crew will spend significant time on their feet, including participating in physically demanding EVAs. For any crew of limited number, the resident geologist(s) will be the best candidate for both sample collection EVAs and in-habitat analysis, and the prospect

Figure 9. A contemporary Earth-based lab space offers workstations to support a variety of working styles, degrees of collaboration, and proximity to physical science work, frequently with a separate write-up area that can also serve as a dry or computational lab, with a visual connection to the primary lab area.[34]

of spending non-EVA work time standing is unlikely to be appealing. Whether this takes the form of an adjustable rolling chair (Fig. 6, 9), a typical desk chair (Fig. 8), or another custom solution, the inclusion of lab bench seating and its stowage will very likely need to be considered.

Another work accommodation strategy is separating workspaces by their programmed activities. An important distinction between a typical volume-constrained lab in space and a best-practices lab on Earth is clearly delineated "wet" and "dry" spaces for conducting primary investigations and writing-up results, respectively. GeoLab combined these functions into a single, multi-purpose workbench and the ergonomics of both activities suffered. Given the central, long-duration nature of both physical sample analysis and write-up tasks, separating the workspaces for each is justified, even at the cost of additional habitat volume. Volume constraints in a lunar lab will almost certainly obviate a substantial separation between these activities, at least for the foreseeable future. However, even a minimally-functional design approach with this objective in mind would be helpful.

E. Prevent contamination and back-contamination with a contained geologic sample area (e.g. glovebox)

Direct access to the sample area through an airlock or antechamber supports EVA sample return and reduces exposure to the contaminants in the habitat environment. The dedicated sample airlock and antechamber utilized in GeoLab is a plausible solution for both problems. While that design had its own challenges, further design iterations could likely address the issues of ergonomics, cleanability, vibration isolation, and unobstructed sample egress. GeoLab also showed the need and difficulty of cleaning the glovebox between samples. On the Moon, this task only becomes more difficult due to the size, shape, toxicity, and static charge of lunar dust particles. This issue is further compounded by the need to minimize lunar dust egress into the habitat environment, as cleaning it there is potentially more difficult and it presents a greater health hazard to the crew.

A positive pressure glovebox needs to be rethought for a lunar lab. The inert gas environment in the gloveboxes at JSC and the Subzero Curation Facility are maintained at positive pressure so, in the event of a breach, the purity of the sample is maintained.[16] For a lab on the Moon, two key differences change this reasoning. First, there is the possibility of breaching the containment of a positive-pressure glovebox in two directions: into the habitat and to the vacuum of space. Second, because the lab is in-situ, sample purity is less of a consideration than it would be for a returned astromaterial sample because a contaminated sample can likely be replaced with relative ease. Also, a glovebox breach either to the habitat or to vacuum could threaten the health and safety of the crew.

Instead, a glovebox atmosphere can be maintained at a slightly negative pressure with respect to the habitat's atmosphere – which will likely be either 8.2 or 10.2 PSI[5,17]– and will necessarily still be at positive pressure with respect to the vacuum outside the habitat. This measure protects the crew over the samples in the event of a breach, preventing dust from entering the habitat from the glovebox. It will also be advantageous to maintain a low atmosphere pressure, rather than vacuum, to aid dexterity for gloved operators. While N_2 can potentially react with some transition metals and salts, leading some researchers to prefer a truly inert gas environment such as Argon,[16] nitrogen is utilized in the JSC gloveboxes for lunar sample handling. Additionally, providing the mass for Argon storage is unlikely to trade well when substantial N_2 is already on board as part of the habitat's atmosphere system.

Finally, temperature sensitivity may be an important consideration for future investigations, for example preserving lunar ice in samples.[13] The Subzero Curation Facility offers relevant lessons for controlling the temperature of a glovebox environment and the equipment needed to maintain a high air-change rate and the cold temperature of that make-up air. While maintaining an appropriately low-temperature in a lunar habitat module is unlikely to be feasible, keeping a glovebox atmosphere cold may be. Tools and procedures may also need to be altered to prevent the unintentional heating of samples during processing and analysis.

