

The EDEN ISS Rack-Like Plant Growth Facility

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Plant cultivation in large-scale closed environments is challenging and several key technologies necessary for space-based plant production are not yet space-qualified or remain in early stages of development. The Horizon2020 EDEN ISS project aims at development and demonstration of higher plant cultivation technologies, suitable for near term deployment on the International Space Station (ISS) and from a long-term perspective, within Moon and Mars habitats. The EDEN ISS consortium, as part of the performed activities, has designed a plant cultivation system to have form, fit and function of a European Drawer Rack 2 (EDR II) payload, with a modularity that would allow its incremental installation in the ISS homonymous rack, occupying from one-quarter rack to the full system. The design phase is toward conclusion, and the system will be developed and tested in a laboratory environment as well as at the highly-isolated German Antarctic Neumayer Station III, in a container-sized test facility to provide realistic mass flow relationships and interaction with a crewed environment. This paper describes the goals and system general design status of EDEN ISS ISPR plant growth facility.

Nomenclature

<i>DLR</i>	=	German Aerospace Center
<i>EDR</i>	=	European Drawer Rack
<i>EI</i>	=	Experimental Insert
<i>ISPR</i>	=	International Standard Payload Rack
<i>ISS</i>	=	International Space Station
<i>TASI</i>	=	Thales Alenia Space Italia

I. Introduction

Food production in space is a critical elements for supporting a sustainable human exploration activity beyond Low Earth Orbit. The use of higher plants-based systems to achieve this objective is of great interest, given the multiple additional benefits carried along the use of these bio-regenerative technologies, such as contribute to air revitalization and water processing, as well as bringing psychological benefit to the crew. The goal of the EDEN ISS Horizon2020 project is to advance controlled environment agriculture technologies beyond the state-of-the-art through demonstration in laboratory and analog environment. The main task of Thales Alenia Space Italia (TASI) within the consortium led by the DLR Institute of Space Systems in Bremen is to develop a rack-like facility targeting at short-term safe food production and operation on-board the International Space Station (ISS), as the next step to past and currently on-orbit operated systems⁶ (e.g. NASA Veggie). The facility, called EDEN ISS ISPR, will first be tested in the TASI Recyclab technological area in Turin. The ISPR will be then shipped to Bremen for integration in a mobile container-sized greenhouse test facility for integrated testing and subsequent shipment in

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2017 to the German Neumayer III station in Antarctica. The station is operated by the Alfred Wegener Institute and has unique capabilities and infrastructure for testing plant cultivation under extreme environmental and logistical conditions. The container-sized system will host also a much bigger greenhouse facility, the FEG (Future Exploration Greenhouse), built under the responsibility of the other EDEN ISS project partners with DLR coordination, which will provide year-round fresh food supplementation for the Neumayer Station III crew.

In September 2015, the EDEN ISS project partners gathered at the DLR Institute of Space Systems in Bremen, Germany to conduct a design workshop for the Antarctic greenhouse system. DLR's Concurrent Engineering Facility (CEF), a design laboratory, was utilized for two weeks to generate the preliminary design of the mobile test facility (MTF). The EDEN ISS project work plan and status, the CE study organization, as well as the MTF preliminary design are described section by section in great detail in Bamsey et al. 2016¹. The cited paper includes a description of the logistics and operations of the facility, as well as an illustration of the preliminary system budgets.

This paper gives a quick overview of the MTF preliminary configuration, focusing then on the preliminary design of the EDEN ISS ISPR, which is being developed as a potential payload for the European Drawer Rack II (EDR II). EDR II will be flown to the ISS in 2017 and will provide interfaces for multiple experimental inserts (EIs). Following the description of the overall design, the different subsystems of the facility will be explained in greater detail. The paper concludes with an illustration of the preliminary system budgets. It should be recalled that this represents the facility design at the completion of the CE study and that, as with any design process the design will still evolve over the course of its development.

II. Mobile Test Facility General Overview

The EDEN ISS MTF is being designed to provide fresh produce for overwintering crews at the Neumayer III Antarctic station, as well as to advance the readiness of a number of plant growth technologies (including the ISPR plant cultivation system demonstrator) and operational procedures. The MTF will be located approximately 200 m south from the Neumayer Station III Antarctic research station, see Figure 1.

