Notional Habitat Science Outfitting for a Lunar Surface Habitat or Mars Transit Habitat

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Science outfitting is often given insufficient treatment in the development of early conceptual studies for lunar surface habitats. In some cases, only control masses and volumes are used as placeholders. In others, one science discipline may be given detailed treatment while others are largely ignored. It is not unheard of for science outfitting to be entirely forgotten in initial concept layouts. This is exacerbated by the reality that spacecraft design studies are often initiated long before science objectives have been established for any given human spaceflight destination. When those objectives later emerge, they can be difficult to accommodate if sizing studies did not allocate sufficient resources for them. A notional science outfitting can be created for virtually any human exploration habitat, however, utilizing data created by the International Space Station and Constellation programs. Biology, human research, physics, and geology science laboratories and a general-purpose work area for a lunar surface habitat will be derived using equipment identified by the Constellation-era Optimizing Science and Exploration Working Group (OSEWG) or flown on the International Space Station. Early science outfitting definition and inclusion in surface habitat sizing is critical for developing an exploration architecture that meets science needs. The mass, volume, power, and use cases associated with these notional laboratories impacts all of the habitat subsystems, habitat dimensions, hatch dimensions, logistics operations, launch vehicles and landers.

I. Nomenclature

AEM = Animal Enclosure Module
BPS = Biomass Production System
BRIC-LED = Biological Research in Canisters-Light Emitting Diode
CGBA = Commercial Generic Bioprocessing Apparatus
CTB = Cargo Transfer Bag
DRA = Design Reference Architecture
DRATS = Desert Research and Technology Studies
DSH = Deep Space Habitat
EVA = Extra-Vehicular Activity
GASMAP = Gas Analyzer System for Metabolic Analysis Physiology
GLACIER = General Laboratory Active Cryogenic ISS Experiment Refrigerator
GN2 = Gaseous Nitrogen
HRF = Human Research Facility
ISS = International Space Station
IVA = Intra-Vehicular Activity
LEO = Low Earth Orbit
LER = Lunar Electric Rover
LIBS = Laser Induced Breakdown Spectroscopy

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MDL = Mid Deck Locker
MDLE = Mid Deck Locker Equivalent
MELFI = Minus Eighty-Degree Laboratory Freezer
MERLIN = Moon Experiment Research Locker Incubator
OSEWG = Optimizing Science and Exploration Working Group
PCM = Pressurized Core Module
PEM = Pressurized Excursion Module
SIGB = Standard Interface Glovebox
SLAMMD = Space Linear Acceleration Mass Measurement Device
WRAIR = Walter Reed Army Institute of Research
XRD = X-Ray Diffraction
XRF = X-Ray Fluorescence

II.Introduction

It is widely accepted that the purpose for NASA exploration missions beyond Low Earth Orbit (LEO) is to perform science. However, outside of the science community it is often nebulous as to what "science" involves. Most are very familiar with the lunar samples retuned by the Apollo crews, but a much smaller number can elaborate on other scientific research conducted during the Apollo missions or on what types of science would be involved in future lunar surface missions. Even fewer can speak to the science that would be conducted on a transit habitat during the voyage between the Earth and Mars. This science, however, can have substantial impacts on the mass, volume, and power requirements for surface habitats and transit spacecraft and they must be sufficiently considered very early in the design process or the resulting vehicles will not be able to adequately meet the needs of the science community.

This work is being prepared to be generally applicable to both Moon and Mars human missions. In the lunar case, it is in the context of a small surface presence that involves crew sizes of two to four operating in a pressurized habitat for missions of 12-90 days in duration. The surface architecture assumes some level of extra-vehicular (EVA) capability that might or might not include mobility assets.

For the Mars case, only transit will be directly discussed and will assume transits of 300-1200 days in duration with a crew size of four. Mars surface is not discussed in this paper, but habitat-based Mars surface missions of 12-90 days could be considered roughly similar to the lunar surface case.

Science outfitting will be constrained to IVA laboratories (facilities inside the pressure vessel) and science equipment either directly mounted to the spacecraft exterior or permanently located in the immediate vicinity of the spacecraft.

While a specific science allocation would be the result of a program-specific process to define science requirements, there are generic capabilities and fields of science that can help inform the creation of placeholders that will be useful in initial mission concept stages in order to aid in design trades, element sizing studies, and human systems integration prior to the development of such requirements. All six domains of NASA Human Systems Integration – human factors engineering, operations resources, maintainability and supportability, habitability and environment, safety, and training – are affected by science outfitting and HSI practitioners must perform concepts of operation and scenario development, task analyses, function allocation between humans and systems, allocation of roles and responsibilities among humans, and iterative conceptual design and prototyping in Pre-Phase A. [1]

The approach presented is not intended as a representation of any current NASA reference architectures but is instead a generic assessment that can be considered to help inform future development by government, commercial, and international partners.

III.Background

Engineers who perform early concept studies for mission architectures often have pre-conceived mental models of science outfitting that may not be fully synchronized with scientific community needs and it is important to change this paradigm as the United States leads the world through the Artemis program.

The Apollo program is well known for the surface geology conducted by the Apollo astronauts and more than fifty years later scientists are still studying Apollo samples. It is therefore not surprising that many lunar architectures since the 1970s have immediately defined science in the context of space suited astronauts walking on the lunar surface collecting rocks. While this is an important scientific activity, lunar science is by no means limited exclusively to geology. Mars mission architectures often take similar approaches, viewing Mars science as EVA sample collection and even viewing the in-space transit to and from Mars as an undesirable source of crew boredom and an unwanted demand on life support resources with little to no inherent science value. However, fractional gravity and microgravity, radiation, thermal environments, and radio-free environments all offer significant opportunities for science research – of not only the local environment, but also of crew and biological payloads, and of distant environments as measured from the local environment.

During the Constellation Program, there were often shortcomings in the notional science placeholders used in mockups and prototypes. In the early days of Constellation, the Habitat Mockups Project built two habitat mockups at Johnson Space Center, one with a horizontal orientation and a much larger habitat with a vertical orientation.

