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The MaMBA-concept for an extraterrestrial base and its first module mock-up

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Abstract

Habitats must enable astronauts to survive in an extraterrestrial environment, but the challenge is not only a technological one: architecture and engineering should be brought together to create an environment in which a crew can perform optimally. With missions to Mars in mind, crew mental health becomes a design driver equally important to the support of physiological functions. We here suggest a habitat concept, MaMBA (short for Moon and Mars Base Analog), which combines the two requirements. In its basic configuration, MaMBA consists of six upright cylindrical, hard-shell pressure vessels as main modules and two airlocks, which are all connected with inflatable corridor modules. We present the current state of the design and particularly focus on the laboratory module, of which we have constructed a mock-up equipped with scientific instrumentation. In the long-term, we plan to develop this laboratory module into a functional prototype including subsystems such as the life support system. Eventually, we aim to create a habitat which can serve as a test platform (for technologies, operations, and procedures) and whose usability is continually validated through iterative testing with human inhabitants. The habitat is open to international partners for simulations.

Keywords: human space exploration, habitat prototype, Mars, Moon

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1. Introduction

The debate over “Moon First” and “Mars Direct” seems to be settled in favor of establishing a permanent presence on the surface of the Moon and testing critical mission hardware there, before heading on to Mars. This plan is reflected by NASA’s long-term *Journey to Mars*, but also by the *Moon Village* envisioned by ESA’s Jan Wörner and the Chinese Lunar Exploration Plan (CLEP) and the announcement of the China National Space Administration (CNSA) to build a research station at the lunar South pole in about 10 years.

Several super heavy-lift launch vehicles are being developed, notably by US-American companies, NASA, Russia and

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China, in order to transport crews and hardware to the surface of the Moon. Meanwhile, plans for said hardware still remain comparatively hazy: for example, most proposals for lunar and Martian surface habitats "remain at a conceptual stage" [1]. Only few of these proposals progress to advanced "Habitation Readiness Levels (HRL)" (a term Connolly et al. coined in [2] with reference to NASA's Technology Readiness Levels), i.e. few habitat concepts are ever built as mock-ups, let alone field-tested.

The majority of habitats that have actually materialized, have been built either for simulating human missions to planetary bodies (such as HERA [3, 4, 5], HI-SEAS [6], MDRS [7, 8], or the Mars-500 facility [9, 10]), or for testing specific subsystems of a habitat (usually life support systems (LSS), such as with Bios-3 [11], HESTIA [12], Lunar Palace 1 [13]). These habitats are usually the means to the end of conducting missions in a confined environment, rather than being built for the testing of the habitat itself. One of the few exceptions is HERA, which was originally built as a test platform for both habitat technology and architecture (see e.g., [5]), although its design process inherently lead to the facility being not fully coherent [14]. Other designs such as the Mars Incubator have been printed at least in part, but not equipped and inhabited yet [15].

The consequence of these scattered efforts is that no coherent and functional prototype for a lunar or Martian base exists to date. With this paper, we intend to fill this gap and present a habitat design that can serve as the basis for a functional extraterrestrial habitat and that shall be built in the next years. The name of the habitat is MaMBA, short for Moon and Mars Base Analog.

Figure 1: Artistic rendering of a habitat based on the MaMBA concept. One can see two of the main modules, one airlock and two of the inflatable connecting modules. The radiation shield is under construction in this image.

In general, an extraterrestrial base must be *habitable*. Habitability is a measure of how well the base "supports human health, safety and well-being to enable productive and reliable mission operation and success" [16, 17]. Space architects divide habitability into the following three pillars (adapted from [17]): (1) life support, (2) behavioral health, and (3) safety.

The first pillar falls into the engineering domains and relates to the overall base structure, particularly the outer shell and hatches that contain the internal atmosphere, air revitalization systems, thermal control systems, hygiene, waste management etc. The pressure vessels of HESTIA at the Johnson Space Center [12] and the Controlled Environment Research Chamber at NASA Ames [18] provide good examples for proven structural design; and bases such as Bios-3 or Lunar Palace 1 provide insights into the requirements of bioregenerative life support systems (BLSS). It has been argued [19, 20] that a truly permanent and autonomous base on Mars needs a bioregenerative rather than physico-chemical system. It is worth to note that the latter two bases used large plant growth chambers, while others favor an algae-based or cyanobacterium-based life support system (e.g. [20, 21]).

The second pillar relates to psychological and social considerations. Historically, these have often been considered "secondary to environmental conditioning" [22], even though, in fact, they greatly affect crew performance beyond mere survival. Typical considerations are the distinction between personal spaces and spaces for social interaction, light quality, colors and textures of the interior. Particularly analog bases that are or have been occupied for extended periods of time can give valuable insights (some useful recommendations were summarized in [23]); for example, former HI-SEAS crews have rated the high ceiling habitat positively [24], while crews inside the cramped Aquarius base felt visibly uncomfortable sharing a tiny table serving too many purposes at once [24].

The third pillar finally is the safety of the crew, i.e. a habitat must protect the crew from environmental hazards such as micrometeoroids and space radiation, and from internal safety hazards such as fires, atmosphere contamination etc. One might expect that even terrestrial simulation bases fulfill basic safety standards, however, this is not always the case (see e.g., [25]). But even habitats based on more user-friendly designs similar to HI-SEAS or HERA could become unusable for an injured crew member (for example, by having a ladder between the hygiene and the sleep compartment that would be difficult to climb with a broken leg). What is more, while being a functional pressure vessel, a base like HESTIA would become completely uninhabitable if, for example, a fire broke out in its one single module. As Perycz et al. pointed out [26], it is arguably just a matter of time until an accident occurs on the Moon or on Mars that permanently or temporarily incapacitates a crew member. Clearly, a lot is left to be done for the resilience of habitat designs towards contingencies, including crew survivability and adequate provision to overcome contingencies [27].

Our goal is to develop the MaMBA-concept based on the three above-mentioned pillars. While there are advanced concepts for the in-situ construction of bases in the far future (e.g. [28, 15, 29]), we focus on a habitat that accommodates first arrivals. For as Cowley et al., who themselves suggested a habitat design based on in-situ utilization of resources, put it, "a terrestrially provided solution has a lower risk overall and offers a number of advantages" [28]. Moreover, our base is designed for an initial crew of 6, but the concept is flexible and can be expanded to house larger crews, or crews with other needs than scientific exploration.

The habitat concept we propose in the following pages should be viewed as part of a larger "village", that is the habitat must be surrounded by infrastructure such as a radiation shield, electrical power plants, and factories for mining in-situ resources, to name a few. Also, a crew on an exploration mission will need surface suits to explore the surroundings of their home. However, we consider these as corollary systems, and explicitly limit the scope of this paper to the habitat itself. We will outline some of the concepts, such as the concept for radiation shielding and the concept for the robotic transport and setup on the lunar surface, but will refrain from delving into details, which will be disseminated separately elsewhere.

One major part of our design process is the construction and testing of a mock-up of the laboratory as the first module. The mock-up is currently used for validating the architectural design, but will later be used for simulations with different focus. We built the mock-up from wood, keeping the inner dimensions exact as those are the dimensions the crew is exposed to. The interior is filled with racks and scientific equipment that was selected with the help of scientists from various disciplines, including geology, biology and materials science. We have already conducted two test runs with scientists evaluating the usability of the laboratory; these results will be published later.

We plan to construct further mock-ups in the future with increasing technology and habitation readiness levels (TRL and HRL, resp.); at the moment our design is what Connolly et al. [2] consider HRL 4 (not to be confused with TRL 4), which refers to full-scale mock-ups whose subsystems are mostly non-functional, but which can be used for verifying the compatibility of human operations with the design [2]. This approach is the major difference to previous work: We design a functional base that incorporates the human experience through iterative testing. Our goal is not to create a base *for* simulation, but we intend to validate the base concept *through* simulation and testing.

We introduce the overall base layout in the following section, and then explain the architecture of the basic module in section 3. In section 4 we describe the construction of the full-size mock-up of the basic module and its setup as a laboratory module. We end this paper with an Outlook (section 5) of the future steps to be undertaken to expand and verify the design of MaMBA for a real mission to the Moon or to Mars.

