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Review and analysis of plant growth chambers and greenhouse modules for space

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The cultivation of higher plants occupies an essential role within bio-regenerative life support systems. It contributes to all major functional aspects by closing the different loops in a habitat like food production, CO_2 reduction, O_2 production, waste recycling and water management. Fresh crops are also expected to have a positive impact on crew psychological health. Plant material was first launched into orbit on unmanned vehicles as early as the 1960s. Since then, more than a dozen different plant cultivation experiments have been flown on crewed vehicles beginning with the launch of Oasis 1, in 1971. Continuous subsystem improvements and increasing knowledge of plant response to the spaceflight environment has led to the design of VEGGIE and the Advanced Plant Habitat, the latest in the series of plant growth chambers. The paper reviews the different designs and technological solutions implemented in higher plant flight experiments. They are analyzed with respect to their functional (e.g. illumination source, grow medium), operational (e.g. illumination period, air temperature) and performance parameters (e.g. growth area, biomass output per square meter). Using these analyses a comprehensive comparison is compiled to illustrate the development trends of controlled environment agriculture technologies in bio-regenerative life support systems, enabling future human long-duration missions into the solar system.

I. Introduction

THERE has been a consistent effort on-orbit to grow higher plants and assess the effect of the spaceflight environment upon them. These efforts have included free-flyer experiments[1], short duration crewed missions (e.g. Shuttle, Shenzhou)[2, 3] as well as those typically of longer duration conducted in Salyut, Mir and the International Space Station (ISS)[4]. In particular, plant growth experiments have been an important part of each space station program since their incorporation into the Soviet/Russian Salyut 1, the first space station. Early on orbit production systems were quite exploratory in nature in that they focused on the fundamental investigations related to the effect of the spaceflight environment on plant growth or technology development associated with providing an appropriately controlled environment on orbit.

II. Plant Growth Chambers in Space

A. Classification

Plant cultivation flight experiments are usually small chambers that are not an active part of the life support system. They are typically utilized to study plant behavior and development under reduced gravity and in closed environments. Other summaries of plant growth chambers have been published in recent years[2, 4-8]. However, the bulk of these publications are not up-to-date and therefore do not contain information about the latest chambers. Although Haeuplik-Meusburger et al. (2014) provides an extensive list of small plant growth facilities, only a select

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number were described in detail. For the present paper, the authors have collected information from a large number of publications, reports and personal communications. Condensed summaries have been compiled for each plant growth chamber and classified with respect to the space station or spacecraft on which they utilized. Figure 1 provides an overview of the plant growth chambers described in the following subchapters. Although not explicitly mentioned as a category, the authors are aware of the experiments conducted on-board Skylab[9, 10] and Shenzhou[3].

