IAC-24-D3.2A.2

LUNAR AGRICULTURE MODULE GROUND TEST DEMONSTRATOR – AN INTERNATIONAL APPROACH FOR REALIZING PLANT-BASED BIO-REGENERATIVE LIFE SUPPORT

Volker Maiwald[a,*], Charmaine Neufeld[a], Michel Fabien Franke[a], Daniel Schubert[a], Vincent Vrakking[a], Conrad Zeidler[b], Jared Stoochnoff[b]

[a]German Aerospace Center (DLR), Institute of Space Systems, Department of System Analysis Space Segment, Bremen, Germany, Volker.Maiwald@dlr.de
[b]Canadian Space Agency

* Corresponding Author

Abstract

Long-term human lunar exploration requires advancement of life support systems. Bio-regenerative life support systems (BLSS) have been shown to have a reduced equivalent mass for such long-term missions compared to more traditional methods, e.g., physical-chemical life support, which reduces mission costs and effort in general. Currently, no such (near) closed-loop systems exist and several challenges for their realization are still present, such as understanding of e.g., scaling of the system, interaction of technical and biological components, interaction and dependency of technical elements, and the microbiome. Beginning with a prototype-test in Antarctica, the German Aerospace Center (DLR) has joined an international effort, comprising the Canadian Space Agency (CSA) and several subcontractors, in now creating a Ground Test Demonstrator (GTD) capable of addressing the many unknowns of designing, developing and operating a Lunar Agriculture Module (LAM). This paper aims to present the current updated status of the design and project and informs about the international effort behind it, highlighting the importance of the project. We present a system overview and inform about how the system will be able to address open issues currently associated with BLSS as well as a roadmap of the LAM-GTD usage and how it will eventually lead to the operation of an actual agricultural module on the lunar surface.

I. INTRODUCTION

After focusing on human spaceflight in low Earth orbit (LEO) for about four decades, currently human spaceflight is strategized for a return to the lunar surface. Preparations begun in earnest with the *Constellation* program and have evolved into NASA's *Artemis* campaign [1], which also involves cooperation with international partners like ESA and CSA.

Similarly, JAXA has series of lunar missions with the most recent one being the *Smart Lander for Investigating Moon*, a technology test for lunar precision landing [2]. China and Russia have plans for a human landing mission as well, targeting the 2030s [3].

Analysis using NASA's concept of system equivalent mass [4], incorporating system aspects such as power, mass, or volume [4], shows that for long-duration missions BLSS outperform physical-chemical life support, as they are smaller in system equivalent mass [5]. BLSS are considered to be an integral part of long-duration human exploration missions, consequently [6].

Research concerning BLSS development has been ongoing for decades by various organizations and countries. A thorough summary of such activities can be found in [7].

However, despite decades of research there are still gaps to be closed, e.g., concerning the system and microbiome [8]. Consequently, CSA and DLR have begun design of the LAM-GTD. This paper intends to update on the significant changes that have occurred in the past two years of work.

II. LAM GROUND TEST DEMONSTRATOR

The LAM-GTD is intended as a test-bed for a system of a LAM, while serving as a research tool for e.g., micro-biome science, data collection for crop grow models and crop selection. A more detailed description of the technical and scientific need for a LAM-GTD can be found in [9]. The LAM-GTD draws heritage from the EDEN ISS prototype operated in Antarctica [9], with the objectives to [9]:

1. Demonstrate ground-based bio-regenerative life support with independent fresh food production for humans.
2. Provide a high level of autonomy (using robotic support).
3. Support related terrestrial applications in harsh environments.
4. Include contributions from global institutional and industry partners.
5. Provide a minimum of 10% of calorie intake for a three-person crew at the end of the demonstrator mission.

The current concept would place the inauguration of the LAM-GTD in about 2028, after which it would be operated for at least three years enabling the development of an actual LAM.

III. DESIGN METHOD

The cornerstone of the current design has been a Concurrent Engineering (CE) study, conducted at the Concurrent Engineering Facility (CEF) of DLR (in Bremen, Germany) in March 2024, after a previous initial study in September 2022 [10]. A detailed description of the CE process as used by DLR can be found in [11]. Further details about the design process in a general view is given in [9].

The process behind the CE study is iterative. Moderated sessions dedicated to specific topics relevant for the whole team occur intermittently with offline sessions, where study participants can work on their individual action items or engage in smaller discussions about specific design challenges.

