

Status of the EDEN ISS Greenhouse after on-site installation in Antarctica

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EDEN ISS is a European project focused on advancing bio-regenerative life support systems, in particular plant cultivation technologies and procedures for space and planetary habitats. Essential Controlled Environment Agriculture technologies were designed, developed and integrated within a Mobile Test Facility, consisting of two interconnected 20 ft shipping containers. The main EDEN ISS cultivation area is called the Future Exploration Greenhouse and is designed as a single cultivation room with unified environmental settings and a 17:7 h light-dark photoperiod. During an analogue test mission at the German Neumayer III research station in Antarctica, the greenhouse provides a variety of fresh pick-and-eat crops for the overwintering crew of 10 members. This is of particular importance during their 6-7 months long isolation phase, when no plane or ship resupply of the station occurs.

This paper provides an overview of the as-built design configuration and outlines the main steps of the assembly, integration and test phase that took place between October 2016 and September 2017. Further, insight into the preparation procedures for the Antarctic mission is given, which led to the final mission preparation and transport logistics of the test facility. In December 2017, the analogue mission officially started with the on-site installation of the facility at Neumayer Station III. The paper gives an overview of the on-site build-up phase and the activities involved in putting the facility into its nominal operations mode. The paper concludes with a lessons learned and off-nominal issue section, gathered during the first months of operation in Antarctica.

Nomenclature

AIT	=	Assembly, Integration and Test
AMS	=	Atmosphere Management System
AWI	=	Alfred-Wegener-Institute for Polar and Marine Research
CDHS	=	Command and Data Handling System
CEA	=	Controlled Environment Agriculture
DLR	=	German Aerospace Center
FEG	=	Future Exploration Greenhouse
FMECA	=	Failure Modes, Effects and Criticality Analysis
FRR	=	Flight Readiness Review
ISPR	=	International Standard Payload Rack
ILS	=	Illumination System
MCC	=	Mission Control Center
MTF	=	Mobile Test Facility
NDS	=	Nutrient Delivery System
NM-III	=	Neumayer III
S/S	=	Subsystem
TCS	=	Thermal Control System
UHB	=	User Home Base

I. Introduction

As humanity further expands into the solar system, human outposts and habitats will play a key role for a continuous human presence in space. Facilitating closed-loop principles and bio-regenerative life support systems will allow human crews to stay longer in space by minimizing the resupply needs from Earth. The EDEN ISS project focuses on the cultivation of higher plants as an essential element within future outpost design scenarios,

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providing not only fresh food to the crew, but also by contributing to other life support tasks like air revitalization and water recycling.

For this reason, the EDEN ISS consortium, which consists of 14 partners from eight countries, designed, built, and tested a greenhouse called Mobile Test Facility (MTF).^{1, 12} The MTF includes all major elements of a possible future space greenhouse and allows accurate testing of plant cultivation.^{2,3,4} The project's main research objective is to validate and fine-tune Controlled Environment Agriculture (CEA) technologies and associated production procedures as a preparatory step for future habitats on the Moon and Mars. Further, microbial investigations, plant health monitoring, food quality & safety, and the psychological impact of fresh produce on the highly isolated crew are additional research questions, the project team investigates.

Beginning of January 2018 and after three years of intensive preparatory work,^{5,6} the final deployment of the MTF took place at the German Neumayer Station III (NM-III) in Antarctica. Within this analogue test mission, the overwintering crew of 10 people will operate the greenhouse system during their isolation phase.

II. Overview of Timeline

The EDEN ISS subsystem integration phase commenced with the delivery of custom ordered shipping containers to DLR in at the beginning of October 2016. From here all necessary subsystems were installed, beginning with the internal structural elements of the service section and the Future Exploration Greenhouse (FEG). The Nutrient Delivery System (NDS), Illumination System (ILS), and the Atmosphere Management System (AMS) were installed in the month to follow.

Figure 1 presents a detailed overview of the main activities and timeline of EDEN ISS Assembly, Integration and Test (AIT) phase. The Thermal Control System (TCS) was delivered in December 2017 and its integration was finalized at the beginning of February 2017 when the TCS free cooler system was initially connected to the ILS and the AMS. In April 2017, the furniture within the Service Section was installed, allowing the team to use the work station for later facility and plant production procedures. Right after the accomplishment of the internal work station, the International Standard Payload Rack (ISPR) (ISS rack-like plant growth system) was delivered and integrated into the Service Section.⁷ Beginning February 2017, the Mission Control Center (MCC) was built up and was continuously improved in the coming months, until it was operational in mid-July 2017.

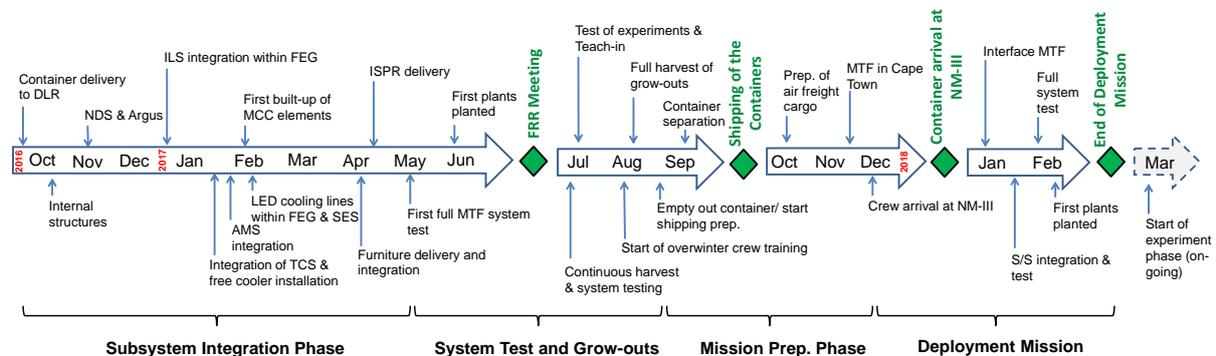


Figure 1: Overview of EDEN ISS project activities from the first AIT activities to the end of the deployment mission.

