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Journal Article as: peer-reviewed accepted version (Postprint)

DOI of this document*(secondary publication): https://doi.org/10.26092/elib/3666

Publication date of this document: 14/02/2025

* for better findability or for reliable citation

Recommended Citation (primary publication/Version of Record) incl. DOI:

Christiane Heinicke, Cyprien Verseux,
The MaMBA facility as a testbed for bioregenerative life support systems,
Life Sciences in Space Research, Volume 36, 2023, Pages 86-89, ISSN 2214-5524,
https://doi.org/10.1016/j.lssr.2022.08.009.

Opinion/Position paper

The MaMBA facility as a testbed for bioregenerative life support systems

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A R T I C L E I N F O

Keywords:
Extraterrestrial habitation
Mars exploration
BLSS
Test platform
Human centered design

A B S T R A C T

The Moon and Mars Base Analog (MaMBA) is a concept for an extraterrestrial habitat developed at the Center of Applied Space Technology and Microgravity (ZARM) in Bremen, Germany. The long-term goal of the associated project is to create a technologically functioning prototype for a base on the Moon and on Mars. One key aspect of developing such a prototype base is the integration of a bioregenerative life support system (BLSS) and its testing under realistic conditions. A long-duration mission to Mars, in particular, will require BLSS with a reliability that can hardly be reached without extensive testing, starting well in advance of the mission.

Standards exist for comparing the capabilities of various BLSS, which strongly focus on technological aspects. These, we argue, should be complemented with the use of facilities that enable investigations and optimization of BLSS prototypes with regard to their requirements on logistics, training, recovery from failure and contamination, and other constraints imposed when humans are in the loop. Such facilities, however, are lacking.

The purpose of this paper is to present the MaMBA facility and its potential usages that may help close this gap. We describe how a BLSS (or parts of a BLSS) can be integrated into the current existing mock-up at the ZARM for relatively low-cost investigations of human factors affecting the BLSS. The MaMBA facility is available through collaborations as a test platform for characterizing, benchmarking, and testing BLSS under nominal and off-nominal conditions.

1. Introduction

Long-term missions to the Moon and Mars will require significant changes to life-support systems (LSS): launch costs, travel times, and risks of resupply failure are such that the crew's dependence on Earth-imported materials should be minimized. Various concepts have been proposed to address this need (e.g., Godia et al., 2002; Tikhomirov et al., 2007; Verseux et al., 2016; Przybyla, 2021) which, compared to mature LSS used in low Earth orbit, tend to put a greater emphasis on recycling and on the utilization of resources available on site. They also integrate more biological modules: while the cumulative mass of purely physico-chemical LSS is typically lower than that of bioregenerative LSS for short missions, it tends to increase faster with mission duration, making the latter increasingly attractive as missions get longer (Eckart, 2013). Which concept (or combination thereof) is most relevant will depend largely on mission requirements and architecture. Even for a given scenario, selection is hindered by difficulties in comparing systems developed by different teams.

LSS assessment tools have been developed. Most notable among them are NASA's Equivalent System Mass (ESM) metric and ESA's Advanced Life Support System Evaluator (ALiSSE), which we outline below. We argue that assessments and comparisons based on such metrics would best be complemented with simulations on Earth in a realistic operation environment, to account for human factors beyond crew time requirements and for other parameters which are beyond the scope of technology-focused evaluators.

A few examples exist of facilities developed as testing grounds for LSS, some of which have been large enough to include human subjects (Salisbury et al., 1997; Fu et al., 2016; Nitta et al., 2000) or rats as a mockup crew for selected physiological functions (Garcia-Gragera et al., 2021). However, they are typically developed around a single LSS concept, limiting the relevance of inter-study comparisons and erasing many of the constraints resulting from the need to adapt the system to a separately designed habitat.

Here we introduce the MaMBA facilities as a testbed for biological LSS (BLSS). Those facilities can help address the shortcomings mentioned above by providing a realistic environment in which LSS prototypes can be integrated. We will briefly describe the facilities and outline how LSS can be integrated, and what research areas can be addressed. We wish to make the MaMBA facilities accessible to interested researchers in the frame of collaborative projects.

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2. Criteria for evaluating life support systems

In this section we describe two tools that have been developed for comparing BLSS with some standardized criteria. We then describe in the following sections how the MaMBA testbed can complement them.

The Equivalent System Mass (ESM) is a measure for the transportation cost of LSS and its associated infrastructure, as the cost to transport a payload is directly related to the mass of that payload. The metric has been developed by NASA to measure the progress of its Advanced Life Support (ALS) Project. The ESM has five components: the actual system mass, plus weighted fractions of the masses of its associated support systems, the power generation and cooling systems, the occupied volume (including pressurized volume necessary for crew access), and the crew time for maintenance over a specific mission duration (Levri et al., 2000, 2003).