The design team comprises experts for each relevant domain, and involves the customer(s), engineers, and scientists, ensuring that all stakeholders are part of the design process. A common data model is used to create a common understanding of the design and identify issues, e.g., concerning power demand or accommodation, early.

After the CE study, the work continued, e.g., with trade-off concerning design options, derivation of requirements and adaptation of the accommodation with regular exchange between all responsible experts.

Nutrient Delivery System

Greenhouse crops require a reliable and near-constant supply of nutrient solution for healthy growth and development. The design concept for the LAM-GTD Nutrient Delivery System (NDS) builds on lessons learned from the EDEN ISS project [12] with a focus on improving reliability, accessibility, and fresh edible biomass production while simplifying crew operations.

For redundancy purposes, the NDS design includes two independent recirculating irrigation loops (Figure 1) with separate nutrient tanks that supply the left and right plant cultivation racks (Figure 5). These loops would use a common injection system for acid, base, CROP system [13] inputs, and concentrated nutrient solution to maintain the desired electrical conductivity (EC) and pH of the nutrient solution. To investigate closing bioregenerative life support loops between the habitat and greenhouse, the NDS system would implement the CROP system capable of extracting nutrient salts for plant production from crew urine.

During maintenance activities or in case of failure, the two nutrient solution tanks will be capable of supplying the plant cultivation racks on the opposite side to prevent disruptions to operations. The NDS system will be designed to accommodate the plant growth trays including lids for various plant species to be cultivated in the greenhouse.

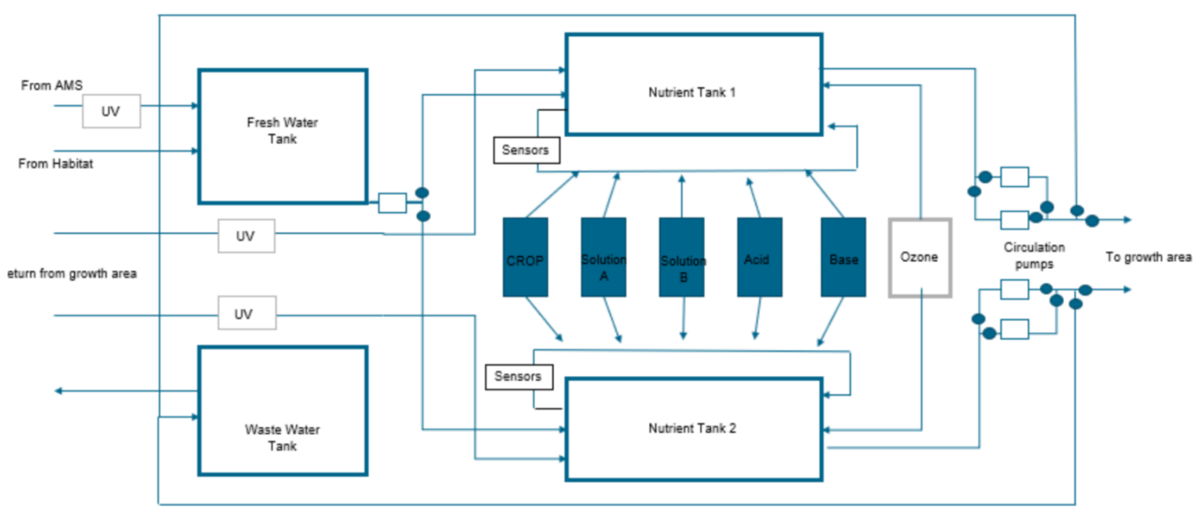

Figure 1: Flow diagram of the Nutrient Delivery System.

Air Management System

This subchapter deals with the Atmosphere Management System (AMS), a Controlled Environment Agriculture (CEA) subsystem that is responsible for all functions related to the monitoring and control of the air composition, condition, and distribution within the agriculture module. The air treatment unit can be compared to a modern HVAC (heating, ventilation, and air conditioning) system used for enclosed spaces on Earth. Its purpose is to ensure crew safety and plant health while also allowing for an exchange of gases and liquids between the AMS and its surrounding infrastructure (a crewed habitat or a Habitat Simulator (HabSim)) or other subsystems (e.g., NDS or Thermal Control System (TCS)). The AMS is designed to actively control the temperature (between 16 °C and 27 °C), relative humidity (between 45 % and 85 %), cabin pressure (at 57 kPa, 70 kPa, and 101.13 kPa), as well as CO_2 and O_2 concentration, among others.