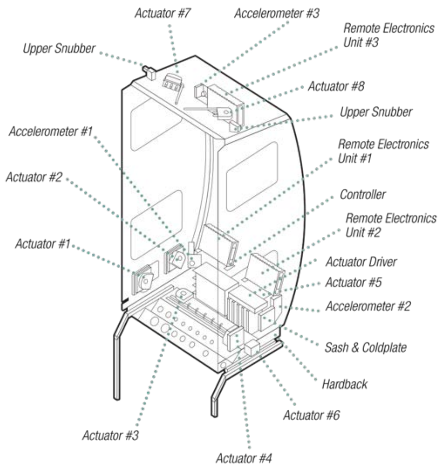

Figure 10. ISPR Active Rack Isolation System (ARIS) damps the ambient vibration environment of the ISS for science racks.[9,35]

F. Isolate lab physical investigation equipment from habitat vibrations

The results from GeoLab reported issues with vibrations disrupting microscopy and visual analysis of samples as a result of the glovebox being fastened directly to the structural ribs of the habitat.[26] ISPRs, which are also fastened to the spacecraft structure through standoffs, utilize a vibration control system locally at each rack: the Passive Damping System (PDS), which uses isolation assemblies at both structural attachment points, and the Active Rack Isolation System (ARIS), shown in Figure 10.[35]

The ambient vibration environment in a surface habitat at 1/6 g is not well characterized. Expected equipment vibration will likely be on par with ISS but will be compounded by crew activity (walking around; greater effects from any exercise equipment) and moonquakes. Exercise and general human activity tends to fall in the 1-3 Hz range, but typical overall frequencies encountered on ISS are in the 0.1-400 Hz range, with significant differences between sleep and waking periods in the lower frequency ranges.[36,37]

The Moon is also known to "ring like a bell," with no water to absorb and dampen seismic vibrations, which may exacerbate the habitat vibration environment.[38] The Apollo Passive Seismic Experiment (PSE) recorded seismic data from 1969-1977 and recorded over 12,000 seismic events from different sources and of varying magnitude.[39] However, most events are comparatively small and will likely be able to be treated with the same isolation methods employed to combat crew and vehicle vibrations on ISS. The rarer magnitude 5+ moonquakes will need to be addressed in overall habitat design, particularly if any kind of ISRU structural solution is utilized.

Despite experimental data from PSE and other experiments, the ambient vibration environment of a lunar habitat is largely unknown, especially with regard to the effect on science experiments. This is potentially an area of future research, but unfortunately may be difficult to advance until Moon landings have resumed and surface effects can be better characterized. In any case, vibration isolation at the scale of the science rack will be an important design requirement and could challenge the feasibility of a modular, casework-style approach.

IV. Conclusion

The first permanent lunar lab will be unlike any other laboratory built to date and will face a unique set of environmental and performance challenges. Orbital laboratories, most notably ISS, offer years of practical experience conducting science in space, and Earth-based space analog missions and astromaterial curation experience provide many lessons for better understanding and anticipating the needs of a lab on another planetary surface. With a better definition of the design problem, the next steps in this work include developing a lab layout, designing alternative approaches to a science rack analogous to the ISPR, better understanding ways to integrate glovebox designs into a constrained workspace, designing a lab bench seating solution appropriate for the space environment and surface of the Moon, and further investigating the anticipated ambient vibration environment expected for a lunar surface habitat. This work will inevitably be constrained to a habitat design with requisite sacrifices in mass, volume, and power to close the engineering budgets. But starting from an idealized solution will help with evaluating those sacrifices and can build a shared understanding of what is given up, both in terms of science returns and the well-being of the crew.

Acknowledgments

Many thanks go to Jennifer Swedell and Alex Korter at CO Architects, who served as resources for lab planning practices and general architectural design thinking, as well as being ongoing supporters of this effort. Thanks also go to Brent Sherwood, whose mentorship and nudges have helped me take my first steps on this new trajectory.

References

[1] National Aeronautics and Space Administration. NASA's Lunar Exploration Program Overview. September 2020.

[2] Lunar Exploration Analysis Group. "The Lunar Exploration Roadmap: Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations, and Priorities." Version 1.3, 2016.

[3] European Space Agency. "Moon Village: Conceptual Design of a Lunar Habitat." CDF Study Report, CDF-202(A), Issue 1.1, September 2020.

