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PFPU – Microgravity Precursor Food Production Unit Development Status and Life Test Results

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Several technical issues have been identified thus far in relation to the development, implementation, and operations of food production systems for space applications. These issues encompass food quality prediction, food safety, integration strategy, microbial contamination, humidity, and nutrient delivery management. Therefore, considering the number of issues and their respective criticalities, it is important to approach the cost-conscious development of a food complement production unit for space application in a step-by-step manner, utilizing a modular technological demonstrator. The Plant Food Production Unit (PFPU) is a study that focuses on developing a modular food complement production unit demonstrator. Its objective is to achieve statistically representative production of edible tuberous plants in microgravity. This study is conducted within the MELiSSA framework under a contract with the European Space Agency. Thales Alenia Space Italia leads an Italian and Finnish consortium in carrying out the study. Over the past two years, the PFPU systems breadboard has been designed, constructed, and extensively tested at both the system and subsystem levels. This testing included life tests involving the cultivation of various types of plants such as lettuce and potatoes. This paper provides an overview of the current development status of PFPU, presents key results from the test campaign (including the executed life tests), and outlines the associated roadmap for future developments.

Nomenclature

BBM = Breadboard Model
CIRiS = (Norwegian) Centre for Interdisciplinary Research in Space
COTS = Commercial Off The Shelf
DI = De-ionised
EC = Electrical Conductivity
EDR = European Drawer Rack
EI = Experimental Insert
ESA = European Space Agency
FPU = Food Production Unit
GCM = Growth Chamber Module
GMM = Gas Management Module
ISS = International Space Station
LEO = Low Earth Orbit
LM = Light Module

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MCCM = Microbial Contamination Control Module
MELiSSA = Micro-Ecological Life Support System Alternative
NM = Nutrient Module
PCDHM = Power Command and Data Handling Module
PFPU = Precursor of Food Production Unit
PGU = Plant Growth Unit
PWM = Pulse Width Modulation
RM = Root Module
TAS = Thales Alenia Space
TEC = Thermo-Electric Cooler
TCM = Temperature Control Module
UNINA = University of Naples Federico II
VWC = Volumetric Water Content

I. Introduction

Food production, along with waste recycling, will play a critical role in a fully closed space life support system. Typically, food production is considered for long-duration missions that go beyond Low Earth Orbit (LEO). In the initial stages, it could be implemented during the first crewed mission to Mars orbit, specifically within the Mars Transit Vehicle, to provide up to 10% of the crew's nutritional needs. It should be noted that food production on the International Space Station (ISS) holds limited significance due to the availability of regular resupply missions. Moreover, the resupplied food meets specific nutritional requirements that are medically controlled, which cannot currently be fully met by on-board systems considering the limited knowledge available. However, the ISS serves as a valuable testing ground for early technological demonstrations in this area.

Currently, we do not possess a comprehensive enough model to accurately predict and control the nutritional quality of food, even in the case of a food complement, to the level required for medical operations. In this regard, over the past few years, several activities within the European Space Agency (ESA) MELiSSA[2] program have been undertaken. These activities aim to enhance our understanding of food production systems, develop engineering tools (such as experimental infrastructure and models) for characterizing and predicting food systems, and conceptualize food production systems capable of producing a full menu. While the complete MELiSSA system primarily focuses on resource loop closure in crewed surface bases on the Moon or Mars[2], much of the fundamental knowledge generated is also applicable to microgravity conditions. Several technical issues have been identified in the development, implementation, and operation of food production systems for space applications. These issues include predicting food quality, ensuring food safety, managing microbial populations, regulating humidity, managing nutrient delivery, and devising integration strategies. Consequently, given the number and criticality of these issues, a cost-conscious approach to developing a food complement production unit for space applications necessitates a step-by-step methodology based on a modular technological demonstrator.