The AMS is divided into an air treatment unit located in the over-head compartment and an air distribution unit in the main area, as can be seen in Figure 2.

The air treatment unit can be compared to a modern HVAC (heating, ventilation, and air conditioning) system used for enclosed spaces on Earth. Thus, its purpose is to provide thermal comfort and an acceptable indoor air quality. The air treatment unit consists of multiple assemblies that exploit physical correlations to measure and control the wanted parameters, like:

- UV-C lamps to sterilize incoming air and condensed water
- Air filters to remove unwanted particulate matter (PM) or gaseous molecules
    - Pre-filters
    - HEPA (High-efficiency particulate air) filters
    - VOC (Volatile organic compounds) filters
- Blowers to induce an air flow
- Dehumidifier to capture excess humidity, which can be purified and recycled within the NDS
- Heater and heat recovery system, which reheat the air after the dehumidification process
- Sensor array (T, RH, CO_2, O_2, PM, VOC, ethylene, volume flow rate, air speed)

The air distribution unit will be needed to ensure that the freshly treated air mixes with the air inside the agriculture module. It also redirects the fresh air to the individual plant's canopy, thus, maintaining air movement around the plants to facilitate the gas exchange of the leaf. To achieve this function, the air distribution unit will consist of multiple fans and some sort of air duct system. At this point in time, the air flow rate is set to 1000 $\frac{m^3}{h}$ and the maximum allowable pressure loss is set to 500 Pa. The desired air speed at the plant's shoot system has been defined as 0.3 $\frac{m}{s}$ to 0.7 $\frac{m}{s}$.

Lastly, the AMS has to offer interfaces to the habitat (exchange of CO_2- and O_2-rich air) and NDS (treatment of the recovered condensate).

Configuration

The main design driver regarding the configuration was the aim to maximize the available plant cultivation area. Previously, the agriculture module was split into a dedicated Service Section and a Plant Cultivation Area, like the approach used in EDEN ISS.

Given the cylindrical primary structure of the agriculture module, this resulted available volumes in the sub-floor and at the ceiling. As such, a more distributed approach to accommodating the various subsystems was investigated, with the NDS and TCS, for example, being

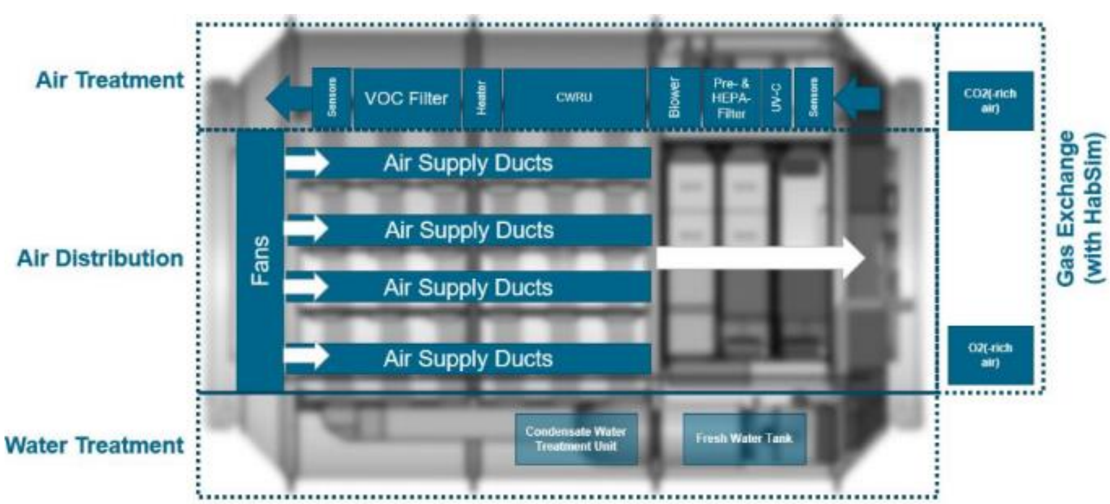

Figure 2: Concept and layout of the Air Management System.

wholly relocated into the sub-floor area. The AMS which had previously been packed into the sub-floor and ceiling areas of the Service Section, were shifted fully to the ceiling area of the agriculture module and re-organized to accommodate the ceiling-mounted robotic system.

As a result of these configuration changes, the number of racks in the Service Section has been reduced by ~66%, allowing for an increase in plant cultivation area from 14.6 m² to 23.52 m².