After a full system test during mid-May, the first plants⁸ were included into the system at the beginning of June 2017. The project Flight Readiness Review (FRR) meeting was held from the 28th to 29th of June at DLR Bremen site. This way the consortium partners, the European Union evaluation board, and the internal EDEN ISS scientific advisory board had the opportunity to visit the MTF during a nominal grow-out phase and raise any final issues that could be acted up prior to the conduct of the deployment mission. The testing phase, including the grow-out trails of plants, continued until the end of August 2017. This period also included initial tests of the scientific equipment for microbial investigations, food quality and safety which provided training and a teach-in opportunity for the associated procedures that would be conducted during the deployment mission by the EDEN ISS overwintering crew member (Paul Zabel). Almost concurrently, the required training for the Alfred-Wegener-Institute for Polar and Marine Research (AWI) coordinated overwintering crew started. The training comprised extensive first aid courses, fire-fighting courses, NM-III station operation procedures and a several day survival/mountaineering course in the Alps. The EDEN ISS on-site crew member, was trained together with the regular nine AWI station crew members, usually foreseen for the isolation phase.

End of August 2017, the system test and grow-out phase was concluded in order to start with the mission preparation phase. All plants within the FEG were harvested, regardless of the present lifecycle stage in order to begin with extensive cleaning procedures. The clean-up phase took roughly one month, where all remaining biomass was removed from the MTF, the nutrient supply lines were cleaned and dried out, and all surfaces were wiped and disinfected accordingly. Finally, the TransMADDS system, which was developed by the consortium partner Airbus Defence and Space was deployed within the MTF (12% hydrogen peroxide aerosol) in order to disinfect the remaining and hard-to-reach areas within the facility.

Mid-September all connections (fluid, thermal, data, and power) between the two containers of the MTF were disconnected and the two containers were separated from each other. Each interface between the containers were sealed with a removable transportation wall in order to allow the save transport via ship. Further, the packing of all essential supplies, spares, and scientific equipment took place during the mission preparation phase. A dedicated 20 foot transport container, provided by AWI, served as main transport- and storage unit for this additional mission equipment as well as for external MTF units (e.g., free cooler, door steps, and external lights). On October 2nd 2017, the two MTF containers and the storage container were picked up in order to begin their journey to Antarctica. After this important milestone, additional last minute equipment was combined into a dedicated air freight shipment, allowing the team to send small quantities via airplane to the NM-III station. At the beginning of December, the EDEN ISS containers arrived in Cape Town, South Africa and were transferred onto the S.A. Agulhas II for the last step of their transport.

The deployment team arrived in Cape Town mid-December and flew in to NM-III on December 17th, which marked the beginning of the on-site deployment mission. Due to organizational and weather-related difficulties, the final offloading of the EDEN ISS containers at Antarctica was shifted to January 3rd, 2018. After connecting the MTF containers on the platform, the internal subsystem integration took place, followed by an overall system test. Then, at the beginning of February 2018, the first plants were inserted into the MTF. Mid-February 2018, the deployment team departure the station and the on-site crew member began with the nominal operations within the greenhouse.

All the listed timeline dates (save the milestones) need to be considered as rough points in time. This means that several activities were also continued far after their official planned end point. This is owed to the fact that during repairs, exchanges and components improvements had to be conducted, which further shifted the actual completion of a certain activity.

III. Test Phase

A. Description of the Test Phase

The MTF consists of two containers, the Service Section container and the FEG container. An overview of their final designs has been presented previously.^{5,6} The assembly and integration of the containers and the different subsystems was carried out between October 2016 and April 2017, at which point the integrated system test phase commenced. As the system test was performed at DLR in Bremen, Germany, which has substantially higher temperatures than the operational environment in the Antarctic, a dedicated cooling unit was used for the testing phase to simulate the performance of the free cooler and to manage the temperatures of the external cooling fluid loop.

A total of 15 different crop types were cultivated in the MTF during the system test and grow-out phase between April and September 2017. These crops ranged from Swiss chard and various lettuce cultivars to cucumber, pepper and tomato. For select crops, such as herbs and radishes, seeding was done directly onto fiber mats, but for easy transfer between the nursery area and the dedicated plant cultivation levels, most of the plants were seeded in rockwool cubes which were placed in specially designed 3D-printed rockwool holders. Compare Figure 2 (Bottom, left). For medium and large crops (e.g., cucumber, pepper), an additional support structure was included, to provide some support to the plants during the initial grow phase. The 3D-printed structures can be seen in Figure 2 (Top). A typical root system that was created within the aeroponic trays can be seen in Figure 2 (Bottom, right).



Figure 2: (Top) Rockwool holder with support structure. (Bottom, left) Rockwool holder with inserted rockwool cube. (Bottom, right) Typical root compartment.

During the system test phase, various tests were performed to determine the optimal MTF system settings and their respective performance characteristics. For example, light measurements were performed to fine-tune the spectral quality and power settings of the LED panels in the different plant cultivation racks. A dedicated safety inspection of the facility was also performed, as well as measurements of the noise level in the containers under various operational scenarios. The worst case noise levels in the Service Section and the FEG are listed in Table 1. In all cases the noise level is below the levels in which hearing protection would be suggested or mandatory (80 and 85 dB respectively) for facility operators according to German law.

Table 1: Worst case noise levels in the Service Section and the FEG.

Frequency (Hz)	Service Section (dB)	FEG (dB)
63	63.57	60.76
125	64.04	66.32
250	60.1	59.51
500	55	62.75
1000	44.68	56.88
2000	41.89	52.82
4000	35.71	48.45
8000	32.69	39.03

Aside from the tests which were performed to validate and characterize the functioning of the different subsystems and components, the test phase was also used to develop and check various operational aspects, such as microbial sampling, biomass sampling, cleaning and decontamination procedures and remote control operations which will be used during the actual operations phase in the Antarctic.

A dedicated Mission Control Center (MCC) has been built at DLR Bremen which will be used to communicate with crew in Antarctica and allow remote observation and control of MTF parameters and set-points. During the test phase, communication between the MTF and the MCC was established via patch antennas, enabling the transfer of camera images and telemetry data. During the operational phase in Antarctica, the MTF will transfer data via a fiber optic cable to Neumayer Station III (with a patch antenna serving as a backup), after which the data is transferred via satellite to Germany.



