Status and Future of the EDEN ISS Mobile Test Facility

Vincent Vrakking[1], Conrad Zeidler[1], Paul Zabel[1], Markus Dorn[1] and Daniel Schubert[1]
German Aerospace Center (DLR), 28359 Bremen, Germany

Within the EDEN ISS project an international consortium designed and built a (semi-)closed loop greenhouse, called the Mobile Test Facility, to investigate and validate techniques for plant cultivation in future bioregenerative life support systems. At the end of 2017 the Mobile Test Facility, consisting of two modified 20 foot shipping containers, was transported to the German Neumayer Station III in the Antarctic for testing in a space-analogue environment. Following arrival in the Antarctic in January 2018, and initial system check-out activities, the Mobile Test Facility began its first operational phase in February 2018. Although the EDEN ISS project foresaw only one year of operations and the project has officially concluded, the Mobile Test Facility remains in the Antarctic, operating at least until the end of 2020 and possibly beyond. This paper describes initial results and lessons learned from the 2018 and 2019 operations of the Mobile Test Facility, and presents an overview of the intended activities for 2020 and beyond.

I. Introduction

THE EDEN ISS project, which ran from March of 2015 until April 2019, aimed to build a closed-loop greenhouse facility and test it in a space-analogue environment in the Antarctic, in order to investigate technologies and procedures for plant cultivation in future life support systems. The resulting facility, labeled the Mobile Test Facility (MTF), was successfully deployed near the German Neumayer Station III (NM-III) in the Antarctic at the beginning of 2018. Following the initial check-out phase, the facility began its first operations phase in February of 2018. The EDEN ISS project, the design of the MTF, as well as the initial set-up and operation of the greenhouse have been the topic of previous publications[1,2,3,4].

One of the members of the EDEN ISS consortium stayed in the Antarctic throughout 2018 as part of the Neumayer III winter crew. During this time, this on-site operator was responsible for maintaining the technical systems, performing plant-related activities such as seeding, pruning and harvesting, and additionally the operator was tasked with carrying out a number of experiments, such as microbial investigations and plant sampling.
Based on the positive feedback from the winter crew and the Alfred Wegener Institute (AWI) which operates the Neumayer III station, as well as the potential of the MTF to yield valuable additional data on performance, reliability and operations of a space-analogue greenhouse, it was decided to extend the operations of the facility through 2020 and possibly beyond, even though the original project funding ended in April of 2019.

To limit the costs of the operations in 2019 and 2020, no dedicated on-site operator will be present in the Antarctic. Instead, basic training was provided to the Neumayer III winter crews during the summer seasons preceding each operations phase. Given that the winter crew has a large number of other activities to complete during the winter season, the crew time available for operation of the MTF is limited, compared to the initial operations phase in 2018. As such, tasks during 2019 and 2020 are limited to the core activities required to operate the facility along with simple measurements of the edible biomass production and crew time demands.

Figure 1 presents an overview of the timeline of the MTF operations from initial deployment at the beginning of 2018 until the start of the 3rd operations phase in March 2020. The actual operations phases of the MTF occur during the Antarctic winter, between March and November of each year as indicated in the figure, aside from the operations in 2019 which started in May instead. Between March and May of 2019 the facility was in a reduced operations mode (or sleep mode). This was done to test the ability to start the facility and initiate plant cultivation remotely.

Despite limiting the scientific activities during mission 2, a fair amount of data has been collected during 2019 to supplement the data from 2018, and additional lessons have been gleaned from the second operations phase, as well as the interactions of remote operators with the 2019 winter crew.