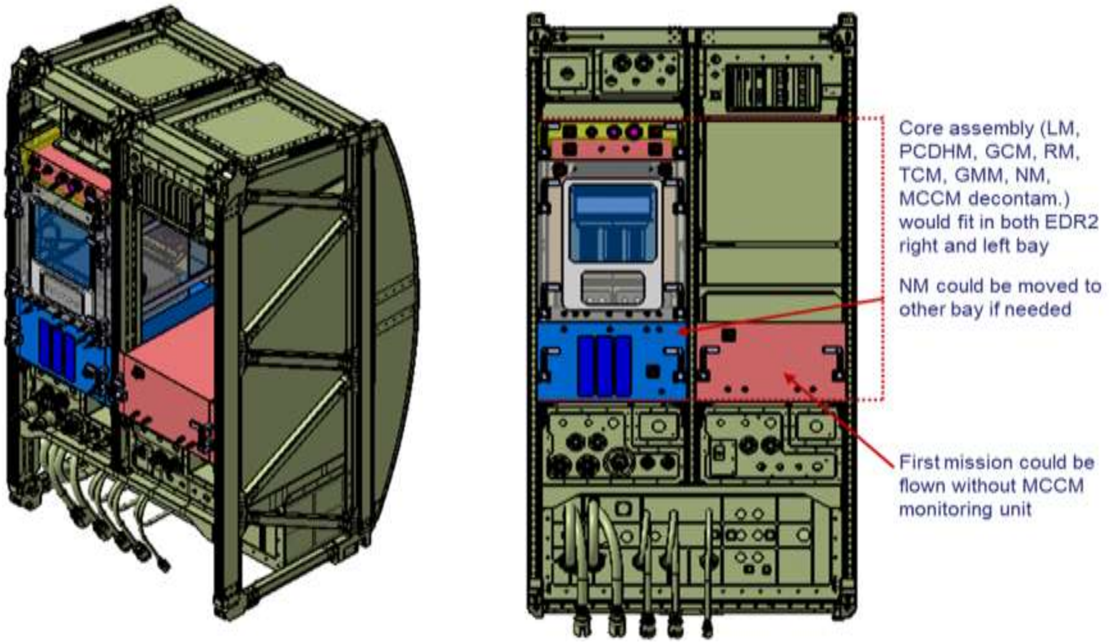
Therefore, in 2014 we started the study of a modular food complement production unit demonstrator within the ESA MELiSSA framework, namely the Precursor of Food Production Unit (PFPU). The overall objective of the activity was to elaborate the system requirements baseline, conceptual design, engineering plan and demonstration strategy of the PFPU, as well as in-depth study, breadboards manufacturing and thorough testing of selected critical technologies (i.e., nutrient module, root module, and microbial contamination control module). In 2018 a second project phase started, with the objective to consolidate the operational concept, system engineering plan and demonstration strategy of the PFPU system. This phase could benefit also from the experience gained through the Antarctica test campaign of a precursor system, the EDEN ISS RUCOLA unit[7]. It included an iteration of the three key modules under development, with different levels of maturity: development and characterization of the Nutrient Module critical components; re-evaluation and testing of the Root Module technology solution. The phase included the test of multiple commercial off the shelf (COTS) components for potential use within the PFPU[8]. The third project phase started then in 2021, with the core objective of developing and testing with and without crops a full PFPU ground breadboard model, as relevant as possible of the final flight unit. The last project phases concluded at the end of 2023 with a successful System Requirements Review (SRR) and after a successful test campaign of the PFPU ground breadboard model (BBM), both at subsystem and system level, including the plant growth test repetitions ("life test"). After an introduction on the overall PFPU concept, this paper reports the main results achieved during the life test phase of the PFPU ground model system and the planned future steps.

II. PFPU System Overview

The objective of the PFPU system is to serve as a microgravity technology demonstrator, specifically targeting the statistically representative and controlled production of edible tubers. This includes managing the entire growth cycle, from tuber-seeds to ready-to-harvest tubers. The production process will be carefully monitored, focusing on plant growth, and the system's design aims to minimize the need for resupplying consumables, including water. To achieve these goals, the PFPU system is being developed using up-scalable modules that are specifically designed for different processes. The aim is to demonstrate each module independently, to the maximum extent possible. As part of the development process, the PFPU demonstrator is being designed to potentially serve as a payload within the European Drawer Rack (EDR) MK II rack[5], allowing for efficient integration and utilization of space resources. The following functional models of a complete food production facility were developed:

- Root Module (RM), controlling the development of the tuber
- Nutrient Module (NM), controlling the nutrient uptake by the plant
- Microbial Contamination Control Module (MCCM), controlling the microbial population in the system
- Gas Management Module (GMM), controlling the gas exchanges of the plant
- Light Module (LM), controlling the light interception of the plant shoots
- Growth Chamber Module (GCM), controlling the development of the plant shoots
- Temperature Control Module (TCM), controlling the temperature and relative humidity in the shoot zone
- Power, Command and Data Handling Module (PCDHM), responsible for power conversion and distribution, data handling, telemetry download, command upload and transmission

A set of considerations were made in support to the physical architecture as detailed in a previous ICES paper[9]. Starting from these considerations, a physical division of the PFPU system into drawers/lockers (as EDR MK II EIs) was generated. Figure 1 shows a preliminary image of PFPU flight demonstrator as an Experimental Insert (EI) of the European Drawer Rack (EDR) MK II. The three identified PFPU drawers/lockers have been arranged within the EDR MK II rack in order to fully occupy the left bay (the largest one) with all the units, except the microbial monitoring one. This disposition will support a stepwise demonstration of the system initially also without the in line microbial measurement systems. Moreover, since the microbial monitoring drawer design is the most uncertain, this disposition shall provide sufficient margin for its re-sizing. The LM is placed on top of the GCM, while the NM is placed beneath it, closer to the RM. The PCDHM is preliminary placed with the LM (a more detailed configuration effort is necessary and ongoing to freeze this disposition). The TCM and GMM are attached behind the GCM.



Core assembly (LM, PCDHM, GCM, RM, TCM, GMM, NM, MCCM decontam.) would fit in both EDR2 right and left bay

NM could be moved to other bay if needed

First mission could be flown without MCCM monitoring unit

Figure 1: Preliminary image of the PFPU flight demonstrator as an Experimental Insert (EI) of the European Drawer Rack (EDR) MK II

Rough Order of Magnitude (ROM) system budgets were also associated to the presented preliminary system physical architecture, excluding the MCCM Monitoring Drawer[9,10]. Based on the previously reported considerations, utilization of the EDR MKII as PFPU hosting facility resulted feasible. However, in the perspective of increasing the flight opportunities for the system, the impact of design adaptation for flight within an EXPRESS Rack will be analyzed in the next project phase.