2. Concept for a functional lunar or Martian base

We start this section with a brief overview (sec. 2.1) of the habitat layout and distribution of major functions. We then discuss technological constraints and design decisions (2.2), followed by decisions dictated by crew comfort and mental health (2.3). In section 2.4 we outline some of our plans for off-nominal situations and recovery from (sub-)system failures.

2.1. Habitat overview

The habitat we propose consists of six connected modules which can accommodate a crew of six. Each module serves one or two primary functions (see fig. 2), ranging from sleeping, eating, socializing, and relaxing on the “habitation” side of the habitat to a greenhouse, laboratory, workshop, and exercise area on the “work” side. The grouping of the habitat modules is based on the recommendation to separate functional areas into “quiet” and “noisy” areas [30, 31].

Generally, work modules shall have two stories, while leisure modules shall have one single story with a high ceiling similar to the HI-SEAS habitat [24]. The high ceiling will help the crew combat the feeling of confinement. However, in the sleep module it is necessary to introduce the intermediate ceiling in order to accommodate all six crew members.

The modules have a six-fold symmetry (the hatches are angled at 60° to each other, in theory allowing up to six hatches per module) in order to allow a greater flexibility for expansion than the common square design (see also section 2.3). The minimum

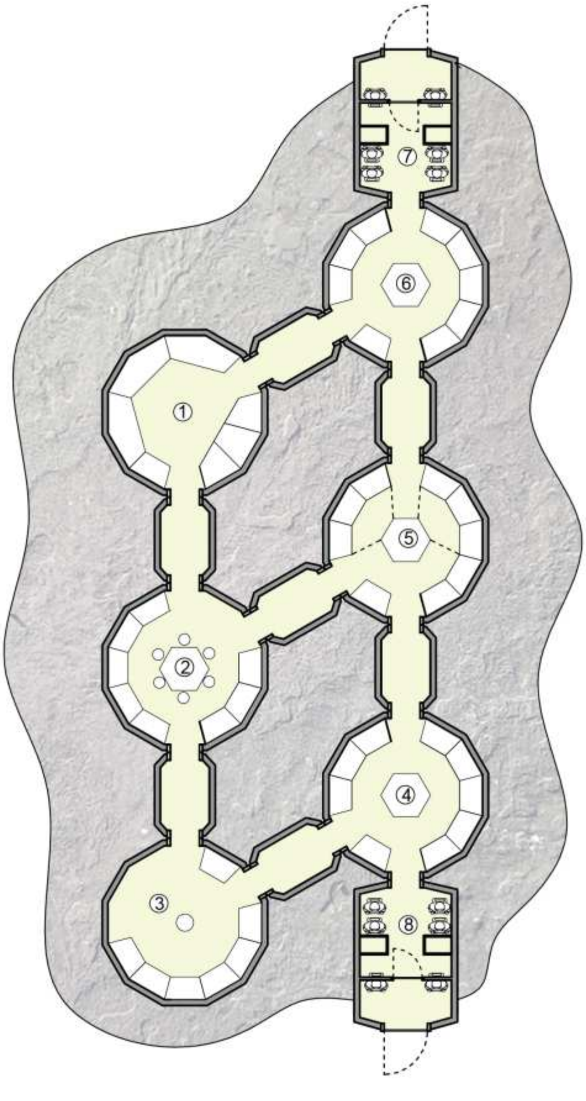

Figure 2: MaMBA layout with 6 connected modules that can be locked off from each other in case of emergency. Each module has one primary function: (1) sleeping, (2) eating and socializing, (3) relaxing, (4) greenhouse, (5) laboratory, (6) workshop. In addition, there are two airlocks (7, 8). Note that the three modules on the right are dedicated to work, whereas the modules on the left are reserved for habitation and leisure.

number of doors in any module is 2 to ensure there are always 2 escape routes from each module. Even though a module could have up to 6 doors, it is a more efficient use of space if there are only 2 or 3 doors: each additional door reduces the space available for furniture or storage; at the extreme of 6 doors, there is practically no room to place racks or other items along the walls. Such a module would mostly serve as a hub between other modules, something that should rather be avoided as the passage between different modules would be blocked if that hub module failed for whatever reason.

In the basic configuration presented here, the habitat is centered around the laboratory module. However, it is possible to extend the base to different users, including tourists or miners.

The leisure or relaxing module is unique in that it shall have a window: Mohanty and Imhof [32] argued that, “Getaways can play a vital role in enhancing the socio-psychological health of the crew, thus improve the quality of life aboard space habitats and ensure mission success.” Similar to the Cupola module on the International Space Station (ISS), the relaxing module could become a favorite leisure spot of the crew.Besides, the window allows a view on the habitat surroundings which may provide extra safety to early extravehicular activities in the vicinity of the habitat.

We estimate the interior space of the MaMBA habitat to be 460 m^3 (6 modules, 9 inflatable corridors, 2 airlocks). This value is likely to change when the design becomes more advanced, nevertheless, it still allows a rough comparison: In the range recommended for a lunar base by Kennedy et al. [33] after a review of existing “station-like” spacecraft, MaMBA is located at the upper end and slightly larger than the ISS

($388\,\mathrm{m}^3$ for a crew of usually 6), which is regularly supplied from Earth. If one considers the corridors and airlocks, the total floor area of the full habitat is $173\,\mathrm{m}^2$ and thus slightly less than the $204\,\mathrm{m}^2$ that the Mars500-crew had, which holds the record for the longest spaceflight simulation to date.

Storage volume is available inside the cylinder ends ($90\,\mathrm{m}^3$, also see fig. 3 and table 1 in sec. 3), in the corridor walls ($25\,\mathrm{m}^3$, see discussion below), in the airlock walls ($53\,\mathrm{m}^3$) and module walls ($120\,\mathrm{m}^3$), plus of course inside the racks ($72\,\mathrm{m}^3$), resulting in a total volume for storage of $360\,\mathrm{m}^3$. We could not find a relevant and dependable estimate of the required storage volume in the litature; the closest estimate is that of de Weck and Simchi-Levi who arrive at a value of 36.5 t (they only give a mass estimate) based on their experience from the Haughton-Mars Project Expedition 2005 [34].

2.2. Technological aspects

All main modules are hard-shell pressure vessels in the shape of upright cylinders, 5.20 m in diameter and 6.50 m in height. They are similar in size and structure to the modules used on the International Space Station (ISS), and could be transported by super heavy-lift launch vehicles that are in development such as the Space Launch System, Long March 9, or the SpaceX Starship.

We decided for rigid shell modules and explicitly against modules made from inflatables or from in situ resources, for the following reasons: First, although we believe that a habitat should be created from in situ resources in the long run, we deem the risk for the inhabitants too high to use a material that has not yet been tested under realistic, in situ conditions. Second, while inflatables are much easier and cheaper to transport, they are much more difficult to set up. Once inflated, subsystems and cargo have to be transferred into the module from the outside, i.e. through the lunar dust environment. As long as there is no strategy for removing dust adhering to objects on the Moon that has been demonstrated to be effective, the best strategy for dust mitigation is to not expose any critical components to the lunar dust environment in the first place. Third, rigid modules allow for pre-integration of all components while still on Earth, where man-power and replacement parts are more readily accessible.

The main modules are connected by corridors formed by inflatable modules [35]. These corridor modules add flexibility to the design (for example, the habitat could be expanded with modules that may differ in size from the original modules), add a safety buffer between the modules (in case of fire or gas contamination, the smoke and gases take longer to spread throughout the habitat), and facilitate the transport to the Moon (by being inflatable, several corridors can be transported at once). If the shape of the inflatable corridors is perfectly cylindrical, their minimum diameter should be 2.4 m. Else a width of about 1 m would be sufficient. In the latter case, the walls of the inflatables offer approx. $25\,\mathrm{m}^3$ of storage volume, depending on their exact shape.

Once the modules are landed on the lunar or Martian surface, they need to be transported to their final location by robots and then set up and coupled. Given the size of each module and the expected mass of several tons, the best solution seems to be a robot swarm, rather than a single rover [36]. The swarm could consist of simple wheel-driven platforms with an exchangeable arm that could later be reused for other tasks, or the swarm rovers could be a more complex, but flexible platform with more degrees of freedom similar to the ATHLETE design, where each limb has a quick-disconnect tool adapter [37, 38]. In any case, due to the swarm approach, the individual rovers could be comparatively small, which would facilitate later re-purposing.