[4] Sherwood, B. "What Will We Actually Do On the Moon?", AIP Conference Proceedings 880, 814-822, 2007.

[5] NASA. "Sustained Phase Human Landing System (HLS) Concept of Operations." HLS-CONOP-006, APP N, Effective Date: June 25, 2021.

[6] Sherwood, B., "Module architecture for in situ space laboratories." 40th International Conference on Environmental Systems, 2010.

[7] National Aeronautics and Space Administration. "The International Space Station: Operating an Outpost in the New Frontier." Dempsey, R. (ed.), NASA-SP-2017-634, Johnson Space Center, 2017.

[8] Kennedy, K., "The Vernacular of Space Architecture." AIAA 2002-6102, 1st Space Architecture Symposium (SAS 2002), Houston, Texas, USA, 10-11 October 2002. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

[9] National Aeronautics and Space Administration, ISS User's Guide-Release 2.0 (2000), P. 21.

[10] JAXA, 2008. Pressurized Module: About Kibo - International Space Station. Last Updated: August 29, 2008. Accessed: Feb. 7, 2022. https://iss.jaxa.jp/en/kibo/about/kibo/jpm.

[11] McCubbin, F.M., et al. "Advanced Curation of Astromaterials for Planetary Science." Space Sci Rev (2019) 215:48, 7 November 2019. https://doi.org/10.1007/s11214-019-0615-9.

[12] Harvey, R.P., Schutt, J., Karner, J., "Fieldwork Methods of the U.S. Antarctic Search for Meteorites Program," in Righter, K., Corrigan, C.M., McCoy, T.J., Harvey, R.P., (Eds.), 35 Seasons of U.S. Antarctic Meteorites (1976-2010): A Pictorial Guide to the Collection, Special Publication 68, First Edition. 2015, American Geophysical Union, John Wiley & Sons, Inc.

[13] Allen, C.C., Allton, J., Lofgren, G., Righter, K., Zolensky, M., "Curating NASA's extraterrestrial samples – Past, present, and future," 2011, *Chemie Der Erde – Geochemistry* **71**:1-20.

[14] Beaty, D.W., Allen, C.C., Bass, D.S., Buxbaum, K.L., Campbell, J.K., Lindstrom, D.J., Miller, S.L., Papanastassiou, D.A., "Planning considerations for a Mars sample receiving facility: summary and interpretation of three design studies," 2009, Astrobiology 9, 745–758.

[15] Calaway, M.J., "Lunar Processing Cabinet 2.0: Retrofitting Gloveboxes into the 21st Century," 2015, Lunar and Planetary Science and Exploration, March 16, 2015.

[16] Herd, C.D., Hilts, R.W., Skelhorne, A., Simkus, D.N., "Cold curation of pristine astromaterials: Insights from the Tagish Lake meteorite," 2016, *Meteoritics & Planetary Science, 51*.

[17] National Aeronautics and Space Administration. "Sustained Phase Human Landing System (HLS) Program System Requirements Document (PrSRD)." NASA-HLS-RQMT-006, DRAFT, Marshall Space Flight Center, June 25, 2021.

[18] Winterhalter, D., Levine, J.S., Kerschmann, R.L., Brady, T.K., "Lunar Dust and Its Impact on Human Exploration: A NASA Engineering and Safety Center (NESC) Workshop," September 2020, NASA/TM-2020-5008219, NESC-RP-19-01469.

[19] National Aeronautics and Space Administration. "Life Support Baseline Values and Assumptions Document." Ewert, M., Chen, T., Powell, C. (eds). NASA/TP-2015-218570/REV2, February 2022.

[20] Carrier, W.D., Olhoeft, G.R., Mendell, W., Physical Properties of the Lunar Surface. In: Heiken, G., Vaniman, D., French, B.M. (Eds.), Lunar Sourcebook. 1991, Cambridge University Press, Cambridge, UK.

[21] National Aeronautics and Space Administration. "Risk of Adverse Health & Performance Effects of Celestial Dust Exposure." Evidence Report, Human Research Program, Space Human Factors and Habitability (SHFH) Element, Johnson Space Center, August 4, 2015.

