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Main performance results of 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 and built a plant cultivation system to have form, fit and function of an 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 construction phase is completed, and the developed system is being tested in a laboratory environment, planned for further validation 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 system as built and the key results of the first ISPR plant growth facility laboratory tests.

Nomenclature

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

I. Introduction

Food production in space is a critical element 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 systems (e.g. NASA Veggie[3]) as extensively analized in a previous CIES

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paper[2]. The facility, called EDEN ISS ISPR[4], has been developed and tested in the TASI Recyclab technological area in Turin. The ISPR was then shipped to Bremen for integration in a mobile container-sized greenhouse test facility for integrated testing and subsequent shipment in later 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[1], 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.

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 all. 2016[1]. The cited paper includes a description of the logistics and operations of the facility, as well as an illustration of the preliminary system budgets. The EDEN ISS ISPR "as designed" status is described in detail in Boscheri et all. 2016[4]. The system is being developed as a potential payload for the European Drawer Rack MKII (EDR MKII). EDR MKII will be flown to the ISS in 2018 and will provide interfaces for multiple experimental inserts (EIs).

This paper quickly recalls the MTF configuration, focusing then on the developed EDEN ISS ISPR the system as built, as well as the main conclusively tested performances.

II. Mobile Test Facility General Overview

The EDEN ISS MTF was 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.

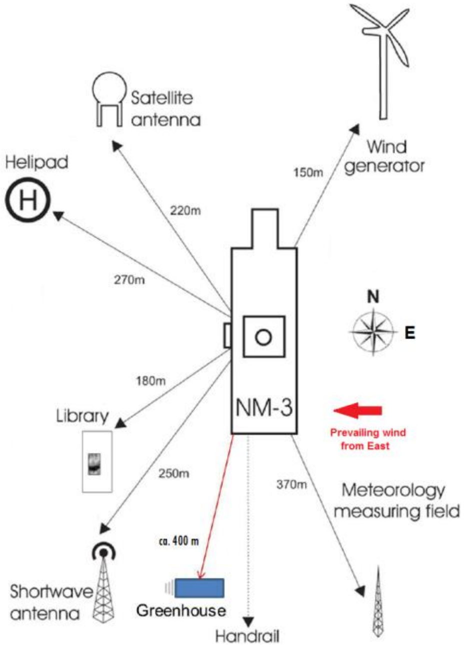


Figure 1. Area map of the Neumayer III station, including the proposed position of the EDEN ISS greenhouse

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.

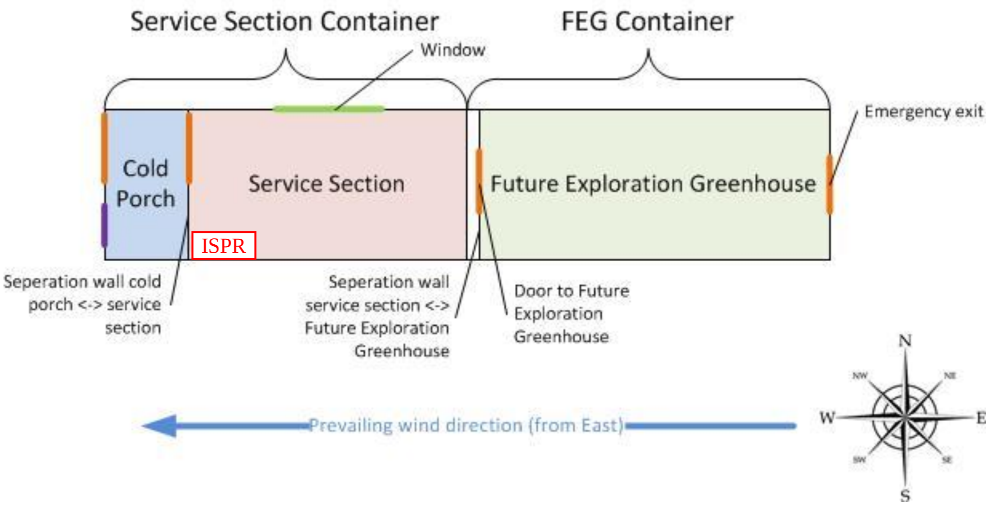


Figure 2. Overview of the EDEN ISS MTF main elements.

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.