After setup (or, in fact, during), the entire habitat shall be encapsulated by an artificial cave (constructed from regolith [39, 40, 41, 42]). The cave can be similar to the one shown in fig. 1, although it is likely more efficient to print the cave walls in horizontal layers, rather than vertical ones as shown in the rendering.

The cave walls should have thicknesses of well beyond 1 m in order to provide adequate shielding against cosmic radiation. In theory, the base could be erected inside a natural cave such as a lava tube, however, lava tubes are usually accessed vertically through skylights, which would significantly complicate the logistics of habitat transport and crew transfer between habitat and the planetary surface. The artificial cave, on the other hand, would have a horizontal entrance and a precisely controlled wall thickness. Moreover, the cave would provide a shelter from radiation for rovers not currently in use and other equipment, as would not be possible if regolith was simply piled up over the habitat modules.

Besides shielding against radiation, the cave also provides protection against micrometeroid impact and the extreme temperature swings on the lunar surface. The habitat itself will be in permanent shadow, but due to the vacuum environment we expect that the complex still needs to be cooled with the help of radiators, which would have to be placed outside the cave.

Power could be provided by either solar panels or radioisotope thermoelectric generators (RTGs). Since most mission architects favor a landing at the lunar South Pole, solar irradiation would not be an issue for the former option; however, dust would be an issue both on the Moon and on Mars. The total power consumption of a lunar base is generally expected to be around 200 kW [43]. It would be desirable to have a consistent power supply in the base, with the same voltage at all outlets that is dictated by technological requirements rather than regional preferences of the module manufacturer.

The life support systems are planned to be bioregenerative (BLSS). Oxygen is generated by algae or cyanobacteria. These can be grown efficiently in large, but flat tanks, where the light needed for photosynthesis does not need to penetrate deep. Due to the flat geometry, the bioreactors are located inside the wall of the vessels, rather than in a separate rack like on the ISS (see sections 3.2 and 3.4 for further details).

The space between inner and outer walls is sufficient: A human requires $\sim$500 l or 20 mol of oxygen per day. Oxygen production rates for algae are on the order of $\sim$1 mmol/hr [44], depending on the species and density of the culture (and other factors). Thus, $\sim 1\,\mathrm{m}^3$ of algal cultures are needed for each crew member. Given that this estimate only includes the liquid medium, it should be considered optimistic. In any case, the LSS is spread across two to maximum three modules, such that there can be at least two independent LSS in the habitat that both can supply a crew of six independently. Hence, if one subsystem fails in one of the modules, that module can still be supplied via the other modules.

A positive side effect of the water tanks in the walls is the additional shielding against radiation [45]; in fact this design choice was inspired by M. Cohen's water walls [46].

Note that a BLSS would be too costly in terms of launch mass if the goals were relatively short missions ($\sim 1\,\mathrm{a}$ or less) to "only" the Moon [47]. However, since most consider Mars their long-term goal, rather than the Moon, we believe that a lunar habitat should include a BLSS so it can be tested thoroughly before being needed for a long-duration mission on Mars (we expect a Mars habitat to be used for at least 10 years).

2.3. Crew comfort aspects

As mentioned above, the habitat is separated into a habitation side and a work side, to allow the astronauts to gain physical space between themselves and their work. With its large floor area, the habitat provides enough room for the crew to find privacy. The kitchen module is a designated central meeting place, and the leisure module is the designated place for the whole crew to relax and spend leisure time together.

The geometry of the basic habitat layout in fig. 2 allows the crew to view larger distances ($\sim 20-\ 30\,\mathrm{m}$) along the longer axes– which will counteract the change in vision that is observed in submarine crews and other crews who are confined in small spaces for long periods of times.

Each of the work modules and the sleeping module consist of two stories, while the leisure and eating modules have a single story with a high ceiling. The lower stories house the functions that are necessary for everyday survival, that is, hygiene compartments, food preparation and intake area, (some) sleep compartments, and the exercise area are all located on the ground floor.

The upper stories house functions that are necessary in an extraterrestrial base, but not for immediate survival: a control room (for communicating with Earth or remote-controlling rovers) is located above the laboratory and the greenhouse is above the gym.

The one exception to this rule is the location of the medical bay, which is also above the laboratory. The reason for this is the need of a crew member seeking medical attention for some privacy, i.e. being "out of the way" of the other crew members. If they cannot make it up the stairs by themselves, they can be pulled up with a stretcher and a winch.

On a more general level, all upper stories serve as "quiet corners", where crew members can move if they need to be alone or concentrate on a specific task.

2.4. Measures against contingencies

Given the ambitious timeline proposed by major space agencies, it is obvious that many questions will remain unanswered before the first crews will enter a permanent station on the Moon. It can be expected that several subsystems will not operate as planned. In order to mitigate the risk to life and health of the crew we consider major failures and contingencies, and direct the habitat design such that it helps the crew overcome such major events. We consider both technical failures (such as gas leaks, contamination, fire) and medical problems (especially temporary or permanent disabilities due to injuries or adverse effects of the lunar environment on the human body).

Modularity. The habitat is split into separate modules so that the crew still has a shelter even if one module malfunctions and needs to be locked off completely, as could happen during a fire and would be done on the ISS [48]. Moreover, all modules have the same shape and structure. Their sixfold symmetry allows various arrangements; the arrangement shown in fig. 2 is just one of many possible options. If one module is defunct beyond repair, it could be replaced with a new module (although this may depend on the reason for the module failure).

Redundant airlocks. The habitat consists of (at least) two independent airlocks; each airlock is capable of transferring the full crew of 6, in case the other malfunctions. This means that each airlock must hold a full set of suits for the crew.

Pressure-tight doors. In order to be able to lock off any one module, each module must be equipped with pressure-tight doors. Similar to the ISS, these doors may be closed only when needed. Since the failure may be a pressure drop on either side, the doors should use a sliding mechanism, rather than a hinge mechanism. The door leaf would be incorporated in the module wall above the door opening, where gravity would help shut it (although gravity alone would be too weak, so a motor would be needed for acceleration). The door frame also contains the coupling mechanism. In order to increase privacy and prevent sound from traveling between the different modules, light curtains or ribbons could be placed in front of the passage.

Second floor. It may seem trivial to require all functions that are necessary to keep a crew alive to be located on the ground floor, but as the examples of HERA, HI-SEAS, and MDRS show, this is too easy to overlook: At these three analog bases the crew sleeps upstairs, while the bathroom and/or kitchen is located down the stairs or even down some ladders. It is impossible for a crew member with an injured foot or leg to reach all these functions independently (and perhaps not even with the help of a fellow crew member).

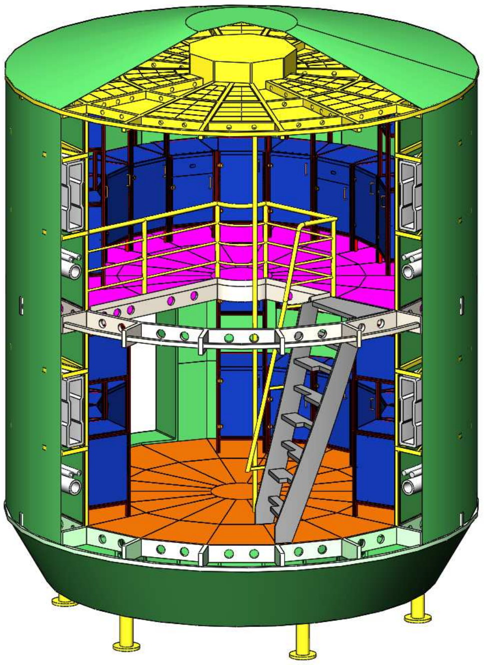

Figure 3: Laboratory module layout showing the upper floor (pink), lower floor (orange), upper storage room (yellow), the stairs between the floors (grey), the LSS inside the module wall (grey), and the racks (blue).