III. PFPU Ground Breadboard Model (BBM) Status Overview

The PFPU Ground Breadboard Model (BBM) was developed with the objective of validating the functional performance of the multiple developed critical technologies in an integrated system in laboratory environment.

Figure 2 shows the fully integrated PFPU BBM in test-configuration at Thales Alenia Space (TAS) laboratory, including PFPU control station (PCDHM, laptop and monitor). Figure 3 shows the modules representative in configuration of the PFPU flight unit (i.e., GCM, LM, TCM and GMM). The LM is attached to a frame representative of the locker to be installed within EDR2. The GCM, containing the RM, is mounted onto rails allowing its partial extraction for crop observation and manipulation activities. The TCM and GMM are attached to the GCM, positioned in the back. Total GCM extraction is also possible for maintenance activities of TCM and GCM. More details on the development status of each module are discussed in the following subsections. The modules' designs and the results of the breadboard test campaign at system and subsystem level are both described in detail in previous ICES papers[9,10]. In the following subsections, the plant growth test campaign is described, including setup, leafy vegetables life test results, and potato life test results.

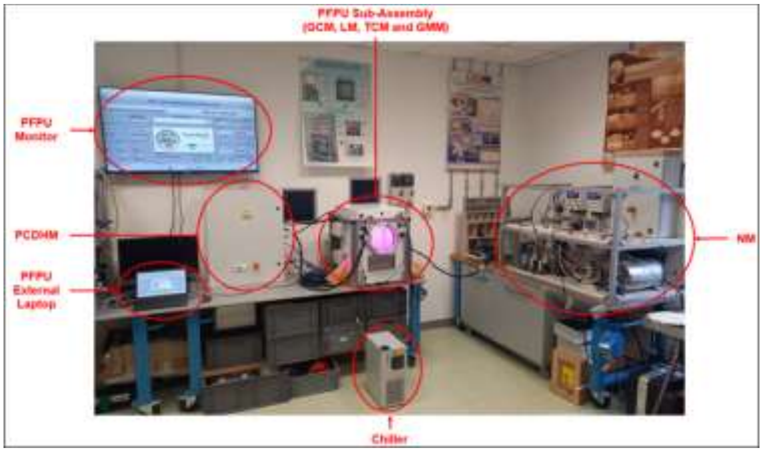


Figure 2: Fully integrated PFPU breadboard model (BBM)


GCM + LM
GMM (GCM back-side)
GMM + TCM (GCM lateral-side)

Figure 3: Pictures of the modules representative in configuration of the PFPU flight unit (GCM, LM, TCM, and GMM)

A. Life Tests Setups

During the last year, the focus of the development effort was mainly on the consolidation of the growing substrate used within the tuber zone and on the humidity management within the tuber zone. So far, two different RM Plant Growth Unit (PGU) concepts have been designed and consolidated during the project development. The first one, designed by the Department of Agricultural Sciences of the University of Naples Federico II (UNINA) in collaboration with TAS during the first two project phases (2016-2020), relies on a PVA (polyvinyl acetate) foam as growing substrate, possibly allowing full occupation of the RM-PGU internal volume (i.e., tuber zone), while shoots grow inside and around the foam itself avoiding, in this way, the need for aeration of the tuber zone. The concept is depicted in Figure 4.

Figure 4: RM-PGU Concept 1

The second concept was designed and manufactured in the last project phase (2021-2023) by the Norwegian Centre for Interdisciplinary Research in Space (CIRiS). This concept relies on an integrated engineered structure realized via additive manufacturing techniques that can cover all RM-PGU functions. The concept is depicted in Figure 5.

Figure 5: RM-PGU Concept 2 (CIRIS 3D-printed PGU)

The first concept (PVA foam) was extensively tested during the first project phases and was already validated for growing potato (and other plants, such as microgreens) at UNINA premises, the results were presented in a previous ICES paper[9]. PVA foam is a hydrophilic material that exhibits high water holding capacity, characterized by high capillarity that ensures effective distribution of water in the substrate under microgravity conditions[11]. However, the design with only PVA sponge, while exhibiting optimal root growth, had some limitations in tuber formation and development. In particular, tuber growth was occurring inside the substrate making harvesting operations difficult for the operator.

In this context, during the last two years, the focus shifted towards a new RM-PGU disruptive design that can ensure both optimal root development and adequate area for tuber growth. As a result, the new 3D printed concepts were designed, manufactured and tested as described in a previous ICES paper[10]. This second concept features a re-usable, soilless manufacturable 3D printed substrate made in PLA. The engineered substrate is made from an open gyroid structure where water and nutrients are distributed using channels and capillary force. A wavy surface of the substrate increases its surface area to provide more area for root attachment and oxygen exchange between the tuber zone atmosphere and the water in the substrate. Aeration is guaranteed via channels located in the lower part of the PGU close to the root zone. Minimization of light exposure (to avoid the tuber greening and the resulting accumulation of toxic glycoalkaloids in tubers) is guaranteed by black walls in the tuber zone, whereas the side facing the light module is kept white to enhance light reflection. The tuber seeds are placed in the center of the hardware, in a dedicated cradle and kept in position by a felt that also acts as a wick for water/nutrients allowing moisture distribution around the tuber-seed and shoots guidance towards the irrigation gyroid.

