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GREENHOUSE DESIGN CONCEPTS FOR MOON AND MARS

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Abstract
This paper will show the methodology used for developing a greenhouse design concept for moon and Mars, derived from the EDEN ISS simulation facility in Antarctica. This document details the preliminary design of a future planetary greenhouse, adapted from the Mobile Test Facility (MTF) which was built and operated as part of the EDEN ISS project. Lessons learned from the Antarctic operations phase, as well as references to existing mission scenarios were considered for establishing system requirements. Based on these requirements, a preliminary design of the greenhouse structure, and plant cultivation subsystems was developed.

The preliminary design presented in this document is a deployable cylindrical structure, with rigid end caps and an inflatable membrane shell. The structure has been sized to fit within the payload fairing of a Falcon 9 launcher (or similar), with a stowed configuration diameter of 4 meters and a length of 6.3 meters. Following deployment, the structure is envisioned to be 12.9 meters long and the membrane shell will expand to a diameter of 5 meters. An estimation of the subsystem volumes was made in order to design the internal configuration. This internal layout offers 30.8 m² of cultivation area, a more than twofold increase over the existing Mobile Test Facility. Differences and similarities between the two facilities are discussed.

I. EDEN ISS MTF INTRODUCTION

Technological innovation for the cultivation of food in space is integral to the success of future, human space exploration. The EU-funded project, EDEN ISS (March 2015-April 2019), designed, built, and tested an analogue testbed greenhouse, for advancing Controlled

Environment Agriculture (CEA) technologies for plant cultivation on earth and in space.

The EDEN ISS Mobile Test Facility (MTF), accommodating an advanced nutrient delivery system, high performance LED lighting system, bio-detection and decontamination system, and food quality and safety technologies, was built to demonstrate and validate these key technologies.

In February 2018, the MTF began its 9.5-month long nominal operations phase in the extreme environmental conditions of Antarctica.

Fig. 1: EDEN ISS stationed in Antarctica, credit: DLR, 2018.

The results included 268 kilograms of cultivated food produced for consumption (REF. 1) by the over-wintering crew members of the Neumayer III station over 9.5 months in an area of 12.5 square metres, along with compiled data sets on system and subsystem performance, as well as subjective data accrued by crewmembers on the functionality of the designed greenhouse configuration. These inputs formed the basis for developing ‘lessons learned’ following the analogue test period.

II. GREENHOUSE FOR MOON/MARS INTRODUCTION

After operation of the Mobile Test Facility in the Antarctic, lessons learned were collected and incorporated into a design for space application. Lessons learned concerned the areas of volume improvements, reliability, serviceability, system performance, crop yield, crew acceptance and contamination.

In a workshop conducted at the German Aerospace Center (DLR), Bremen (25.-27. March 2019) results and lessons learned from the Antarctic mission were reviewed. A Concurrent Engineering (CE) process was conducted with an aim towards optimization of the built and tested EDEN ISS facility into a greenhouse design suitable for space application. The applied Concurrent Engineering (CE) process is based on the optimization of the conventional established design process characterized by centralized and sequential engineering. During the workshop, domain experts from partner institutions, DLR, LIQUIFER Systems Group (LSG) and Arescosmo (AS) were present to cover all technical and procedural aspects and create a consistent design.

Integral to the CE study in Bremen was the definition of mission objectives for bringing the space greenhouse from its origin point on earth to its destination on moon or Mars, definition of mission and system requirements, and identification and selection of options. The Study Phase included configuration and budget estimates (for mass, power, volume, etc.), iterations on existing subsystem(s) and equipment designs (trade-offs considered for several options), and new subsystem design.

Fig. 2: Space greenhouse design based on lessons learned from EDEN ISS MTF in Antarctica, credit: EDEN ISS Consortium, visualisation: LIQUIFER Systems Group, 2019

Top-level objectives of the CE Study

The top-level objectives for the CE study, are to enable sustainable, human exploration of Mars or moon, for a duration of 2 to 10 years, with the provision of fresh, nutritious food for psychological and physical wellbeing.

Both designs, EDEN ISS MTF, and the space greenhouse demonstrate economical design principles, aimed at providing the highest level of functionality and optimization, with the least required space and maintenance.

It was deemed important, that the outcome of the study would enable a single-launch per greenhouse module and that each module shall provide at least 25 m² of grow area, at least twice as much grow area as the EDEN ISS MTF.