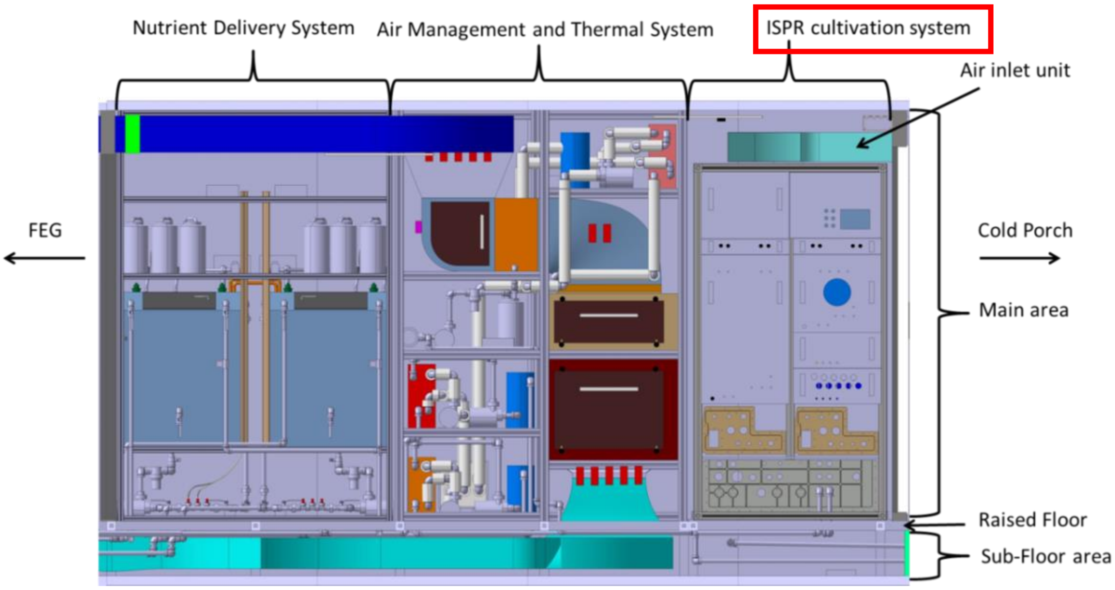
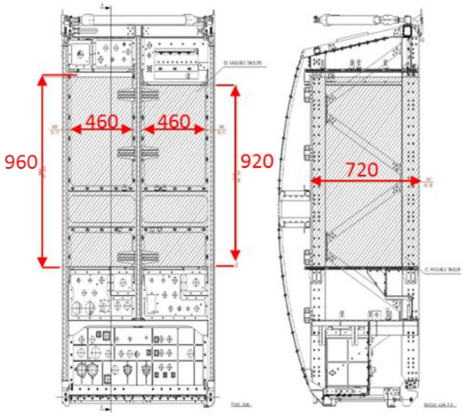


Figure 3. Service Section cut view with ISPR – South side

III. ISPR Cultivation System As Built 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 m^2 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)