Distribution of the LSS. The LSS should be spread across separate modules of the habitat, as described in section 2.2. An additional safety factor could be the use of dissimilar LSS, although duplicate LSS have the advantage of easier maintainability (also see sec. 3.4).

3. Concept of the base module

Figure 3 shows a sectional view of the basic module, including the two floors, the LSS and the racks. In the following section the ISS [48]. Moreover, all modules have the same shape and structure. Their six-fold symmetry allows various arrangements; the arrangement shown in fig. 2 is just one of many possible options. If one module is defunct beyond repair, it could be replaced with a new module (although this may depend on the reason for the module failure).

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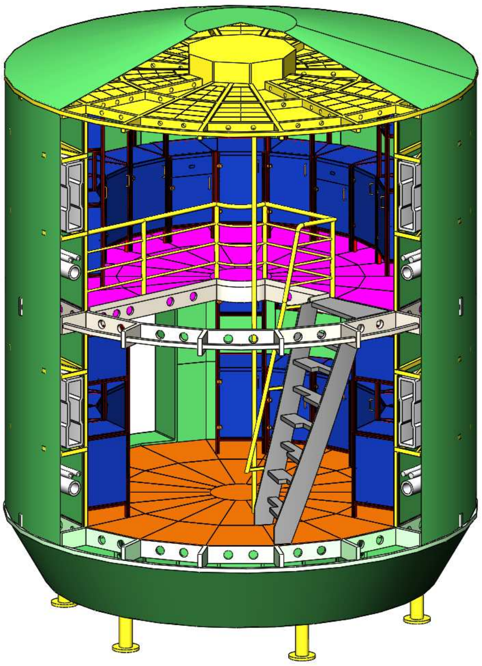

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3. Concept of the base module

Figure 3 shows a sectional view of the basic module, including the two floors, the LSS and the racks. In the following section (sec. 3.1), we present the dimensions of the module. Then we will outline—similar to section 2—some of our design choices, starting with technical constraints (3.2) and considerations to support the mental health of the crew (3.3), followed by design decisions driven by contingencies (3.4). Since the racks used on the ISS (International Standard Payload Racks, ISPRs) are not suited for a surface base, we will describe a possible re-design of the racks for use in a gravity environment in section 3.5.

3.1. Module overview

The basic module is an upright cylinder, with an inner diameter of 4.40 m, which is subdivided internally into two floors (2.30 m ceiling height each), and two storage compartments in the upper and lower cylinder ends (approx. 1 m high). Some modules do not have the division into 2 floors, as described in section 2.1. the interior volume of the basic module is 70 m^3, of which 15 m^3 are occupied by racks (see table 1).

The habitable part of the cylinder is enclosed by straight wall segments, such that the floor takes an octodecagonal shape (a polygon with 18 corners). Since the inner and outer walls are about 30 cm apart, the module offers 20 m^3 of storage in the walls, which is mostly reserved for the door mechanism and LSS. There is an additional 15 m^3 in the storage compartments at the upper and lower ends of the cylinder.

Each ground floor has an area of 15 m^2, whereas the upper floor has only 11 m^2 due to the stairs. Approx. 7 m^2 of the module area are covered by racks (see table 1).

3.2. Technological aspects

The wall storage of 20 m^3 is spread across 12 of the 18 wall segments, covering a wall area of approximately 42 m^2. The storage volume is partly reserved for the BLSS (see sec. 2.2).

The remaining third of the walls is occupied by the passageways, 2 segments for the doors and door mechanisms for each of the 3 doors. As mentioned in section 2.1, the minimum number of doors in any module is 2; unless a module is to serve primarily as hub, it should have no more than 3 doors, to leave enough wall space for racks and storage. The mock-up described in section 4 has 2 doors plus 1 blind door reserving the space for the third door that is depicted in the base layout in fig. 2.

3.3. Crew comfort aspects

Although each module serves a specific function, all modules have the same basic design. This enables flexibility: furniture (i.e. racks) may be re-arranged, brought to different modules, or re-assembled into different geometries. Flexible interior configurations allow the crew to adapt to different requirements, ranging from private work spaces to activities demanding a lot of room, such as construction projects or social group activities. Besides, changes in interior help the crew break through the monotony of their confinement and overfamiliarization [24].

The ground floor of the base module is large enough (15 m^2) to accommodate the full crew of six at once, enabling the crew to undertake various tasks and leisure activities together, thus enhancing their social cohesion. The lack of such a meeting space in the ISS has been criticized by astronauts [50, 30].

Sound insulation has been a notorious problem in spaceflight [50] and spaceflight analogs [12, 24]. The problem could be alleviated with resin foam similar to the payload cladding in the Ariane 5 launcher [51],

	Basic module	Full habitat	Habitat per c.m.	ISS	Mars500
Pressurized volume [m^3]	90	825	138	916	550
Habitable volume [m^3]	55	460	77	388	-
Total floor area [m^2]	26	173	29	n.a.	204
Circulation area [m^2]	19	134	22	n.a.	-
Wall area (LSS) [m^2]	42	254	42	n.a.	n.a.

Table 1: Volumes and areas that are available to the crew. The numbers for the full base include volume and area of the (inflatable) corridors and airlocks. "Wall area (LSS)" refers to the area available to the LSS, that is excluding the cylinder segments where the doors and door mechanisms are located. The respective values for the ISS [49] and the Mars500 habitat [9] are included for comparison. "c.m." = crew member.

which could be attached to free surfaces next to racks or even onto racks or wall panels directly. At the very least, it should be avoided to have large, continuous surfaces in the interior. For example, rather than having solid sheets as rack walls, the sheet surfaces could be broken with patterns (triangular as in fig. 4, or other).

The light concept is based on artificial lighting—mimicking natural lighting. Ceiling lights in the MaMBA concept are adaptable, with the color scheme depending on the time of day (a more bluish light in the morning and during mid-day, warmer tones during the afternoon and evening). This helps the crew maintain a stable circadian rhythm (24 h on the Moon, 24.6 h on Mars), plus, changing color and brightness help the crew overcome fatigue and be overall more productive [23, 52]. Lights change automatically, but can be overridden manually. Ideally, the ceiling lights would form a ring around the center of the ceiling; a more feasible approximation is to use rectangular dimmable LED-panels that are arranged in a ring. There are bright, cold-white LED lights at the work stations to supplement the ceiling lights.

A positive side effect of the biological LSS is the possibility to include biomonitors such as AquaHab [53]. Besides registering possible contaminants in the air and water, the biomonitor can be integrated into the wall similar to aquariums in restaurants, allowing the crew to feel more connected with their terrestrial home.

3.4. Measures against contingencies

Removable wall panels. Since the LSS is located behind the inner wall, the wall panels of that wall must be easily removable. We split each of the 18 segments into 3, so that the panels are better manageable. The racks can be moved aside easily. At the positions of workbench racks (see section 3.5), the middle wall panels can be removed without having to move the racks.

Commonality. We aim to design all parts such that they can be assembled with one pre-defined set of hardware and tools. At the small scale, this manifests in a limited selection of screws, at the larger scale, the commonality should lead to re-using the same parts and subparts for the LSSs in each module [54], thus reducing the number of spares to be taken. Even if there is no spare (left), parts may be taken from similar systems in other modules–for example, a pump from an otherwise broken water reclamation system may be salvaged to repair another water reclamation system whose pump is broken.

Quick escape. In case of emergency, the crew may choose to evacuate the upper floor via an escape pole, rather than descend the stairs. Gravity on the Moon is so low ($\frac{1}{6}g$) that one would have to jump from six times the height as one would on Earth to achieve the same momentum ($mv = m\sqrt{2(\frac{1}{6}g)(6h)}$). In other words, if we assume the upper floor to be 2.40 m above the ground floor for the sake of simplicity, then jumping from the second floor at $h = 2.40$ m on the Moon corresponds to jumping from 40 cm on Earth, or not even common chair height (the height on Earth corresponding to $h = 2.40$ m on Mars is 0.9 m, or desk-height). However, the long duration of the 2.40 m fall on the Moon (1.7 s) is likely to make the fall itself less controllable. The escape pole would help stabilize the jump.