Hence, given the two different PGU concepts, two life tests have been carried out. The first one, **Leafy Vegetables Life Test** (Section III-B), was performed at TAS premises with the core objective of demonstrating that the PFPU BBM could sustain the growth of a relevant crop (from seedling to harvestable size) by making use of resources (i.e., energy, water, CO_2) as per applicable requirements. The test was performed using the fully integrated PFPU BBM (hardware and software) and lettuce as relevant crop. Lettuce was selected instead of potatoes for allowing shorter growth cycles and therefore, more test runs, while still being relevant in terms of required resources and loads (e.g.

water vapor generation) to the system. Additionally, taking into account that the PVA foam concept was already validated for growing edible plants, this was selected as baseline PGU for the test.

The second test, **Potato Life Test** (Section III-C), was performed at UNINA premises with the core objective of validating also the CIRIS 3D-printed PGU for growing edible plants, specifically, potatoes. The agronomical issues that emerged during the test highlighted several optimization features for the concept design to be exploited in the next project phase.

B. Leafy Vegetables Life Test Results

The results reported in this document refer to the test executed from 04/07/2023 to 25/07/2023. Several aspects were monitored during test execution and investigated in the post-processing analysis, namely: (1) Crops Monitoring (images); (2) Resource 1: Water; (3) Resource 2: GCM Atmosphere Carbon Dioxide (CO_2); (4) GCM Atmosphere Temperature and Relative Humidity; (5) PFPU BBM Power Consumption. Target parameters and control accuracy achieved during the test are summarized in the following Table 1.

Table 1: PFPU Lettuce Life Test Target Parameters

Growth Target Parameters	Target	Control Accuracy
Temperature	23°C (day) and 18°C (night)	± 0.5°C
Relative Humidity	65% (during both day and night)	± 5%RH
CO_2 Concentration	1000 ppm (minimum level)	± 100 ppm
Nutrient Solution EC	1.2 mS/cm	± 50 uS/cm
Nutrient Solution pH	5.2 points	± 0.1 points
LED Intensity	200 µmol/m²/s	Dimmable (9 levels) up to 600 µmol/m²/s
Power Consumption	500 W (maximum average consumption) 1 kW (maximum peak power)	7.4 kWh/day 370W during 16h-day phase (average) 185W during 8h-night phase (average)
Water Recovery Rate	90%	Up to 95% of used water was recovered

1. *Crop Monitoring (images)*

Crop images were programmatically acquired during the whole test's execution. Images were collected via two different cameras: one board-camera located in the LM and one mini-camera placed internally to the GCM environment and attached to the top roof. Figure 6 shows the plants' status at the beginning of the experiment (T0, 04/07/2023), while Figure 7 shows the last photos taken on 25/07/2023 from an external camera shooting via the front circular window.

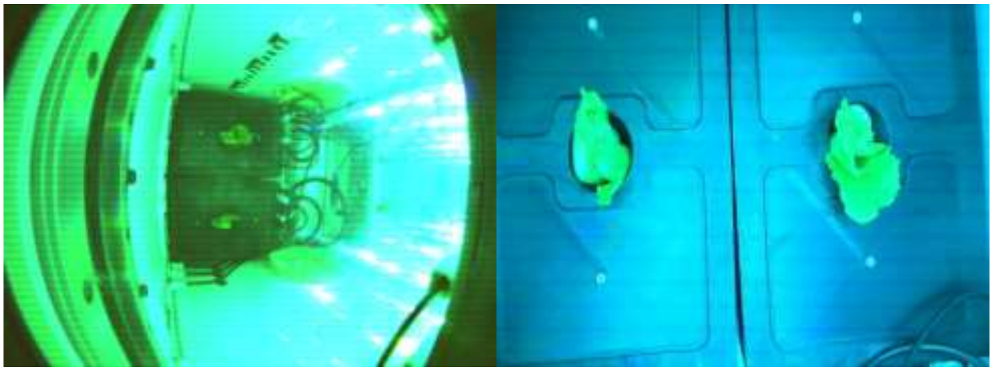


Figure 6: Lettuce plants at T0 (day 1, 04/07/2023)

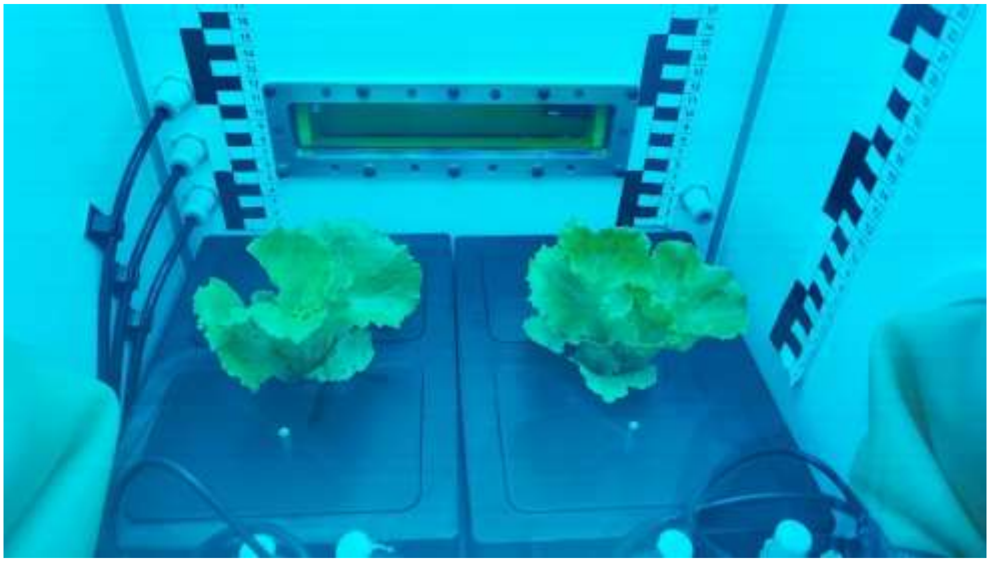


Figure 7: Lettuce plants at the end of the experiment (25/07/2023)