The horizontal habitat mockup, shown as a CAD model in Fig. 1, focused heavily on crew systems, with four different crew quarters designs to evaluate which features better enable lunar habitation. It also included an elaborate galley/wardroom area and two waste management facilities – one offering adjacent full body hygiene and the other located next to the airlock for post-EVA use. However, science facilities (along with medical, exercise, maintenance, and vehicle subsystems) were largely neglected. [2]

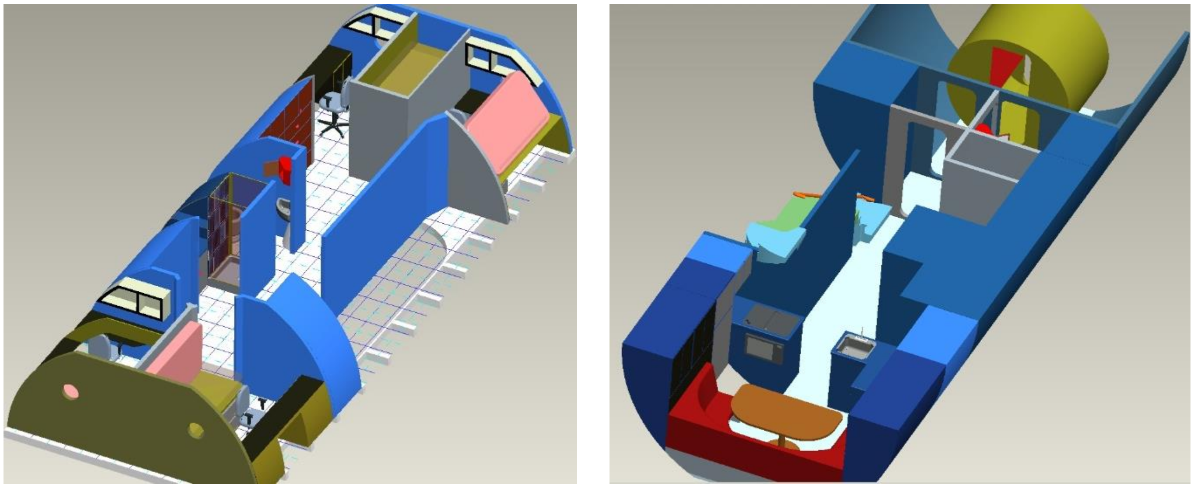

Fig. 1 Horizontal Habitat Upper and Lower Decks

The vertical habitat, shown in Fig. 2, due in part to its larger size, did allocate volume to many of the facilities missing in the horizontal habitat. It did allocate some volume to separate physical science and biological science workstations, shown in Figures 3 and 4, though human-in-the-loop evaluations indicated that both workstations lacked sufficient volume. [3]

Fig. 2 Vertical Habitat Mockup at NASA Johnson Space Center

Fig. 3 Vertical Habitat Physical Science Workstation

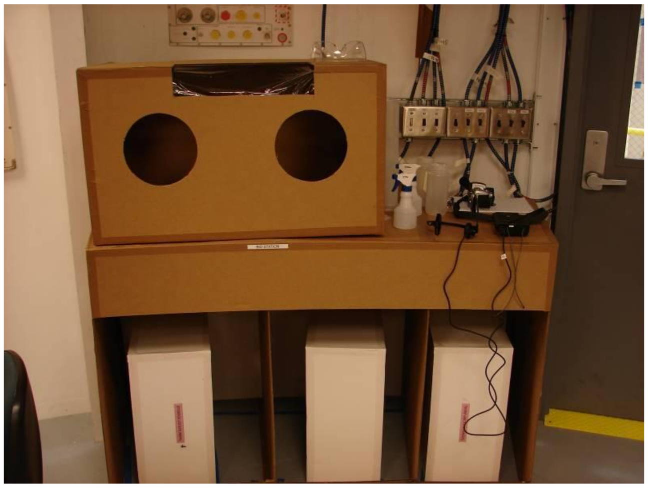

Fig. 4 Vertical Habitat Biological Science Workstation

The Constellation Lunar Surface Systems Project Office next conducted a series of surface habitat sizing activities. A comparative evaluation was conducted to trade 3-meter and 3.5-meter diameters for modular habitat elements. One module of each dimension was mocked up, shown in Fig. 5. Despite the wide-ranging impacts of this module diameter decision, science workstations were not evaluated in these mockups. The interior was fabricated as a crew quarters mockup with only four bunks, a waste containment system, and a system monitoring station included. [4]

Fig. 5 3-meter and 3.5-meter Horizontal Habitat Mockups

The most elaborate lunar habitat study under the Constellation Program was centered around Lunar Surface Scenario 12.1, a modular architecture that used a combination of large diameter single-deck habitat modules, an airlock, and four Lunar Electric Rovers (LERs) to form the lunar outpost, shown in Fig. 6. [5] This outpost configuration placed a Geology Lab in the Pressurized Excursion Module (PEM) and a Biology Lab in the Pressurized Core Module (PCM). Unfortunately, only the PEM and Airlock, shown in Fig. 7, and two LERs were ever advanced to the prototype stage. These four elements represent the Excursion Configuration of this outpost – they can travel away from the outpost site for extended field geology science as shown in Fig. 8. The Excursion Configuration was tested in NASA's Desert Research and Technology Studies (DRATS) in 2010, shown in Fig. 9. [6]