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[1] Research Associate, Institute of Space Systems, Robert-Hooke-Straße 7, 28359 Bremen, Germany

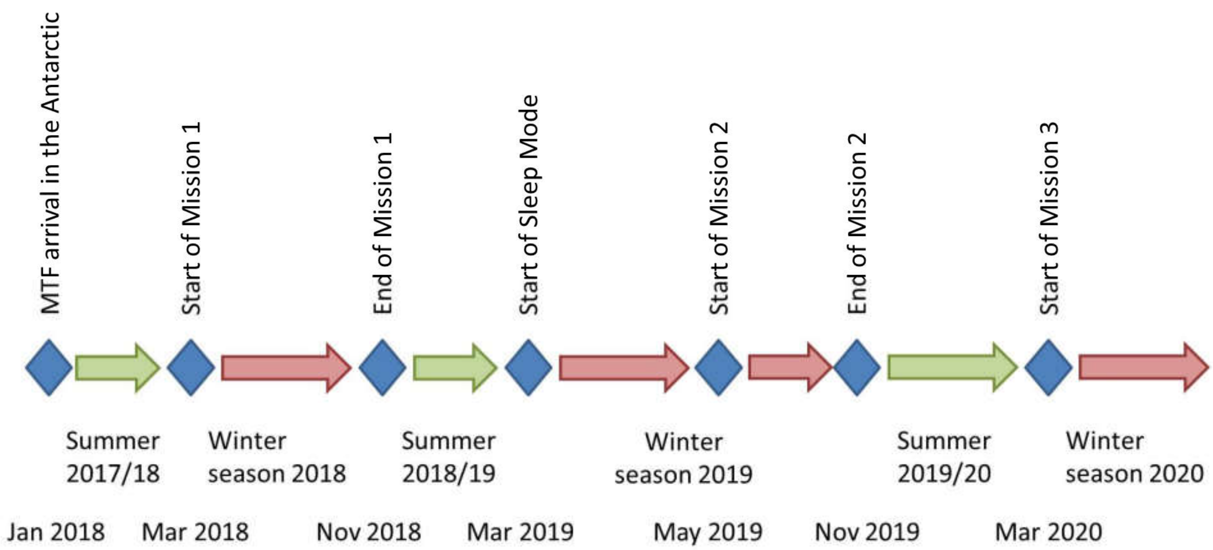

Figure 1: EDEN ISS Mission timeline (Milestones indicated by blue diamonds, summer season indicated by green arrows, winter season indicated by red arrows

II. Initial Results and Lessons Learned

Some data from the 2018 operations phase has already been published, such as the performance of the Plant Health Monitoring System[5], the impact of plants on crew well-being[6], crew time measurements[7], data on microbial contamination[8], as well as more detailed information on the biomass production[9]. About 268 kg of fresh edible biomass were harvested during mission 1. A significant amount of fresh biomass was also harvested during the 2018/19 summer season, though this was not tracked as it fell outside of the official operations phase. Figure 2 shows the interior of the Future Exploration Greenhouse in the 2018/19 summer season just prior to harvesting in January of 2019.

Figure 2: Future Exploration Greenhouse before harvest and cleaning in January 2019

For the 2019 winter season, as mentioned, one objective was to investigate the possibility of running the facility in a stand-by mode for some months and then starting operations remotely. For this purpose, attempts were made to germinate seeds directly in the plant cultivation trays, as opposed to in a dedicated nursery. Unfortunately, these germination attempts were not successful as the rockwool substrate did not absorb enough moisture from the aeroponic nutrient solution spray. Changes have been made to the design of the 3D-printed rockwool holders to increase the exposure of the rockwool cubes to the nutrient spray, and additional germination tests are planned.

As these germination experiments failed, completely autonomous starting of operations from the remote Mission Control Center was not possible, and the overwinterers had to assist by seeding plants in the nursery and subsequently transplanting them. Nevertheless, the facility ran in a reduced mode between February and May of 2019 and was then successfully switched to nominal operations mode without issue.

In the initial grow out phases during the 2019 winter season, a large accumulation of microbial contamination occurred, which required a significant crew effort for additional cleaning and decontamination measures. As a similar contamination occurred early on during the 2018 winter season, also following an in-depth cleaning and sterilization process, it is assumed that this rapid growth is due to the reduced microbiome diversity, allowing one or a few micro-organisms to multiply without restraint. Once the plants in the facility reached a higher maturity, the issue resolved itself and microbial contamination was very limited[8].