The Advanced Life Support System Evaluator (ALiSSE) is a multi-criteria tool that has been developed by a consortium around ESA, as NASA's metric based on mass as the single criterion was considered not comprehensive enough (Brunet et al., 2010). The criteria used in ALiSSE are: system mass, mean and maximum power consumed during a mission, and crew time spent on operation and maintenance, plus, in addition to the ESM, global risk for humans, system reliability, and system sustainability (MELiSSA Consortium, 2010).

Both ESA's and NASA's metrics are valuable tools for engineers to compare advanced life support systems under nominal mission conditions. NASA's metric is the easiest to use, although Levri et al. (2000) caution that the ESM only allows for the direct comparison of two systems if they provide the same life support product quantity and quality, and satisfy the same reliability and safety requirements.

It should be noted that both tools compare technological and economical parameters of LSS only, and do not or barely account for human factors. Those, however, can be significant. Tending to plants can for instance contribute to the psychological health of various communities (Clatworthy et al., 2013), and authors have argued that it could similarly benefit crew members (Anderson et al., 2017; Allen, 1991; Bates and Marquit, 2011; Odeh and Guy, 2017).

Limiting risks to the ones *for* humans also ignores the risks imposed *by* humans: humans make errors, and the cognitive decline of long-duration isolation will certainly not help reduce the associated risks. Hence the LSS has to be not just reliable, but also resilient to errors and resistant against contamination. Design and training can help reduce such risks, but are not accounted for in the current technology-focused metrics.

Furthermore, LSS – and BLSS in particular – can indirectly pose a biohazard to Mars via leakage and transport of contamination (e.g., Conley and Rummel, 2008). Risks to planetary protection objectives should thus be accounted for when assessing life-support processes and technologies (Race et al., 2008).

We acknowledge that incorporating these points in a quantitative measure that is intended for swift comparison, like the ESM, is hardly feasible. Nevertheless, we would like to stress that these "soft" factors are similarly important in evaluating a LSS as the "hard" engineering criteria (Mohanty et al., 2006; Horneck et al., 2006; ESA, 2001) and a methodology should be developed to evaluate them in the future.

3. MaMBA as a life support system test facility

This section is focused on the MaMBA facility and its potential as a BLSS testbed. In the following subsection (Section 3.1), we describe the basic MaMBA concept with focus on aspects that are relevant to BLSS. In Section 3.2 we outline our plans for the concrete testbed and in Section 3.3 we outline potential research questions that could be answered with the facility.

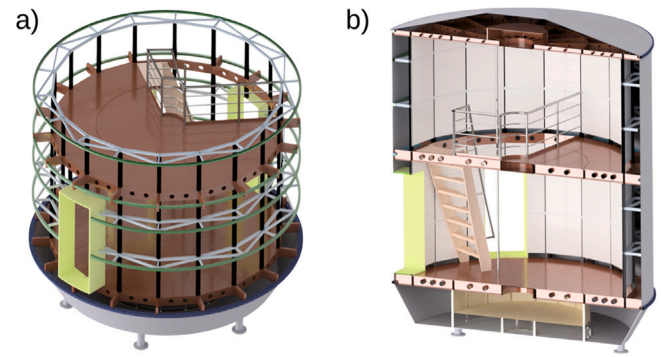

Fig. 1. **(a)** CAD-model of the basic MaMBA module, showing the interior structure of the pressure vessel (not the hull itself). It consists of 2 stories; the lower story has 3 doors, of which one is shown on the left. **(b)** Different view of the same model, showing the inner and outer vessel walls. The exterior wall is cylindrical, the interior wall consists of 18 segments. Both walls are min. 30 cm apart. In this view, one door is shown half on the left, another one is behind the stairs.

3.1. *The MaMBA concept from a life support system perspective*

The MaMBA concept has been described in detail in Heinicke (2019) and Heinicke et al. (2020), hence we will only briefly summarize the concept for context and focus on the additional information relevant for BLSS.

The overarching goal of the concept is to serve as a blueprint for a lunar or Martian habitat that is both functional from a technological perspective and livable from an architectural and human well-being perspective. In its basic configuration, the MaMBA concept consists of six main modules in the shape of upright cylinders, each of which fulfills its own primary function: sleeping, eating/socializing, relaxing, repair workshop, laboratory, and greenhouse. There are two airlocks; all eight modules can be isolated from the rest such that even if any one module is lost entirely (due to fire or other emergencies), the remaining habitat maintains its functionality.