Besides the internal configuration of the agriculture module, there were significant changes and modifications to the other elements of the LAM-GTD as the design matured throughout the CE study.

Habitat Simulator

The purpose of the HabSim is to precisely track the inputs and outputs of the agriculture module and simulate the exchange of resources between a habitat and the agriculture module in a closed-loop system. The HabSim should allow demonstration and comparison of different air exchange strategies, e.g., direct air exchange vs. batch air exchange, to determine the optimal strategy for a BLSS, or hybrid physico-chemical/ bio-regenerative life support system to balance and maintain environmental conditions between different modules with different target conditions. Additionally, the water exchange between the modules, as well as the power, data and thermal infrastructure of the lunar habitat need to be simulated.

Naturally, the agriculture module design will be the main driver on the HabSim design, as the desired environmental conditions, as well as the environmental disturbances caused by the agriculture modules (e.g., O_2 production, VOC and trace gases, microbial and particulate contamination), will define the requirements for the HabSim.

Similarly, the habitat design will have an impact on the HabSim design. As there is no concrete design yet for a future lunar habitat, a range of assumptions have been made to allow the design process to continue. These range from crew size, to environmental conditions (such as CO_2, pressure, and relative humidity setpoints), to the power and data architecture of a future habitat. Based on the various design drivers, an initial design of the HabSim was iterated throughout the CE study.

IV. RESULTS

The current design of the LAM-GTD is shown in Figure 3. The constituents are the prototype lunar agriculture module, housing the grow area for the plants, the HabSim, which is an external system used to simulate inputs and outputs of gases, fluids, data and power from the habitat to the agriculture module, an airlock module

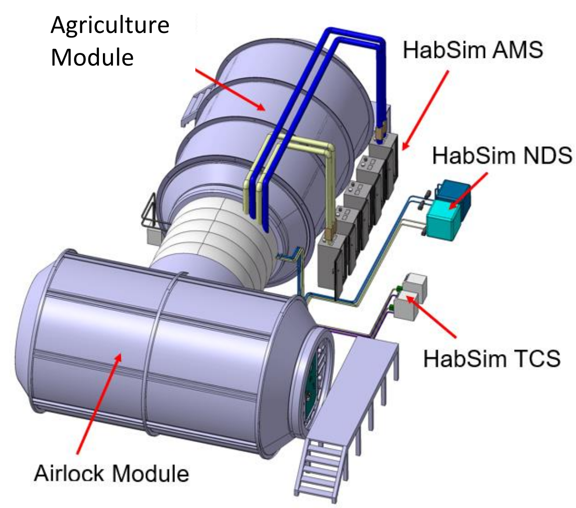

Figure 3: Current configuration of the LAM-GTD.

containing not only the airlock but also a working environment at reduced pressure. Not shown is the mission control center, possibly multiple ones, used to control the overall system remotely.

Internal Pressure

One major outcome of the study has been the need to simulate different internal environments depending on the mission scenario, here mostly due to number of extra vehicular activities (EVA). According to NASA [11], early mission phases will have more EVAs and thus need for lower internal pressure to ease the transition from internal activity to EVA for the crew.

Three pressure environments are foreseen for the LAM-GTD:

1. 57 kPa & 34% oxygen
2. 70 kPa & 26% oxygen
3. 111.46 kPa & 21% oxygen

For testing purposes, 20% margin in total pressure are foreseen (e.g., for structural loads or pump capabilities).

Operation

The design foresees an autonomous operation of 42 days, which allows time for crop cultivation in preparation of crew arrival in case of a non-continuous operation, as likely in early operation scenarios. The 42 days resulted from the assumption that a minimum of 28 days will be required for leafy greens to become ready for harvest, plus an additional 14 days of reduced performance to pass over a lunar night (if necessary).

In addition, four operational modes were defined for the LAM-GTD:

- **Nominal:** Ordinary operations
- **Safe:** Keeping the system alive and allowing repairs.

- **Hibernation:** Keeping plants alive but reducing performance to pause grow for times of reduced power availability, e.g., due to lunar night situation.
- **Dormancy:** The system runs on minimal power demand, without any plants, to maintain system conditions needed to survive periods without use.

Configuration and System Budgets

The system budget for the agriculture module is given in Figure 4. With harness and all margins, the total mass sums up to approximately 12,400 kg. In the current design, the primary and secondary structure comprise about 80% of that mass. All components have associated margins, based on their TRL, i.e., TRL 1 to 3 have 20% margin, TRL 4 to 6 have 10% margin and TRL 7 to 9 components have 5% margin. There is an additional system margin of 20%.