A number of changes were implemented to counteract the large microbial contamination build up during the initial seeding and germination at the beginning of the operations phase. For one, a procedure was established for regular dosing of the bulk nutrient solution tanks with hydrogenperoxide (Huwa-San AGRO 7,9%). Secondly, the fibre grow mats used for the cultivation of various herbs were removed from the facility, as these mats were found to be particularly susceptible to contamination. Lastly, during the 2019/20 summer season, facility cleaning procedures were adapted to reduce the use of chemicals during cleaning of the Nutrient Delivery System piping, with the assumption that this would allow the existing microbiome to survive, thereby preventing the initial higher level of contamination which had been observed previously. Based on the initial observations during the 2020 operations phase, these changes have been successful in preventing the contamination build up which occurred during previous years. Further investigations will be carried out in the future to determine the impact of the individual countermeasures.

Biomass production

Table 1 shows the amount of biomass harvested each month during the 2019 operations phase. As mentioned previously, the facility was put in a standby mode until May of 2019, at which time the first seeds were germinated. First harvest occurred in June and the last harvest occurred in November. In preparation of, and during, the 2019/20 summer season, only part of the available cultivation area of the MTF was used during the months of October and November in order to reduce crew time demand even further.

Table 1: Monthly fresh edible biomass harvest during the 2019 winter season

Month	Biomass Yield [kg]
June	4.87
July	14.74
August	25.29
September	26.67
October	23.97
November	11.02

Based on feedback from the first operations phase in 2018, the amount of crops available for cultivation in the MTF had been greatly increased for the 2019 winter season. However, for many of these new cultivars no laboratory testing had been done to determine optimal growing conditions and as such some of the new crops did not yield significant edible biomass, thereby reducing the average yield per cultivation area.

Crew time

For the 2019 mission, the overwintering crew of the Neumayer III was asked to track the amount of time which was spent on activities related to the operation of the MTF. These activities included regular communication with the project team at DLR, nominal operations in the facility such as cleaning, seeding and harvesting, as well as off-nominal activities in case of, for example, component failures. Communication with other partners in the EDEN ISS project was handled by the project team at DLR, with information subsequently relayed to the winter crew. The maximum amount of time needed by the crew during the 2019 winter season was 102.5 hours during both July and August. For the other months, the time was less either due to a reduced amount of plant handling activities and/or fewer off-nominal events.

Only a rough time tracking was carried out during 2019 and the same is foreseen for 2020. Acquisition of an improved time tracking system is planned but is dependent on the availability of funding and the amount of components needed for repair and replacement of MTF hardware.

Crew time was also tracked for remote operations by the DLR team. Activities carried out by the remote operators involved regular communication with the on-site operators, as well as preparation of the 2019/20 summer season by ordering spare parts and consumables, and preparing logistics and relevant documents for transport to the Antarctic. About 30 hours were needed for remote operations during May 2019, increasing to a maximum of about 50 hours in August of 2019 and then decreasing again as preparations for the summer season concluded and the winter crew began winding down on-site operations towards the end of the winter season. A publication with a detailed crew and operations time breakdown is in the works.

Microbial contamination

Throughout the first operations phase, samples were taken of harvested biomass, and probes were taken from different surfaces and liquids within the EDEN ISS greenhouse. These samples were returned to Europe for analysis. Reasoner's 2A (R2A) agar and Potato Dextrose Agar (PDA) agar were used as growth media as part of the microbial contamination investigations. PDA is a standard medium used for growing fungi or bacteria, whereas R2A is better suited to slow-growing species, such as bacteria which might inhabit water.

Initial results indicated that the overall microbial load is low compared to that found on commercially available produce as indicated in Figure 3.