Mission Scenario and requirements developed in the CE Study

Mission scenarios for location specific architectures on the moon or Mars are currently incomplete, as no detailed plans yet exist for actual missions to the moon and Mars. Therefore, the mission scenario and design requirements are subject to the following 'rationale-based assumptions' and 'informed speculations', as determined in the CE study:

- Deployment of the greenhouse module into Low Earth Orbit (LEO) via Launcher
    - *Requirement / Assumption - it is assumed that the Falcon 9 (REF. 1), or Falcon 9 Heavy is the baseline launcher for the greenhouse*
- Utilizing an Attitude Orbital Control System (AOCS), the greenhouse module is stabilized in position and attitude
    - *Requirement/Assumption - it is assumed that an attitude control system is accommodated and integrated with the greenhouse module prior to launch*
- The module is docked to a transfer vehicle* and is transferred to its target location (either towards a target infrastructure in target orbit or directly to orbit)
- A landing vehicle* docks with the greenhouse module and lands it on the target surface
- Robotic infrastructure unloads the module and transports it to its final destination on ground
- The greenhouse module is attached to an existing habitat
    - *Requirement/Assumption - it is assumed that a base infrastructure exists at the target location (e.g. moon or Mars) providing power, thermal control, and life-support for the crew*
- The expandable greenhouse module is deployed, extends to its full length, and is covered by regolith
    - *Requirement/Assumption - for moon and Mars applications, onsite construction tools/robotics for constructing a regolith radiation shield are assumed for protection against radiation and debris*
- The deployed section is fitted with all remaining equipment (plant growth trays and the plant seedlings)
    - *Requirement – greenhouse subsystems are pre-installed in pressurized Service Module prior to launch, requiring only an interface connection to an existing habitation module for power and thermal heat load transfer before operation*
- The greenhouse begins operation

**Note: Transfer, landing, and positioning of the greenhouse module on a planetary surface is assumed and reside outside the scope of this design study. Massing configurations were estimated however for the inclusion of a docking vehicle, capable of passive docking with a transfer vehicle in LEO, in the final launch estimations. It is hypothetically possible to include a docking vehicle composed of a Service Module similar to that used by Cygnus (1700 kg) (REF. 3), with a lightweight radiation and MMOD shield similar to the Mars TransHab shield (950 kg)(30cm thick with areal density ~10 kg/m²) (REF. 4), for a combined weight of 2650kg.*

Other Considerations

A good portion of the CE Study was committed to the design and configuration of the space greenhouse, since the main focus is on plant cultivation technologies. The form, structure, and configuration of the EDEN ISS greenhouse Antarctica, and the space greenhouse vary, largely determined by the environmental conditions of the target mission locations, and by the ferrying method of transporting the greenhouses to their target location.

In addition, space parameters create more stringent requirements and entail a greater level of safety design due to the inhospitable environment presented on both moon and Mars for human survival. In comparison, the EDEN ISS MTF was tested in an extreme environment, but not one that poses an immediate threat to the wellbeing and survival of its crew members.

Transportation logistics

For the mission in Antarctica, the MTF was transported from its building and (pre-)testing site at DLR in Bremen, Germany, to the Neumayer III German Research Center in Antarctica, at the Ekström Ice Shelf on the Princess Martha Coast of Queen Maud Land. Two containers, similar to standardized shipping containers and deemed logistically and economically ideal for land and sea transport, were designed to accommodate all essential plant growth technologies for the mission. The EDEN ISS MTF was transported via freight truck from Bremen to Hamburg, Germany, where it was loaded onboard the Golden Karoo, for sea transfer to Cape Town, South Africa. It was further transferred onto the AGULHAS II, for transport to the Antarctic ice shelf. The MTF was brought to its mission location by a team of piston bullies, used for traversing snow and ice terrain. A standard crane lifted the facility onto a pre-constructed platform.

Ferrying methods for transporting equipment to space require stringent measures in keeping mass and volume at a minimum. For the EDEN ISS space greenhouse, it was reasoned that the launch shall not exceed 22.800 kg for accommodation in the Falcon 9, and its dimensions be limited to the 4.6 m in diameter, and 6.6 m in length for the same vessel. Due to the cylindrical configuration of the launcher, a cylindrical form for the space greenhouse was conceived to maximize use of the given internal volume of the launcher. In the stowed configuration, the designed greenhouse system is 4 m in diameter and 6.3 meters in length.