Figure 3: Interior of the FEG at the end of the test phase in Bremen, Germany.

A final harvest was conducted at the end of the test phase, in preparation of the facility cleaning and packing procedures prior to transport. Figure 3 shows the interior of the FEG some days prior to this harvest event, with the system nearly at full capacity and most of the plants in a fully matured state. Roughly 23 kg of edible biomass was obtained from the MTF during this final harvest, with approximately 25% of this harvest used for food safety and quality tests. A subset of food safety test results is presented below, in Table 2, along with the tolerable daily intake levels for various phthalate plasticizers for a person weighing 60 kg.⁹ Based on the test results, the overwintering crew in the Antarctic should be able to safely consume the produce from the MTF without any health risks due to MTF equipment/construction materials. Additional testing will be carried out during the operational phase to verify the consistency of these results throughout the life cycle of the facility.

Table 2: Phthalate contamination levels in edible biomass samples.

Phthalate	Leafy Greens (mg/kg)	Tomato, Pepper, Cucumber (mg/kg)	Tolerable Daily Intake (mg/day)
Di-butylphthalate	<0.1	<0.1	0.6
Di-ethylhexylphthalate	<0.1	<0.1	3.0
Di-iso-nonylphthalate	<0.5	<0.5	9.0
Di-iso-decylphthalate	<0.5	<0.5	9.0
Benzyl-butylphthalate	<0.1	<0.1	30.0

B. Mission Preparation Steps and Transport

From project inception, the EDEN ISS project always worked with a hard ‘launch’ date. In addition to being analogous to a space mission the ‘launch’ date represented the once a year date that large equipment destined for Antarctic could be put on a ship for transport to Antarctica. Ship access to Antarctica is only available during the Austral summer and if this window would be missed, than then project would need to wait a subsequent year for shipment to Antarctica. The launch date in which the EDEN ISS containers would be picked up from the DLR Institute of Space Systems was set as October 2, 2017. The overall transport chain to Antarctic followed the following pathway:

- October 2, 2017: Truck pickup of the three EDEN ISS containers at the DLR, Institute of Space Systems in Bremen and shipment to Hamburg harbor.
- October 9, 2017: Loading of the EDEN ISS containers onto the Golden Karoo container ship in Hamburg for ship transport to Cape Town, South Africa (Figure 4).
- November 9, 2017: Arrival of the Golden Karoo in Cape Town, South Africa and subsequent offloading of the EDEN ISS containers.
- December 1, 2017: Loading of the EDEN ISS containers onto the South African research vessel, S.A. Agulhas II for transport to vicinity of NM-III in Antarctica (departure from Cape Town December 8th, 2017) (Figure 4).
- January 3, 2018: Arrival of the S.A. Agulhas II in the NM-III vicinity and offloading of the EDEN ISS containers onto the sea ice for tracked vehicle transport to NM-III.



Figure 4: (Left) Loading of the EDEN ISS containers onto the Golden Karoo container ship in Hamburg, Germany (Photo credit: DLR/Hafenspedition). (Right) EDEN ISS containers on the S.A. Agulhas in Antarctic water (Photo credit: Will Jelbert).

The three EDEN ISS 20 ft shipping containers shipped to Antarctic included: the Service Section container, the FEG container and a standard transport container used to bring consumables, externally installed hardware and spare parts of the project. All three of these containers had to undergo a number of steps to prepare them for shipment. This involved the general sequence of events of; removing externally installed hardware (free cooler, external lights, antenna, etc.), the de-integration and separation of the Service Section and FEG containers, the removal of internally installed hardware considered fragile the securing of the remainder of the installed internal hardware, the general cleaning of the facility, the disinfection of the Service Section and FEG containers.

Container De-Integration

External hardware from the EDEN ISS containers was removed so that the facility could be transported as per standard shipping containers. That said, the Service Section and FEG containers were transported as ‘general cargo’ and did not have to meet the most stringent Convention for Safe Container (CSC) tests which are particularly relevant related to stacking of containers during storage or shipment. Although this restricted how the custom containers would be transported on the various ships, it reduced cost and certification requirements. Such a decision should be an early decision point for others considering employing shipping containers in their greenhouse or facility designs. The de-integration of the containers was the next hurdle in shipment preparation and because the activities would essentially be repeated in reverse upon arrival of the containers in the Antarctica, the team further documented the de-integration steps as they were being conducted and stored all hardware into two main tool chests so that all

bolts, fasteners and other hardware could be easily found and accessed in Antarctica. De-integration involved the following main actions:

- Disconnecting all power and sensor cabling from the power box and Argus control box for those devices that were connected directly from these locations to a place in the FEG container
- Disconnection of the two feed and two return lines for the nutrient delivery system
- Disconnection of the feed and return lines for the thermal control system cooling lines running to the LEDs
- Disconnection and storage for shipment of the 16 (eight each side) air management system flexible ducts
- Removal of ceiling, sidewall and floor panels around the container to container interface
- Removal of the four primary structural bolts holding the two containers together
- Use of a crane to separate the containers
- Installation of a transport wall onto the open side of each of the two containers

Container Shipping Masses

During this separation operation (September 13, 2017) the Service Section and FEG container were weighed to help the team further ensure that the container transport masses stayed below the 10 ton limit driven by the NM-III on-site crane that would be used to lift the containers onto the elevated platform. This weighing would also help dictate if additional project supplies could be shipped directly into the Service Section or FEG containers or if all project supplies would be shipped within the blue transport container. On this date, the Service Section container had a mass of 9.7 tons (metric) and the FEG container had a mass of 7.7 tons. All EDEN ISS containers were subsequently reweighed on October 2nd in their final shipping configuration. The Service Section container which included no additional boxes had a mass of 9.6 tons, the FEG container including 16 shipping boxes had a mass of 8.5 tons, while the blue transport container which included the remainder of the EDEN ISS project supplies (122 items/boxes) had a mass of 6.2 tons.