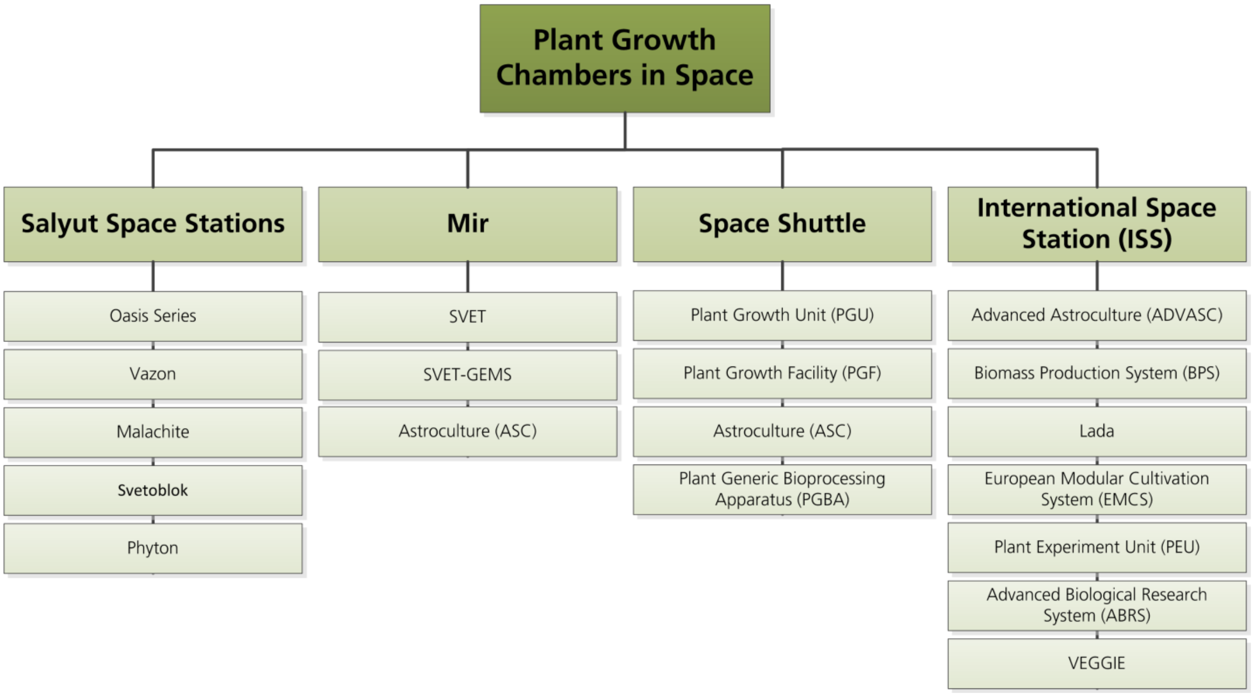

Figure 1. Overview of plant growth chambers in space.

B. Salyut Space Stations

The Soviet Salyut stations were the first crewed space stations and were the predecessors of the Mir space station and the ISS. The first facility, Salyut 1, was launched in 1971. The Soyuz 11 crew spent 23 days on-board Salyut 1 and performed several experiments including the Oasis 1 plant growth system. After a series of technical problems and failures, the Salyut program continued with Salyut 3-5 between 1974 and 1977. Salyut 3 and 5 were military missions, also known as Almaz. Although continuous improvements were implemented, the basic design of the stations remained the same. Salyut 6 (1977-1982) and 7 (1982-1987) incorporated several design improvements (e.g. an additional docking port for Progress resupply vessels) allowing for longer utilization and extended crew stays.

1. The Oasis Series

The first Soviet Union flight experiment was the Oasis 1 plant growth system. It was part of the Salyut 1 mission in 1971. During the mission *Brassica capital*, *Linum usitatissimum* and *Allium porrum* were grown in the eight cultivation slots of Oasis 1. Fluorescent lamps provided the necessary illumination. Oasis 1 was the first in a number of successful Oasis series chambers. Oasis 1M, an upgraded version of Oasis 1 was operated on Salyut 4. Problems with the water metering system were solved and a new nutrient delivery system was utilized. Oasis 1AM was the next plant growth system of the Oasis family and was flown on Salyut 6. The illumination system was modularized to facilitate maintenance. Furthermore, the watering system was modified. Oasis 1A was installed in the Salyut 7 station and was the last of the Oasis experiments. Compared to its predecessors, Oasis 1A was capable of providing increased aeration to the root zone. Further enhancements were made to the grow chamber. The new system allowed the movement of plants for better illumination, ventilation and gas exchange[1, 4, 7].

Figure 2. Oasis 1 as exhibited in the Memorial Museum of Astronautics in Moscow[11].

2. Vazon

Vazon is another plant growth system of the Soviet Union. Its first flight was on Soyuz 12 in 1973. Unlike Oasis, Vazon had no separate lighting system. Illumination was provided by the lighting system of the spacecraft. The system was designed to grow bulbous plants. Vazon was modified several times and was also operated onboard Salyut 6, Salyut 7 and the Mir space station[4].

3. Malachite

Malachite, flown on Salyut 6, was the first experiment specifically designed to investigate the psychological benefits of crew interaction with plants. From that perspective, orchids were the chosen crop and were grown in four Malachite planting boxes. The system was equipped with an ion exchange resin, water supply and an illumination system[4].

4. Svetoblok

Svetoblok, on Salyut 7, was the first plant growth system capable of growing plants in a sterile environment. According to Porterfield, et al. (2003), this advantage led to the first successful flowering of plants grown in space during a 65-day experiment. However, no viable seeds were produced. Updated versions of Svetoblok were also flown on the Mir space station[7, 12].

5. Phyton

The success of Svetoblok led to the initiation of the Phyton project, which had the goal to undertake seed to seed cultivation. The system consisted of five removable glass cylinders in which the plants were grown. Phyton also had an automated seed sowing apparatus, a ventilation system including bacterial filters and a separate illumination source. The Phyton plant growth system was used to conduct the first seed to seed cycle in space during a mission on Salyut 7[4].