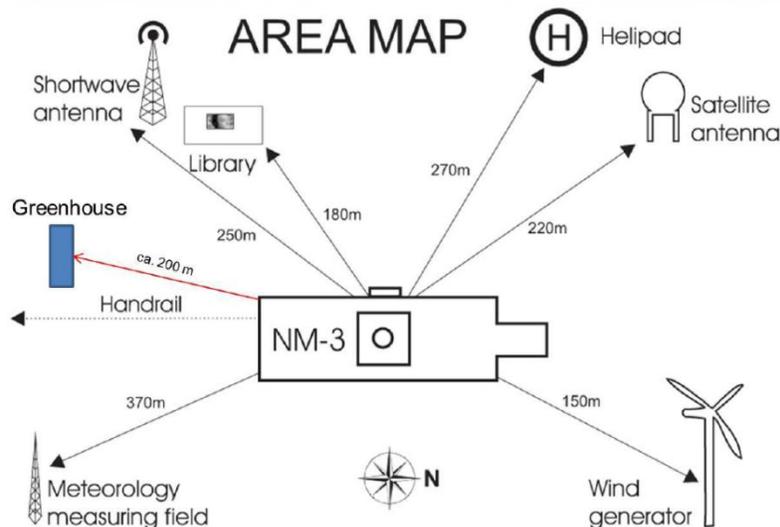


Figure 1. Area map of the Neumayer III station, including the proposed position of the EDEN ISS greenhouse

The actual MTF consists of two 20 foot high cube containers, which will be placed on top of an external platform. The MTF is subdivided into three distinct sections, as shown in Figure 2:

- Cold porch: a small room providing storage and acting as a buffer to prevent the entry of cold air into the plant cultivation and main working areas when the main entrance door of the facility is utilized.
- Service Section: houses the primary control, air management, thermal control, and nutrient delivery systems of the MTF as well as the ISPR plant growth demonstrator.
- Future Exploration Greenhouse (FEG): the main plant growth area of the MTF, consisting of multilevel plant growth racks operating in a precisely controlled environment.

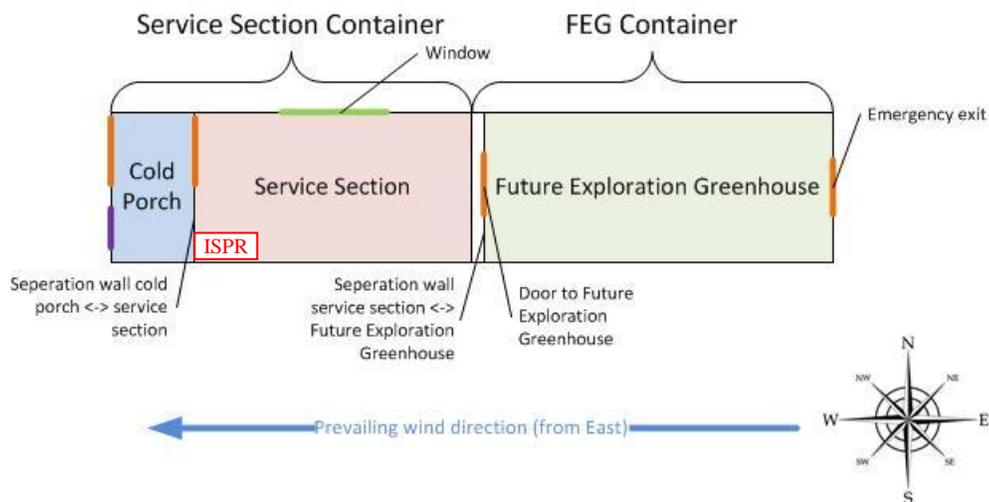


Figure 2. Overview of the EDEN ISS MTF main elements.

Most of the subsystems are housed in a rack system along the South-facing side of the Service Section, see Figure 3. It was decided to place the ISPR as close to the cold porch as possible, since there are no interfaces between the ISPR and the FEG, as opposed to the other subsystems which do interface with the FEG.