Environmental Concerns

Due to the lack of atmosphere on the moon and limited atmosphere on Mars, pressurization of the greenhouse is essential for operation. The service module, with all pre-installed subsystems is pressurized prior to launch. Once the greenhouse has been completely deployed, the entire system shall be pressurized with atmosphere being supplied by the habitat already at base camp. For continuous operation, the greenhouse system is designed to detect a rate of pressure change with > 1 mbar/ h, and allow pressure control at a rate of 0.5 mbar/ h.

Due to the frequency meteorite and micrometeorite events on the moon and high levels of radiation on moon and Mars, a mission requirement for radiation and debris shielding is included.

Safety Factors

The system design permits one-fault tolerance for functions relevant to keep the plants and crew alive and provides additional features for fire detection and suppression. Furthermore, the system provides contingency equipment for breathing in case of a fire.

III. SPACE GREENHOUSE DESIGN

The structure of the greenhouse has been preliminarily sized based on considerations regarding the launch system and the possibility to expand its volume both in longitudinal and radial directions. In particular, the mass and volume budgets for each of the structural elements, which are to be assembled into the full greenhouse module, were estimated based on past and present structures and concepts.

In the stowed configuration the greenhouse has a length of 6.3 m and a diameter of 4 m, and in the deployed configuration, the overall length of the deployed greenhouse module is 12.9 meters, with a diameter of 5 meters. A length of 3 meters is needed for the rigid Service Section and the actual cultivation areas has a length of 9 meters.

The baseline configuration is a hybrid concept composed of rigid and deployable sections.

Primary Structure

The structure is composed of two rigid end caps, one functioning as the service section, with all subsystems pre-installed, and the other as a docking interface and secondary means of ingress/egress. The Cygnus Pressurized Cargo Module (PCM) is used as reference for the design for the service section, being a rigid pressurized module with cylindrical aluminium shell. The docking cap consists of a rigid conical section and adapter ring structure. Between the end caps are five structural frames with telescopic elements that expand outward during deployment, increasing the overall diameter to 5m. The deployed frame extensions are supported by integrated struts.

Four of the structural frames additionally expand longitudinally along the ground plane during deployment. To obtain the desired spacing between the frames upon deployment, deployable spacers, longerons and floor elements are implemented. Additionally, these elements serve as the structural bracing, as well as the shelving elements which are later installed by crew members.

The frame structures, spacers and longerons are all assumed to be made from aluminium. Future investigations will determine whether alternative materials would be preferable based on mass, cost or other considerations. The deployable floor elements are made from MadFlex, a flexible, foldable, light, and durable material; the shelves are similarly made from this material, specifically the translucent ‘LUX’ variant.

Membrane shell

The membrane shell interfaces with the structural frame and represents the expandable part of the module. It shall contain 1 bar pressure and protect the inner habitable volume from the outer space environment (protection from micrometeorites and cosmic radiation shall be provided by a regolith cover, external to the design). The membrane is composed of several functional layers, together providing a high degree of airtightness and strength. Included is an Internal Barrier layer (Kevlar), Air Containment Bladder (Coretech Hydroguard), Structural Restraint Webbing (Zylon+VITON), Multi-Layer Insulation (MLI)(20 layers Mylar/Kapton), and External Barrier layer (2 layers Kevlar), each one providing one or more specific function(s). (Options and trade-offs for materials, REF. 5).

In the deployed configuration, the membrane shell acquires a cylindrical shape with toroidal ends. In the stowed configuration, the flexible layers are folded between the structural frames. (REF. 6)

The main structural properties of the membrane are provided by the structural restraint webbing, which consists of Zylon ribbons oriented in longitudinal (meridian ribbons) and circumferential (parallel ribbons) direction. The ribbons form an interwoven net and are stitched together at crossing points and ends by a strong “Ferrari” stitching pattern. The eyelets on the ends of ribbons are connected by rings to metal bulkheads on the rigid end caps. The membrane shell functional layer design, along with the Zylon restraint webbing and rigid-flexible interface designs, are based on past projects, such as the project STEPS2 (Project co-funded by EU on the "Misura Piattaforme Innovative" - Phase 2 of POR ERDF 2007/2013).

A restraint cover is foreseen to protect the inflatable membrane while it is compressed among the structural components in the stowed configuration.

Supports: Legs and Pillows

In order to support the greenhouse module in its place, a system of legs and ‘pillows’ was designed to stabilise the structure along its axis and to improve thermal insulation by decreasing thermal bridges with underlying terrain.