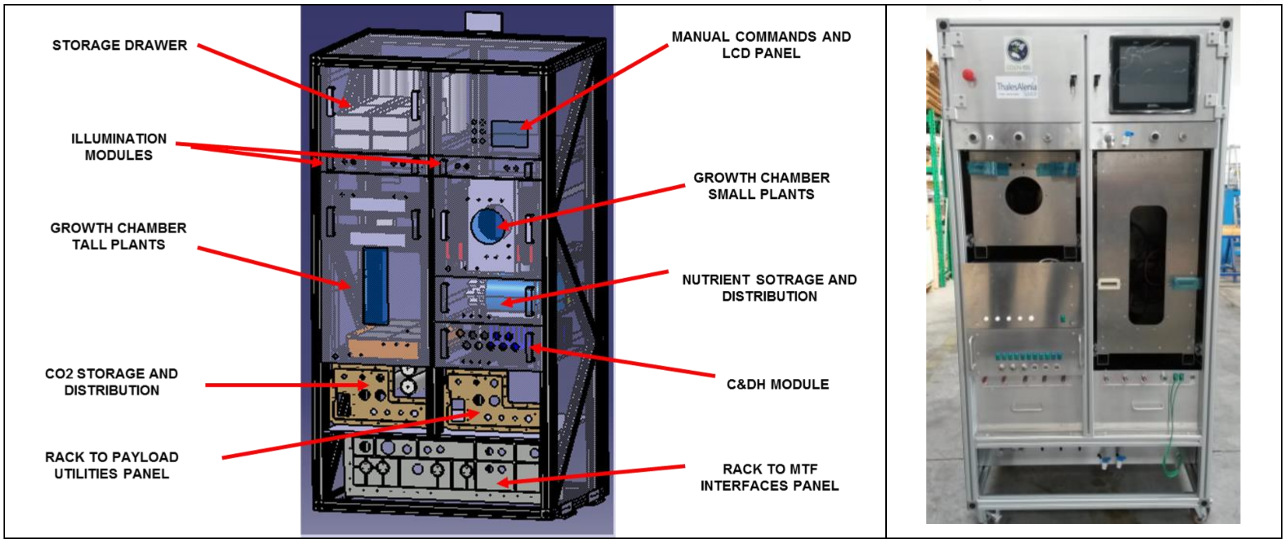


Figure 5 is an image of the EDEN ISS ISPR system as built. As can be seen, it is designed as precursor of ISS European Drawer Rack EDR II plant growth payload.

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.

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

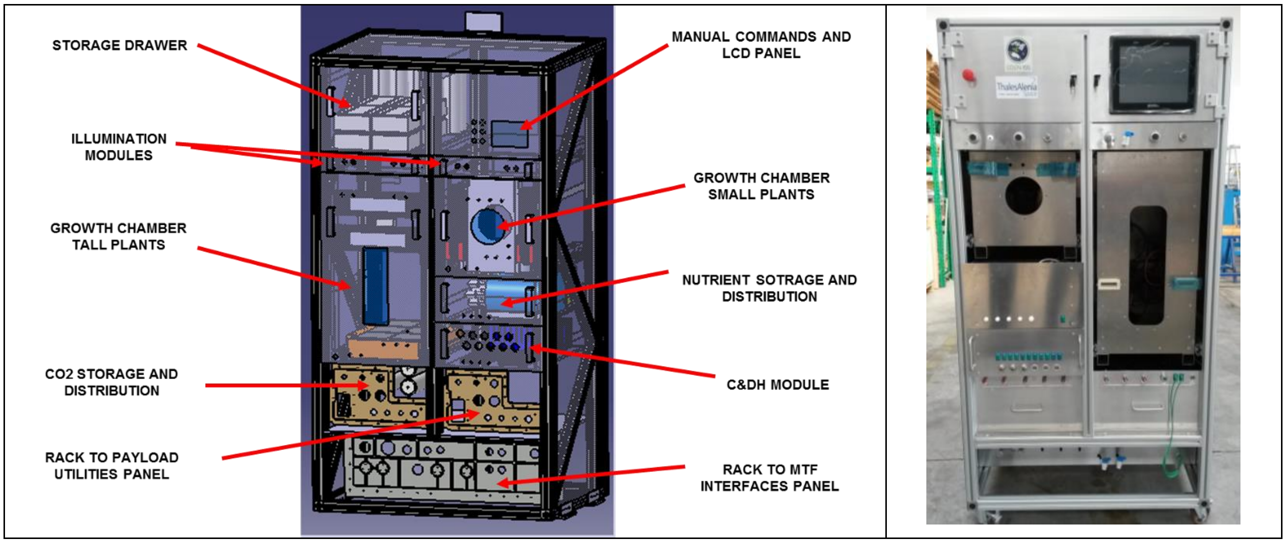


Figure 5. The EDEN ISS ISPR cultivation system 3D image (left) and almost complete rack photo (right).

IV. ISPR Laboratory Performance Testing Main Results

Multiple performance tests were carried on in laboratory environment to validate the unit before shipment to Bremen for the integrated system test campaign. The majority of the tests were performed at subsystem level or even on prototypes for eventual design improvements. The major concluded outcomes of this investigation are presented in the following subsections.

A. Temperature and humidity control subsystem performance

Each of the 2 growth volumes has an independent temperature and humidity control subsystem. Identical components have been used for both the tall growth chamber (GCT, 192L volume) and short growth chamber (GCS, 84L volume), despite the different volumes. 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 0.2µm filter 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 connected to a chiller external to the rack. The overall air management subsystem block diagram is reported in Figure 6.