As one of the design drivers was to maximize the plant grow area of the system, the agriculture module is primarily comprised of grow area (see Figure 5). In difference to previous designs, there is no dedicated service section. As mentioned previously, to optimize the available cultivation area, the subsystems are distributed throughout the sub-floor area, ceiling area and the normal

Sum over all [kg]		12390
Harness [%]	10	1126
System Margin [%]	20	11263
Totals	7957,51	9386
Subsystem	Total Mass [kg]	Mass w/ Margin [kg]
AMS	437	478
DHCS	13	16
LCS	129	155
NDS	347	396
PCDS	83	100
PHM	23	26
Primary Structure	4750	5700
Robotics	222	249
Secondary Payload (CROP)	91	98
Secondary Structure	1590	1880
TCS	58	62
Safety	77	81
Cargo	137	144

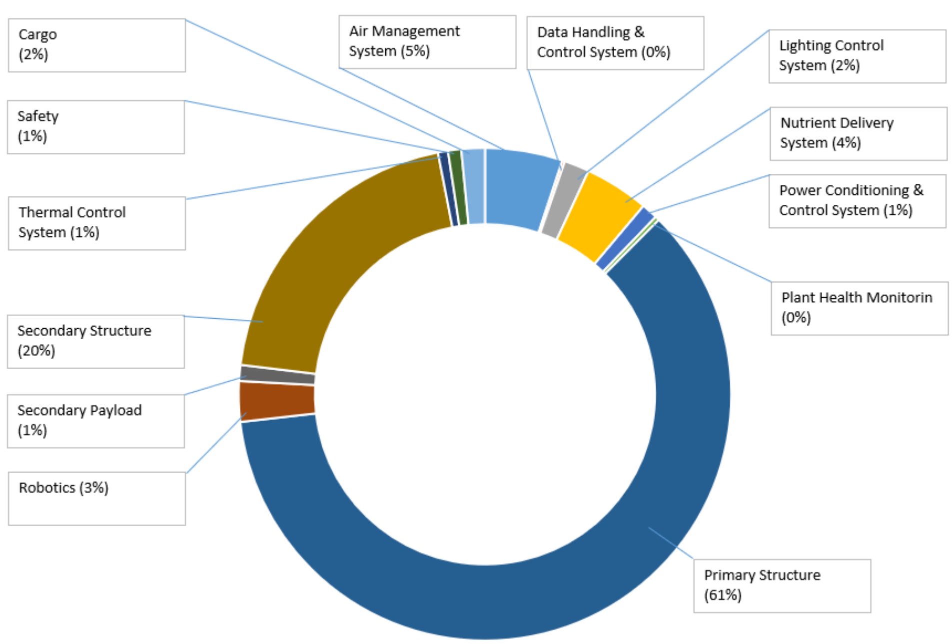

Figure 4: Absolute mass budget of the agriculture module (top) and relative mass budget (bottom). In both cases numbers have been mathematically rounded.

working area. Only the Power Conditioning and Distribution System (PCDS) and Data Handling and Control System (DHCS) components, along with a storage area, workspace and nursey are integrated adjacent to the plant cultivation racks, with the remaining subsystem elements integrated in the sub-floor or along the ceiling. The robotic system (versatile assistant) is ceiling-mounted and can be stored next to the end-effector storage, which houses the arm's interchangeable tools.

The AMS has been split into two separate units, which will handle the left and right plant cultivation racks respectively and improve the system redundancy. Preliminary sizing of the components indicates there is sufficient space to install and access the AMS while still accommodating the robotic system centrally along the corridor. Related to the reorientation of the AMS components, the air distribution ducting has also been updated from the previous vertical, curved, ducts, to horizontal ducts which run along the structure wall.

The agriculture module's NDS has been designed for nutrient film technique (NFT) water delivery. The low-pressure NFT pumps and components improve system reliability and can reduce operational and hardware costs compared to high-pressure systems required for aeroponics.

The plant growth trays will be integrated into a sliding rail system (drawers) so that each tray can be slid into the corridor to facilitate harvesting and maintenance. Sliding plant growth trays into the corridor also eliminates the need to manually transport the trays from the cultivation racks to a dedicated working area for standard maintenance tasks. Furthermore, the piping connections of the plant growth trays (e.g., inlets and outlets) will face the corridor to simplify accessibility, maintenance, and operations while improving the system reliability.