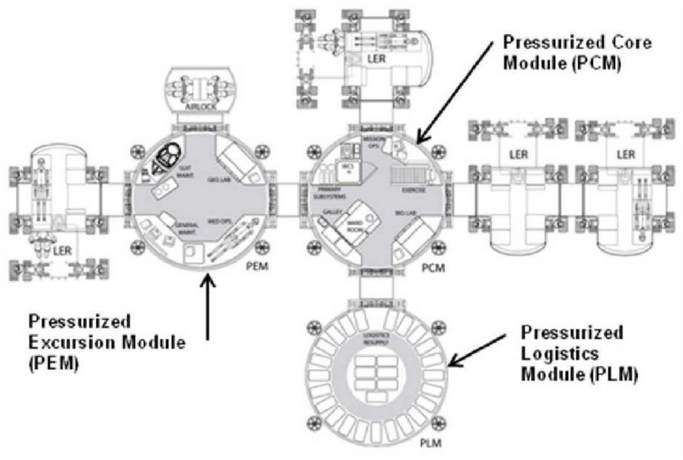

Fig. 6 Lunar Surface Scenario 12.1 Outpost

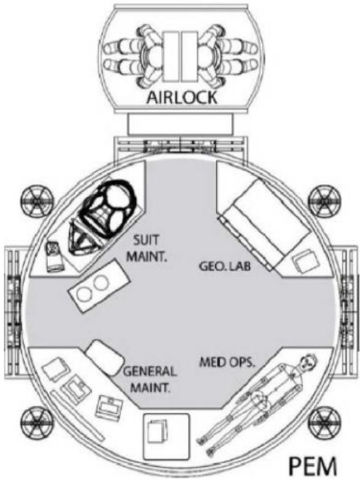

Fig. 7 Pressurized Excursion Module and Airlock

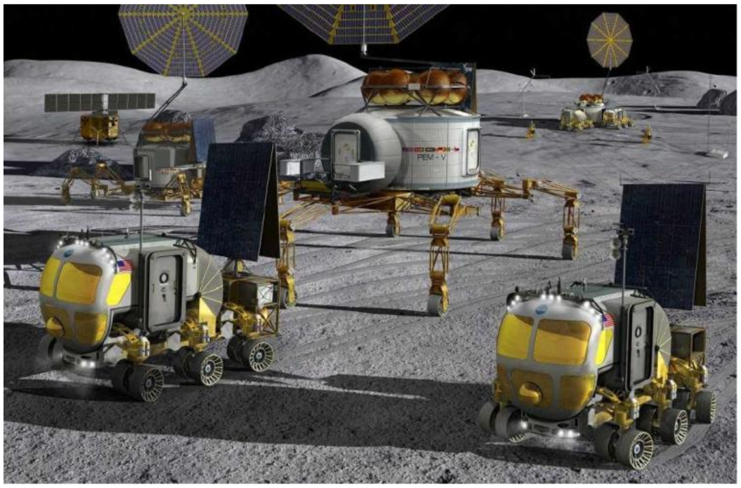

Fig. 8 Lunar Surface Scenario 12.1 Excursion Configuration

Fig. 9 PEM, Airlock, and two LERs at 2010 DRATS

Fig. 10 PEM Geology Lab

As can be seen in Fig. 10, the Geology Lab consists of only a glove box and computer with two displays. Assorted handheld spectrometers and other tools were brought into the PEM for testing during DRATS, but there was only one overhead stowage location (one mid deck locker equivalent) where such equipment would be stored were this an actual space mission.

Immediately after the cancellation of Constellation, the PEM was repurposed into a Deep Space Habitat (DSH) mockup by adding an upper inflatable habitation section and attaching a hygiene and waste management module in support of a deep space asteroid rendezvous mission being considered by NASA at the time. The DSH was tested at the 2011 DRATS and in a Mission Operations Test onsite at Johnson Space Center in 2012. Unfortunately, the loss of the PCM meant that the DSH did not have a Biology Lab. As a result, an attempt was made in the 2011 and 2012 tests to merge life sciences with the Medical Operations Workstation, though fidelity of the life science content was extremely low. The 2011 test included a collapsible glove box that was deemed acceptable, though test activity only involved setup and disassembly. [7] The 2012 test replaced this with a fixed glove box (that permanently blocked a hatch), an incubator, centrifuge, microscope, and assorted lab supplies, shown in Fig. 11. [8] This did not work well, and numerous test crew comments indicated that this merging of functionality cluttered the workspace and caused task interference. [9] [10] [11] The science outfitting was also extremely limited, constrained largely to items the test team was able to borrow or acquire at low cost and not matched to any established science objectives. While it is not quite clear in the images, the glovebox visible on the right side of the right image is directly in front of a docking hatch, rendering the hatch unusable.

Fig. 11 Mission Operations Test with Combined Medical and Life Science Workstation

Limitations have also been present in Mars architecture studies. Mars Design Reference Architecture (DRA) 5.0 provides no clear indication of IVA science capability. In DRA 5, Monolithic Hab Concepts 1 and 2 allocate 248 kg and 262 kg respectively to “outfitting”, which presumably includes science as well as other items. The Descent/Ascent Vehicle allocates 1000 kg to “science” with no further definition. The Transit Habitat allocates 4210 kg and 29.7 m^3 to “Crew Accommodations,” which may or may not include science combined with habitation systems. The only biologic science objective listed was surface sample analysis to search for evidence of life. [12]

IV.Data sources for bottoms-up notional science outfitting

NASA science is generally organized by its Human Research Program and by the five divisions of NASA’s Science Mission Directorate: Astrophysics, Biological and Physical Sciences, Planetary Science, Heliophysics, and Earth Science. However, during early concept development it is generally not possible for spacecraft design engineers to turn to science program requirements because they by definition will not have been established yet. However, if the science outfitting estimated during early concept development is insufficient (as was the case in the previously cited habitat concepts), habitat systems sizing design cycles will make improper mass, volume, power, and layout decisions that are difficult if not impossible to later adjust. Further, habitat mass and dimension estimates will be used to drive launch vehicle and lander decisions. In a worst case, this can have a multi-billion-dollar impact, forcing the program to add additional flights and elements to the manifest to accommodate capabilities that were not initially considered during architecture sizing exercises or excluding what would otherwise have become important science objectives from ever being considered – they will be deemed infeasible in light of vehicle limitations. Thus, it is incumbent on the habitat design team to improve the fidelity of science outfitting estimates as early in the design as possible.

Fortunately, there are data sources that can be used to generate bottoms-up science outfitting information that can be used to inform early conceptual designs prior to the existence of program requirements. It is helpful to first consider which science domains may have potential relevance to a given mission architecture. As previously noted, any surface mission will inherently involve geology. It is also reasonable to assume such missions will involve surveying. It is also valuable to examine the International Space Station to gain an understanding of the fields of science under investigation. It is reasonable to suspect that any field of science that is practiced both on Earth and on ISS will also be relevant to surface or microgravity destinations beyond Low Earth Orbit.

In addition, during the Constellation Program, NASA’s Exploration Systems Mission Directorate and Science Mission Directorate jointly formed the Optimizing Science and Exploration Working Group (OSEWG). The OSEWG was established to help inform the development of exploration and science investigations. [13] In the summer of 2006, the OSEWG initiated work on a spreadsheet that itemized lunar science payloads that they intended for use in the Constellation Program’s lunar outpost. While its contents were not incorporated into any of the habitat concepts during Constellation, the spreadsheet continued to be maintained after the cancellation of Constellation. It included payloads for use in a Geology Lab, Biology Lab, Physics Lab, and external to the habitat. The OSEWG did not include representation from the Human Research Program and consequently the OSEWG spreadsheet did not include payloads associated with human research.