Spares, Packaging, Cleaning

Overall the project shipped 138 items with the three containers and subsequently shipped another six boxes via air transport from Cape Town to Antarctica and another six boxes on the German Polarstern icebreaker which was planned to arrive nearing the end of January 2018 (too late for the EDEN ISS containers). The bulk of these items were metal Zarges boxes filled with consumables and replacement parts. The project had conducted a detailed spares analysis which commenced with a Failure Modes, Effects and Criticality Analysis (FMECA)¹⁰ and acquired replacement parts for as many subsystems as possible. Each shipping box was inventoried and the compiled electronic inventory was a useful on-site reference in Antarctica for the deployment team to find any required hardware. The project required dangerous goods (nutrient salts, acid, base, CO₂, calibration gases, cleaning supplies, batteries and construction materials) were further documented and boxed up by a professional shipping company before being distributed between the FEG container and the blue transport container to satisfy safe storage requirements. No styrofoam packing peanuts were used in any of the EDEN ISS boxes to limit the risk of polluting the Antarctic environment. Once the bulk of the packaging was complete, the EDEN ISS containers were cleaned and the Service Section and FEG containers were disinfected using the project developed disinfection system, TransMADDS. In particular, the EDEN ISS team drained all fluids from all systems (e.g., nutrient delivery system, thermal control system, condensate in the atmospheric management system, the general sink and water lines as well as the fresh water and waste water tanks in the cold porch) and used a bleach solution to clean the tanks and supply and drain lines. This was followed by vacuuming up any debris within the facility and then a manual surface cleaning using mikroZid AF (Schülke) and paper towels. Subsequently the TransMADDS disinfection system with a 12% hydrogen peroxide solution was used in both the Service Section and FEG containers to clean surfaces that would otherwise not be accessible using its fine mist generator. This was followed by the installation of blue and yellow sticky card pest traps. All of these actions helped ensure that upon arrival in Antarctica the facility could be re-started in the completely clean state, while at the same time helped better ensure that the project would live up to its Antarctic Treaty commitments through the German Environmental Agency (Umweltbundesamt) and reduce the likelihood of the introduction of any non-native species.

Temperature during Shipment

Although estimates were made on the temperature environment that the EDEN ISS containers and equipment contained within would be exposed to in their shipment from Bremen, Germany to Neumayer Station III in Antarctica, several temperature loggers (Extech TH10) were installed within the containers prior to shipment. The temperature log over the shipment to Antarctica can be seen in Figure 5.

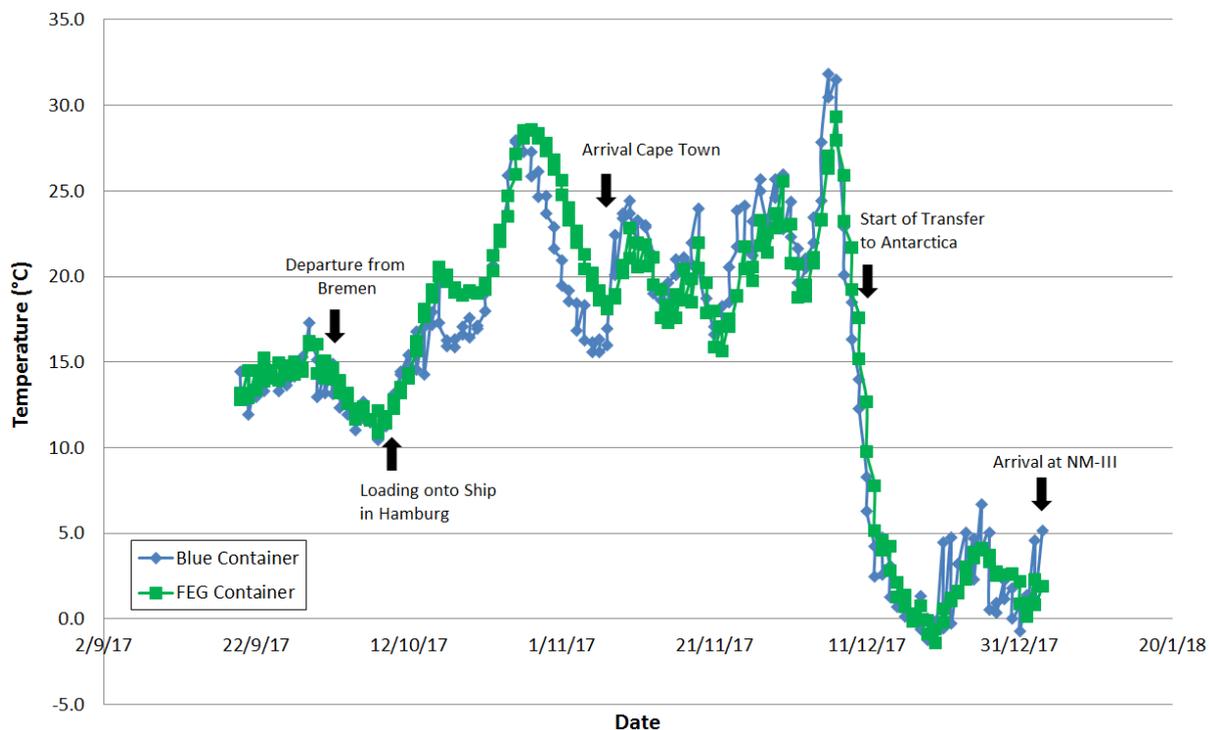


Figure 5: Plot of EDEN ISS transport temperature during transport to Antarctica.

As seen from

Figure 5 the EDEN ISS containers and hardware were exposed to temperatures between just below 0°C and just above 30°C during their transit from Bremen to NM-III. One temperature maximum approaching 30°C occurred when the Golden Karoo transited over the equatorial regions while the actual maximum occurred just after loading onto the S.A. Agulhas while the ship was still in harbor in Cape Town. Their placement on the deck of the S.A. Agulhas (Figure 4) also meant that the containers were cooled close to ambient temperatures during the Antarctic transit phase as is evident in Figure 5. These plots better help logistics planning for later project years whereby the transport temperature and durations can be better estimated for future equipment or project consumable shipments.