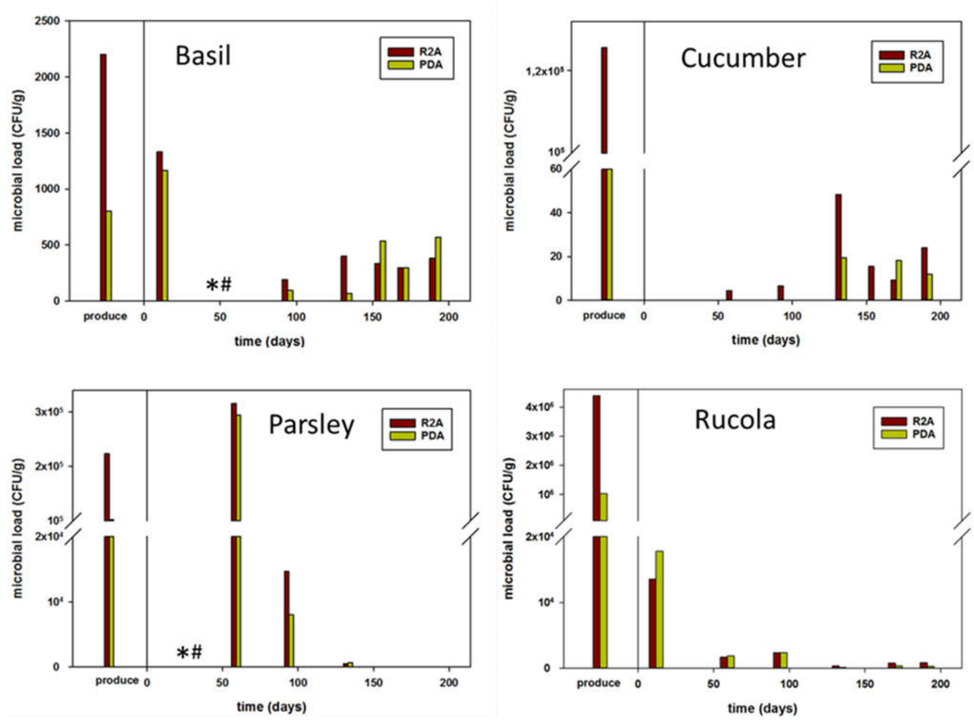

Figure 3: Microbial load of commercially available produce (left-hand side of each plot) and samples from EDEN ISS-produced biomass (right-hand side of each plot).

The microbial load on the EDEN ISS biomass, as well as the microbial load in the bulk nutrient solution tanks and on various surfaces throughout the MTF are published in a separate publication as mentioned previously[8]. The bioburden in the nutrient solutions increased over the duration of the 2018 operations phase, but remained below values found for commercial greenhouse production systems. There were high differences between the microbial burdens measured in the various sections of the MTF, with the plant cultivation area having a higher bioburden than the Service Section as was expected. However, even in the plant cultivation area the number of organisms (bacteria and fungi) was found to be non-critical.

III. Upgrades and Maintenance Work

During the 2018/19 summer field season four project members from the German Aerospace Center, and two project members from the University of Florida, stayed at the Neumayer Station III for some weeks in January and February 2019 in order to prepare the EDEN ISS Facility for the second operations phase.

Among the work carried out in this period were repair, maintenance and upgrade activities on the Plant Health Monitoring system. This included replacement of various cameras with higher resolution cameras, as well as installation of additional cameras, and modification of some cameras with specialized filters.

Furthermore, the Service Section Atmosphere Management System (AMS) components were removed from the facility as the system had malfunctioned early on in the 2018 operations phase. A description of the Service Section AMS was presented in a previous publication[3]. Though there were some issues with condensation on the walls during especially cold periods, the Service Section temperature and relative humidity control remained within the desired set points even without the Service Section AMS and as such it was decided to remove the system rather than repair the malfunctions.

The plant cultivation rack which had been installed in the Service Section for the 2018 operations phase had been removed from the facility in December 2018 and shipped back to Europe for further development. The space previously occupied by this rack was repurposed to provide space for the larger nutrient stock solution tanks, as well as a standalone dehumidifier (model: Remko ETF360) which was intended to reduce the humidity in the Service Section in order to minimize condensation. Figure 4 depicts the new stock solution tanks as well as the dehumidifier, installed in the MTF Service Section.

Figure 4: (Left) New stock solution bottles with level sensors. (Right) Stand-alone dehumidifier for the MTF Service Section

The new stock solution tanks have much larger volumes and as such need to be exchanged less frequently, reducing the amount of work effort needed by the overwinterers during the second operations phase. Additionally, the increased volume of the stock solution tanks allowed the use of level sensors to obtain an alert whenever the stock solution is running out. To further reduce the required crew labor/time in making up hydroponic nutrient solutions, ready-to-mix nutrient solution bottles were prepared prior to the second and third operations phase.