Thanks to the DRATS testing, the OSEWG Geology Lab data can be viewed in conjunction with human-in-the-loop data obtained during the DRATS field tests in 2010 and 2011 as well as the 2012 JSC Mission Operations Test. Lessons learned from the testing can help develop lab layouts that enable the crew to work effectively and efficiently.

The OSEWG did not include the Human Research Program, neither did any Lunar Surface Systems Project mockups, and as a result no data can be gleaned from the Constellation Program to anticipate human research science needs. The next best data source is human research on the International Space Station. The International Space Station (ISS) features two Human Research Facilities (HRF-1 and HRF-2) and experiment payloads that have flown on those two facilities can serve as examples.

Technology development / demonstration is sometimes included in IVA laboratories, but insufficient data was found to define any associated capabilities or associated equipment. Any program-specific IVA laboratory would need to include any such capabilities and equipment associated with that program.

These data sources can lead to a reasonable estimation, but not an exact configuration. Much of this data is greater than ten years old and may not reflect currently available instrumentation. Also, some listings in the OSEWG spreadsheet were not fully populated with mass, volume, or power data. Additionally, differences in science priorities between programs will lead to different priorities in equipment selection. Nonetheless, it remains one of the most comprehensive compilations of science equipment available to NASA habitat designers.

V.Creation of Notional Habitat Science Outfitting

With the previously mentioned data sources and caveats in mind, a notional habitat science outfitting concept can be created. The context for this concept is a lunar surface habitat with 4 crew and a 12-90-day surface mission where the crew has access to one unpressurized rover and one pressurized rover. (However, this general process could be applied to other mission destinations, different crew sizes, different durations, and different surface assets.)

Excluding equipment with established, unique shapes such as gloveboxes, science payloads will be modeled as the dimensionally closest of four mid-deck locker (MDL) equivalent shapes: standard MDL, double MDL, half height MDL, or half width MDL. This is by no means the only viable convention, but it allows for a common frame of reference for volume and packaging discussions that is well established in human spaceflight and can readily be compared with flown instances from Shuttle and ISS history.

MDLs are intentionally used here instead of Cargo Transfer Bags (CTBs) due to the presence of gravity. In gravity, any individual MDL within a vertical stack can be opened to retrieve contents. This cannot be done with a vertical stack of CTBs – only the top bag can be opened without disturbing others. Consequently, it is easier to retrieve items from MDLs than from CTBs in much the same way that in a terrestrial home it is easier to retrieve items from a dresser than from a stack of suitcases.

Secondary structures and supporting utilities are not modeled at this stage of analysis. While utilities in particular are very important to consider (some payloads will require power, data, gas, and fluid connections) the detail required to model these with any degree of accuracy may not be a value-add due to subsequent iterations that will ripple through the architecture as requirements are eventually defined.

The types of science payloads identified through this bottoms-up estimating are grouped into science laboratories and modeled in CAD software to create science facility layouts that can be included in habitat CAD models. The science capabilities identified in the previously mentioned data sources group into four distinct laboratories: human research, biology, physics, and geology, plus some shared workspaces and external science equipment. No assessment is made with respect to sequencing of use of science-related assets, or any utilization rates.

Where data sources identified multiple types of items that appeared to have similar functions, these were generally consolidated into a single, representative version of that item. For instance, if three different types of plant growth chambers were identified and the author was unable to determine a requirement for three different types of chambers, then only one generic type of plant growth chamber is incorporated.

Items that appeared to be components of other items or that appeared to be utilities connections/adapters were not included.

Items with names that appear associated with specific companies or partners are genericized (e.g. an Italian Mouse Drawer System identified in the OSWEG spreadsheet is represented generically as Mouse Drawer System).

Even in cases where a name is recognizable as a specific, previously flown item, its usage in this analysis only represents a generic functional analog and should not be taken to imply the flown item.

Small instruments, particularly those not intended to be permanently deployed, are not counted individually but are instead grouped into volumetric equivalents and represented by an appropriately sized stowage locker.

Types and quantities of consumables (e.g. microscope slides, chemicals, etc.) are not known, introducing a degree of uncertainty into the stowage volume. Any additional needed stowage is presumed to be accounted for in an overall habitat logistics strategy with bulk stowage in a separate location.

Laptops and display monitors are added where deemed appropriate to laboratory workspaces.

No assumption is made as to how the habitat is initially outfitted with laboratory equipment or payloads (e.g. prior to habitat launch, subsequent outfitting flights, and/or resupply/upgrade missions). It is assumed that all needed equipment and payloads (including live organisms) can be delivered to the habitat.

The payloads and experiment facilities selected are used to provide order of magnitude dimension, volume, power, and mass estimates useful in early studies for long-duration human spaceflight facilities. Selection of specific experiments/facilities for sustained lunar surface missions and definition of operational requirements would be tied to program-specific future solicitations and awards.

Only the IVA science facilities themselves are considered. There is no assessment of external staging areas, transfer areas, or other non-laboratory facilities. Also not included are other spacecraft facilities that have a different primary purpose but may support science activity, such as exercise equipment, or medical facilities. Also not included in this assessment are windows placement or any form of airlock or transfer lock.

A. Human Research Laboratory

The Human Research Laboratory serves the purpose of researching how astronauts' bodies and minds adapt to the extreme environment of space in order to protect astronaut health and performance from the five key hazards of spaceflight: radiation, isolation and confinement, distance from Earth, gravity, and hostile/closed environments. [14] Aboard the ISS, HRF-1 includes or has included the Ultrasound 2 and the Space Linear Acceleration Mass Measurement Device (SLAMMD). [15] HRF-2 includes or has included the Gas Analyzer System for Metabolic Analysis Physiology (GASMAP), Refrigerated Centrifuge, HRF Payload Drawer, HRF Centrifuge, Pulmonary Function Module, Photoacoustic Analyzer Module, and Gas Delivery System. [16] Both HRF-1 and 2 included computers, Cooling Storage Drawer, and 8PU Utility Drawers. [15] [16] A notional configuration for a lunar surface habitat Human Research Laboratory is depicted in Fig. 12, with individual lab equipment indicated in Fig. 13.