2. ***Resource 1: Water***

Water was monitored with three different measurements: tanks levels, volumetric water content (VWC) in the substrates, and the atmospheric condensate recovered by the TCM. Neither tanks' re-fills, nor nutrient solution EC/pH corrections, nor de-ionized (DI) water irrigation were required during the considered test execution. Irrigation was performed twice a day based on the substrates' VWC readings and via the nutrient solution tank. Figure 8 reports the total amount of spent water from initial conditions to the end of the experiment in terms of nutrient solution tank (T2). According the associated data, 1.12 L of water was spent in 22 days of experiment.

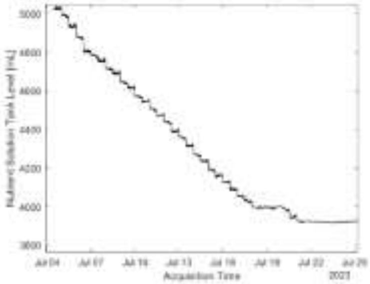


Figure 8: Total Amount of Water employed in the experiment (Nutrient Solution Tank Level)

In terms of delivered quantities, 42 irrigation commands were successfully executed delivering 1.38 L of nutrient solution over the 22 days of experiment (computed value). Figure 9 shows the delivered water computed by the software based on sensors data. No irrigation was performed in the last three days.

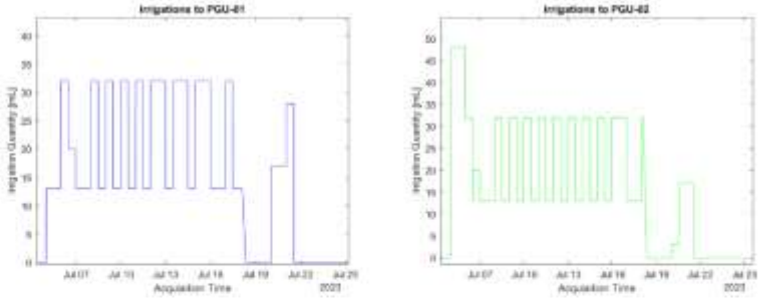


Figure 9: Irrigation quantities to both Plant Growth Units (22 days)

According to Figure 9, the first irrigation of the day (at 11:30 of each day) was always lower than the second (at 23:30 of each day). During the day phase when lights are ON and the temperature was higher, more water evaporates and therefore, the substrate dries-off faster resulting in a lower VWC (21.5%) and a higher delivery request (second irrigation of 30 mL) with respect to the post-night conditions (23.5% VWC and first irrigation of 13mL).

The computed total amount of delivered water (1.38 L, Figure 9) was slightly different from the one computed based on the tank level (1.12 L, Figure 8). The tank sensor levels were considered as a more accurate measurement since the delivered water was controlled via solenoidal pumps actuated by a digital pulse width modulation (PWM) with no feedback on the actual delivered water (only the flow sensor on the line). Errors between computed and delivered water were expected. However, the difference of 260 mL was very small if compared to the number of irrigations performed (42) and considering the number of PGU (2) requiring different fluidic path and pumps. Taking into account all these variables, the actual delivery overestimation is: 3.1 mL/irrigation/PGU (fully in line with the ranges specified in the requirements, 5 mL, and with the results obtained in the BBM tests[10]).

Condensate recovery was strongly affected by the leakage rate of the GCM. As a consequence, the condensate recovery line was singularly captured in a dedicated tank in order to properly compute the condensed water without overflowing the DI water tank. The condensate tank was periodically monitored and manually emptied by the operators while recording the tank's level. Table 2 reports the condensate recovery data acquired during the experiment period (from 04/07/2023 to 25/07/2023).

Table 2: Condensate Recovery Data

Date	Quantity Recovered
04/07/2023	Emptied before experiment start-up
07/07/2023	≈ 300 mL
11/07/2023	≈ 400 mL
13/07/2023	≈ 300 mL
18/07/2023	≈ 500 mL
20/07/2023	≈ 300 mL
26/07/2023	≈ 500 mL (experiment end)
TOTAL	**≈ 2300 mL**

Due to the high leakage rate of GCM and TCM subsystems, laboratory air was partially entering the GCM inner volume and excess of water was condensed in the TCM. Indeed, 2.3 L of water was recovered versus 1.12 L of water injected into the system. In addition, the discrepancies between the T/RH sensors at inlet and outlet of the TCM (different models and types with different measurements and accuracies) and airflow rate calibration led to an overestimation of the results in computing the recovered condensate (the software estimated 40 L of recovered condensate).