Navigation under limited visibility. The crew must be able to navigate the habitat even with limited visibility due to smoke, light failures, or damage to their visual system. Each module has its own color which helps differentiate the different modules; each exit from a module is labeled with the color of the module the exits leads to.

3.5. Racks

As mentioned above, the ISPRs that are currently used on the ISS are not suited for a gravity environment: Their mass (104 kg) and geometry make it difficult for humans to move them in a gravity environment and through narrow passage ways. Instead, we suggest reducing the size of the racks to more manageable dimensions: to a width of 19 inches (48.3 cm) plus the thickness of the outer aluminum profiles (in our case 4 cm, but this is subject to optimization).

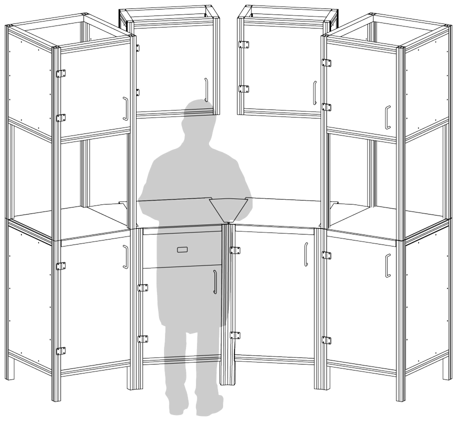

Figure 4: Rack layout. There are three different rack types which are assembled from the same set of standardized items: workbench racks that provide a work area, tall racks that provide storage space and (some) additional work space, and hanging racks that provide additional storage space for smaller items. Please see figure 6 for a photograph of the actual setup.

We expanded on the flexibility of the Random Access Frame design [55], but have refrained from the monolithic, ISPR-based design and separated our racks into 3 types, somewhat similar ergonomically to a standard household kitchen—in fact, the racks are supposed to be used not only in the laboratory, but in the kitchen module, as well. The rack types are: bench-size rack, tall racks, and hanging rack.

The workbench racks have stainless steel surfaces at a height of 1 m, whereas the tall racks extend from the ground almost all the way to the ceiling, with a total height of

225 cm. Both rack types have 10 cm stands to allow for better interior ventilation and room for the crew's feet. The tall racks are assembled by mounting a top piece onto a bench rack.

The hanging racks have a height of 60 cm, which is the same as the height of the bench racks minus two drawers. The depth of bench and tall racks is 60 cm, while the hanging racks are only 30 cm deep to make room for the heads of the crew.

The rack walls are made of steel sheets with holes that allow for better ventilation and that give room for the crew to attach items to the sheets (with ties, strings, etc.). All shelves can be adjusted in height, but the doors and walls have two standard heights that fit either (1) bench rack and lower half of a tall rack or (2) hanging rack, upper part of a tall rack, and lower part a tall rack if supplemented with drawers.

Tall racks could be enclosed in side walls and doors over the entire height (as the tall rack with the sink on the left in fig. 6), or they could be left open mid-height (as the two other tall racks fig. 6), effectively enlarging the working space and creating a more open space.

The racks are made from aluminum and have thus to be grounded. Bench tops are made from stainless steel because it is both durable and can easily be sterilized for scientific experiments. A small extra table can be extended from below the work bench to increase the work area.

All racks have a rectangular base area, which allows them to be pulled away from the wall without having to move neighboring racks. The resulting almost triangular gaps between the racks are closed with small "flaps" that are placed between the bench tops to create a continuous work area. Extendable rolls make it even easier to remove the racks from the walls.

In addition to the racks at the walls of the module, it is recommendable to have either further racks or a table at the center of the room. In the lab, this may provide extra room for work, in the kitchen this table would serve as the common eating and meeting place.

4. Laboratory module concept and mock-up

Figure 5: Photo of the mock-up exterior. The two-story mock-up is constructed from wood and dry wall and located inside Hall 2 of the ZARM.

The laboratory module was constructed as a mock-up in the first half of 2019. Following the construction, four scientists volunteered as test subjects and conducted a set of experiments according to pre-written protocols. Based on the feedback from the first test run, we improved the mock-up interior in the subsequent months. Finally, we conducted a second test run with three scientists to validate the changes to the mock-up. The results from both test runs will be

Figure 6: Photo of part of the laboratory module interior with seven racks: full-size water and storage racks, four bench-size racks and hanging racks forming two work spaces. Depth perception camera is visible in the top middle of the photo, aiming at the opposite line of racks between doors 1 and 2.

published elsewhere; here we will focus on the design status at the second test run.

In the following section, we present the mock-up structure (sec. 4.1). We then describe the laboratory racks (sec. 4.2) and the equipment (sec. 4.3) that was used by the scientist-volunteers for the test runs. Finally, we present the equipment that we used to evaluate the scientists' movements and the ergonomics of the laboratory interior (sec. 4.4).

4.1. Set-up

Geometrically, the mock-up resembles the laboratory module (module 5 in fig. 2), has two exits plus one blind door (all doors would normally lead to the other modules of the habitat), and two stories. The laboratory is located in the ground floor.

The entire support structure is constructed from wood and clad with dry wall. Since the load-bearing parts of the structure need to be thicker than if they had been built from metal, the mock-up is slightly larger than the actual design. However, the interior dimensions are the same, that is, the inner diameter is 4.40 m and the space in the wall is roughly 30 cm. Ceiling height is 2.30 m, although the ceiling itself is 40 cm thick.

Electrical systems are Earth based and European standard—we explicitly left out the questions of what voltage will be available on the Moon and what shapes the plugs and outlets will have (at least for now) and selected a standard that allows us to purchase our lab equipment (see sec. 4.3) off-the-shelf. Each wall segment accommodates six outlets: one for the racks and the equipment inside the racks close to the ground, two next to the hanging racks, mostly for the workplace light, and three above the work areas for laptops and other tabletop equipment.

Sensors are located on the walls above the work benches and record temperature, humidity, pressure and concentrations of CO_2, O_2, and CO. There are further sensors in the (currently unused) upper story, in the bottom storage compartment and on the outside wall of the mock-up; power consumption can be recorded at pre-defined intervals. All sensors can be read from an interface inside the mock-up or from the outside via VPN.

All wall segments are labeled and attached with screws with star knobs to be easily removable. The racks were built from standard aluminum profiles and associated accessories as described in section 3.5. At the bottom, they have a switch mechanism to either rest them on their stands or to lift them slightly and set them on two wheels. In fact, our scientist test subjects who were untrained in the mock-up wall system were able to remove both the racks and the wall panels to reach the wall space behind within a few minutes, following an instruction manual.

One rack is dedicated to supplying the crew with water. As there is no water reclamation system inside the mock-up (yet), our low-threshold solution are off-the-shelf tanks filled with distilled water that are placed above a standard stainless steel sink which drains into another tank. Since the lab water is used for laboratory purposes only (and not for consumption or hygiene other than washing hands), the typical water usage does not exceed a few liters per day.

The lights are as described in sec. 3.3. In the case of a power outage (e.g., when the emergency shut-off is activated), a battery-powered emergency lighting system turns on guiding the way through the mock-up.

4.2. Racks

The racks are constructed from aluminum profiles, with thin stainless steel sheets as side walls and doors. The steel sheets have triangular holes that serve multiple purposes: (1) saving mass, (2) reducing sound reflection off the walls, and (3) providing space for attaching items with hooks or cable binders or similar.

The steel of the bench tops is slightly magnetic; it can be held in place on top of the rack frame with thin magnetic strips. These strips also prevent the bench tops from rattling, but still allow the flaps to be removed very easily so that the whole rack can then be pulled out from its position and away from the wall.

During the test runs, the open design of the tall racks turned out to be more flexible than anticipated: For example, the crew darkened one of the middle compartments for some IR-spectrometry experiments with the help of a simple towel attached to the aluminum frame.

A glovebox is placed on a mobile table for work with hazardous materials such as regolith, and with biological materials that are susceptible to contamination. The crew may remove the glovebox and use the extra central work space as needed. It is planned to later integrate the glovebox into one of the racks.

We also plan to add pull-out tables to give more surface area for working. These tables can be used while seated, different from the workbench racks which can only be used while standing.