Fig. 12 Human Research Laboratory with 99th Percentile Stature Human Mannequin

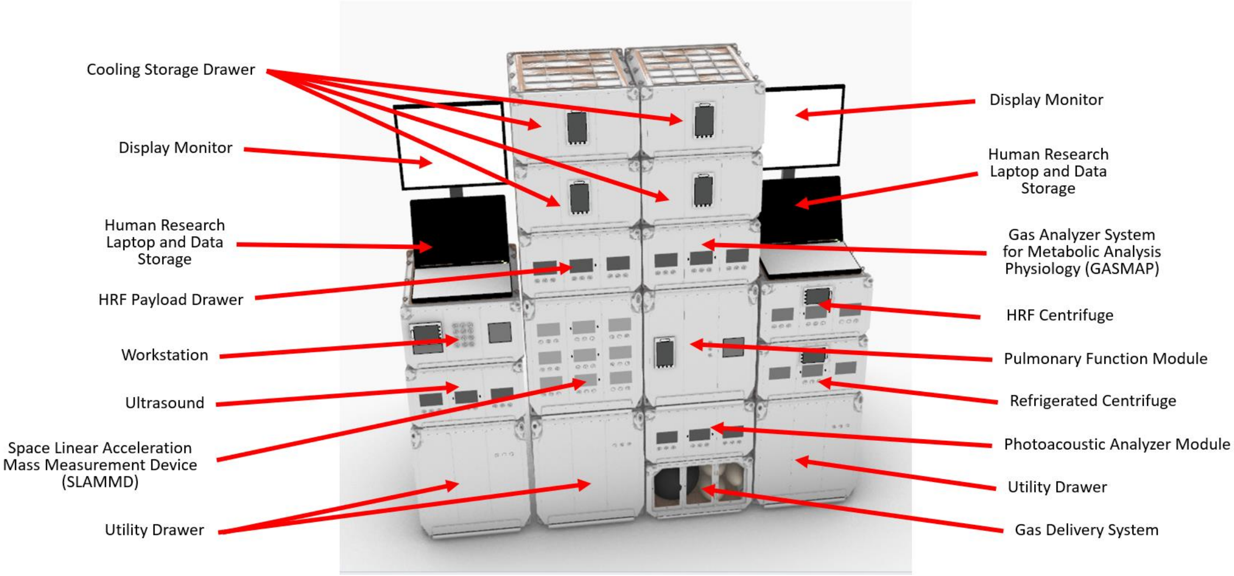

Fig. 13 Equipment Locations within the Human Research Laboratory

B. Biology Laboratory

The Biology Laboratory has some overlap with human research but serves a broader focus that also includes plants and animals, from molecules to cells, from tissues to organs, and from systems to whole organisms. Research investigates how living systems regulate and sustain their growth in space, including processes of metabolism, reproduction, and development, as well as how organisms repair cellular damage and protect themselves from infection and disease in conditions of microgravity. This research has the dual purpose to not only understand how living organisms adapt to spaceflight, but also to apply this understanding to improving life on Earth. [17]

The following biology components are indicated in the BioLab tab of the OSEWG lunar payloads spreadsheet: Modular Cultivation System (genericized version of European Modular Cultivation System listed in OSEWG), Biomass Production System (BPS), Animal Enclosure Modules (AEM), Animal Access Unit, Mouse Drawer System (genericized version of ISS Mouse Drawer System listed in OSEWG), BioServe Commercial Generic Bioprocessing Apparatus (CGBA), Walter Reed Army Institute of Research (WRAIR)-Cell Culture Module, Biological Research in Canisters-Light Emitting Diode (BRIC-LED), Avian Development Unit, Drosophila Containers and Platforms, Single-Loop Cell Culture, Standard Interface Glovebox (SIGB), General Laboratory Active Cryogenic ISS Experiment Refrigerator (GLACIER), Moon Experiment Research Locker Incubator (MERLIN) and Gaseous Nitrogen Dewar (GN2). [18] Additionally, 1 MDLE Science Housekeeping and 6 MDLE Science Consumables are included for small items listed in the OSEWG spreadsheet. A laptop and display monitors are also added to complete the laboratory. A notional configuration for a lunar surface habitat Biology Laboratory is depicted in Fig. 14, with individual lab equipment indicated in Fig. 15.