IV. Deployment Mission

A. Deployment at Neumayer Station III

The 2016-2017 Neumayer Station III summer field season was utilized to install the EDEN ISS elevated platform and install the large power cable and fiber optic cable running from NM-III to the platform. Having completed these activities the previous summer field season helped accelerate the actual EDEN ISS deployment schedule during the 2017-2018 NM-III field season. The deployment team arrived at the station via aircraft on December 20, 2017. The original planned date of the EDEN ISS containers arrival was ca. December 26, 2017 but due to weather and ice conditions, this was pushed back to January 3, 2018, when the S.A. Agulhas II arrived in the NM-III vicinity and dropped off the EDEN ISS containers. The offloading location as well as path used by the tracked vehicles that transported the containers to NM-III is shown in Figure 6.

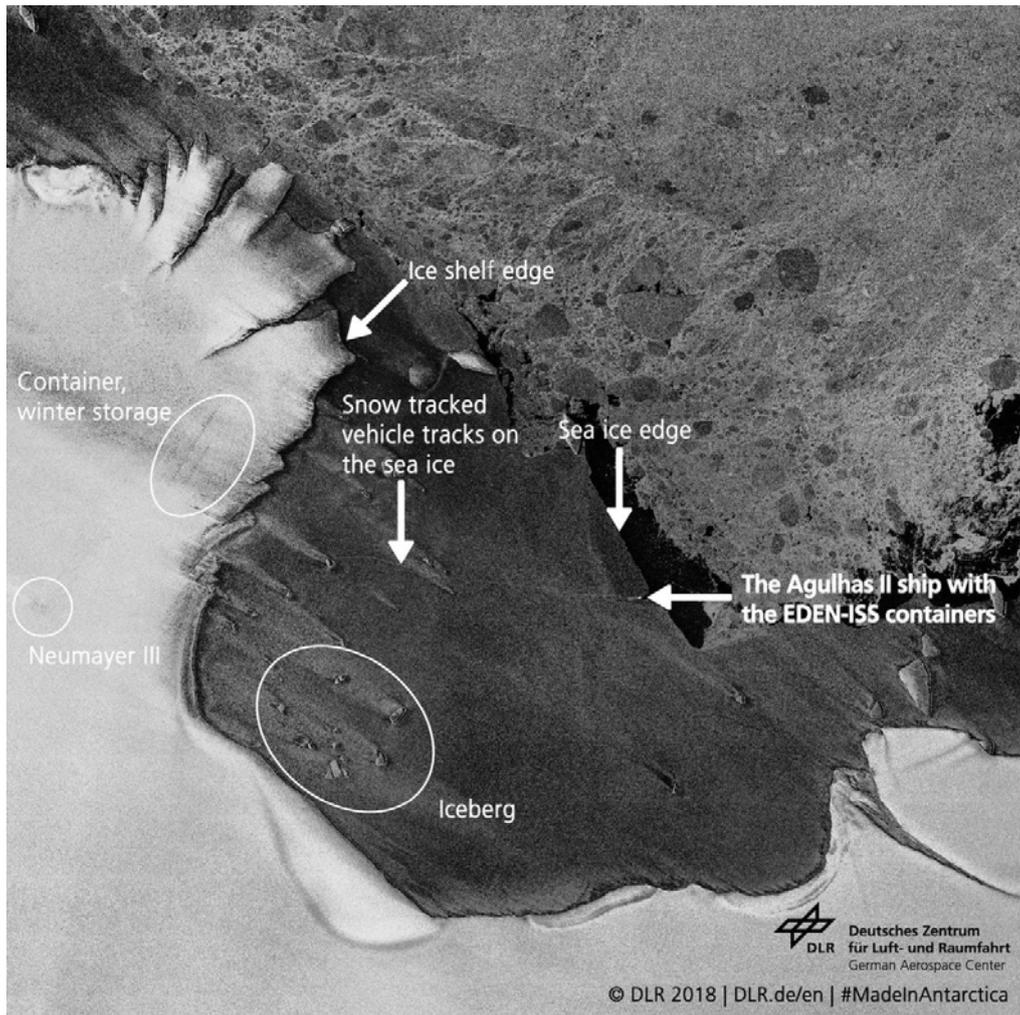


Figure 6: Offloading location of the S.A. Agulhas II research vessel. The EDEN ISS containers were offloaded onto the sea ice and driven on sled pulled by tracked vehicles to Neumayer Station III.

The initial deployment activities of the EDEN ISS containers involved the following:

- Parking of the containers in the direct vicinity of NM-III to empty a wide range of project supplies into NM-III (e.g., laboratory supplies, dangerous goods, temperature sensitive supplies).
- Pulling of the containers ca. 400 m to the EDEN ISS elevated platform. The Service Section container and FEG container were parked directly beside the platform while the blue transport container was parked ca. 20 m from the platform.
- Organizing supplies and setup of the blue transport container as a temporarily work space.
- Removal of the container transport walls.
- In conjunction with the AWI construction team, the Service Section container was temporarily installed onto the elevated platform and then removed so that the container twist locks could be welded to the platform.
- Reinstallation of the Service Section container.
- Installation of several pieces of container to container interface hardware that was required to be installed prior to the final placement of the containers together (subfloor air ducts, pull FEG disconnected cables back through the Service Section to FEG separation wall, prepare four container to container interface bolts).
- Placement of FEG container onto platform to ensure the container to container fit is appropriate.
- Remove FEG container from platform and weld the FEG container twist locks.
- Reinstall FEG container onto platform and tighten bolts connecting the two containers.

Although perfect alignment of the containers was not possible, following several attempts of readjusting the FEG container with respect to the Service Section container, a suitable container to container interface/alignment was achieved. The completion of the installation of the containers onto the platform also allowed the large NM-III crane to be used to install the free cooler and roof ladder onto the top of the Service Section container. This was followed by the installation of a wide array of external hardware and removal of some final transport hardware (e.g., window covers, covers for cable/pipe pass-throughs). The following overview timeline presents the main on-site activities that were conducted during the EDEN ISS deployment phase:

Week 1 (January 4 - 10)

- Install of containers on platform (Figure 7)
- Setup of communications hardware in NM-III multipurpose laboratory
- Installation of external hardware including, roof ladder, free cooler, free cooler cooling fluid pipes, cable channels, CO₂ distribution system, external lights, door bumpers, small stairs, chimney H-cowl, roof safety rails, cable and piping pass-throughs (rubber) in external walls
- Complete the connection of the NM-III to MTF power cable
- Setup of the energy monitoring system sensors in the power box
- Unpack tools in the MTF
- Activate internal heaters
- Complete air duct, NDS and thermal control system piping interface connections
- Insulate the container to container interface



Figure 7: Installation of the EDEN ISS containers onto the previously installed elevated platform.