The distance between the vessel wall and the (cosmetic) wall panels is currently planned to be 30 cm (shown in Fig. 1). The inner diameter of the module is 4.40 m; for easier installation the wall panels are flat (not curved), hence the interior floor of the module is shaped as an octodecagon. The outer height of the module is 6.50 m, with 2.30 m for each of the 2 stories, and approx. 1 m each for the end caps. In total, the volume between the inner and outer walls amounts to approx. 20 m^3.

Each module has up to 3 doors, each of which requires 2 out of the 18 wall segments per floor; i.e. 1/3 of the total volume in the wall is reserved for the doors and door mechanisms, leaving approx. 13 m^3 for BLSS components.

The LSS foreseen within MaMBA include an air revitalization module based on photosynthetic microorganisms (eukaryotic algae or cyanobacteria). The preferred option is to grow these organisms in flat panel photobioreactors that can be placed behind the wall panels, immediately inside the walls of the pressure vessel. Full-scale systems could be accommodated: conservative estimates of the culture volumes required to perform air revitalization are below 2 m^3 per crew member (e.g., Detrell, 2021; Alemany et al., 2019), and it has been suggested that volumes as low as 20 L could suffice (Javanmardian and Palsson, 1992; Gitelson, 1992).

It should be noted that each wall segment consists of 3 wall panels (see Fig. 2): 1 at the bottom, 1 at mid-height and 1 at the top. The racks and the stairs between the two stories are designed accordingly, such that most panels at mid-height can be removed directly. The remaining wall panels are by default obstructed by the racks—we made it a high priority for the rack design that they can be removed very fast, should a specific part of the BLSS require quick access for repair (and not be easily accessible through the mid-height wall segment).

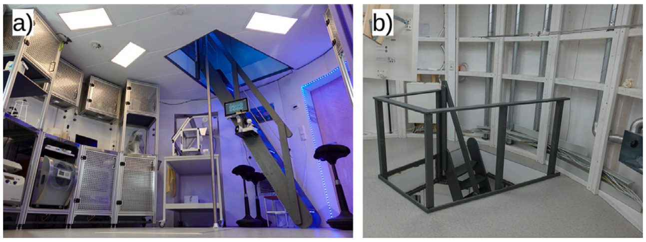

Fig. 2. **(a)** Photo of the MaMBA mock-up built in 2019 with the laboratory interior. One can see the different types of racks and, behind the racks, the 3-segmented interior walls. The drawing on the wall behind the stairs represents a BLSS compartment. **(b)** Photo of the upper floor of the mock-up during construction. The interior wall panels are removed and the compartments behind them are visible (they are smaller in the wooden mock-up for structural reasons). The horizontal and vertical beams have dedicated holes, such that pipes and electrical systems (both shown in the photo) can pass through and connect the two floors.

Similar to the wall segments, the racks consist of (up to) 3 segments (shown in Fig. 2a): a bottom segment that may serve as a bench-top, a top component which may be hung on the wall, and a mid component that may connect the two such that the rack is effectively as high as the entire room (only if the mid-component is left out can the bottom be used as a bench-top). The width of these racks corresponds to the 19 inch (48.3 cm)-standard rack width. If necessary, multiple racks can be combined to form a full size International Standard Payload Rack, although we doubt that their size and weight would be appropriate outside the microgravity environment of the International Space Station.

One of the main reasons for placing the LSS behind the wall panels is to save room for extra equipment in the work modules and to provide a cozier atmosphere in the habitation modules by hiding the technical nature of the habitat. It is, however, still possible to place (parts of) the LSS in the racks.

Another reason is that some BLSS subsystems, which may perhaps contain aquatic animals, could be integrated into the walls of the habitat and be visible: such a sight may have positive effects on crew members' mental well-being (e.g., Cracknell et al., 2016). These subsystems could be made visible in racks, too, but not all of the habitation modules necessarily contain racks.

Finally, this geometry provides additional protection to the crew from space radiation, albeit the majority of the radiation is expected to be shielded by a thick layer of regolith which would also protect the habitat from micrometeoroid impacts.

3.2. Current plans for module construction

We built a mock-up of the laboratory module in 2019 and validated its architecture and usability with scientist volunteers (Heinicke, 2019; Heinicke et al., 2020). In particular the size of the module, the arrangement and the layout of the work areas and the general room characteristics (e.g., light and acoustics) were evaluated as adequate.

The mock-up is built from wood. Adjustments were made during construction to the internal structure to account for the different material (wood instead of a metal vessel; e.g. the floor thickness was increased), but the interior dimensions that the crew would be exposed to remained the same (in the example with the floor thickness: room height was kept the same, so that the resulting module was higher than if it had been built from metal).