Aside from the new dehumidifier in the Service Section, further measures were implemented to counteract condensation, both in the Service Section and the Future Exploration Greenhouse (FEG), by installing a number of additional fans (model: Honeywell HT900E) in the sub-floor area to improve air circulation. For the Service Section, a number of floor plates were exchanged for perforated plates (see the lefthand image in Figure 5) to enable air exchange between the areas above and below the floor.

Additional work carried out during the summer season involved modification of the power control and distribution system and the command and data handling system, including installation of new sensors and actuators.

Also, all the high pressure pumps of the Nutrient Delivery System (NDS) were replaced. Rather than keeping a single high pressure pump per plant cultivation rack, one pump was used for two of the single level, as well as the two level, cultivation racks. The pumps and the plant cultivation rack system were discussed in a previous publication[4].

The fans on the roof-mounted heat rejection unit were replaced, as were the various filters, UV lamps and other consumables within the facility. Furthermore, the old CO_2 sensors, which had a 2000 ppm measurement limit, were replaced with new sensors with an increased measurement range of up to 5000 ppm (model: E+E EE820-C6xPP-005S), as opposed to the previous 2000 ppm limit. Lastly, the overwintering crew was provided detailed instructions on the layout of the facility, and the various operational procedures.

Figure 5: (Left) New Service Section floor plate design. (Right) New subfloor fans

During the 2019/20 summer season only two project members from the German Aerospace Center traveled to the Antarctic to carry out maintenance and repair work, and to install a few upgrades to the facility. Although the focus was primarily on routine activities, such as cleaning, sensor calibration, filter exchange and training of the overwintering crew, a number of potential upgrades were planned for this period as well.

In particular, the misting nozzles in the plant cultivation trays were exchanged with new nozzles which have a slightly larger 0.024 inch orifice (model: Mistcooling MC43020), which should hopefully reduce issues with clogging and cleaning of the nozzles. Additionally, control over the free cooler, the roof-mounted heat rejection unit, was improved by adding control over the fan speed as opposed to the previous on/off control. Also, a hydrogenperoxide dripping system was installed in the Nutrient Delivery System rack to further counteract any microbial contamination of the nutrient solutions.

IV. Future Activities

NASA collaboration for 2021

Expanding upon the previous collaboration, NASA will fund an on-site operator to manage the EDEN ISS greenhouse during the 2021 Antarctic winter season. The on-site operator will be part of the Neumayer Station III winter crew and will carry out all nominal and off-nominal operations related to the MTF, as well as a variety of experiments, such as microbial sampling.

Plant cultivation experiments will continue with the NASA cultivars provided for the 2019 and 2020 operations phases, and will be expanded to include a number of additional cultivars. Finally, a possibility is being explored of implementing some hardware, which is under development at NASA, within the EDEN ISS MTF.

SPORA – Space Plantation Optimization using Robots and Augmented Reality

A collaboration has been initiated between a number of institutes of the German Aerospace Center, the Jülich Research Center and the Alfred-Wegener Institute to investigate the applications of Augmented Reality (AR) and robotics within a space greenhouse. The proposed project foresees development of a robotic arm which would be capable of carrying out a large portion of the plant-handling activities (e.g. harvesting) within the MTF.

Additionally, an AR system would assist the on-site operators with maintenance, repair and plant-handling activities. The project is currently in the proposal stage, but, if successful, would see the continuation of the MTF operations in the Antarctic through 2023.

SkolTech collaboration

Discussions are ongoing with SkolTech regarding the possibility to implement artificial intelligence systems, under development at SkolTech, in the Command and Data Handling System of the EDEN ISS MTF. Research topics would include anomaly detection, optimization of resource consumption and computer vision for plant health monitoring. The SkolTech project could have a possible synergy with the SPORA project in the development of AR and robotic systems, as well as with the currently ongoing plant health monitoring research.

Atmosphere Management System & Nutrient Delivery System redesign

Based on the performance of the Mobile Test Facility through the 2018 and 2019 operation phases, and experience gathered from the maintenance and handling activities for the AMS and the NDS, the project team aims to implement significant design changes in both these systems.