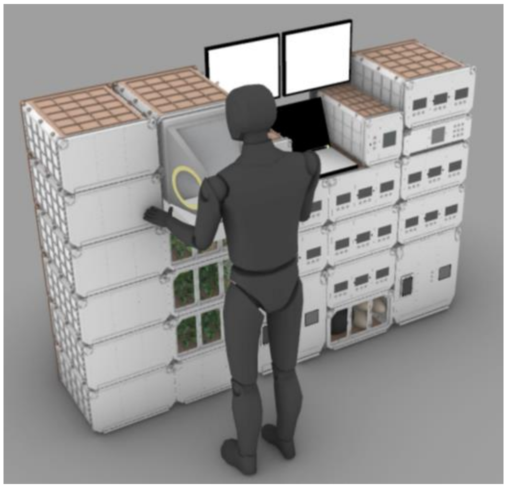

Fig. 14 Biology Laboratory with 99th Percentile Stature Human Mannequin

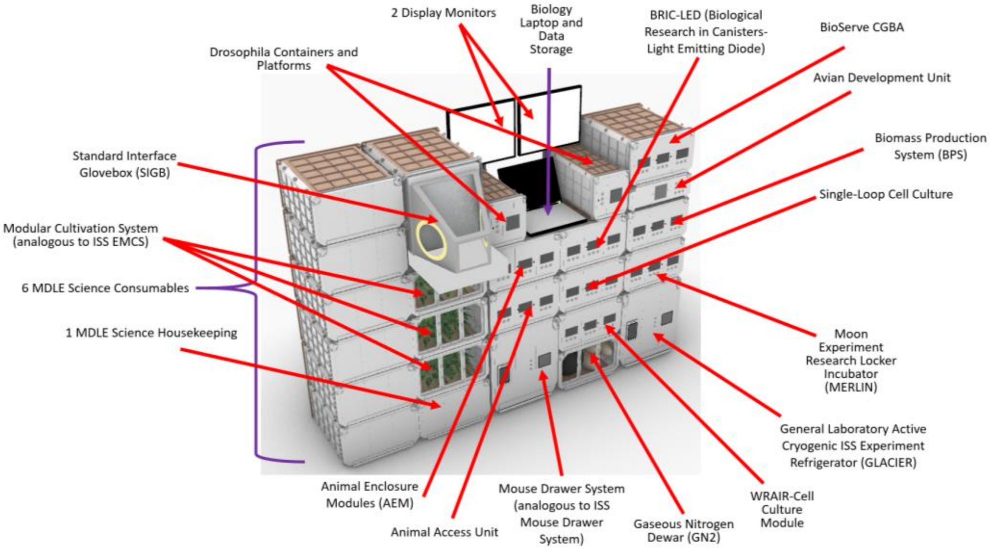

Fig. 15 Equipment Locations within the Biology Laboratory

C. Physics Laboratory

The Physics Laboratory focuses on fundamental research of physical phenomena and fundamental laws of the universe as well as applied research of space exploration technologies. This is inclusive of disciplines such as biophysics, combustion science, complex fluids, fluid physics, fundamental physics, and materials science. [17] This lab also includes control over external remote sensing platforms, which are described later in this paper.

The PhysicsLab tab of the OSEWG lunar payloads spreadsheet indicates a Combustion Chamber and a Fluid Mechanics Chamber. [18] Based on science subject matter expert recommendation, a multi-purpose glovebox is also included for physics investigations that require an enclosed environment but do not require either the combustion or fluid mechanics chambers. One laptop is included for physics investigations while a second one along with three displays are used to interface with the external remote sensing platforms. Four MDLE of stowage accommodates instruments used inside the chambers and glovebox and imagers for celestial observation. A notional configuration for a lunar surface habitat Physics Laboratory is depicted in Fig. 16, with individual lab equipment indicated in Fig. 17. On a program-specific basis, additional work is needed to identify science tasks requiring windows and the direction(s) such window(s) face. One or more optical quality windows is expected to be needed to mount instruments for celestial and/or surface observation.

Fig. 16 Physics Laboratory with 99th Percentile Stature Human Mannequins

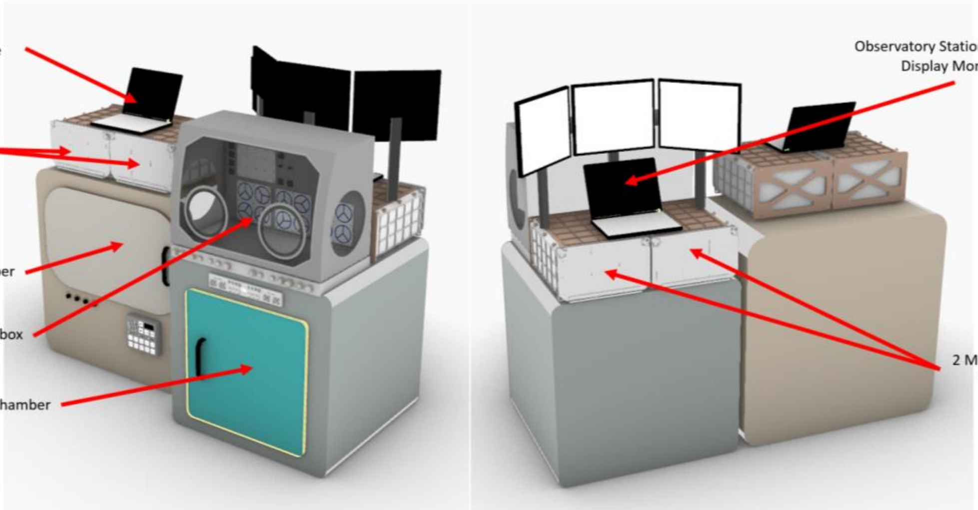

Fig. 17 Equipment Locations within the Physics Laboratory

D. Geology Laboratory

The Geology Laboratory engages geology disciplines including minerology, stratigraphy, structural geology, and petrology to provide laboratory support to robotic and EVA field geology through IVA analysis of surface and subsurface samples that are not designated for return to Earth. (Earth return samples generally are not analyzed inside the habitat.)

The utility of a geology facility beyond LEO is something that has been debated for decades. Most advocate that samples to be returned to Earth should not be touched until they are in laboratories on Earth. This, however, does not mean that there is no need for in-space laboratories. It is a likely consequence for any mission greater than a few days that the vast majority of samples collected will never be returned to Earth.

Apollo 17 spent three days on the surface of the Moon and returned 110.5 kg of samples. [19] This equates to an average collection rate of roughly 37 kg per day. Assuming samples are only collected during pressurized rover excursions and assuming 14 days of pressurized rover geology EVA activity (which could be credibly achieved or exceeded in a 30-day surface mission), 518 kg of samples will be collected. The HLS NextSTEP-2 Appendix H BAA Final Release for the Virtual Industry Forum established a performance requirement for the lander to return 35 kg of samples with a goal to return 100 kg. [20] Under such a scenario, and in the unlikely case that none of the other sciences have any samples to return (clearly some of the other disciplines will have return samples), 418 to 483 kg of the collected samples cannot be returned to Earth. They also cannot be returned on any subsequent mission because those missions will also have the same imbalance of samples collected versus samples returned. Thus, the only investigation that can be performed on the overwhelming majority of surface samples collected is that conducted in the lunar Geology Laboratory.

While this limitation might change in an architecture that achieves lunar cargo ascent through some means other than HLS, or an HLS provider may emerge with performance that greatly exceeds HLS requirements, the current Artemis program only assumes a sample return capability in line with HLS requirements. Generally, Mars architectures studied by NASA over the past several decades have had a comparable bottleneck in the Mars Ascent Vehicle. Emerging architectures based on the use of the SpaceX Starship do have the potential for greater surface cargo return, though this is dependent on the propellant strategy chosen and is not an inherent given. Any Starship-based architecture, however, does also have a dramatically increased ability to deliver habitat laboratory equipment mass and volume to a Moon or Mars surface.