It is planned to build a second module within the next few years. This second module shall be functional, i.e. built from metal (likely either steel or aluminum) and airtight.

The module will be attached to the first (wooden) module, but will be functionally separate. That is, there will be no air exchange between the two modules while the doors of the new module are shut. The combination of the two modules can be used for human factor studies, BLSS experiments, or a combination of both.

Furthermore, the two stories of the module can be closed off from each other so that different components of a BLSS could be tested independently from each other, if needed. One possible application for this would be the testing of components with plants, which would be in the upper room rather than in the walls like the flat panel photobioreactors.

The mock-up is equipped with sensorboards, each measuring temperature, relative humidity, pressure, and carbon dioxide and monoxide concentration at its respective location. The new module will be equipped with extended versions of these sensorboards, capable of monitoring more gas components (e.g., oxygen, methane or hydrogen sulfide, depending on the nature and objectives of the performed experiments) and integrated into a wireless network that allows the monitoring of the air from both the inside and the outside of the module.

Part of the MaMBA concept is a conversational user interface (CUI) that supports the crew in monitoring and controlling their environment; this CUI is integrated within the module and facilitates the crew's interaction with the life support system and performance of laboratory work (see e.g., Freitas et al., 2021).

Once constructed, the full module can serve as a testbed for BLSS and BLSS components. Our focus will be on the air revitalization part of BLSS, but other processes can be integrated into the module.

3.3. Potential research questions

The purpose of this paper is to introduce the MaMBA facility as a test facility to the community and show how the facility can be used to support BLSS development through enabling experiments with BLSS prototypes. The research questions that can be addressed with the help of this facility are outlined below.

There are two modes that the facility will be able to be run in: (1) "dry"-mode, where the gas exchange in the interior is regulated via valves and gas tanks (i.e. "used air" rich in CO_2 is supplied by gas tanks), and gray and black water to be recycled within the facility are supplied externally (i.e. from tanks as well): the gas/water tanks shall provide what normally the human inhabitant would provide to the life support system; and (2) "wet"-mode with humans in the loop who replace the storage tanks and supply the inputs to the BLSS.

The "wet" mode can utilize both MaMBA modules which allow experiment durations of approx. one to two weeks in the near future. Longer durations will become more feasible when the base is extended with more modules, in a few years.

The MaMBA facility will be open for research on the following topics:

- **Human–machine interaction.** Integration of humans into the technological environment of the habitat and interaction with BLSS-interfaces in particular, user-friendly design, resilient and user-friendly communication exchange between BLSS controls and human users, optimization of crew time use, etc.
- **Effect on crew's mental well-being.** Usability and perceived benefits from BLSS in various configurations and interfaces, workload distribution and optimization of performance, influence on stress levels, etc.
- **Logistics.** Transport and integration into facilities other than the home facility in general, logistics of replacement of system components (particularly for repair situations in existing extraterrestrial bases), etc.
- **Training.** Teaching volunteers with various academic backgrounds various aspects of maintenance and repair of the BLSS, developing training materials, comparing different training modes, etc.
- **Errors and recoverability.** Determining effective reactions to various failure modes during operation, especially with regard to different levels of training and latency in communication, anticipation and avoidance of human error, determining pathways of contamination, etc.

- **Planetary protection and leakage.** Propagation of viable BLSS components throughout the habitat and towards the airlock, pathways of and reaction to leaks, etc.
- **Long-term stability (months).** Changes to the BLSS with humans and human-related microbes as potential contaminants, reliability of components under nominal (i.e. not laboratory) use. These tests would be carried out exclusively in the airtight metal module.
- **Scalability.** Distribution across multiple modules to spread the risk of catastrophic module failures; addition of further components, redundant and complementary, and their interaction with the initial components, etc.
- **Others.** Further questions of relevance to BLSS in extraterrestrial habitats can be addressed after discussion with the authors.

An example of a timeline for BLSS testing is given below (note that actual durations will greatly vary with technologies and research questions), excluding pre-testing preparation work:

- Month 1: Transport and systems integration.
- Months 2–4: Initial tests.
- Months 5–10: Medium- to long-duration "dry" tests.
- Months 11–18: Experiments with humans in the loop.

4. Conclusion

We presented standardized tools currently available for comparing BLSS and suggested that they could be complemented with assessments pertaining to "soft" human factors, resilience, and planetary protection. We described the potential of the MaMBA facility as a testbed to characterize and improve BLSS with regard to these factors.

We invite researchers working on BLSS to contact us should they wish to discuss how the facility could benefit their work through collaborative projects. Furthermore, we are welcoming inputs on the prioritization of research questions and design requirements to make MaMBA most useful to the BLSS research community.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors would like to thank Marc Avila for his support.

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