C. Mir Space Station

The Russian Mir space station was designed based on the experience gained with the Salyut stations. The first module was launched in February 1986. A number of additional modules (Kvant, Kvant 2, Kristall, Spektr, etc.) were attached during the subsequent years. The Mir station was nearly permanently inhabited, except for short periods in 1986 and 1989) until the departure of Soyuz-TM 29 on the 28th of August in 1999. The Mir space station was used for a large number of scientific experiments. The start of the Shuttle-Mir Program, a cooperation agreement between the US and Russia, in 1994 set the basis for the building of the ISS.

1. SVET

The Russians continued their bio-regenerative life support system (BLSS) research efforts on the Mir space station with the SVET space greenhouse. The first SVET experiment conducted in collaboration with Bulgaria was launched on the 31st of May in 1990. The module successfully docked to the Mir station on the 10th of June and was subsequently installed inside the Kristall (Kvant 3) module. SVET was initiated on the 15th of June with a number of system tests that proved the functionality of the system[13, 14].

SVET consisted of a plant chamber with a grow area of approximately 0.1 m^2, a light and ventilator unit, an air supply system, a water supply system, power supply and a control unit. The plant chamber was outfitted with a removable root module in which the plants were cultivated. Illumination was provided by 12 small fluorescent lamps. The ventilator was mounted close to the lamps to provide proper cooling and an air flux up to 0.3 m/s. The main purpose of the air supply system was the provision of oxygen to the plant roots. Furthermore, inside the plant chamber, a sensor package was used to measure several environmental parameters. The system was capable of observing the air temperature in the lower compartment, the air temperature within the plant canopy, the humidity and the illumination duration. Sensors were placed within the growth medium ("Balkanin") to measure substrate temperature and moisture levels. The SVET space greenhouse was designed to be an automated system, thus it was the first plant flight experiment to utilize its own microprocessor. The processor was capable of receiving data from environmental sensors and controlling the illumination system, the ventilation and a compressor[13, 14].

The first plants were grown in a 53-day experiment in the summer of 1990. Radish and Chinese cabbage were selected for this experiment. Compared to ground experiments, different moisture values inside the substrate were measured due to the absence of gravity. During the experiment plant samples were taken and brought back to Earth together with the crops harvested on the last day. According to Ivanova (1993), the plants had a healthy appearance, but were stunted compared to the control plants grown on Earth. The leaves had a characteristic dark green color and a rough surface. The arrangement of the leaves was normal.

2. SVET-GEMS

The Shuttle-Mir Program, a cooperation between Russia and the United States of America, started in 1994 and encompassed a number of cooperative missions on the Space Shuttle and the Mir space station. In 1995 the Space Shuttle successfully docked to the Mir station. During this mission the SVET space greenhouse was reinitiated as part of the Shuttle-Mir Program. Some of the old equipment was updated and new systems provided by the Americans were added to SVET. The new equipment consisted of an Environmental Measurement System (EMS) and a Gas Exchange Monitoring System (GEMS), leading to the name SVET-GEMS for the new system[15].

The EMS replaced the old sensor package and provided new sensors for monitoring air and soil conditions, leaf temperature, irradiance and oxygen. The new system also greatly increased the number of sensors, e.g. from two root moisture sensors to 16. Furthermore, the gathered data was sent to Earth daily, which enhanced the data quantity and quality. For the GEMS, the original sole air stream for cooling the lamps and providing gas exchange for the plants was divided into two separate air streams. This was achieved by putting the plants of each root module into a transparent bag with separate air in- and outlets. GEMS was able to analyze the air entering and exiting the plant bags for its absolute and differential CO_2 and H_2O levels as well as absolute and differential pressures. GEMS was utilized to measure the photosynthesis and transpiration rate of the plant canopy under microgravity, which was calculated from differential CO_2 and H_2O measurements. Therefore GEMS had an increased capability compared to the first measurements in space using chlorella and duckweed. The high amount of data and the increasing complexity of the control mechanisms required a new control system, which was implemented on an IBM notebook[15-18].

Between 1995 and 1997 several experiments with super-dwarf wheat were conducted and the SVET greenhouse received small design updates with each subsequent experiment. During the first experiments in 1995, several system failures occurred. On the 15th of August, three lamp sets failed. On the next day, the control unit started to malfunction and failed completely in the beginning of September. On September the 18th the fans failed while the lamps were powered on, leading to a significant temperature increase in the plant chamber to 35 – 37 °C. Most of the failures were addressed with updates for the 1996/97 experiments[19, 20]. Another finding during the 1996/1997 experiments led to the conclusion, that high levels of ethylene led to aborted seed production in wheat. As a result all subsequent plant experiments included ethylene filters and trace contaminant control[21].