In conclusion, it was not possible to precisely estimate the recovery rate of the system. However, the results are promising and the recovery rate can be assessed around the 90/95%.

3. *Resource 2: Atmosphere Carbon Dioxide (CO_2)*

Figure 10 reports the trends of the CO_2 in terms of both the concentration in the GCM atmosphere and in the CO_2 tank/bottle's (relative pressure). Measurements of O_2 (20.9%) and total pressure (14 psi) were mostly constant considering the leakage rate of the GCM and TCM and that CO_2 concentration was controlled within a range of 100 ppm (between 1000 ppm and 900 ppm) and, as a consequence, CO_2 partial pressure-changes were not high enough to significantly impact on both O_2 concentration and air total pressure (sensors' accuracies were not precise enough to detect very small steps of ppm and psi).

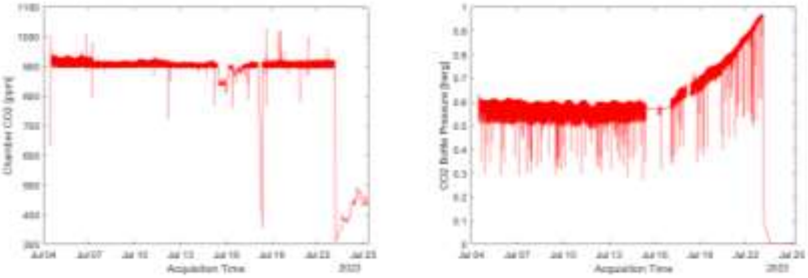


Figure 10: CO_2 and CO_2 Bottle Pressure (22 days)

Additionally, Figure 10 offers a very interesting overview of the CO_2 consumption and control during the experiment: the system was fully capable of maintaining the CO_2 concentration within the desired range, while at the same time avoiding useless waste of the resource. The last tank/bottle of CO_2 was substituted on 15/06/2023 and lasted until 23/07/2023 (PFPU was ON for the whole period of time, always settled with the same control law for CO_2 and the GMM never reported any functional issue). Basing on that, the computed CO_2 consumption is one bottle (total 1.2 kg of CO_2) in 38 days. Figure 11 shows the period of time (23/07/2023) when the CO_2 tank/bottle finished and the CO_2 was no longer controlled: CO_2 dropped to normal atmosphere level (i.e., 400/450 ppm) while CO_2 bottle pressure dropped to 0 barg (relative pressure).

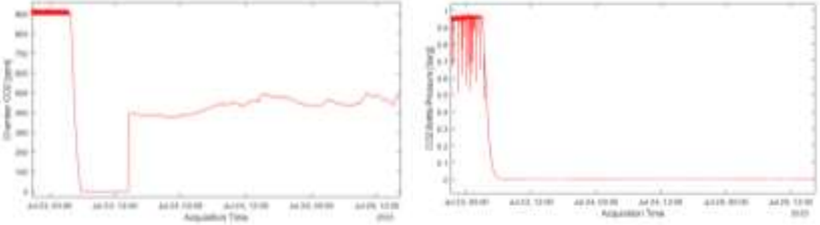


Figure 11: CO_2 and CO_2 Bottle Pressure (2 days, 23/07/2023 to 25/07/2023)

4. *Atmosphere Temperature and Relative Humidity*

Figure 12 and Figure 13 show the temperature and relative humidity readings at TCM inlet (i.e., GCM pre-treatment warm air, Air IN graphs colored in red) and TCM outlet (i.e., post-treatment cold air, Air OUT graphs colored in blue). The inlet air (left) reports the target temperature and relative humidity based on which heater and thermos-electric cooler (TEC) were controlled. The trends clearly show that the hardware and software were fully capable of controlling the temperature and relative humidity within the desired range:

- Day phase temperature target: 23±1°C. Average experiment temperature achieved: 22.3°C
- Night phase temperature target: 20±1°C. Average experiment temperature achieved: 19.3°C
- Day phase relative humidity target: 65±5%RH. Average experiment relative humidity achieved: 66%RH
- Night phase relative humidity target: 65±5%RH. Average experiment relative humidity achieved: 66%RH

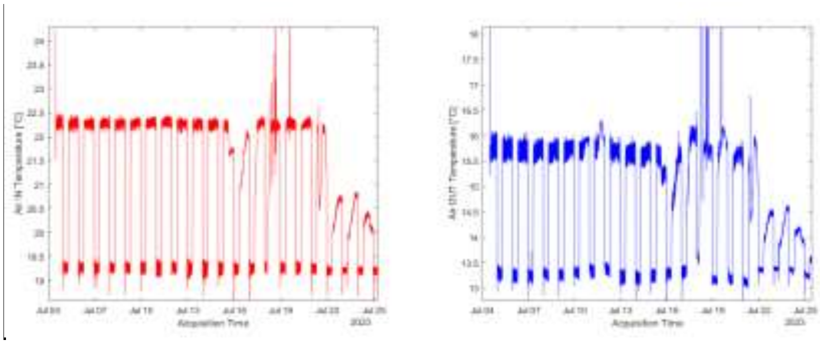


Figure 12: Temperatures at TCM INLET (left) and OUTLET (right) (22 days)