Week 2 (January 11 – 17)

- Install patch antennas on MTF and on the NM-III station
- Complete Argus sensor wiring
- Fill the thermal control system with cooling fluids
- Complete air management system setup (install filters)
- Illumination system operational
- NDS tray installation, fill NDS with fresh water and perform leak check (Figure 8)
- Complete basic setup of multipurpose laboratory in NM-III (e.g., reverse osmosis system running)
- CDHS setup and testing
- Testing of gas safety system
- Arrival of the second part of EDEN ISS deployment team (January 13)



Figure 8: NDS hardware located in the FEG subfloor area as shown during the early on-site setup of the EDEN ISS greenhouse in Antarctica (several cameras and sensors remain covered with hand gloves so as to protect them from TransMADDS sprayed hydrogen peroxide).

Week 3 (January 18 – 25)

- Complete CO₂ distribution system connections
- Installation of CO₂ flowmeter
- Test of AMS and thermal control system via software
- ISS rack-like plant growth system setup
- Improve FEG atmospheric closure (tape air ducts, insulate/better seal connections)
- Insulate external cable and piping pass-throughs
- Raising of the platform and installation of primary platform stairs
- Improve the structural rigidity against wind of the free cooler electronics box by installing a metal brace
- Install multi wavelength imagers for plant health monitoring



Figure 9: EDEN ISS facility following the elevation of the platform and installation of the platform stairs.

Week 4 (January 26 – February 1)

- Employ the TransMADDS in the FEG
- Antarctica to Europe communication troubleshooting
- First planting in the MTF
- Troubleshooting of various MTF subsystems (external lighting, CO₂ delivery)
- Continued ISS rack-like plant growth system setup and testing
- Calibration and final testing of various sensors (pH, electrical conductivity, condensate collection, CO₂ flowmeter, leak sensors)
- Installation of protection for the fiber optic cable as it runs along the external platform
- Prepare the FEG nursery
- NDS fully operational

B. Initiation Phase of the MTF

Although troubleshooting of various subsystems continued into early February, increased focus was placed on testing and readying the MTF for overwinter operations. During this phase, seeds were germinated within the dedicated nursery of the FEG. Further MTF initiation directed activities included:

Week 5 & 6 (February 3 – 14)

- Initiation of control system/enabling all system alarms and appropriate thresholds
- CO₂ leak test within FEG and ISS rack-like growth chambers
- Planting of first crops in the nursery (start of germination)
- Final teach-in of EDEN ISS overwintering crew member (Paul Zabel) on various systems
- Last sensor calibration within the AMS
- Solving of additional Argus control problems
- Inventory and final reorganization of spares and supplies within the station and the MTF
- Start germination process within the ISPR
- Test of multi wavelength imagers with maturing plants
- Test of communication lines between MTF and NM-III as well as to the MCC (Germany)
- Troubleshooting with microbial contamination within the nutrient solution during ramp-up phase

FEG Leakage Test

During the initiation phase of the MTF, an air exchange test with CO₂ as tracer gas was performed. The results of this test can be used to estimate the air exchange between the internal environment of the FEG and the surrounding environment (in particular, the greatest amount of leakage is expected to be through the FEG and the Service Section separation wall). The FEG atmosphere has an elevated concentration of CO₂ in order to increase plant growth rate. For future project calculations such as CO₂ uptake by the crop, it is important to quantify the atmospheric closure/leakage rate of the FEG.

The air exchange rate test was conducted by first increasing the CO₂ concentration well above the level of the surrounding environment. The concentration in the FEG was raised to 2000 ppm, while the surrounding environment has an average concentration of around 400 ppm. As test results can be influenced by the metabolism of plants or humans, it was conducted before plants were planted in the FEG and without anyone in the facility. The concentration decay of CO₂ can then be used to calculate the air exchange rate. Figure 10 shows the results of the test conducted during the initiation phase of the MTF. The CO₂ concentration was logged for a period of almost 24 hours. Over this period the concentration dropped from 2000 ppm to 1550 ppm. The calculated air exchange rate is lower than 50% air volume per day. For comparison, the maximum permitted leakage requirement defined at the beginning of the project was 500% air volumes per day. In the case of FEG leakage rates, a more accurate value could be obtained with a longer duration test (i.e., allowing the FEG CO₂ concentration to drop to values closure than actual ambient values). This was, however, not possible during the MTF initiation phase as the deployment team members needed to work in the facility to complete their tasks before the end of the field season. A longer duration test is thus planned for the next MTF maintenance period between November 2018 and January 2019.