Even if the bottleneck in sample return capacity is one day eliminated, there is still value in the person who made a discovery in the field following it up in the lab. There is an inherent value in flying a geology expert to the Moon (or Mars) and equipping that expert with both field tools and lab tools to make the best possible use of that person's expertise.

The OSEWG identified a need for a lunar surface geology laboratory and the GeoLab tab in the OSEWG lunar payloads spreadsheet are the following: Surface Samples Glovebox and transfer port, Gaseous Nitrogen Connection (GN2), Sampling handling and transfer kit, Sample Preparation and Separation Kit, Polarizing Microscope with attachments , Scanning Electron Microscope/Analyzer, Dual Use Handheld spectrometers and meters, Geochemical Toolkit: X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF), Laser Induced Breakdown Spectroscopy (LIBS), Sample Hand and Power Tools, and Video and Still Cameras.

Two Sample Supply Kits are also included, representing mass and volume placeholders for samples transfer and storage containers. A single mid deck locker is allocated for stowage of geology consumables and housekeeping supplies. And a single laptop with supplemental display monitor is included.

One item recommended in the OSEWG spreadsheet but not included is a Petrology Screening Package. This is listed as a 500 kg, 1.5 m3, 300W system to select samples for placement in a lunar surface archive or designate for return to Earth. This appeared to be a notional device in the spreadsheet (as opposed to all of the others that had either terrestrial or Apollo counterparts) and at the time of this writing, based on conversations with NASA geologists, it was not clear if this laboratory analysis is a desired approach for the selection of return samples. Due to the uncertainty surrounding this instrument it was excluded, though such an instrument would potentially double the floorspace of the Geology Laboratory if needed.

A notional configuration for a lunar surface habitat Geology Laboratory is depicted in Fig. 18, with individual lab equipment indicated in Fig. 19. Potential exists for sample pass through ports in the habitat to connect directly with the Surface Samples Glovebox and the habitat exterior, but this is dependent on specific habitat concepts.

Fig. 18 Geology Laboratory with 99th Percentile Stature Human Mannequin

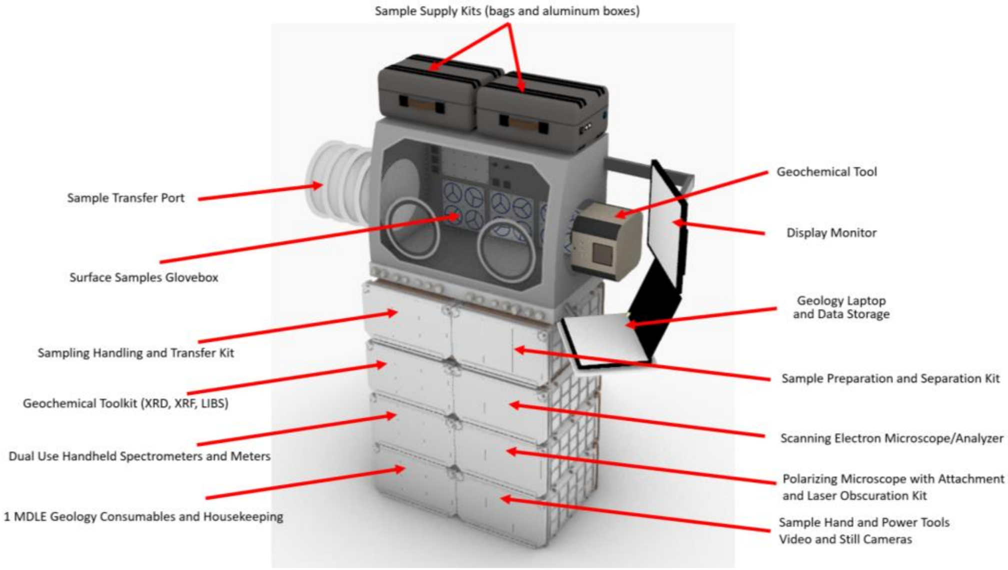

Fig. 19 Equipment Locations within the Geology Laboratory

E. General-Purpose Work Area

The general-purpose work area offers a common space that can be used by the crew for equipment setup, experiment staging, device calibration, and multipurpose horizontal surfaces. It also provides volume for large equipment shared by multiple labs such as freezers and four mid deck lockers for stowage of samples that do not require conditioned stowage. Shared by Biology, Human Research, Physics and Physical Science, and Geology laboratories, it is sized to provide an approximately 2.5 m^2 horizontal work surface area. The volume beneath this work surface is allocated to freezers, with four MELFI (Minus Eighty-Degree Laboratory Freezer for ISS) units (+4°C to -80°C) [21] and four CryoChiller units to provide cold stowage (-80°C to -185°C) for human research, biology, physics, and geology samples.

The MELFI and CryoChillers are used to notionally represent freezer volume. The actual freezer selection will depend on the program-specific thermal needs of samples collected or generated. It is important to keep in mind that multiple science disciplines generate samples requiring temperature-controlled sample storage and some programs will require multiple freezer types to accommodate the range of sample stowage temperatures. A notional configuration for a lunar surface habitat General Purpose Work Area is depicted in Fig. 20.

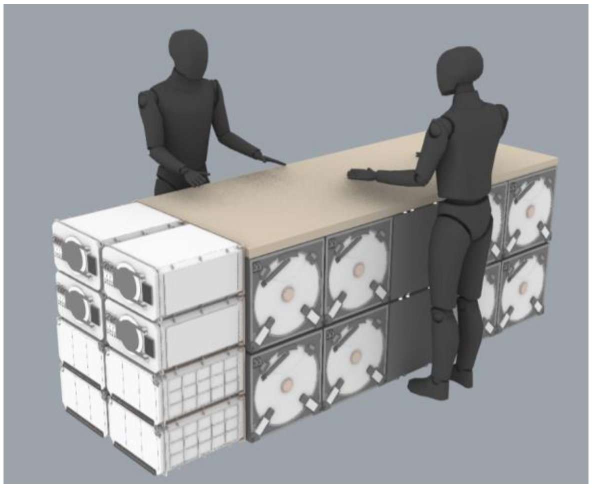

Fig. 20 General Purpose Work Area with 99th Percentile Stature Human Mannequin

F. External Remote Sensing Platforms

External remote sensing platforms support astrophysics, heliophysics, planetary science, and Earth science. [22] [23] [24] [25] They make use of the lunar basecamp location and the stable platform of the lunar surface as a unique vantage point for observation and measurement.