4.3. Laboratory equipment

Although we anticipate that a laboratory on the Moon or on Mars can accommodate pre-integrated experiments similar to the ISS, we suggest that the base laboratory shall be used additionally, if not primarily, for investigations and analyses that would otherwise be impossible or at least impractical. We expect the laboratory to be used for the following three primary purposes: (1) experiments utilizing the lunar/Martian environment (reduced-gravity, vacuum, and radiation, as in e.g. [56, 57, 58, 59, 60]), (2) analyses of samples of lunar rock and regolith in high numbers and masses, (3) preliminary analyses and selection of samples to be sent to Earth for more detailed, specialized analysis.

Besides geology, we expect the main scientific disciplines represented in a lunar or Martian laboratory to be materials sciences, astrochemistry, astrobiology, and medicine/human physiology.

For such a laboratory, it is required that a selection of "basic" equipment that is relevant for one or more disciplines is made available, supplemented perhaps with a limited number of pre-assembled experiments similar to experiments on the ISS today. We have developed a list of equipment that would satisfy the needs of the above mentioned disciplines [61, 62]. There, we had determined three categories of equipment (I-III), of which the first two were considered as "must have" by more than one discipline and "necessary" by one of the above mentioned disciplines. Those two categories are repeated in table 2. An updated list is in preparation [62].

Our final selection of instruments for the MaMBA-laboratory is a compromise of this list, additional requirements made by the scientist volunteers for their specific experiments, and budgetary constraints (see table 2). For example, we included more equipment for biological experiments, as the costs could be shared with the Laboratory of Applied Space Microbiology of the ZARM, while much of the materials science equipment was substituted by pre-integrated experiment that had originally been built for the Bremen Drop Tower.

4.4. Simulation equipment

Two depth-perception cameras are placed on two opposite racks such that the entire work place is monitored. This enables the extraction of the 3D position data of the test subjects automatically and subsequently to create "heat maps" of where individuals spent most time and thus which racks and rack compartments where used the most.

Instrument	Recommendation	Actual inventory
Optical microscope	x	x
UV-Vis-IR spectroscope	x	x
Raman spectroscope	x	x
Scales	x	x
Environmental sensors	x	x
Glovebox	x	x
Fluorescent microscope	x	
Scanning Electron Microscope + Energy Dispersive X-Ray Analysis	x	
Gas chromatograph + mass spectrometer	x	
Crushers	x	
Sieves	x	
Shaker	x	x
Centrifuge	x	x
DNA sequencer	x	x
Biosensor arrays	x	x
Oven	x	x
Strength and hardness meas. dev.	x	
Rock cutter + polisher	x	
Thin section cutter	x	
X-Ray Diffractometer	x	
3D printer		x
Gel imager		x
Electrophoresis system		x
Desiccator		x
Microwave		x
Heating/Cooling dry block		x
Refrigerator		x
Freezer		x
Autoclave		x
Drop capsule		x

Table 2: Overview of the category I and II equipment suggested in [61] ('x' in the 2nd column) and included in the mock-up ('x' in the 3rd column). The materials science equipment was replaced by a single materials science experiment pre-integrated into a drop capsule of the Bremen Drop Tower that replaced one of the racks.

Test subjects wear color-coded lab coats, and standard laboratory safety equipment.

A common user interface (into which the sensor interfaces are integrated) is accessible via web browser and can be used to deliver the crew (and researchers) with data or questionnaires at the end of a test run.

We have incorporated a conversational user interface which mimics an artificial intelligence (AI). The interface is dubbed Marvin and supports the crew in their execution of the experimental protocols. Preliminary results have been published recently [63, 64], a more in-depth analysis is in the works. Generally, the simulated AI has been used for retrieving technical information (e.g. requesting material properties of specific chemicals), resolving scheduling issues, and trouble shooting.

5. Outlook

MaMBA aims to combine engineering and architecture to create a habitat prototype that is both technologically functional and human-centered in design. As such it is necessary to validate its concepts with humans in the loop during their development, rather than validate any (semi-)final design: Our approach is to "inhabit, improve, inhabit" in the style of NASA's "fly, fix, fly" [65]. We therefore built our laboratory mock-up as a blueprint of the basic module, which can later be replicated to form the full habitat.

Before aiming for replication, however, we intend to (1) validate the usability of the design from a human factors stand point and (2) consecutively replace various components and subsystems (such as the pressure vessel for the wooden shell, functional LSS for the current AC, or advanced electrical systems) to reach a higher TRL and thus a higher HRL. Following test uses of the laboratory mock-up presented here, we thus plan to construct (2a) a mock-up airlock for testing ingress and egress technologies and procedures, and (2b) a pressure-tight version of the basic MaMBA module.

The mock-up and its successors shall be used as a testbed for subsystems, operations and procedures here on Earth. We expressly invite scientists and engineers worldwide to both integrate subsystems for testing and inhabit the mock-up to help create a proper prototype for an extraterrestrial base. Possible test areas include, but are not limited to:

- life support functions (mostly oxygen production),
- communication/data transfer systems,
- energy production, storage, and distribution,
- vacuum systems (pumps, hatches, airlocks),
- robotics (habitat setup, maintenance, crew support inside the habitat)
- human-computer interaction,
- operations under time delay, and
- interior design.

When fully constructed, the MaMBA habitat is planned to be similarly open to the international scientific and engineering communities, with the additional scope of:

- life support functions (including water reclamation, food production, and waste management),
- surface suits,
- planetary protection and dust mitigation.

The current duration of simulations is several hours continuously, although this could be extended to multi-day (overnight) stays relatively easily with the mock-up. In its final six-module form, the habitat is planned to be able to accommodate a crew of six for significantly longer periods of time.

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References

[1] Scott J Porter and Fiona Bradley. Architectural design principles for extra-terrestrial habitats. *Acta Futura*, 10:23–35, 2016.

[2] Jan Connolly, Kathy Daues, Robert L Howard, Jr, and Larry Toups. Definition and development of habitation readiness level (HRLs) for planetary surface habitats. In *Earth & Space 2006: Engineering, Construction, and Operations in Challenging Environment*, pages 1–8, 2006.

[3] NASA Human Research Program. *Human Exploration Research Analog (HERA) Facility and Capabilities Information*, 2016. Accessed: 2018-10-10.

[4] William B Vessey, Ronita L Cromwell, and Steven Platts. NASA's Human Exploration Research Analog (HERA) for Studying Behavioral Effects of Exploration Missions. In *88th Aerospace Medical Association (AsMA) Annual Scientific Meeting, Denver, CO, United States*, 2017.

[5] A. Scott Howe, Kriss J. Kennedy, Tracy R. Gill, Russell W. Smith, and Patrick George. Nasa habitat demonstration unit (hdu) deep space habitat analog. In *AIAA SPACE 2013 Conference and Exposition*, page 34, Reston, Virginia, 09102013. American Institute of Aeronautics and Astronautics.

[6] Bryan J Caldwell, Peter G Roma, and Kimberly Binsted. Team cohesion, performance, and biopsychosocial adaptation research at the hawai'i space exploration analog and simulation (hi-seas). In *31st Annual Conference of the Society for Industrial and Organizational Psychology, Anaheim, California*, 2016.

[7] Benjamin D Sawyer, PA Hancock, John Deaton, and Peter Suedfeld. Finding the team for mars: a psychological and human factors analysis of a mars desert research station crew. *Work*, 41(Supplement 1):5481–5484, 2012.

[8] Matthew Allner, Sheryl Bishop, Vadim Gushin, Chris McKay, and Vadim Rygalov. Crew performance nalysis of a simulated mars mission at the mars desert research station (mdrs) in utah, usa. In *59th International Astronautical Congress 2008, IAC 2008*, pages 11–23, 2008.

[9] ESA. Mars500 Isolation Study. Information Kit, May 2010.

[10] Carole Tafforin. The mars-500 crew in daily life activities: An ethological study. *Acta Astronautica*, 91:69–76, 2013.

[11] Frank B. Salisbury, Iosef I. Gitelson, and Genry M. Lisovsky. BIOS-3 - siberian experiments in bioregenerative life support. *BioScience*, 47(9):575–585, 1997.