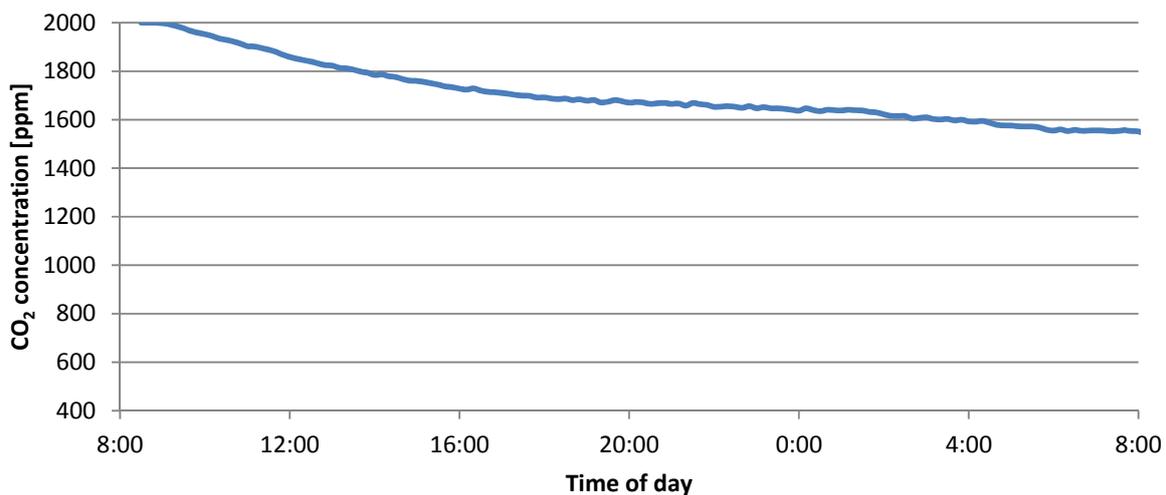


Figure 10: CO₂ concentration inside the FEG during the air exchange test with carbon dioxide as tracer gas.

Mission Control Center

In the EDEN ISS Command and Data Handling System (CDHS) various software tools are used to control EDEN ISS equipment, and to generate data/images which will be made available to the EDEN ISS network. To briefly summarize, there are two different categories:

- Real time dataflow, providing the capability of hardware control to remote centers
- Data logs and images that are periodically acquired and stored on the MTF computers

This data has to be distributed to project remote sites (User Home Bases – UHB), even if in a different way depending on the responsibilities and tasks of each individual remote center (not all the data has to be requested by all the remote centers). The real time dataflow (telemetry/telecommand) has to be managed by means of the server/client features of the provided tools. The client applications have to be installed at each UHB and connected to the server applications in the MTF over the EDEN ISS remote operations network. The remote operations network is composed of:

- DLR – Bremen (Germany)
- UHB – Thales Alenia Space Italia (Italy)

- UHB – University of Guelph (Canada)
- UHB – Telespazio (Italy)
- UHB – University of Wageningen (Netherlands)
- UHB – University of Florida (USA)

The handling of project data logs and images is done by software application developed by the EDEN ISS project team. These software programs are installed on the MTF computers providing the possibility to manually or automatically transfer data and images from the MTF to NM-III for backup and to the MCC at DLR in Bremen (see Figure 11). The baseline foresees the use of software in automatic way with the scheduling of one single image and one or more data log transfer events per day. The images and data logs are routed from the MTF to the MCC in Bremen via the NM-III station using the already in place satellite connection between NM-III and AWI in Bremerhaven, Germany. Project data is stored on a FTP server in the MCC and retrieved using a FTP connection by the respective UHBs.



Figure 11: Mission Control Center at DLR Bremen (Photo credit: Bruno Stubenrauch).

The MCC is responsible for the overall operations of EDEN ISS and therefore it is provided with the capabilities to remotely control all MTF equipment (including the ISPR rack and the plant health monitoring imaging system). In addition, it is possible to receive, visualize, store as well as distribute the recorded data logs and images for more detailed analysis.

C. Off-Nominal Issues during Deployment Mission

Although the EDEN ISS containers were delivered later than planned, the actual on-site deployment activities shadowed the timeline and the actual activities that were included in the field plan developed in the lead-up to the field season. So although the MTF facility was in the anticipated/planned state at the time of departure of the deployment team, there were several unexpected events that occurred during the field season and a subset of these off-nominal issues are described here:

- *Service Section to FEG door not opening fully.* As described previously, great effort was placed on getting the Service Section and FEG containers to line up properly on the elevated platform. The result was that the containers were approximately 1 to 1.5 cm further separated from each other than they were in Bremen (where the containers were installed directly on the ground) and that one container was angled slightly with respect to the other. The latter was apparent from the perspective that the Service Section to FEG door (installed on the frame of the FEG container) could not be fully opened, as it would bump directly into the Service Section floor. Several adjustments had to be made to the door, the first is that it was moved up as

much as possible on its hinges and the rubber installed on the underside of the door was removed. As removing the rubber insulation on the bottom of the door reduced the atmospheric closure of the FEG, a permanently installed bar including a band of rubber insulation was installed directly onto the floor of the FEG. When the door was closed it would push up against the rubber and seal the door connection (Figure 12, left).