Potential instruments include electron and ion particle analyzers, DC and AC electric field and magnetic field analyzers, dust detectors, and telescopes. Some of these platforms may be mounted directly to the habitat exterior, while others may be emplaced on the surface some distance away from the habitat. These instruments are not sized as they do not occupy interior volume of the habitat. However, they should be considered during habitat design as they will occupy space within the launch vehicle shroud and lander payload envelope. Additionally, these systems may require IVA volume for operator consoles, accessories, or spares. In this paper, only the observatory station within the Physics Lab is allocated to support external remote sensing platforms.

G. Outfitting Summary

Based on the mass, volume, and power data contained in the OSEWG spreadsheet and ISS HRF-1 and HRF-2 data, the science outfitting described in this paper sums to a total of 8678.03 kg and requires 16.33 kW electrical power. The mid deck locker equivalent payloads and stowage units sum to 66.5 MDLE (roughly 4.56 m^3). This locker volume does not include the volumes of equipment that do not approximate mid deck locker dimensions: the Biology Lab's Standard Interface Glovebox, Physics Lab's Combustion Chamber, Fluid Mechanics Chamber, and Multi-Purpose Glovebox, the Geology Lab's Surface Samples Glovebox or Sample Supply Kits, or the General Purpose Lab's MELFIs. It also does not include the volumes of the laptops and display monitors.

This notional science outfitting was based on a lunar surface mission, but the same philosophy could be applied to Mars surface habitats, microgravity transit habitats, or space stations. Most science disciplines will be applicable regardless of spacecraft destination. Geology, however, may have different requirements for microgravity habitats, depending on whether those habitats receive samples from surface missions that require onboard analysis or stowage. External science platforms may be mounted to the spacecraft exterior – whether the habitat module(s) or other parts of the vehicle. Alternately, some may be deployable free fliers that separate from the spacecraft for specific observation periods.

Crew size can play a role in science outfitting, but perhaps not as large as might be expected. It would be fallacious to attempt to create parametric relationships to express science outfitting in terms of mass or volume per crew member. The outfitting as shown in this paper is driven by the need to accommodate the spectrum of science disciplines applicable to human missions beyond LEO. Any reduction in outfitting volume eliminates the ability to perform work in certain sub-disciplines. Thus, this level of outfitting is appropriate until the number of crew rises to a level where this outfitting cannot accommodate the working crew. Assuming the crew schedule allows all crew to perform science investigations in parallel, this capacity is likely not exceeded until the crew size exceeds nine or more, though choke points for specific instruments or chambers may emerge at smaller crew sizes.

However, there can be a reverse effect. Science outfitting can instead have impacts on the crew size, mission duration, and/or number of missions. If there are not enough crew onboard to conduct the science investigations required by the program-level science goals, then stakeholders may begin to withdraw support from the program as it becomes clear that objectives important to their constituencies cannot be met or will not be met in what they perceive as a reasonable amount of time. This is not to say that every goal must be achieved in every crew expedition. It is possible, for instance, that one expedition may focus primarily on geology while another shifts the focus to space biology, in the same manner that the shuttle program often conducted shuttle flights focused on specific investigations (e.g. the STS-90 Neurolab shuttle mission). The combination of number of expeditions, length of each expedition, and number of crew in each expedition must result in sufficient crew-hours to conduct the needed research.

VI.Conclusions

Most of the prior habitat concepts (e.g. Constellation, Mars DRA 5.0) investigated by NASA in the past two decades never attempted to provide the level of habitat science outfitting suggested by this paper. This may cause some to believe that this level of outfitting is impossible, cost prohibitive, or otherwise unachievable. Anecdotal conversations at the level of working engineers at Johnson Space Center have often included comments along the lines of, “we know we can’t have the same level of science on the Moon that we have on ISS.” This does not make sense. Is science less important on the Moon than in LEO? Of course not. What is being expressed is a semi-subconscious fear is that science cannot be accommodated beyond LEO. Fortunately, this is a fallacy. It is not that science cannot be accommodated. The actual truth is that science is challenging to accommodate in space architectures that were never designed to accommodate it.

Early identification of science outfitting needs is critical for sizing an exploration architecture that meets science needs. As has been shown, science capabilities can be significant drivers of habitat mass, volume, and power, with implications not only for virtually every spacecraft subsystem but also for launch vehicles, landers, and other spacecraft in the architecture.

If, for instance, a habitat completes an initial design cycle with an arbitrary allocation of 1000 kg and 1 m^3 for science, not only the design but potentially the entire architecture may be broken if a science outfitting as described in this paper is imposed in the next design cycle. It is simply too much mass and volume growth to absorb as it will require virtually all other subsystems to grow to support it. Habitat subsystems may have been improperly sized to accommodate thermal, avionics, life support, or power demands of the science equipment. The habitat may be physically unable to contain the physical space required to accommodate the equipment and operator volumes, requiring a larger habitat or the addition of one or more elements. This in turn increases the lander mass, potentially requiring a larger lander or an additional lander mission. And this increases the Earth launch mass, potentially requiring a larger launch vehicle or an additional number of launch vehicle flights.

The later in the development cycle these science needs are made known, the greater the likely disconnect between vehicle concept and science needs and the less likely the full spectrum of science needs can be accommodated. This can result in a program that is fundamentally unable to live up to the stakeholder needs that initially established the program.

While it is difficult to add 8.68 tons of science equipment to a habitat initially sized, for instance, to a control mass of 10 tons for the entire habitat, there are no laws of physics violated in sizing a program to deliver a 20, 30, 40-ton, or greater habitat to the lunar surface (provided this habitat mass is considered in launch vehicle and lander selection). Further, US industry is currently demonstrating that such systems are within their technological capacity and can be provided…if there is a documented need for such performance.

The laboratories sized in this paper do not reflect vetted and confirmed science allocations for lunar missions. But they do offer science allocations that scope the breadth and depth of science disciplines relevant to human lunar surface operations.

With this information available early enough in the program, the entire architecture can be sized appropriately. With the utilization activities established, including EVA activity, IVA science activity, and other crew work, the program can make informed decisions regarding crew size, mission duration, and number of missions required to achieve key program objectives. This in turn can drive habitat sizing and launch campaign development.

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