All NDS-related tanks are positioned in the LAM-GTD subfloor allowing gravity return of the nutrient solution and eliminating the reliance on a sump pump, which could represent a single point of failure.

For disinfection, filtration systems and UV-C LED sterilization units will be used to treat the nutrient solution flowing back from the plant growth trays to the main tanks, as well as the condensate from the AMS. Furthermore, both nutrient solution tanks are equipped with electrochemical oxidation units that generate recirculating aqueous ozone in-line the NDS loops.

The HabSim consists of four different components to study the exchange of inputs and outputs between the habitat and the agriculture module. The HabSim NDS, TCS, and AMS, as indicated in Figure 3, and a PCDS and DHCS component.The HabSim NDS consists of a set of tanks, pumps and valves to simulate the flow of liquids (e.g., fresh water, waste water, or nutrient soultion) to and from the agriculture module.

The HabSim TCS utilizes heat rejection units to control the temperature of coolant flowing to the agriculture module, with pumps and valves controlling the flow rates of the supply and return lines.

The HabSim AMS design consists of a Habitat Atmosphere Reservoir (HAR) which simulates the supplied air from the habitat to the agriculture module, and a separate reservoir which accepts the air from the agriculture module. To allow the HabSim to simulate

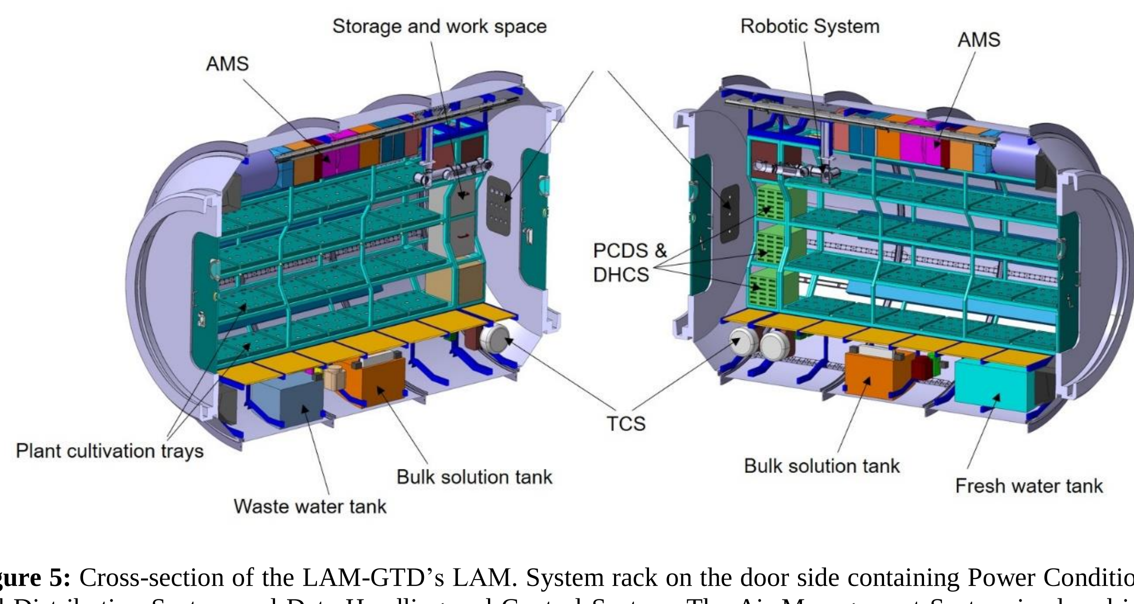

Figure 5: Cross-section of the LAM-GTD's LAM. System rack on the door side containing Power Conditioning and Distribution System and Data Handling and Control System. The Air Management System is placed in the ceiling. An emergency exit can be found at the other end of the module. All tanks required for the Nutrient Delivery System are integrated in the subfloor.

different habitat atmospheric conditions, the HAR has a mixing chamber which is supplied by gas constituents from pressurized bottles. The desired gas mixture will be prepared and stored inside this mixing chamber before being injected into the agriculture module. Thermal mass flow controllers will control the flow of gas to and from the agriculture module.