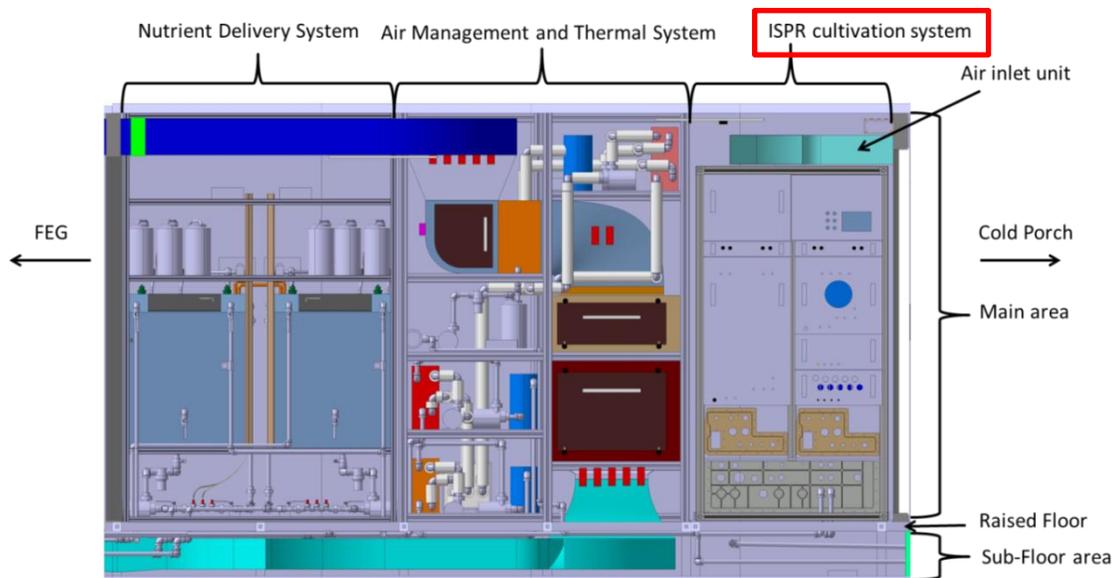


Figure 3. Service Section cut view with ISPR – South side

III. ISPR Cultivation System Preliminary Design Overview

The main objective of the laboratory and Antarctica ISPR system demonstration is to advance the TRL of the plant growth facility technologies, in view of a near term experiment on the ISS. The facility shall represent an increment with respect to current flight capabilities represented by the NASA Veggie system, mainly in terms of:

- Higher available growth surface (0.5-1,0 m² range)
- Longer production cycle possible by complete nutrient solution circulation (and not only watering of substrate with slow release fertilization)
- Robust and reliable safe and high quality food production (while Veggie control capability may be considered limited)
- Taller crop can be accommodated (up to 60 cm available for tall growth chamber shoot zone)

In order to target a feasible ISS exploitation scenario, the system is being designed as an EDR II payload (see Figure 4). EDR II is a European rack, capable of hosting up to three experimental inserts (EIs). EDEN ISS ISPR will be modular and capable of operating either:

- as a single EI, 1/4 rack, to test critical subsystems (i.e. nutrient delivery system)
- as a single EI, 1/2 rack, to test a complete system with one growth chamber (of incremental complexity)
- as multiple EIs, 3/4 or full rack, with up to three independently controlled growth chambers (note that the current design baselines two growth chambers)

Figure 5 is an image of the CAD model of the EDEN ISS ISPR system preliminary concept. As can be seen, it is clearly designed as precursor of ISS European Drawer Rack EDR II plant growth payload.

The lower section of the rack is dedicated to the interfaces (power, data and cooling water) with the Mobile Test Facility. Above this section are placed the interfaces between the rack and the plant growth facility, exactly as for EDR II EIs interface panels. In the central portion of the system, the following payload drawers are accommodated (see dedicated sections for more details):

- Power, Command and Data Handling Module
- Nutrient Storage and Distribution Module
- Growth chamber Modules (1 for short plants, 1 for taller plants), including each chamber dedicated air management systems, root modules and crop shoot-zone volumes
- Illumination Modules (one for each growth chamber)

In the top portion of the rack, a panel for manual monitoring and control of some of the rack's key functional parameters will be housed, together with a storage drawer.

The ISPR subsystems preliminary design is detailed in the following sections.