The telescopic legs are made of aluminium and extended from the rigid service section end cap to rest on the planetary surface. The inflatable ‘pillows’, 8 m in length, with a total surface area of about 11 m2, will be used to support the membrane shell.

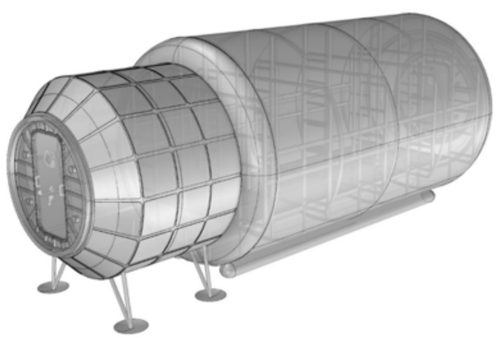

Fig. 3: Space greenhouse baseline configuration, credit: EDEN ISS Consortium, visualisation: LIQUIFER Systems Group, 2019

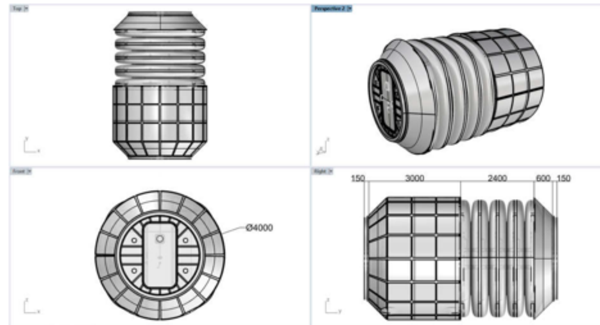

Fig. 4: Greenhouse module in stowed configuration, credit: EDEN ISS Consortium, visualisation: LIQUIFER Systems Group, 2019

Structural Components	**Mass (kg)**
Service Section	2000
Docking interface	500
Internal Structural Frames	3500
Spacers and Longerons	851.2
Floor Panels	84
Plant Shelves	65
Membrane Shell	746
Restraint Cover	36
Support structure - Legs	300
Support structure - Pillows	30.8
Total Mass	**8113**

Table 1: Mass estimates for structural design of space greenhouse

IV. GREENHOUSE SUBSYSTEMS

The subsystem design is based on the as-built system of the EDEN ISS Mobile Test Facility, and a scaling factor has been estimated for a growth area increase of factor 2. Final calculations were scaled to reflect the overall growth area of 30.8 m².

The greenhouse module, as well as service section, including all pre-installed equipment, shall withstand launch loads and loads during transfer and landing on the planetary surface.

Power Control and Distribution System (PCDS)

The power control and distribution system consists of the main power box, an energy measurement system, cable channels and power cables, and the internal and external lighting (excluding the plant illumination system).

The three-phase line from the habitat is split into lines for each subsystem, which are further split into independent lines to each of the subsystems’ different components.

Atmosphere Management System (AMS)

The AMS counteracts the deviations of the air from the nominal conditions, as a result of gas exchanges and thermal loads, by filtering (undesirable micro-organism growth and trace gases such as ethylene), and dehumidifying the air in the greenhouse.

A liquid-air cooling coil is used to dehumidify air, and the recovered condensate water is subsequently filtered, sterilized and pumped to the fresh water tank for re-use.

Nutrient Delivery System (NDS)

The overall NDS design is based on an existing hydroponic concept, developed by DLR Institute of Space Systems, which is a hybridization of classic NFT and aeroponics.

The entire NDS solution loop is closed and recirculating; nutrient solution is pumped into the cultivation zone of the plants and excess solution is collected to a central reservoir and pumped back to the nutrient tanks housed in the Service Section.

Water from the fresh water tank is injected into the nutrient tanks in response to the predetermined tank water level, or as required for nutrient composition control.

In contrast to the MTF, which incorporated one high-pressure pump per plant rack, the preliminary design for the space greenhouse foresees the use of two large pumps (1 active, 1 spare) for each of the nutrient tanks for delivery of the nutrient solution to the plants. Reduction in the number of pumps in the system, reduces the number of expected component failures.

Thermal Control System (TCS)

The thermal control system is an active system, which uses liquid cooling loops to dissipate the heat from the AMS and LED panels, and transport the excessive heat to the connected and external habitat. Additionally, heaters are present to ensure the temperature does not drop below 5°C (TBC) in case of subsystem failures.

Control and Data Handling System (CDHS)

The baseline control and monitoring system design consists of two PCs connected over an Ethernet switch to the network. The Main Control Server PC, including RAID system, is used to control and monitor all systems and the Camera Control PC is dedicated to processing camera images and buffering control data.