[12] HW Lane, RL Sauer, and DL Feeback. Isolation: NASA Experiments in Closed-Environment Living: Advanced Human Life Support Enclosed System. *American Astronautical Society-Science and Technology Series*, 104, 2000.

[13] Yuming Fu, Leyuan Li, Beizhen Xie, Chen Dong, Mingjuan Wang, Boyang Jia, Lingzhi Shao, Yingying Dong, Shengda Deng, Hui Liu, et al. How to establish a Bioregenerative Life Support System for long-term crewed missions to the Moon or Mars. *Astrobiology*, 16(12):925–936, 2016.

[14] T. R. Gill, J. C. Merbitz, K. J. Kennedy, T.O. Tri, and A. S. Howe. Integration Process for the Habitat Demonstration Unit: Presentation and accompanying article. In *AIAA Space 2010 Conference*, August 31 - September 2, 2010.

[15] Robert P Mueller, Tracie J Prater, Mon-

serrate C Roman, Jennifer E Edmunson, Michael R Fiske, and Peter Carrato. NASA Centennial Challenge: Three Dimensional (3D) Printed Habitat, Phase 3. In *70th International Astronautical Congress (IAC), Washington, D.C., 21-25 October 2019*, 2019.

[16] Sandra Häuplik-Meusburger. *Architecture for astronauts: an activity-based approach.* Springer Science & Business Media, 2011.

[17] Olga Bannova Sandra Häuplik-Meusburger. Space architecture and habitability: An asset in aerospace engineering and architectural curricula. *Acta Futura*, 10:9–22, 2016.

[18] Anthony R Gross, David J Korsmeyer, Lynn D Harper, and Edwin L Force. The NASA Ames Controlled Environment Research Chamber-Present Status. Technical report, SAE Technical Paper, 1994.

[19] Peter Eckart. *Spaceflight life support and biospherics*, volume 5. Springer Science & Business Media, 2013.

[20] Ines Wagner, Markus Braun, Klaus Slenzka, and Clemens Posten. Photobioreactors in life support systems. In *Microalgae Biotechnology*, pages 143–184. Springer, 2015.

[21] Cyprien Verseux, Mickaël Baqué, Kirsi Lehto, Jean-Pierre P de Vera, Lynn J Rothschild, and Daniela Billi. Sustainable life support on mars—the potential roles of cyanobacteria. *International Journal of Astrobiology*, 15(1):65–92, 2016.

[22] Christina Ciardullo, Michael Morris, Kelsey Lents, Jeffrey Montes, Melodie Yashar, Ostap Rudakevych, Masayuki Sono, and Yuko Sono. Mars Ice House: Using the physics of phase change in 3D printing a habitat with H2O. In *46th International Conference on Environmental Systems*, 2016.

[23] Jack W Stuster. Space station habitability recommendations based on a systematic comparative analysis of analogous conditions. Technical report, NASA Contractor Report 3943, 1986.

[24] Sandra Häuplik-Meusburger, Kim Binsted, and Tristan Bassingthwaighte. Habitability studies and full scale simulation research: Preliminary themes following HI-SEAS mission IV. In *47th International Conference on Environmental Systems*, 2017.

[25] Zac Trolley Sarah Jane Pell, Ryan L. Kobrick. Technical recommendations to improve Mars Desert Research Station safety, simulation, and science. In *69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018*, 2018.

[26] Malgorzata Perycz, Piotr Konorski, Lucie Davidova, Christiane Heinicke, and Aleksander Wasniowski. What can go wrong, will go wrong: the bug-out procedures tested during ICAres-1 analog mars mission at the lunares habitat at pila, poland. In *69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018*, 2018.

[27] G Madhavan Nair, KR Sridhara Murthi, and MYS Prasad. Strategic, technological and ethical aspects of establishing colonies on Moon and Mars. *Acta Astronautica*, 63(11-12):1337–1342, 2008.

[28] Aidan Cowley, Barbara Imhof, Leo Teeney, René Waclavicek, Francesco Spina, Alberto Canals, Juergen Schleppi, and Pablo Lopez Soriano. An isru-based architecture for human habitats on mars: the ‘lava hive’ concept. *Acta Futura*, 10:109–119, 2016.

[29] Barbara Imhof, Diego Urbina, Peter Weiss, and Matthias Sperl. Advancing solar sintering for building a base on the Moon. In *68th International Astronautical Congress (IAC), Adelaide, Australia*, 2017.

[30] Susan D. Baggerman, Cynthia M. Rando, and Laura E. Duvall. Habitability and human factors: Lessons learned in long duration space flight. In *Space 2004 Conference and Exhibit*, 2006.

[31] Alexandra Whitmire, Lauren Leveton, Hugh Broughton, Mathias Basner, Anne Kearney, Laura Ikuma, and Michael Morris. Minimum acceptable net habitable volume for long-duration exploration missions. Technical report, NASA, 2015. Subject Matter Expert Consensus Session Report NASA/TM-2015-218564.

[32] Susmita Mohanty and Barbara Imhof. Microcosmic getaways aboard space habitats. *Thresholds*, pages 42–49, 2005.

[33] Marianne Rudisill, Robert Howard, Brand Griffin, Jennifer Green, Larry Toups, and Kriss Kennedy. Lunar architecture team: Phase 2 habitat volume estimation: “caution when using analogs”. In *Earth & Space 2008: Engineering, Science, Construction, and Operations in Challenging Environments*, pages

1–11, 2008.

[34] Olivier de Weck and David Simchi-Levi. Haughton-Mars Project Expedition 2005 Final Report. Technical report, Massachusetts Institute of Technology and Kennedy Space Center, Florida, 2006. NASA/TP—2006–214196.

[35] Nathan Wells. Bigelow Expandable Activity Module (BEAM) ISS year-three: Technology demonstration, utilization, and potential future applications. In *ISS R&D Conference Atlanta, GA, 30-July-2019*, 2019.

[36] Ashley Stroupe, Avi Okon, Matthew Robinson, Terry Huntsberger, Hrand Aghazarian, and Eric Baumgartner. Sustainable cooperative robotic technologies for human and robotic outpost infrastructure construction and maintenance. *Autonomous Robots*, 20(2):113–123, 2006.

[37] Brian H Wilcox, Todd Litwin, Jeff Biesiadecki, Jaret Matthews, Matt Heverly, Jack Morrison, Julie Townsend, Norman Ahmad, Allen Sirota, and Brian Cooper. ATHLETE: A cargo handling and manipulation robot for the Moon. *Journal of Field Robotics*, 24(5):421–434, 2007.

[38] A Scott Howe and Brian Wilcox. Outpost assembly using the ATHLETE mobility system. In *2016 IEEE Aerospace Conference*, pages 1–9. IEEE, 2016.

[39] Carlos Montes, Kaylin Broussard, Matthew Gongre, Neven Simicevic, Johanna Mejia, Jessica Tham, Erez Allouche, and Gabrielle Davis. Evaluation of lunar regolith geopolymer binder as a radioactive shielding material for space exploration applications. *Advances in Space Research*, 56(6):1212–1221, 2015.

[40] N Gerdes, LG Fokken, S Linke, S Kaierle, O Suttmann, J Hermsdorf, E Stoll, and C Trentlage. Selective laser melting for processing of regolith in support of a lunar base. *Journal of Laser Applications*, 30(3):032018, 2018.

[41] Alexandre Meurisse, A Makaya, C Willsch, and M Sperl. Solar 3D printing of lunar regolith. *Acta Astronautica*, 152:800–810, 2018.

[42] Gweneth A Smithers, Mary K Nehls, Mary A Hovater, Steven W Evans, J Scott Miller, Roy M Broughton Jr, David Beale, and Fatma Kilinc-Balci. A one-piece lunar regolith bag garage prototype. Technical report, NASA/TM—2007–215073, 2007.

[43] Peter Eckart, Yoji Ishikawa, and Kriss J. Kennedy. Designing, Sizing, and Integrating a Surface Base - Chapter 13. In *Human spaceflight: mission analysis and design*, page 438. Mc Graw-Hill Higher Education - Space Technology Series, 2000.

[44] Kyong-Hee Park, Dong-Il Kim, and Choul-Gyun Lee. Effect of flashing light on oxygen production rates in high-density algal cultures. *Journal of Microbiology and Biotechnology*, 10(6):817–822, 2000.