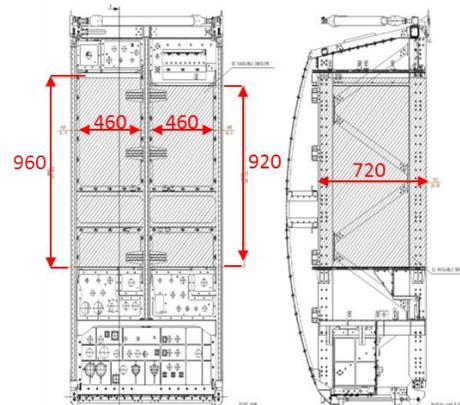


Figure 4. EDR II Experimental Inserts (EIs) available volume

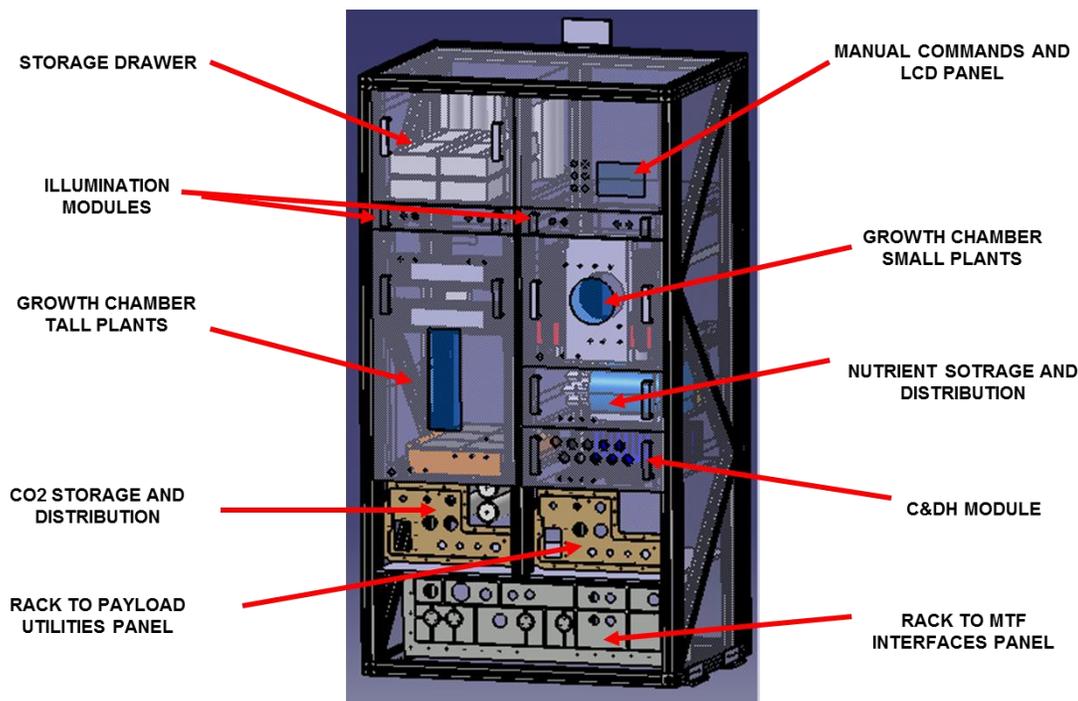


Figure 5. EDEN ISS ISPR cultivation system concept.

A. ISPR Structure Subsystem

A general overview of the main structure-related aspects is provided in Figure 6.

The main ISPR structure is composed from Bosch Rexroth aluminum profiles to favor implementation of multiple configurations in the rack development process, while limiting the unit mass. This flexibility has been required by the necessity of the system of being used as a research and development tool. Removable aluminum panels enclose the profiles frame in order to provide a barrier to the MTF environment while allowing easy accessibility for maintenance activities.

The structure is sized to be close to an ISS International Standard Payload Rack. From the front, the rack presents a structure extremely common to the ISS rack also from the visual point of view.

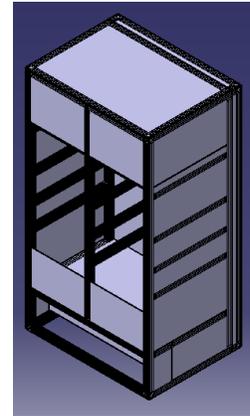


Figure 6. ISPR structure.

B. ISPR Illumination Subsystem

The ISPR illumination system relies on water cooled LEDs. The LED panel preliminary specifications are the following:

- The light sources will be controllable via an IP based control protocol over Ethernet cable. Each wavelength in the light source can be controlled individually.
- The light spectrum will have the following composition:
 - 15% blue (400-500nm)
 - 10% green (500-600nm)
 - 75% red (600-700nm)
 - 2% far-red (700-750nm)
- Each light source will have a temperature sensor and over temperature protection.
- The light sources will be water cooled with water at 20°C.
- The light distribution pattern will be designed to create the best uniformity 15 cm above the plant tray.

The illumination module preliminary drawing is given in Figure 7.

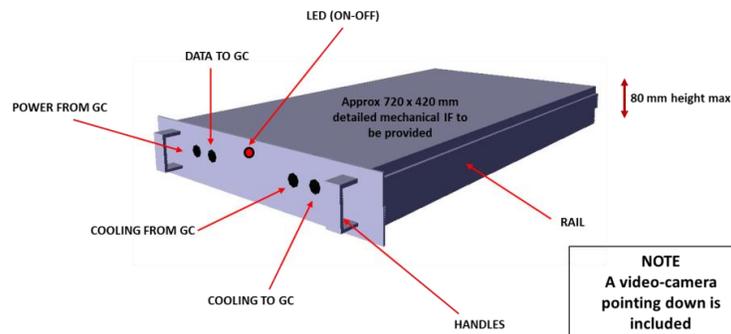


Figure 7: Illumination module preliminary representation, including interfaces to growth chamber (GC)

C. Atmosphere Management Subsystem and Thermal Control Subsystem

Each growth volume will have an independent air management system. The air management system will include:

- Temperature and humidity control system (THC)
- Major constituents control system (MCCS), managing the environmental pressure, as well as O₂ and CO₂ concentration
- Trace contaminants and microbiological control system (TCCS), removing organic gaseous contaminants (i.e. ethylene) as well as filtering out microbes and viruses.

The air management system has been preliminary designed in order to be easily accessible and maintainable. Further upgrade of the selected technologies is also possible in this way. The overall system preliminary block diagram is reported in Figure 8.