The HabSim PCDS and DHCS consists of the voltage converters, switches and safety components to transform the power from the electrical grid to the 120 VDC power supply which is assumed for future lunar surface infrastructure, as well as data transfer, storage and communication equipment to simulate agriculture module to habitat and habitat to Earth communication. A dedicated HabSim control unit has been envisioned to allow users to monitor and control the HabSim equipment without entering the agriculture module.

V. DISCUSSION

The proposed design of the LAM-GTD is different to previous testing infrastructure by approaching an operation, which is as representative as possible to actual lunar operation. This includes selection of components, which are analogous to the actual space hardware, where possible. While gravity inside the LAM-GTD cannot be simulated to that on the lunar surface, every other aspect is intended to be similar. Since the system configuration is similar to that on the lunar surface, even operational procedures can be tested and lessons learned can be drawn to adapt for actual implementation on a space mission.

As the agriculture module must operate autonomously in preparation for crew arrival the design, implementation, and interaction/ cooperation of the robotic versatile assistant will be a key point of investigations. The robotic arm's ability to e.g., take over specific grow care and harvesting tasks reduces crew time (at the expense of development time and costs) and allows an autonomous operation, enabling the application of the agriculture module for missions which are not continuous. This increases the utility of the future LAM.

The involvement of international collaborators is ongoing and further collaboration is being sought to ensure that the best expertise is applied. Since the final mission will be an international cooperation as well, acceptance is improved by beginning cooperation as early as possible on the system design.

Operation at Reduced Pressure

One major research topic for the LAM-GTD is how plants will react to the artificial grow environment. This includes the ambient pressure, which is likely to be reduced compared to Earth's standard atmosphere during operation on the lunar surface. System layout and possibly interaction (e.g., concerning heat transfer) will also depend on the pressure environment, i.e., system testing will become more realistic using an operational scenario at reduced pressure.

Nevertheless, operating at a a reduced poses possible safety and health risks, requiring higher standards to keep the crew safe. Further safety regulations must be adhered to in the design process and legal considerations need to be regarded. To ensure a suitable working environment without having to leave the reduced pressure atmosphere regularly, certain laboratory space and/or facilities for human needs must be included in the volume of reduced pressure, which could increase the overall system complexity and costs.

Nonetheless, due to the better adherence to a realistic lunar surface scenario, the current baseline is to use a reduced pressure volume for the LAM-GTD. One option to reduce safety and health issues would be to limit crew presence to conditions of minimum 70 kPa and have the 57 kPa situation run only autonomously.

Open Issues

With the status of LAM-GTD still in the design phase, there are numerous technical questions still unanswered, e.g., choice of cooling fluid, sizing of components. Thermal, aerodynamic and further simulations are next steps to close these gaps.

Furthermore, the exact operational scenario, including governance needs to be further designed detailing operation site(s), selection of experiments, and duration of test campaigns.

With the addition of the airlock module, to allow for reduced pressure operations, further investigations about its design and integration are needed. Furthermore, the gas exchange between the airlock module and the agriculture module and the impact on the measurement accuracy of the inputs and outputs of the various gas constituents needs to be analyzed in further detail.

Regarding the NDS design, there are several topics that need to be addressed in future studies. For example, it is not yet clear how the NFT system will perform in partial gravity and how we can model or test this terrestrially. There is also a need to investigate ion selective sensor technologies able to monitor individual ions within the recirculating nutrient solution to prevent solution imbalances. The nutrient solution requirements for the different crops and how these change at various growth stages must be considered in future designs. How often the nutrient solution is returned to the habitat and whether the habitat can handle the return of a full nutrient solution tank or only the gradual return of smaller amounts will require additional research. Terrestrial CEA plant production systems use large amounts of concentrated acid (nitric or phosphoric acid) for pH control. Thus, in-situ acid production methods or alternative methods of pH control need to be investigated in the context of future space missions with limited resupply capacities. Finally, additional CROP-specific research and development tasks are needed regarding the preparation of the nutrient bulk solution or hardware and the effects on plant growth when using the CROP solution with high nitrogen, sodium, and calcium concentrations.

Sizing of the AMS has to be optimized and a flow simulation has to be conducted, once the internal layout has been finalized, to ensure sufficient airflow and air distribution within the grow area. Air ducts needs to be optimized for the best velocity profile.

The thermal control system has to be further designed with the help of a thorough simulation as well, ensuring that no heat or cold pockets will form during operation. This will have to be linked with the flow simulation.

VII. CONCLUSION

This paper has shown the further evolution of the LAM-GTD design study. It is intended as basis for a future decision-making process involving the current collaborators and possibly further organizations for actual implementation.