According to Ivanova (1998) and Salisbury (2003), the results of the 1996/97 experiments were better than expected. The produced biomass was much higher than expected and the plant health, especially root health, was much better than in any previous experiment. The leaves had a healthy green color and 280 wheat heads were produced. However, none of them contained any seeds. It was assumed, that pollen was either not formed or not released.

D. Space Shuttle

The Space Shuttle was an American re-usable crewed spacecraft. The first orbital test flight was conducted in 1981 and regular operations began in 1982. Until 2011, 135 missions, divided between the five orbiters Atlantis, Endeavour, Columbia, Challenger and Discovery, were launched until the Shuttle was decommissioned in 2011. For many years the Space Shuttle program was the backbone of the American human space flight program. The Space Shuttles played a key role in the assembly of the ISS and in many other scientific space missions (e.g. Hubble Space Telescope, Spacelab). During several missions a number of plant growth chambers of different designs were operated onboard.

1. Plant Growth Unit (PGU)

The Space Shuttle Program was the first opportunity for American BLSS researchers to perform regular flight experiments. The Plant Growth Unit (PGU) was the first experiment and was flown on STS-3 in 1982. The system was designed to study seedling growth and lignification. The dimensions of the PGU were 51 cm x 36 cm x 27 cm and fit into a middeck locker. One PGU consisted of six Plant Growth Chambers (PGC) and systems supporting plant growth. Three fluorescent lamps provided the necessary illumination. The lighting system was controlled by a timer. Furthermore, the environment could be regulated by fans and a heater. The PGU system was used for experiments over the next 15 years[4, 22].

2. *Plant Growth Facility (PGF)*

In 1997 the Plant Growth Facility (PGF) had its first flight on STS-87. The PGF was an updated PGU with the same dimensions, but enhanced equipment. The output of the lighting system was greatly improved from 50-75 µmol/(m² s) to 220 µmol/(m² s). Further enhancements were made to the air management system, which was now capable of controlling humidity, CO_2 and temperature. An ethylene filter was also installed[4, 23]. The PGU and PGF were also used to investigate plant reproduction in microgravity during the CHROMEX experiments that showed that CO_2 enrichment and adequate ventilation were required for ensuring normal seed production in microgravity. This work led to the notion that secondary effects of microgravity can significantly affect normal plant development[24].

3. *Astroculture (ASC)*

Figure 3. ASC-8 flight hardware installed in a middeck locker[24].

The Astroculture series was another plant growth chamber designed for the Space Shuttle. Its first flight (ASC-1) was on STS-50 in 1992, followed by continuous updates and corresponding qualification flights (STS-57, -60, -63, -73, -89, -95)[25]. At one time an ASC chamber was also operated on board the Mir space station. The first three ASC experiments were designed to perform system tests and verification. ASC-1 tested the nutrient and water delivery subsystem[26, 27]. An LED lighting subsystem was added to the system for the ASC-2 experiment[28] and a temperature and humidity control subsystem for ASC-3[29, 30]. Further subsystems (pH control subsystem, nutrient composition control subsystem and CO_2 and atmospheric contaminant control subsystems) were continuously added to the system. The flight experiment was designed to fit into a middeck locker (MDL) and had a cultivation area of 177 cm². A shoot-height of 23 cm was available, while 4.5 cm of height was reserved for the root zone. The last experiment with the Astroculture™ system was performed in 1998. ASC-8, as shown in Figure 3, consisted of a temperature and humidity control system, a LED lighting system, a fluid delivery control system and an ethylene scrubber unit. The experiment grew roses and investigated the effects of microgravity on the production of essential oils[24].