- *External damage to the underside of the containers during transport.* Although only first noticed following the installation of the containers onto the elevated platform, it was evident that the Service Section and FEG container bottoms had been pierced during transport to Antarctica. Although one of the two damage locations was significantly deeper, both were insulated with spray foam and then taped over with aluminum tape.
- *Leaks in the thermal control system and NDS piping.* Several leaks in the plastic piping of the thermal control system and NDS were found during early testing/leak checks of these systems with water. It is obvious that the transport to Antarctica was the primary reason for these leaks but as they were somewhat minimal, the project would not have taken any additional measures pre-shipment to reduce the number of leaks that were apparent. These leaks were fixed either by removing a section of piping and installing a freshly glued section or applying additional glue to the connection in question. That said, as one of the leaks of the thermal control system occurred from a union connection, it is suggested that following long duration transport, such as occurred with the EDEN ISS containers, that all union connections should be checked/re-tightened prior to system initiation. Although this was already a known issue with the tightly compact thermal system rack, a lesson learned that should be carried over to future greenhouse system designs is that all connections should be better accessible and systems rack should not be built in such a compact manner if they limit access to all installed components. Thus in addition to providing better access to all connections following shipment, this would simplify repairs and maintenance activities on the thermal control system (on-site maintenance and repair should always be considered a high priority in subsystem design).
- *Removing air from the thermal control system.* Several issues arose in the initial operation of the thermal control system in which the appropriate cooling fluid temperatures in the thermal system could not be maintained. Although considerable time was spent manually releasing air via the various thermal system air release valves, it was obvious that further air was trapped within the roof-top free cooler and this was resulting in less optimal heat transfer. As the free cooler was only used for several hours in Bremen (due to the summer weather during the Bremen test phase) and a large standalone electric cooler was used, such issues were not observed during the AIT phase. The opening and closing of the various air release valves during the Antarctic deployment phase resulted in one of the air release valves breaking. In particular, although the valve could be reclosed it could not be reopened to release air as otherwise a leak of the Tyfoxit F50 cooling fluid would permanently occur. A project decision was made to change the air release valve while the full deployment team was on-site to reduce the possible heavy workload for the single overwintering operator should this air release valve be further required. Additionally a solid protocol for getting the air out of the free cooler loops was developed which involved adjusting thermal control system pump settings and manually opening and closing the various other valves in the system, both of which helped force further fluid through the system and further dislodging any remaining air bubbles.
- *Blockage of flow through the secondary CO₂ regulator.* Although detailed analysis showed that problems due to low temperature were not likely to arise with the CO₂ distribution system even if it were to be placed outside the MTF, on several of the cold days of the deployment phase it was observed that even with the internal CO₂ solenoid valve open, no CO₂ would flow into the FEG. Following leak checks, testing and additional observations, it was concluded that this was a result of CO₂ freezing up within the secondary regulator of the CO₂ distribution system (Linde W20/B regulator with 0.5 to 10.5 bar output, part number: 7616606). When a small amount of heat was applied to the regulator a small grain of CO₂ ice could be heard as it was dislodged and CO₂ could then flow again. To combat this problem, a small electric heater was installed directly onto the regulator body and a minor amount of insulation added (see top regulator in Figure 12, right). Control logic was built into the Argus control system to activate the heater on a set schedule and no additional blockages in the CO₂ delivery system were observed.
- *Microbial contamination in the NDS.* Early in the deployment the NDS was filled with nominal NM-III water to test the system for leaks. This water was later drained and the system refilled with reverse osmosis water and concentrated hydroponic stock solutions added to their respective NDS tanks. Several NDS check-out tests were conducted to ensure that the system could maintain the desired pH, electrical conductivity, tank level set-points while testing NDS hardware in the lead-up to plants being added to the FEG. Plants were added approximately a week later and approximately two days later the team remarked that the solution in NDS tank 1 (salad crop hydroponic solution) was cloudy, had a small amount of foam

buildup floating on the surface and was emitting a moderately foul odor. This was followed by the observation of a white/pinkish fungus on the surface of the rockwool plugs that some of the plants were growing in. Images of both the growth tray fungus and state of the hydroponic solution were taken and sent along to the EDEN ISS science team in Europe. Samples were also collected for later analysis. Although the on-site team reacted initially by increasing the duty cycle of the ozone generators feeding the NDS tanks, which resulted in some improvement over the period of a day, considering input from the remote science team and the fact that the deployment team would be departing in less than a week, leaving the on-site operator alone, the deployment team decided that proceeding with a full-system clean-out was the preferred option prior to their departure. The team proceeded in removing all plants from the MTF, draining the entire NDS, cleaning all accessible surfaces (e.g., plant trays, inside of NDS tanks) with appropriate disinfectants, filling the NDS with a concentrated bleach solution and operating all pumps and components for a period of 5 hours. The system was then drained, filled with water, re-drained and left to dry. In conjunction, additional seeds were germinated in the station and the ozone generator settings reassessed and further increased. The results and analysis of the samples returned will be reported upon in a later publication.



Figure 12: (Left) Floor installed door bar with insulating rubber. (Right) CO₂ distribution system with installed secondary regulator heater.

- The external communication lines to the MTF control PC (Argus) were not stable and remote access to this control PC (through personnel from Argus or other members of the EDEN ISS project remote operations team) was not possible. This situation lasted several days and the planned upgrades and improvements could not be made to the CDHS. Eventually the situation was resolved by the AWI information technology department by readjusting the firewall settings within the server architecture in Bremerhaven.

Another key element of the EDEN ISS MTF is the International Space Station rack-like plant growth system. Although several of the top-level on-site activities with the rack-like system have been described here, a full description of its deployment and early operations is described elsewhere.¹¹

V. Status after four Months of Operation

MTF Power Consumption

An energy measurement system was installed within the MTF power box to monitor subsystem power draws. The measurement system is called Diris Digiware and is sold by the company Socomec. Diris Digiware is a modular system with different modules for voltage and current measurements. The system implemented in the EDEN ISS MTF consists of a voltage measurement module which constantly measures the electrical voltage of the 3-phase main power supply, seven current measurement modules which measure the electrical current of 19 different subsystems or components, a liquid-crystal display in the power box and a communications module to transmit the data to the MTF computer network. Preliminary results taken from the energy measurement system during the early phase of Antarctic operations are presented in Table 3.

Table 3: MTF Measured Power Draws over the period of one week from February 26 to March 4, 2018.

Subsystem	Energy used over one week (kWh)	Average Power (kW)	% of Overall Draw
Overall MTF	1445	8.60	N/A
CDHS	93	0.55	6.5%
ILS	437	2.60	30.4%
NDS	22	0.13	1.5%
AMS	470	2.80	32.7%
ISPR	48	0.29	3.3%
Thermal	291	1.73	20.2%
Common equipment	77	0.46	5.4%

The values in Table 3 demonstrate that the MTF draws an average of 8.6 kW. It also illustrates that as would be expected the ILS and AMS represent the major power draws of the greenhouse. It should be noted that as the “Overall MTF” energy in kWh is a measured value and does not perfectly equate to the sum of the energy use measured for the other subsystems (difference only ca. 7 kWh). Also, it should be noted that the presented values represent what is expected to be an average week of MTF operations, but that measurements will be continued throughout the entire Antarctic operational phase and that some variation in these values is to be expected.



Figure 13: Multipurpose laboratory within the NM-III station, which was outfitted with dedicated EDEN ISS equipment in order to support the post-harvest analysis and sample preparation.

In support of the nominal experiment phase, a dedicated laboratory (multi-purpose lab) within the NM-III station was outfitted. Compare Figure 13. The laboratory is equipped with tools for microbial investigations, food quality and safety measurements and general equipment for post-harvest analysis. The lab is also used for sample preparation and stabilization. All samples (food quality- and safety related as well as microbial samples) are stored in a mobile freezer at -40°C. A dedicated sample-return strategy was worked out in order to transport the samples back to Europe for further analysis after the experiment phase will end (~end of November 2018).

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