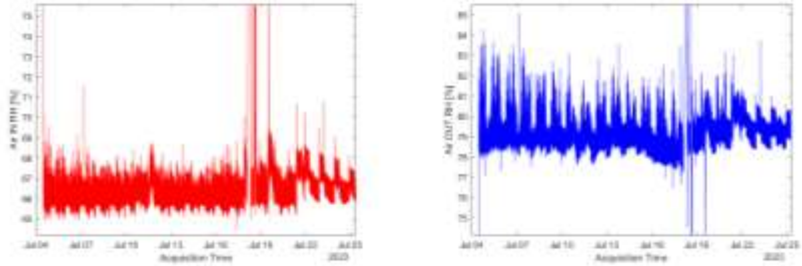


Figure 13: Relative Humidity at TCM INLET (left) and OUTLET (right) (22 days)

During the day phase, with LED and other equipment ON (such as valves for irrigation), the system is affected by a heavier heat load with respect to the night phase, and consequently, the evaporation rate was higher as well as the changes in temperature which strongly affects the relative humidity. As result, the dehumidification dynamic was slowed down which translate in more significant oscillations in relative humidity values. Indeed, during the day phase oscillations were much higher than during the night phase (66±0.5%RH versus 66±0.3%RH). This aspect is highlighted in Figure 14 showing the TCM inlet air's relative humidity graph zoomed to a 2-day period.

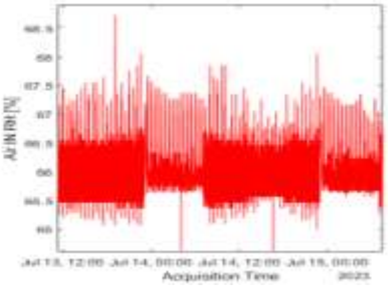


Figure 14: Relative Humidity at TCM INLET zoomed in (2 days)

5. ***Breadboard Power Consumption***

Power consumption data were acquired by means of the remotely controllable switch, which enabled the user to both remotely switch ON/OFF the experiment as well as to acquire hourly and daily electrical consumption information. Table 3 reports the power data for each experiment day (intended as 24 hours). Due to several blackouts that occurred at TAS premises and in the whole city of Turin in the period 16th to 18th of July, power consumption data of these days was discarded.

Table 3: PFPU Daily Power Consumption

Day (24h)	Reference Period	Power Consumption [kWh]	Comment
0	04/07/2023 – 00:00 to 10:08 04/07/2023 – 11:41 to 23:59	7.10	Approx. 22h (Life Test started at 11:41, after new plant seedling)

Day (24h)	**Reference Period**	**Power Consumption [kWh]**	**Comment**
1	05/07/2023 – 00:00 to 23:59	7.58	24h
2	06/07/2023 – 00:00 to 23:59	7.58	24h
3	07/07/2023 – 00:00 to 23:59	7.63	24h
4	08/07/2023 – 00:00 to 23:59	7.51	24h
5	09/07/2023 – 00:00 to 23:59	7.58	24h
6	10/07/2023 – 00:00 to 23:59	7.50	24h
7	11/07/2023 – 00:00 to 23:59	7.49	24h
8	12/07/2023 – 00:00 to 23:59	7.61	24h
9	13/07/2023 – 00:00 to 23:59	7.64	24h
10	14/07/2023 – 00:00 to 23:59	7.50	24h
11	15/07/2023 – 00:00 to 23:59	7.26	24h
12	16/07/2023 – 00:00 to 23:59	**6.81**	24h (Blackouts in Turin)
13	17/07/2023 – 00:00 to 23:59	**6.90**	24h (Blackouts in Turin)
14	18/07/2023 – 00:00 to 23:59	**5.00**	24h (Blackouts in Turin)
15	19/07/2023 – 00:00 to 23:59	7.13	24h
16	20/07/2023 – 00:00 to 23:59	**2.60**	24h (LM entered Safe Mode)
17	21/07/2023 – 00:00 to 23:59	**4.11**	24h (LM entered Safe Mode)
18	22/07/2023 – 00:00 to 23:59	7.10	24h
19	23/07/2023 – 00:00 to 23:59	7.09	24h
20	24/07/2023 – 00:00 to 23:59	7.09	24h
21	25/07/2023 – 00:00 to 15:55	**6.66**	Approx. 16h

Considering the results presented in Table 3 above, PFPU consumes an average of 7.42 kWh/day (not considering **red** data where PFPU was in emergency conditions) meaning an instant power of:

- 370 W during 16h-day phase (average)
- 185 W during 8h-night phase (average)

C. Potato Life Test Results Using a Reusable 3D Printed Root Module Design

The potato life test was performed at UNINA premises in a ground COTS environmental chamber in order to validate and demonstrate the growth of potato tubers in the 3D-printed PGU developed by CIRIS. The results presented in this section refer to the test executed between 26/05/2023 and 28/07/2023.

Figure 15 shows the potato plants at the beginning of the experiment (T0) when the tuber-seeds were transplanted from the germination chamber into the 3D-printed PGUs. Initially, to promote roots growth and to help them to find the water, the felt made of a capillary mat is equipped with “wings” that are used as a bridge to guide roots toward the water and out of the cradle. Additionally, a small PVA foam/sponge disc is added right below the tuber-seeds to improve and ensure nutrients uptake from the 3D-printed substrate (i.e., capillary gyroid).