[45] Sherwin Gormly, Michael Flynn, and A Scott Howe. Space cargo transport bags through membrane water treatment elements to space architecture building element: A total product sustainability and life cycle design optimization experiment. *Journal of Green Building*, 7(1):71–84, 2012.

[46] Marc M Cohen, Renée L Matossian, François Levy, and Michael T Flynn. Water walls life support architecture: system overview. In *44th International Conference on Environmental Systems*, 2014.

[47] Harry Jones. Moon base life support design depends on launch cost, crew size, and mission duration. In *49th International Conference on Environmental Systems*, 2019.

[48] Thomas Uhlig, Frank-Cyrus Roshani, Ciro Amodio, Alessandro Rovera, Nikola Zekusic, Hannes Helmholz, and Matthew Fairchild. ISS emergency scenarios and a virtual training simulator for Flight Controllers. *Acta Astronautica*, 128:513–520, 2016.

[49] NASA. *Reference guide to the International Space Station*. NASA, Washington DC, 2010.

[50] Scott Kelly. *Endurance: My Year in Space, A Lifetime of Discovery*. Knopf Publishing Group, New York, 2017.

[51] M. Oetken. Psychological aspects in architecture during long-term missions under extreme environments. Bachelor Thesis, Frankfurt University of Applied Sciences, 2019.

[52] Sarah Laxhmi Chellappa, Marijke CM Gordijn, and Christian Cajochen. Can light make us bright? Effects of light on cognition and sleep. In *Progress in Brain Research*, volume 190, pages 119–133. Elsevier, 2011.

[53] K Slenzka, M Dünne, and B Jastorff. Biomonitoring and risk assessment on earth and during exploratory missions using AquaHab®. *Advances in Space Research*, 42(12):1944–1950,

2008.

[54] Andrew Owens and Olivier De Weck. Limitations of reliability for long-endurance human spaceflight. In *AIAA SPACE 2016*, 2016.

[55] A Scott Howe and Raul Polit-Casillas. Random Access Frames (RAF): Alternative to Rack and Standoff for Deep Space Habitat Outfitting. In *44th International Conference on Environmental Systems*, 2014.

[56] Jens Hauslage, Sebastian M Strauch, Olaf Eßmann, Ferdinand WM Haag, Peter Richter, Julia Krüger, Julia Stoltze, Ina Becker, Adeel Nasir, Gerhild Bornemann, et al. Eu:CROPIS–Euglena gracilis: Combined Regenerative Organic-food Production in Space-A Space Experiment Testing Biological Life Support Systems Under Lunar And Martian Gravity. *Microgravity Science and Technology*, 30(6):933–942, 2018.

[57] JZ Kiss. Plant biology in reduced gravity on the Moon and Mars. *Plant Biology*, 16:12–17, 2014.

[58] Guenther Reitz, Thomas Berger, Pawel Bilski, Rainer Facius, Michael Hajek, Vladislav Petrov, Monika Puchalska, Dazhuang Zhou, Johannes Bossler, Yury Akatov, et al. Astronaut's organ doses inferred from measurements in a human phantom outside the International Space Station. *Radiation Research*, 171(2):225–235, 2009.

[59] Francis A Cucinotta, Myung-Hee Y Kim, Veronica Willingham, and Kerry A George. Physical and biological organ dosimetry analysis for International Space Station astronauts. *Radiation Research*, 170(1):127–138, 2008.

[60] Elke Rabbow, Petra Rettberg, Simon Barczyk, Maria Bohmeier, Andre Parpart, Corinna Panitz, Gerda Horneck, Jürgen Burfeindt, Ferdinand Molter, Esther Jaramillo, et al. The astrobiological mission EXPOSE-R on board of the International Space Station. *International Journal of Astrobiology*, 14(1):3–16, 2015.

[61] Christiane Heinicke, Steven Jaret, Jens Ormö, Miranda Fateri, Nina Kopacz, Mickaël Baqué, Cyprien Verseux, Bernard Foing, and Alberto Razeto. How a laboratory on the Moon should be equipped. In *69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018*, 2018.

[62] Christiane Heinicke, Cyprien Verseux, Solmaz Adeli, Mickaël Baqué, Giuseppe Correale, Miranda Fateri, Steven Jaret, Nina Kopacz, Jens Ormö, and Lucie Poulet. Equipping an extraterrestrial laboratory: Overview of open research questions and desirable instrumentation (working title). In preparation for submission to Acta Astronautica.

[63] C. Heinicke and J. Schöning. Marvin: Identifying design requirements for an ai powered conversational user interface for extraterrestrial space habitats. In *Workshop "Künstliche Intelligenz in der Luft- und Raumfahrt", Garching, 9 October 2019.*, 2019.

[64] J. Schöning and C. Heinicke. Marvin: Design guidelines for a conversational user interface in extraterrestrial habitats. In *ACM IUI 2020, Cagliari, Italy, March 17-20, 2020*, 2020.

[65] Frederick D. Gregory. *Looking Backward, Looking Forward. forty years of u.s. human spaceflight symposium*, chapter Making Human Spaceflight as Safe as Possible. NASA, 2002.

similar systems in other modules–for example, a pump from an otherwise broken water reclamation system may be salvaged to repair another water reclamation system whose pump is broken.

Quick escape. In case of emergency, the crew may choose to evacuate the upper floor via an escape pole, rather than descend the stairs. Gravity on the Moon is so low ($\frac{1}{6}g$) that one would have to jump from six times the height as one would on Earth to achieve the same momentum ($mv = m\sqrt{2(\frac{1}{6}g)(6h)}$). In other words, if we assume the upper floor to be 2.40 m above the ground floor for the sake of simplicity, then jumping from the second floor at $h = 2.40$ m on the Moon corresponds to jumping from 40 cm on Earth, or not even common chair height (the height on Earth corresponding to $h = 2.40$ m on Mars is 0.9 m, or desk-height). However, the long duration of the 2.40 m fall on the Moon (1.7 s) is likely to make the fall itself less controllable. The escape pole would help stabilize the jump.

Navigation under limited visibility. The crew must be able to navigate the habitat even with limited visibility due to smoke, light failures, or damage to their visual system. Each module has its own color which helps differentiate the different modules; each exit from a module is labeled with the color of the module the exits leads to.

3.5. Racks

As mentioned above, the ISPRs that are currently used on the ISS are not suited for a gravity environment: Their mass (104 kg) and geometry make it difficult for humans to move them in a gravity environment and through narrow passage ways. Instead, we suggest reducing the size of the racks to more manageable dimensions: to a width of 19 inches (48.3 cm) plus the thickness of the outer aluminum profiles (in our case 4 cm, but this is subject to optimization).

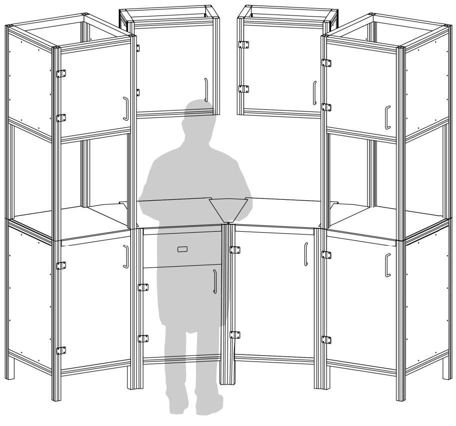

Figure 4: Rack layout. There are three different rack types which are assembled from the same set of standardized items: workbench racks that provide a work area, tall racks that provide storage space and (some) additional work space, and hanging racks that provide additional storage space for smaller items. Please see figure 6 for a photograph of the actual setup.

We expanded on the flexibility of the Random Access Frame design [55], but have refrained from the monolithic, ISPR-based design and separated our racks into 3 types, somewhat similar ergonomically to a standard household kitchen—in fact, the racks are supposed to be used not only in the laboratory, but in the kitchen module, as well. The rack types are: bench-size rack, tall racks, and hanging rack.

The workbench racks have stainless steel surfaces at a height of 1 m, whereas the tall racks extend from the ground almost all the way to the ceiling, with a total height of