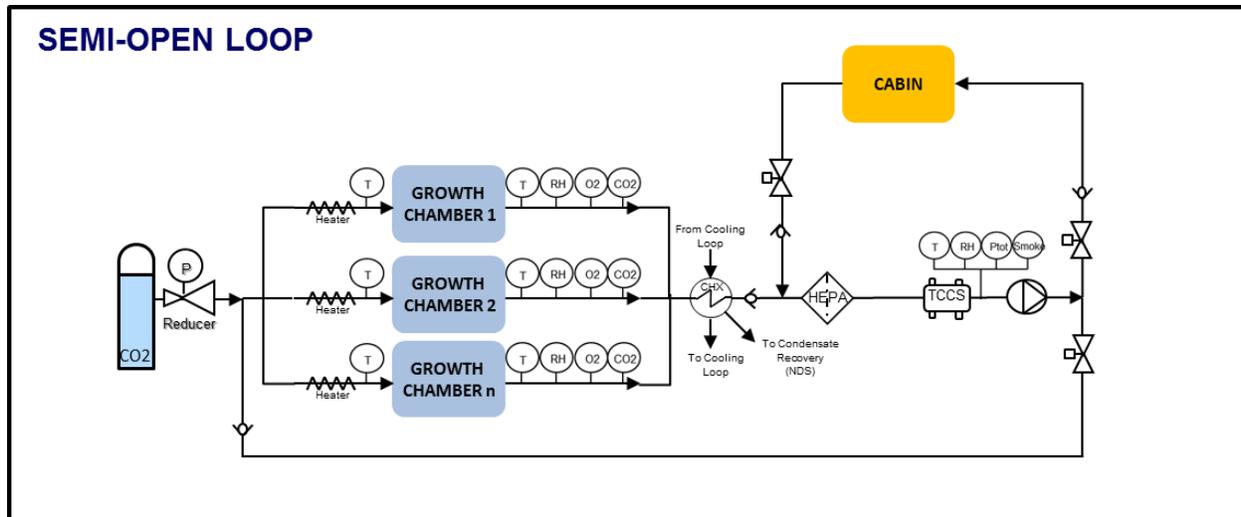


Figure 8: Overall air management system conceptual block diagram

Temperature and humidity control

The air extracted from the shoot-zone volume is cooled by a thermo-electric cooler (TEC, using Peltier effect) to remove sensible heat loads as well as latent heat loads through condensation of water vapor. The water vapor is then collected by gravity in a custom designed recipient, and then pumped through a UV-LED based disinfection system to the DI water reservoir within the Nutrient Storage Module. The TEC is an air to water heat exchanger, and the heat collected at the water side is removed by a cooling water loop.

Major constituents' control

For oxygen and carbon dioxide concentration control, a semi-open loop strategy is implemented. In normal operations the shoot-zone air is circulated in a closed loop until the O_2 concentration rises to a certain threshold (i.e. not acceptable fire risk). Then air is exchanged with the MTF by electro-valves to equalize O_2 concentration and reach back normal levels. CO_2 is added as needed via a dedicated 500g CO_2 bottle.

Trace contaminants and microbiological control

After passing through the THC elements, air passes through a 0.2 μm membrane for filtering of bacteria, viruses and particulate. An additional passive filter for organic contaminants removal is then placed downstream, prior to the reintroduction of the air within the growth chamber shoot-zone volume.

Given the periodic air exchanges between the MTF crewed environment and the shoot-zone volume (as per semi-open loop strategy described above), the following precautions for limiting cross contamination have been implemented:

- Air collected from the MTF is introduced downstream the THC and upstream the TCCS (so no energy is wasted to cool/dehumidify air already at lower temperature and humidity)
- Air rejected to the MTF is first processed through both TEC and TCCS (to reduce system water loss and avoid rejection of contaminants to the outer environment)

D. Nutrient Delivery Subsystem

The Nutrient Delivery System (NDS) is divided among multiple modules (ISPR drawers):

- The nutrient storage and distribution module/drawer, containing the reservoirs (stock solutions, acid/base, DI water, nutrient solution), the delivery pumps and the UV-C condensate bactericidal system
- The root module within each growth chamber module/drawer, containing the growth substrate, its container and the sensors and actuators needed to guarantee appropriate distribution of water and nutrient solution within the different area of the substrate.