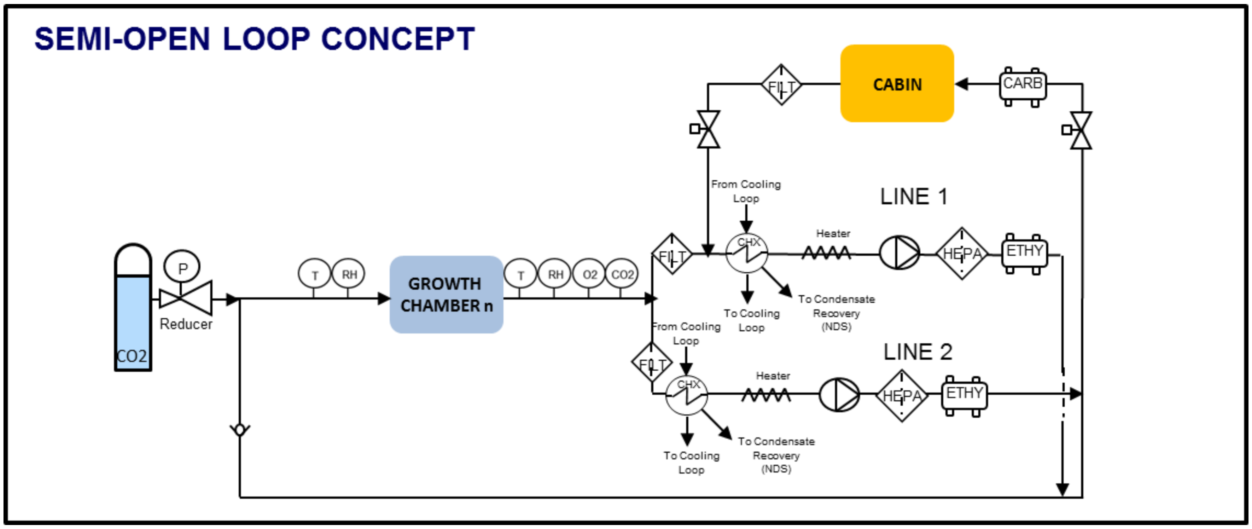


Figure 6. Overall air management system conceptual block diagram

The major performance results of the built system are reported in Table 1 for both the tall (GCT) and short (GCS) growth chambers. No plants were inside the chambers during testing.

In order to verify the reported performance, 40W sensible heat was introduced in the growth chamber by turning on the LED illumination system as a heater. To identify the correct set point for the lamps, the lamps were dimmed until achieving a 10°C temperature increment into the growth chamber into a set-time dependent on the chamber volume and measured air hygrometric conditions.

A constant latent head load of 25±5W was introduced as water vapour from an external aerosol generation unit.

Table 1. Temperature and humidity control subsystem performance (no plants included)

Performance Type	As Designed	As built and tested	
		GCS	GCT
Temp. control range (sensible heat load <40W latent heat load <25W)	15-30°C ± 1.5°C	15-30°C ± 1.9°C	15-30°C ± 2.4°C
Humidity control range (sensible heat load <40W latent heat load <25W)	60-80% ± 5%	60-80% ± 6% (only de-humidification)	60-80% ± 7% (only de-humidification)

Temperature and humidity were measured in 9 points along the same longitudinal plane in the growth chamber symmetry axis (Figure 7) at the following temperature and humidity set-points combinations: 15°C – 60% RH; 15°C – 80% RH; 30°C – 60% RH; 30°C – 80% RH. The values reported in Table 1 are the worst case performance results.

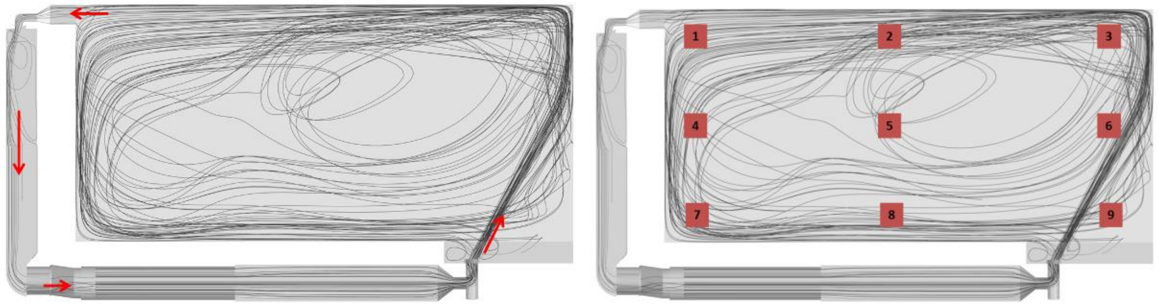


Figure 7. Growth Chamber cross section with air flow major streamlines (left); temperature and Humidity monitoring points along chamber longitudinal cross-section (right)