Illumination System (IS)

The Illumination System consists of LED panels which are integrated into the undersides of the shelves used in the greenhouse for accommodating the plant growth trays. For initial sizing, the setup in the MTF is referenced, with one water-cooled LED panel per tray.

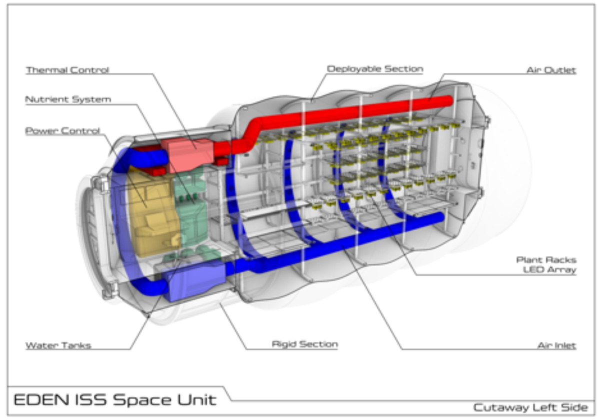

Fig. 5: Section view of greenhouse module, credit: EDEN ISS Consortium, visualisation: LIQUIFER Systems Group, 2019

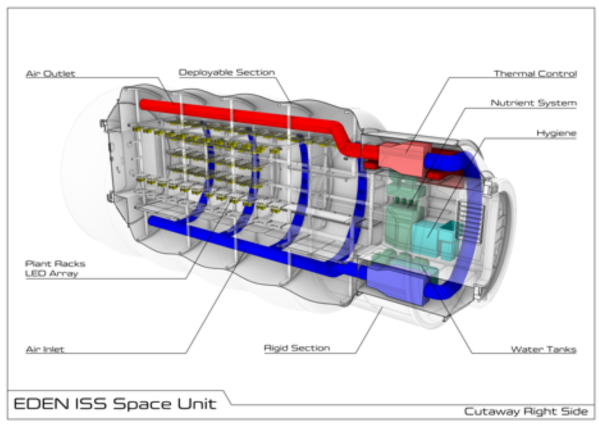

Fig. 6: Section view of greenhouse module, credit: EDEN ISS Consortium, visualisation: LIQUIFER Systems Group, 2019

Subsystems	**Mass (kg)**
Structure	760
AMS	884
NDS	766
TCS	990
IS	900
CDHS	691
PCDS	680
Other/Misc. (tools & consumables)	65
Total Mass	**5736**

Table 2: Mass estimates for subsystems of space greenhouse based on EDEN ISS MTF

V. INTERNAL LAYOUT AND SUBSYSTEM DESIGN – TRANSFORMATION FROM ANTARCTIC TO SPACE EXPLORATION APPLICATION BASED ON LESSONS LEARNED

1. The service section corridor as designed in the MTF was considered too small for performing tasks and for properly accessing equipment
Actions:
- work desk has been re-located to the cultivation area
- subsystems have been reconfigured and corridor width increased

2. Cleaning facilities in EDEN ISS proved to be insufficient in size and impractical at the operational level
Actions:
- a washing machine has been introduced into the Service Section of the greenhouse module, which can be filled with (plant) trays and valves for cleaning purposes

3. Piping and harness is in a too confined configuration for large-scale and effective cleaning and,
4. piping design for the thermal systemled to bubbles
Actions:
- the subfloor area of the greenhouse has been rearranged by placing the piping below the racks and lower on the floor for better access from all sides
- piping has been arranged in a way to prevent the formation of bubbles

5. The modular configuration for tall growing plants was found advantageous, however improvements should be made on removability of plant trays, for cultivation and cleaning purposes
Actions:
- racks have been designed to be modular with greater capacity for alteration depending on the requirements of the space mission. The greenhouse cultivation area accommodates a 60/40 split between short and tall crops.
- due to the increased dimensions of the space greenhouse, additional racks can be accommodated in the middle of the structure, while still providing sufficient corridor space on both sides to facilitate the crew-plant interactions.
- a mobile ladder has been implemented in the planetary greenhouse
- a washing machine has been introduced into the Service Section of the greenhouse module, which can be filled with (plant) trays and valves for cleaning purposes

6. water recovery of AMS was considered inadequate due to the condensation of the plants. plate-heat-exchanger too small, cooling liquid has to be on a lower temperature, more buffer required for heat-exchanger
Actions:
- Air Management System (AMS) has been enlarged