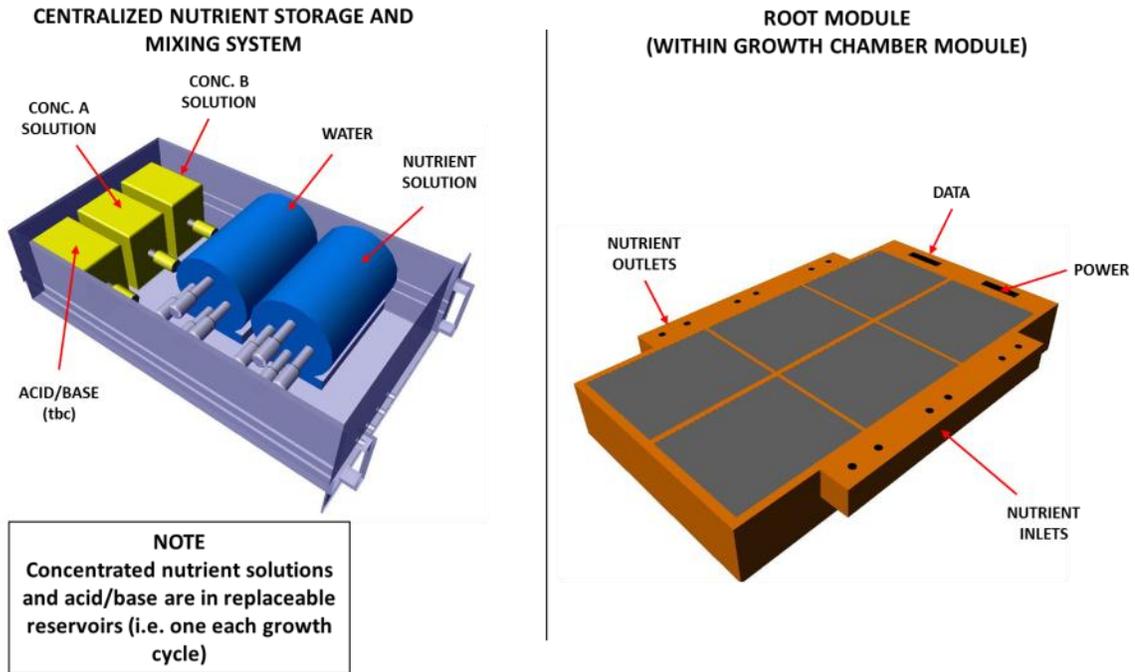


Figure 9: Nutrient storage and distribution module/drawer (left); root module (right)

The NDS block diagram is reported in Figure 10. Either DI water or nutrient solution can be delivered to the root modules. The block diagram is explained as follows.

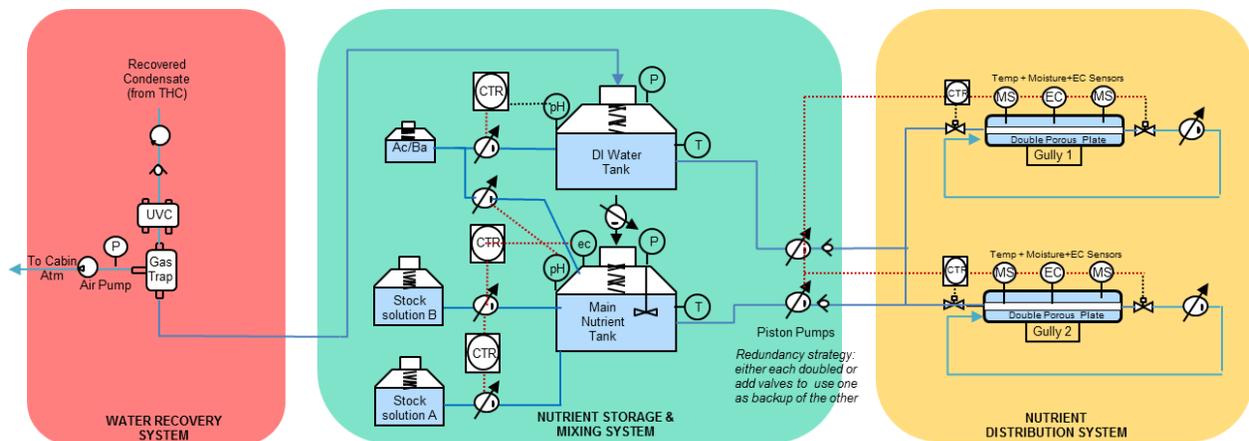


Figure 10: Nutrient Delivery System Conceptual Block Diagram

Nutrient storage and distribution

DI water is used in case of salt accumulation within the root module (EC increment within the substrate or porous elements cleaning to prevent clogging). The DI water pH will be monitored and controlled by acid/base injection. The nutrient solution EC and pH will be monitored and controlled by water or stock solution (from dedicated reservoirs) injection. Injection will be allowed by LabVIEW® controlled piston pumps. Concentrated solution tanks will be flexible, replaceable (self-locking QD), stored dry and filled with water only before use. Water and nutrient reservoirs current baseline solution is a bellow tank. A solution for preparation of concentrate nutrient solution from dry nutrients possibly compatible with a microgravity environment will be tested.

Water recovery

Condensate recovered from the THC will be disinfected with UVC-LEDs and then passed through a membrane contactor (gas trap) to separate the air from the water flow.

Root module

Particular attention is given to the root module. Porous stainless steel plates are used for nutrient solution distribution and reclamation (in case of over watering) throughout multiple (4) substrate pillows. The plates are passivated to favor priming of the pores. Substrate moisture, EC and temperature are monitored via sensors connected to a common data downlink port. Three moisture sensors per pillow will be used. The substrate pillows reusability will be investigated (at least two growth cycles), as well as proper maintenance procedures developed for the Neumayer testing phase to be applicable to operation on ISS. EC will be monitored powering only one sensor each time, to prevent interference.

Electro-valves (or pneumatic valves), connected to a common power bus, regulate the water flow (with a single outlet and inlet per each root module) through the multiple porous plates.