B. Nutrient Delivery Subsystem Performance

The Nutrient Delivery System (NDS) contains the reservoirs (stock solutions, acid/base, DI water, nutrient solution), the delivery pumps, the nutrient solution quality monitoring sensors, and the condensate recovery system. DI water is used also 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 is monitored and controlled by acid/base injection. The nutrient solution EC and pH are monitored and controlled by water or stock solution (from dedicated reservoirs) injection. Injection is allowed by LabVIEW® controlled piston pumps. Concentrated solution tanks are flexible, replaceable (self-locking QD), stored dry and filled with water only before use. Water and nutrient reservoirs rely on a polymeric bellows. Both solutions are studied for microgravity applications.

Figure 8. Nutrient Delivery System breadboard photo

The NDS block diagram is reported in Figure 9. Either DI water or nutrient solution can be delivered to the root modules. The block diagram is explained as follows.

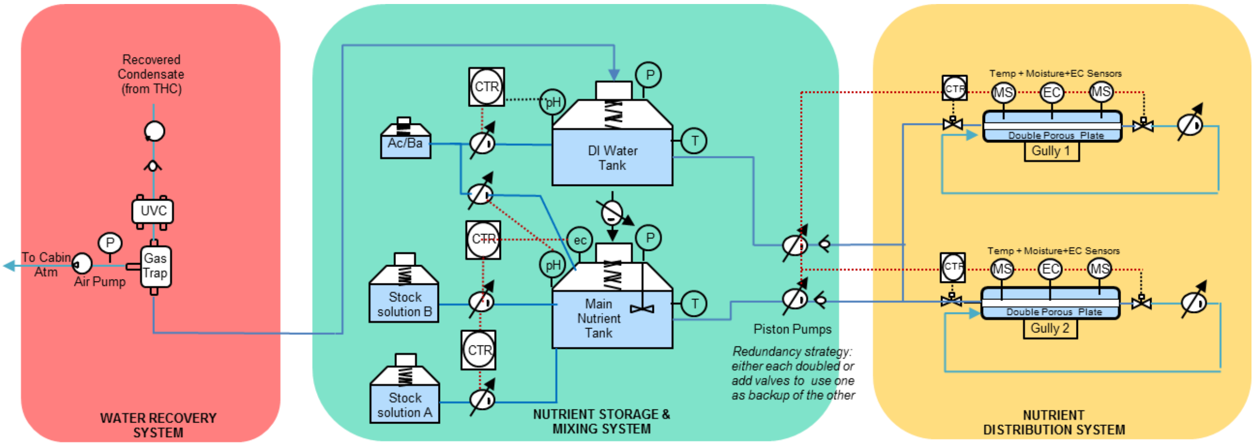


Figure 9. Nutrient Delivery System Conceptual Block Diagram

The performances of the main subsystem components were tested against the initial specifications. The results are summarised in Table 2.

Both the Main Nutrient Tank and the DI Water Tank are relying on a polymeric bellows technology, capable of allowing long term chemical and microbiological stability of the contained solutions and of operating also in microgravity conditions. From the preliminary analysis performed in the design phase a much rigid bellows was expected needed to withstand the targeted Maximum Design Pressure (MDP). However, it was possible to achieve the target with a less thick (thus lighter) unit, reducing the operative pressure range as a consequence. The reservoirs have been proof tested at 1.5 barg and operate from -0.1 (empty reservoir) to 0.1 barg (full reservoir).