7. Thermal system too compact for access/ repairs
Actions:
- Thermal Control System (TCS) has been enlarged

8. Cold porch and window obsolete for space applications
Actions:
- cold porch and window are eliminated from design

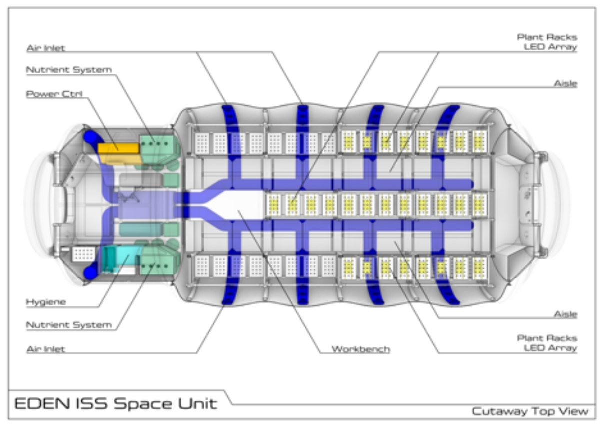

Fig. 7: Section view of greenhouse module illustrating central row of grow space, credit: EDEN ISS Consortium, visualisation: LIQUIFER Systems Group, 2019

VI. CONCLUSION

A preliminary design of a greenhouse module for future crewed Mars missions has been developed. Based on lessons learned from the Antarctic operations phase of the Mobile Test Facility, as well as an initial mission scenario concept, assumptions and requirements were defined which drove the greenhouse module design. The lessons learned were furthermore implemented in the design of the greenhouse subsystems, with an aim towards more reliable, efficient and effective performance.

	Mass (kg)
Structural Components	8113
Subsystems	5736
Total Mass	**13,849**
Total Mass with 20% margin	**16,618.8**

Table 3: Total mass estimates for structural design and subsystems of space greenhouse

Mass estimations for the space greenhouse indicate that a single launch using a Falcon 9 launcher, with a carrying capacity of 22,800 kg is feasible. Furthermore, it can be concluded that the mission may also support an additional docking vehicle with an estimated weight of 2650 kg (with 20% margin 3180 kg).

Areas for further study

All of the subsystem designs require further development efforts in order to obtain a system which can be qualified for space missions. However, some key aspects have a higher level of uncertainty and as such need to be prioritized in future project phases.

Gas Exchange System

The integration of a greenhouse into the life support system of a habitat, or planetary base, can provide significant benefits but also comes with a number of challenges. In particular, the air exchange between the habitat and the greenhouse, in order to optimally benefit from the natural processes of plants, is something which needs to be studied in further detail. In previous design studies the possibility of periodic direct air exchange between the habitat and the greenhouse was considered, where oxygen-rich air is vented to the habitat and CO2-rich air is provided to the greenhouse. An alternative to such a system could be the implementation of CO2 and O2 capture and storage systems, with dedicated supply systems transporting the captured gases to the desired location. A detailed trade-off needs to be done on the different options as early in the design process as possible.

Nutrient Delivery System

The nutrient delivery system with pressurized tanks instead of dedicated pumps as proposed here has not been tested yet in the EDEN ISS Mobile Test Facility or in the laboratories of the project partners. A test system should be developed as soon as possible to determine whether or not the expected benefits occur or not and to assess potential unforeseen disadvantages and operational challenges. The results of this test should be used to review the nutrient delivery system design.

Importance of building prototypes

Building the EDEN ISS and testing in Antarctica yielded significant results for future technology developments which could not have been estimated with a sole paper study or in developing single subsystems for testing. Additionally, the benefits for the overwintering crew were so positive that the EDEN ISS greenhouse still remains as supplementary and complimentary infrastructure next to the Neumayer III Station to support the crew with fresh vegetables during the long and isolated winters.

II.I ACKNOWLEDGMENTS

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II.II Acronyms

Air Management System	AMS
Command and Data Handling System	CDHS
European Space Agency	ESA
Illumination System	IS
Low Earth Orbit	LEO
Micro-meteoroid and orbital debris	MMOD
Mobile Test Facility	MTF
Nutrient Delivery System	NDS
Orbital Sciences Corporation	OSC
Power Control and Distribution System	PCDS
Pressurized Cargo Module	PCM
Redundant Array of Independent Disks	RAID
Thermal Control System	TCS

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