E. Command and Data Handling Subsystem

The Command and Data Handling (C&DH) System is housed in the Power, Command and Data Handling module/drawer (Figure 11).

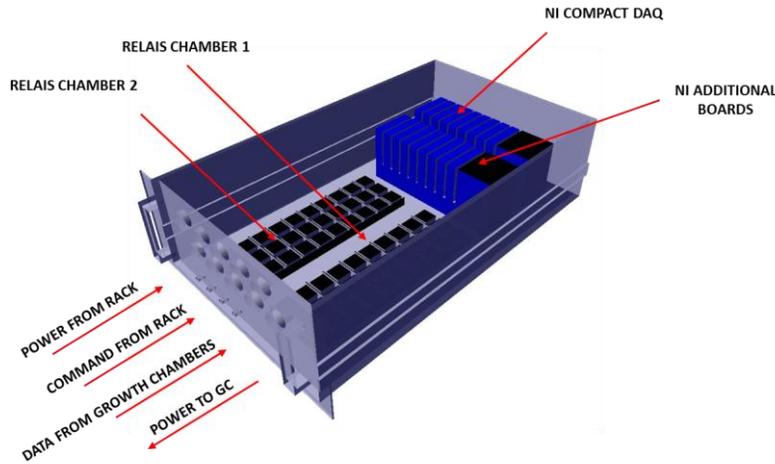


Figure 11: Power, Command and Data Handling module/drawer

The general conceptual schematic of the C&DH system is given in Figure 12. Data are collected from the P/L drawer sensors into a NI Compact DAQ (cDAQ) board via dedicated I/O modules. Commands are generated by feedback control implemented within the cDAQ controller, and transferred to power relays via internal Digital Output (DO) modules. The different programs can be loaded onto the cDAQ board via rack-external signal, generated by a LabVIEW based computer and transmitted by LAN interface. The same interface is used for telemetry downlink.

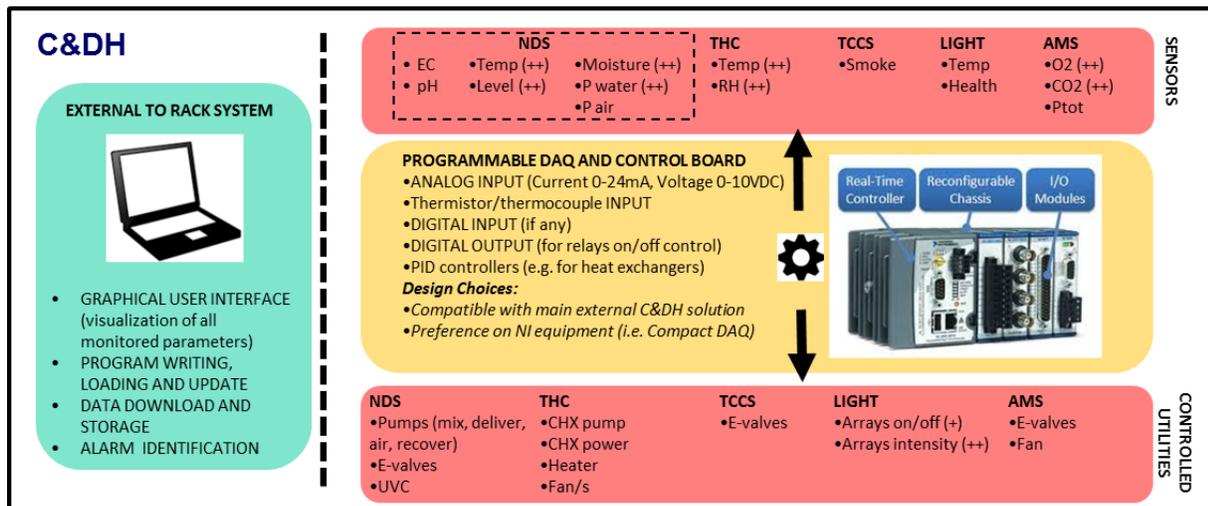


Figure 12: Command and Data Handling system conceptual schematic

F. Power Distribution and Control Subsystem

Figure 13 reports the Power Distribution and Control System conceptual schematic.

Power will be delivered from the MTF to the ISPR via 230 VAC, 10 A electrical IF (230 VAC connector –plug - characteristics to be identified by DLR). 230 VAC to 24 VDC conversion will be provided within the ISPR volume, under the responsibility of TASI. DLR shall provide AC/DC converters models eventually used in the FEG, in an effort to increase commonality and have common spare parts.

The power will be then distributed to the different utilities via the commanded relays placed in the Command and Data Handling module/drawer (Figure 11).

Moreover, manual override of key utilities (i.e. illumination, irrigation) on/off conditions will be possible, especially to favor maintenance.