4. *Plant Generic Bioprocessing Apparatus (PGBA)*

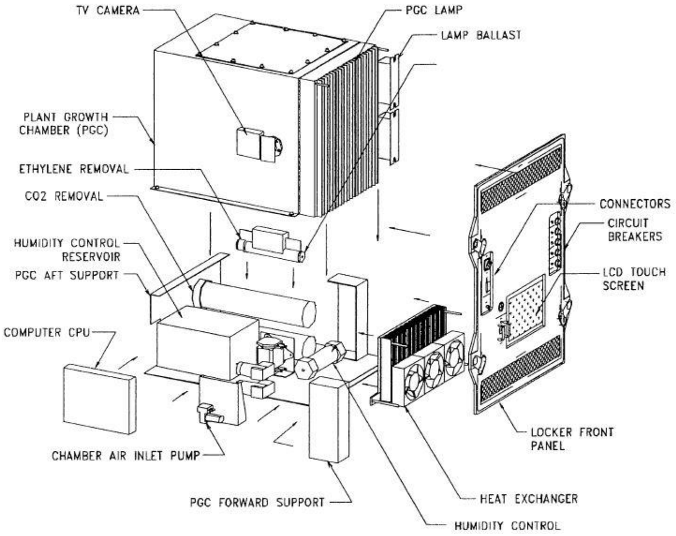

Figure 4. Exploded assembly drawing of the PGBA[31].

The Plant Generic Bioprocessing Apparatus (PGBA) was derived from the Generic Bioprocessing Apparatus (GBA). The GBA flew on several Space Shuttle missions (STS-50, -54, -57, -60, -62, -63, -69 and -73). Consequently, the design of the experiment was already partly flight verified. The first flight of a PGBA was on STS-77 in 1996. Similar to Astroculture™, the PGBA was designed to fit into two middeck lockers. A containment structure, a plant growth chamber, a thermal control system and an electrical subsystem were part of the PGBA. Figure 4 shows an exploded assembly drawing of the PGBA with all its major parts highlighted[31]. The PGBA was operated during three Space Shuttle missions (STS-77, STS-83, STS-94) with durations of 4, 10 and 16 days respectively[2]. In 2002 the PGBA was also used for experiments onboard ISS during Expedition 5[32].

E. International Space Station

The ISS is the largest man-made laboratory so far constructed in Earth orbit. With its first plans dating back to the American Space Station Freedom (SSF) and the proposed Russian Mir-2 station, the assembly of the ISS began with the launch of the Russian Zarya module in 1998. Over the following years a large number of assembly flights from all ISS partners (USA, Russia, Europe, Japan and Canada) subsequently built up the station to its current configuration. Since November 2nd, 2000, the ISS has been permanently inhabited by multi-national crews. The ISS has unique capabilities for a wide range of experiments (e.g. life sciences, material physics). With expected operation until at least 2020, and a high probability of another extension period until 2024, the ISS serves as a testbed for future human space exploration missions into the Solar System.

Figure 5. Advanced Astroculture ISS plant growth chamber[34].

1. *Advanced Astroculture (ADVASC)*

The Advanced Astroculture (ADVASC) experiment was the first plant growth chamber flown on the ISS. The design is based on the original Astroculture flown several times on the Space Shuttle. However, ADVASC has twice the size[4]. ADVASC is able to autonomously provide stable environmental conditions for plant cultivation under microgravity. Due to its increased size, ADVASC required two single middeck lockers inserts which could be installed into an EXPRESS Rack.

One insert contains all support systems, lower insert shown in Figure 5, while the other contains the plant growth chamber, top insert in Figure 5. Like other flight experiments, the ADVASC has all subsystems to support plant development: a plant growth chamber, a light control module, a temperature and humidity control unit, a fluid nutrient delivery system and chamber atmospheric control[33]. During the ADVASC-1 experiment (2001), a seed-to-seed experiment with *Arabidopsis Thaliana* was performed. Several seeds were gathered[34]. These 1st generation seeds were used for the ADVASC-2 (2001/2002) experiment to investigate whether they are able to complete another full life cycle under microgravity and how the genes were affected. At the end of the experiment, 2nd generation seeds were gathered. ADVASC-3 (2002) was the first experiment to grow soybean plants in space. The goal was to complete a full life cycle and to investigate the produced seeds. After 95 days, a full life cycle was completed. Analyses of the produced seeds showed that the seeds were healthy and the germination rate was comparable to commercial seeds in terrestrial agriculture[35].

2. *Biomass Production System (BPS)*

The Biomass Production System (BPS) was a plant growth chamber operated on the ISS in 2002 during Expedition 4. It was designed to validate subsystems under orbital conditions. Two experiments were carried-out during this mission, the Technology Validation Test (TVT) and the Photosynthesis Experiment and System Testing and Operation (PESTO) experiments. PESTO demonstrated that plants grown in space do not differ from ground controls when the secondary effects of the spaceflight environment are mitigated. Evidence was identical rates of photosynthesis and transpiration that were corroborated with identical biomass between spaceflight and ground control plants[32, 36]. The system was first designed to fit into the Shuttle Middeck and the SpaceHab Module, but was later adapted for installation into an EXPRESS Rack to be able to fly to the ISS. The BPS contained four individual plant growth chambers. Each chamber had its own independent control system for temperature, humidity, lighting and CO_2. An active nutrient delivery system was also part of the experiment. The overall BPS had a depth of 52 cm, a width of 46 cm and a height of 55 cm. The total mass was 54.4 kg[32]. The total grow area was 1040 cm² divided equally among the four chambers with each 260 cm². The subsystems and technologies validated with the BPS were later used within the Plant Research Unit (PRU)[38].