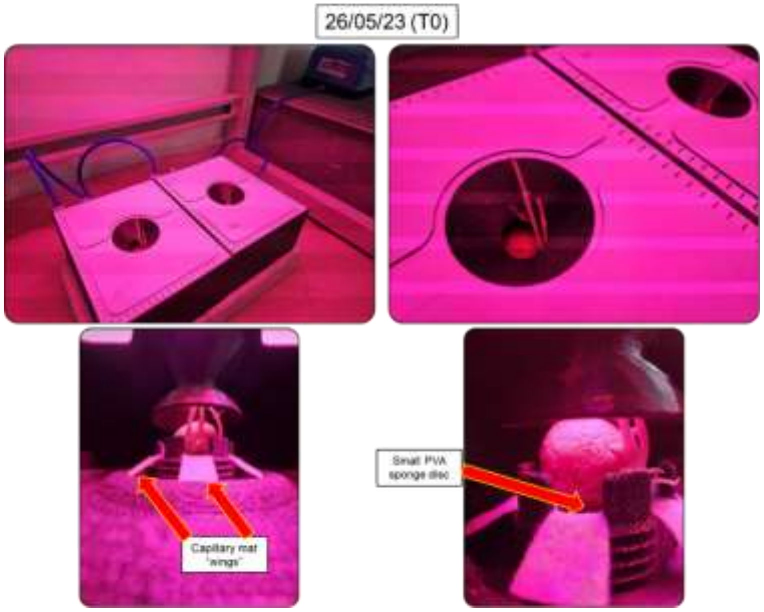


Figure 15: Potato plants at T0 (26/05/2023)

After three weeks, roots were fully expanded (able to find the water/nutrient solution) in the substrate, successfully over-passing the gyroid's wavy surface (Figure 16, on the right), as well as the first small leaves appeared and started to grow (Figure 16, in the center). However, the design demonstrated to not be fully light-tight and as a matter of fact, some roots tried to escape the PGU cover and to grow towards the light (Figure 16, on the left).

Figure 16: Tuber plants at T0+3/3.5 weeks (13th and 16/06/2023)

In the fourth week, the shoots and stolons started to grow and the leaves started to expand notably (Figure 17, shoots and stolons depicted on the left and right images, leaves in the center one).

Figure 17: Tuber plants at T0+4 weeks (19/06/2023)

After five weeks, roots were expanding all over the PGU internal volume, while the shoots reached around 20cm in height (Figure 18).

Figure 18: Tuber plants at T0+5 weeks (27/06/2023)

At the sixth week (Figure 19), new tubers started to grow. In this case, the first tuber grew right below the tuber-seed, probably because of the better humidity conditions (considering the irrigation path and the presence of the PVA disc). Conversely, the roots farther from the irrigation path started to dry at this stage, highlighting a not perfect uniform distribution of water/nutrient solution in the root zone.

Figure 19: Tuber plants at T0+6 weeks (07/07/2023)

From the seventh week onward, the tubers started to grow also in the tuber zone (Figure 20) and interestingly, the newly formed tuber became so strong that was able to break the teeth of the tuber-seed cradle. Finally, Figure 21 shows the harvested tubers at the end of the experiment.

Figure 20: Tuber plants at T0+7 weeks (17/07/2023)

Figure 21: Tuber plants at the end of the experiment, T0+9 weeks (28/07/2023)

Many conclusions and lessons learned can be inferred by the outcome of the potato life test. The 3D-printed PGU was demonstrated capable of sustaining and supporting the growth of potatoes, concluding the crop cycle with the formation of new tubers. The combination of the capillary mat (felt) and the PVA disc strongly improved the nutrient solution uptake from the 3D-printed substrate. The roots successfully expanded above the 3D-printed substrate covering the bottom area of the PGU. The 3D-printed substrate did not consent root penetration and consequently, some superficial roots dried up and necrotized (with mold formation). The PGU cover requires design optimization in order to avoid light leakage inside the tuber and root zones as well as to prevent lifting due to the growth of tubers below the tuber-seed itself. Some shoots failed to emerge through the central hole and remained trapped inside the PGU despite the inverted funnel designed to convey the shoots to the hole. The water retention capacity and the nutrient solution distribution in the 3D-printed substrate under microgravity should be investigated, because they could affect the root penetration and distribution.

IV. Conclusion and Future Perspectives

One of the core objectives of the ESA MELiSSA PFPU study is the development of a cost effective microgravity technology demonstrator aiming at a statistically representative and controlled production of edible tuberous plants (i.e., potatoes) from tuber-seeds to ready-to-harvest. Project phase B1 was successfully concluded at the end of 2023 following the PFPU BBM model Post-Test Review (PTR) and the PFPU Flight System Requirements Review (SRR). The major objectives of the last phase were to mature the technologies of some of subsystems or components previously developed for the Precursor of Food Production Unit (PFPU), to study in detail the other modules (e.g. the temperature control module, the illumination module, the growth chamber, etc.), as well as to integrate them into a system breadboard for thorough testing, in support of a system requirements review. All objectives were successfully achieved.

The PFPU is a precursor of an operative microgravity food production unit (FPU) for exploration missions. The closest utilization scenario is considered to be the Mars Transit Habitat, the spacecraft that will bring the first crewed mission to Mars orbit.

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