For the AMS, the current cooling coil was found to be undersized. Although the desired temperature and relative humidity levels in the FEG could be maintained by adjusting flow rates and temperatures of the liquid coolant flowing through the cooling coil, it is nevertheless the intent to replace the cooling coil with an improved design to optimize performance of the AMS and the connected Thermal Control System.

With respect to the NDS, the piping system originally implemented within the FEG is more complex than it needs to be and it also does not adequately allow for cleaning of the piping system. Furthermore, the current set-up with dedicated high pressure pumps for each plant cultivation rack is deemed to be sub-optimal. As the pumps are among the most likely components to fail, the aim is to develop a new architecture which reduces the amount of pumps in the system. The current plan foresees the use of a reduced number of pumps which would periodically pressurize tanks. These pressurized tanks would then force the nutrient solution to the plant cultivation trays.

EDEN NEXT Gen

As part of the EDEN ISS project, the consortium carried out a preliminary design study to adapt the MTF towards an actual mission on Moon or Mars. During the study, a mission scenario was developed from which requirements could then be derived. Additionally, lessons learned from the design, construction and operation of the MTF were taken into account to improve the overall performance of the system.

The developed EDEN NEXT Gen concept, see Figure 6, is a hybrid rigid-inflatable cylindrical structure. Analogous to the Service Section in the MTF, the space greenhouse would have the subsystems supporting plant cultivation located primarily in the rigid section of the greenhouse. The inflatable shell would provide the volume needed for plant cultivation by expanding both longitudinally and radially. A number of rigid frames would provide structural support for the inflatable shell, and provide interface points for secondary structure and outfitting elements (e.g. lamps, air ducts, floor and ceiling panels).

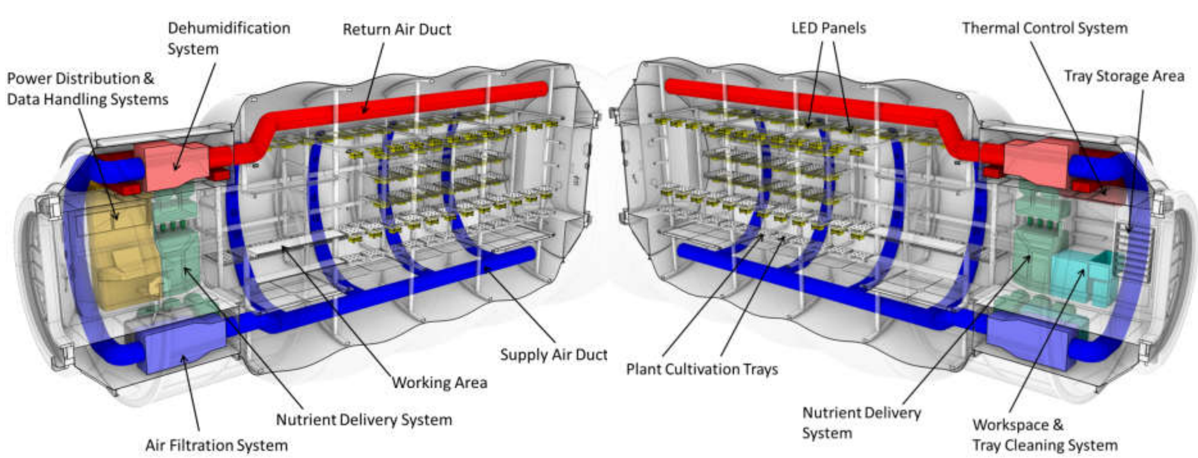

Figure 6: Cross-section view of the EDEN NEXT Gen greenhouse concept

The greenhouse concept would allow for a single launch scenario to LEO of the greenhouse module, including a docking vehicle, with a Falcon 9 or Falcon 9 heavy. On orbit, the docking vehicle would enable passive docking with a transfer vehicle which would transfer the greenhouse to an orbit around the target body (e.g. Moon or Mars). From there, a landing vehicle would transport the greenhouse to the surface, where it would be moved to the final location and connected to an already available habitat. A detailed description of the mission scenario, requirements and the EDEN NEXT Gen concept is presented in ref. 10.

The EDEN NEXT Gen greenhouse will be a main priority of the DLR project team in the coming years, with the aim of, ideally, having an actual full-scale greenhouse module built between 2025 and 2030.

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