[22] American Cleanroom Systems Presents Cleanroom Classifications, 2022. Accessed: April 10, 2022. https://www.americancleanrooms.com/cleanroom-classifications/

[23] Biosafety in Microbiological and Biomedical Laboratories (BMBL), 6th Edition, June 2020, Centers for Disease Control, National Institutes for Health. https://www.cdc.gov/labs/BMBL.html

[24] NASA. Inside the Deep Space Habitat Science Glovebox. Posted Apr 26, 2012. Accessed: February 23, 2022. https://www.nasa.gov/exploration/technology/deep_space_habitat/gallery/scienceglovebox.html.

[25] Howe, A., Kennedy, K., Gill, T., et al. "NASA Habitat Demonstration Unit (HDU) Deep Space Habitat Analog" AIAA Space Forum, September 10-12, 2013, San Diego, CA.

[26] Evans, C., Calaway, M., Bell, M.S., Young, K., "GeoLab—A habitat-based laboratory for preliminary examination of geological samples." Acta Astronautica 90.2 (2013): 289-300.

[27] Heinicke, C., Orzechowski, L., Avila, M., "The MaMBA-concept for an extraterrestrial base and its first module mock-up." Acta Astronautica, Volume 173, 2020, Pages 404-413, ISSN 0094-5765, https://doi.org/10.1016/j.actaastro.2020.04.026.

[28] Bannova, O., Häuplik-Meusburger, S. "Space architecture and habitability: an asset in aerospace engineering and architectural curricula." Acta Futura. 10 (2016) 9–22.

[29] Heinicke, C., Jaret, S., Ormö, J., Miranda, F., Kopacz, N., Baqué, M., Verseux, C., Bernard, F., Razeto, A., "How a laboratory on the Moon should be equipped." 69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018, 2018.

[30] Hugh Broughton Architects. Halley VI British Antarctic Research Station: A pioneering relocatable polar science research station. Accessed: Feb 20, 2022. https://hbarchitects.co.uk/halley-vi-british-antarctic-research-station/

[31] Broughton, H. "Polar Research Facilities: Living in Isolation" 46th International Conference on Environmental Systems, 10-14 July 2016, Vienna, Austria.

[32] Broughton, H. "Halley VI Antarctic Research Station" in Howe, A.S. and B. Sherwood, B. (eds.), Out of This World: The New Field of Space Architecture (Chapter 27, p. 363-370). Reston, Virginia, USA: American Institute of Aeronautics and Astronautics. 2009.

[33] Klaus, D. "Functional integration of humans and spacecraft through physics, physiology, safety and operability." 2017 IEEE Aerospace Conference (2017): 1-7.

[34] Labov, A. "Diverse, Modern Research Labs for Space-based Solar Engineering at Caltech." CO Journal, CO Architects. Published: March 1, 2017. Accessed: February 23, 2022. https://coarchitects.com/diverse-modern-research-labs-for-space-based-solar-engineering-at-caltech.

[35] Davis, T. B., Adams, J. B., Fisher, E. M., Prickett, G. B., and Smith, T. G., "Express rack technology for space station", in *Space Technology and Applications, International Forum – 1999*, 1999, vol. 458, pp. 531–550. doi:10.1063/1.57698.

[36] Rogers M.J., Hrovat K., Moskowitz M.E. "Effects of exercise equipment on the microgravity environment." Adv Space Res. 1999; 24(10):1283-7. doi: 10.1016/s0273-1177(99)00734-6.

[37] Jules, K., Hrovat, K., Kelly, E., Reckart, T. "International Space Station Increment-6/8 Microgravity Environment Summary Report." NASA Technical Memorandum. NASA/TM-2006-213896 (NASA Technical Reports Server, United States, 2006).

[38] Bell, T. "Moonquakes." Science@NASA. Website. Posted: March 15, 2006. Accessed: Feb 25, 2022. https://science.nasa.gov/science-news/science-at-nasa/2006/15mar_moonquakes.

[39] Nakamura, Yosio, Gary V. Latham, and H. James Dorman. "Apollo lunar seismic experiment—Final summary." Journal of Geophysical Research: Solid Earth 87.S01 (1982): A117-A123.