Table 2. Nutrient Delivery Subsystem Performance Testing Results

Component/ Performance Type	As Designed Value	As Tested Value
Main Nutrient Tank/ DI Water Tank		

Component/ Performance Type	As Designed Value	As Tested Value
Deliverable water volume	7 L	7.05 L
Maximum allowed water ullage	0.7 L	0.13 L
Maximum Design Pressure (MDP)	1 barg	Ok at 1.5barg
Operative Pressure Range	-0.1 to 0.7 barg	-0.1 to 0.1 barg (*)
Laser Displacement Sensor		
Reservoir water volume measurement range	0 to 7 L	0.2 to 7 L (*)
Reservoir water volume measurement accuracy	70 ml	12.5 ml
Piston Pumps		
Flow rate at 0.7 barg	10 ml/min	Pump oversized (*)
Continuous operative time	Up to 1 min	Variable performance (*)
Stock solution soft reservoir		
Deliverable water volume	1.0 L	>1.2L
Maximum allowed water ullage	10ml	4ml
MDP	0.35 barg	Ok at 0.5barg
Concentrated acid soft reservoir		
Deliverable water volume	0.5 L	>0.6L
Maximum allowed water ullage	5 ml	4ml
First Containment MDP	0.35 barg	Ok at 0.5barg
Second Containment MDP	0.35 barg	Ok at 0.5barg

Values marked with (*) are discussed in the text

Tanks water level is monitored via a laser displacement sensor placed solidal to the unit inlet, referred to a target placed on the bellows end plate. As visible in Figure 10 no relevant hysteresis is observed at operative filling/draining flow rates and the relation between reservoir water volume and sensor signal is linear. Moreover, the required accuracy (1% of full tank volume) was achieved with overperformance (0.02% of full tank volume).

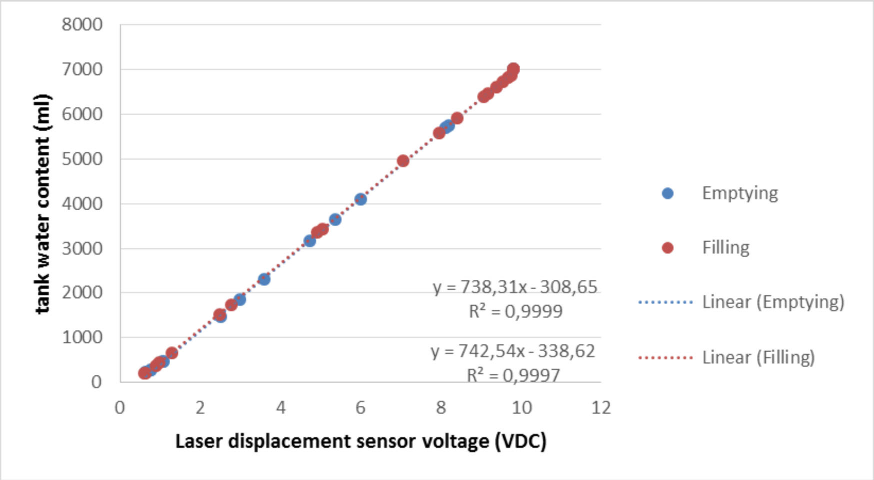


Figure 10. Laser displacement sensor performance result – no relevant hysteresis is observed at operative filling/draining flow rates and the relation between reservoir water volume and sensor signal is linear

Each tank is equipped also with a gauge pressure sensor, with the main objective of assuring not to reach destructive pressures. The possibility to use the sensor as a backup water level sensor was investigated. As visible in Figure 11, showing Nutrient Solution Reservoir pressure sensor reading against the laser displacement reading, the sensor pressure measurement cannot be used as backup solution for laser displacement sensor, since the bellows tank pressure operative range in really narrow and the measurement fluctuations to wide.