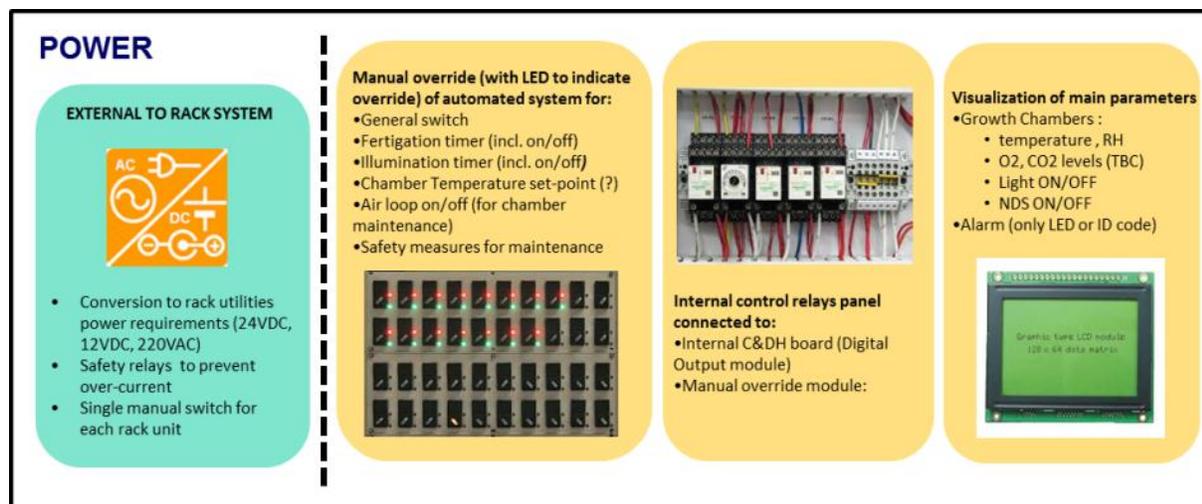


Figure 13: Power Distribution and Control System conceptual schematic

G. Overall system budgets

During the CE-study the overall system budgets (mass, electrical energy and power, data generation, water usage, nutrient usage and biomass production) were tracked for all domains. The following sections show the estimates of the ISPR system mass and power budgets as of the end of the study. These values are preliminary and will likely change over the course of the project. Final system budgets will be published later in the project.

Table 1: ISPR system mass and power preliminary budgets

	Mass	Peak power	Peak Power day - nominal mode	Peak Power night - nominal mode
ISPR test facility	335 kg	1124 W	1124 W	470 W
Spares, consumables, tools	146 kg	n.a.	n.a.	n.a.
TOTAL	481 kg	1124 W	1124 W	470 W

IV. ISPR Preliminary Crop Selection

The limitations on crop cultivation, in terms of available cultivation area within the ISPR and the limited Antarctic campaign duration, require selecting only a number of crops suggested for space life support systems³. Researchers from Wageningen University and Research (WUR), experts in terrestrial greenhouse cultivation, developed a crop selection methodology⁴. However, also peculiar interests of the project partners were considered based on space-related experiments heritage (analogy with current NASA Veggie testing as well as Italian heritage of Rucola on-orbit testing). The result is the following crop list:

- Dwarf Tomato (cultivar 2011-281M, F1 1202 or F12414)
- Rucola (cultivated, cultivar to be selected)
- Chinese cabbage Tokyo Bekana
- Outredgeous lettuce

The selected crops will be grown in climate rooms at Wageningen University starting in early 2016. Initially, growth experiments will be conducted in order to define the optimal light recipes (spectral quality, light intensity and duration), as well as to optimize water and nutrient use. Afterwards specific experiments will be performed under similar conditions (size and constraints) as in the ISPR in order to test the cultivation and management of (combinations of) crops. The main features of the experiments will entail the determination of light recipes, optimizing CO₂ dosage in accordance to plant growth rates, and relative humidity and temperature in relation to the light system being used. I/O flows (energy and mass) will be monitored throughout the experiments. A monitoring protocol will be defined to determine whether the crops grow as desired.

V. Summary and Next Steps

This paper summarizes the results of the design workshop conducted to generate the preliminary design of the EDEN ISS ISPR test facility. The design is already advanced to a state where subsystem developers can start with the detailed design. There are still some open issues remaining, especially regarding the hardware and software interfaces. Only a few subsystems, mainly the nutrient delivery system, are still in a very early design stage. The overall system architecture and subsystem allocation within the facility are fixed. The described key values (e.g. mass, power) however, are still preliminary. Concrete values for those parameters will be available once the hardware development phase is over or only when the first overall system test are performed.

EDEN ISS is well under way and within the scheduled timeframe. The first phase of the project, the design phase, was concluded with the Critical Design Review in March 2016. The following 18 months until September 2017 are devoted to the hardware development, integration and testing.

The assembly, integration and testing of the subsystems is supposed to be finished in spring 2017. From there on the EDEN ISS team has a couple of months for subsystems and overall system tests. The mobile test facility is scheduled for shipping to Antarctica in October 2017.

Acknowledgments

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