The accommodation of equipment has been further driven by increasing the size of the grow area to approximately 24 m², leading to more than 60% enhancement.

The NDS has been updated to an NFT system and generally, operation will occur at reduced pressure – between 57 kPa and 70 kPa. Both lead to significant changes compared to the previous design iteration.

Currently, the agriculture module design fits within launch mass and size envelope required for a Falcon 9, which was a self-imposed requirement based on a realistic launch vehicle.

ACKNOWLEDGMENTS

The authors wish to thank the teams at Canadensys, University of Guelph, McGill University, and the National Research Council for their conceptual design contributions during the planning phase of the LAM-GTD.

REFERENCES

[1] NASA, “Artemis,” [Online]. Available: https://www.nasa.gov/humans-in-space/artemis/. [Accessed 15th July 2024].

[2] J. Davenport, “Japanese H-IIA launches X-ray telescope and lunar lander,” NASA Spaceflight, 6th September 2023. [Online]. Available: https://www.nasaspaceflight.com/2023/09/xrism-slim/. [Accessed 16th July 2024].

[3] L. Lee, J. Roulette, J. Brock and E. Baptista, “China lands on moon's far side in historic sample-retrieval mission,” Reuters, 2nd June 2024. [Online]. Available: https://www.reuters.com/technology/space/china-lands-uncrewed-spacecraft-far-side-moon-2024-06-01/. [Accessed 16th July 2024].

[4] J. A. Levri, J. W. Fisher, H. W. Jones, A. E. Drysdale, M. K. Ewert, A. J. Hanford, J. A. Hogan, J. A. Joshi and D. A. Vaccari, “Advanced Life Support Equivalent System MAss Guidelines Document,” NASA, 2003.

[5] C. Lasseur, “Regenerative Life Support - Status & Challenges,” in *MELiSSA-Agrospace-Workshop*, Rome, Italy, 2018.

[6] M. Bamsey, T. Graham, M. Stasiak, A. Berinstain, A. Scott, T. Rondeau Vuk and M. Dixon, “Canadian advanced life support capacities and future directions,” *Advances in Space Research,* no. 44, pp. 151-161, 2009.

[7] C. M. Escobar and J. A. Nabity, “Past, Present, and Future of Closed Human Life Support Ecosystems - A Review,” in *47th International Conference on Environmental Systems*, , Charleston, South Carolina, USA, 2017.

[8] M. Anderson, D. Barta, G. Douglas, B. Motil, G. Massa, R. Fritsche, C. Quincy, M. Romeyn and A. Hanford, “Key gaps for enabling plant growth in future missions,” in *AIAA Space and Astronautics Forum and Exposition*, Orlando, 2017.

[9] V. Maiwald, K. Kim, V. Vrakking and C. Zeidler, “From Antarctic prototype to ground test demonstrator for a lunar greenhouse,” *Acta Astronautica,* vol. 212, pp. 246-260, 2023.

[10] V. Maiwald, K. Kim, C. Philpot, D. Schubert and V. Vrakking, “Lunar Eden: Roadmap and Demonstrator Design of a Lunar Greenhouse Based on an Antarctic Prototype,” in *73rd International Astronautical Congress (IAC)*, Paris, France, 2022.

[11] A. Martelo Gomez, s. Jahnke, A. Braukhane, D. Quantius, V. Maiwald and O. Romberg, “Statistics and evaluation of 60+concurrent engineering studies at DLR,” in *68th International Astronautical Congress*, Adelaide, Australia, 2017.

[12] V. Vrakking, C. Zeidler, P. Zabel, M. Dorn and D. Schubert, “Status and Future of the EDEN ISs Mobile Test Facility,” in *ICES*, Lisbon, Portugal, 2020.

[13] M. J. Pardo Spiess, A. Cowley, S. Belz, B. Lehner, J. Hauslage and G. Detrell, “C.R.O.P.® Demonstrator for Human Space Exploration: Experiment Analysis and System Model Development,” in *68th International Astronautical Congress (IAC)*, Adelaide, Australia, 2017.

[14] NASA, “Life Support - Baseline Values and Assumptions Document,” 2015.

[15] L. Poulet and O. Doule, “GREENHOUSE AUTOMATION, ILLUMINATION AND EXPANSION STUDY FOR MARS DESERT RESEARCH STATION,” in *Currently under work for the International Astronomical Congress*, Toronto, 2014.