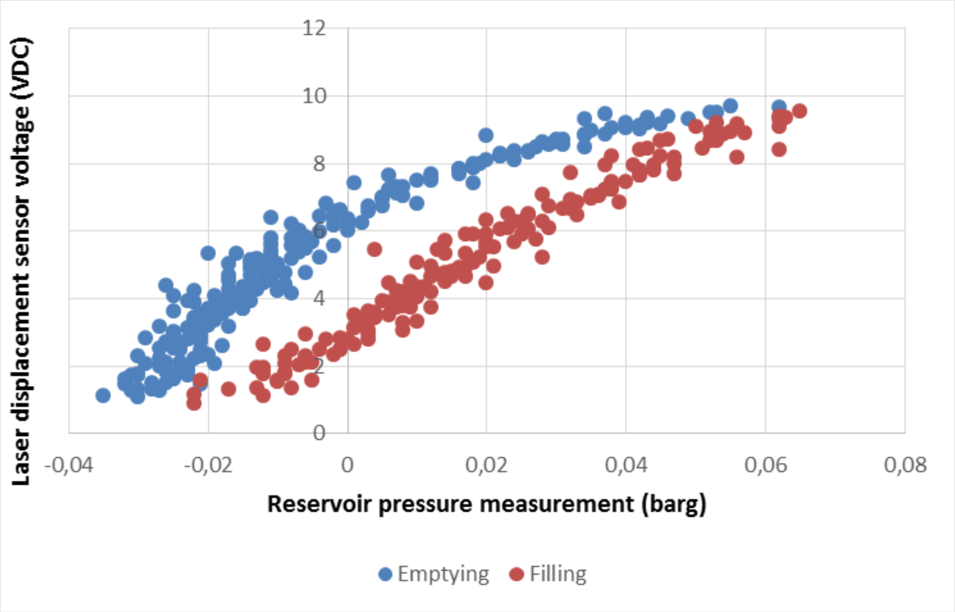


Figure 11. Nutrient Solution Reservoir pressure sensor reading vs laser displacement reading – the sensor pressure reading cannot be used as backup for laser displacement sensor

Another performed step was the characterization of the selected piston pumps, used to move solutions from and to the bellows tanks. Figure 12 shows piston pump delivered flow rate as function of continuous operating time and of reservoir filling status. The control SW being realized need to consider both variables to provide predictable stock solution and acid injection, since the flow rate is also sensibly dependent on pump continuous operating time (influencing pump temperature and so performance).

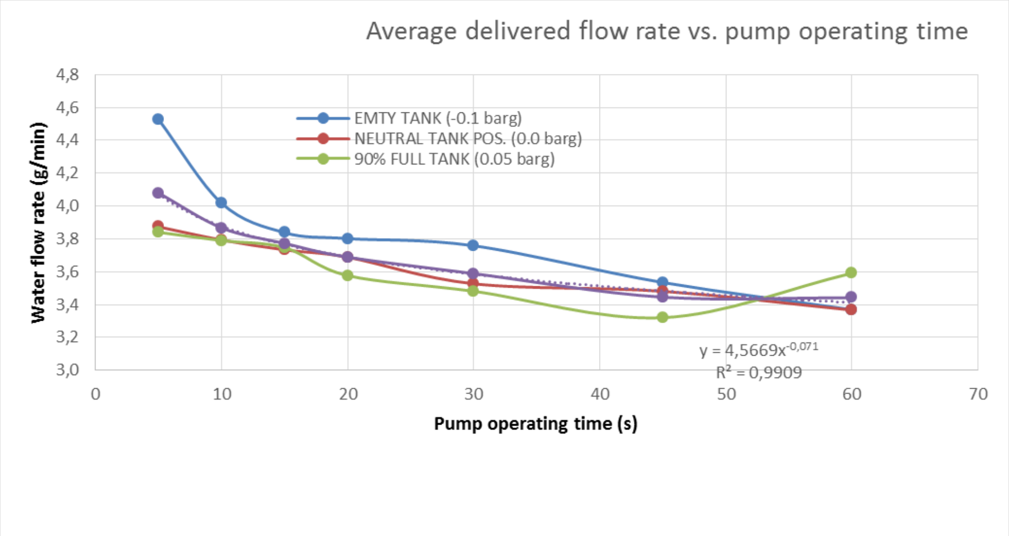


Figure 12. Piston pump delivered flow rate as function of operating time and of reservoir filling status – the control SW need to consider both variables to provide predictable stock solution and acid injection

V. Summary and Next Steps

This paper summarizes the results of the main currently concluded subsystem functional tests for the EDEN ISS ISPR system. Results are presented for the temperature and humidity control system performances compared with expected specifications, as well as for the key components of the Nutrient Delivery System.

The functional testing of the subsystems and complete system in Laboratory environment is in completion within mid 2017. This will be followed by an additional set of overall system tests in the Bremen MTF facility. The mobile test facility is scheduled for shipping to Antarctica in October 2017 for analog test site testing along all of 2018.

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