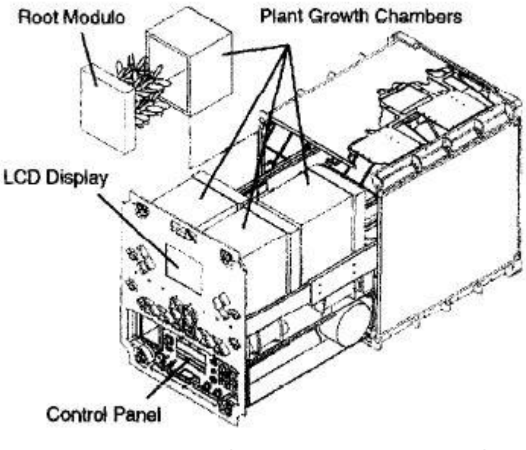

Figure 6. Design of the BPS including four individual plant growth chambers[38].

3. Lada

The Lada greenhouse is a plant growth system developed for the ISS and flown in 2002[39]. The system partly reused equipment from the SVET-GEMS experiment. The subsystems of Lada are spread amongst four modules: the control and display module (Figure 7 upper center), two growth modules (Figure 7 left and right) and a water tank (Figure 7 bottom center). The modules were built to be attached to the cabin wall of the Russian Zvezda Module. The two growth modules could be controlled independently and consisted of a light bank, a leaf chamber and a root module[40]. The light bank could be outfitted either with fluorescent lamps[41] or LEDs[40]. A sensor tree mounted at the light bank is capable of measuring air temperature and light spectrum at three different levels. The leaf chamber is 25 cm high, but could be replaced by chambers of different height to support different crops. The chamber walls are covered with a reflective film to increase plant illumination. The root module is 9 cm deep and holds the substrate for the roots. Several sensors are placed inside this module to investigate the behavior of the plants' root zone. Six moisture probes and four micro tensiometers were arranged in three levels to gather data across the whole root zone. Furthermore, two wick moisture probes and four O_2 sensors were placed in the root module.

Figure 7. Lada; control and display module (upper center), growth modules (left and right), water tank (bottom center)[40].

During the first on-orbit experiment Mizuna plants were grown in Lada's growth modules to a height of 20 cm. For the first time in on-orbit greenhouse module research the psychological effects of the interaction between the crew and plants were investigated[40]. Some reactions of the ISS crew to the consumption of space-grown plants are cited by Bingham (2003). From 2003 to 2005, genetically modified dwarf pea plants were grown during five experiments with Lada. These experiments investigated morphological and genetic parameters over several generations of space grown plants[42]. LADA was also used to develop the hazard analysis and critical control point (HACCP) plan for vegetable production units[43, 44].

4. European Modular Cultivation System (EMCS)

The European Modular Cultivation System (EMCS) was launched on STS-121 in July 2006[45]. EMCS was installed on-board the ISS within the US Destiny module[46]. In April 2008 the experiment was moved to the European Columbus Module[47]. The EMCS contains two rotors to apply different levels of gravity (0.001 g to 2.0 g) to the contained experiment containers (EC), see Figure 8. Each rotor can hold up to four ECs. They also provide a simple life support system, reservoirs, lamps and a video camera system for experiments. One EC is 60 mm high, 60 mm wide and 160 mm long with an internal volume of 0.58 liters[48]. The EMCS was used to carry out different European plant growth and plant physiology experiments (e.g. GRAVI, GENARA, MULTIGEN and TROPI)[46]. It was also utilized by the Japanese Aerospace Exploration Agency (JAXA)[49]. The EMCS was designed to conduct plant research and other biological experiments in space. The size of the EC and the whole experiment setup did not allow the growth of vegetables or other plants for food production.

Figure 8. EMCS in EXPRESS Rack-3 inside ESA Columbus Module (since April 2008)[47].

5. *Plant Experiment Unit (PEU)*

The Japanese Plant Experiment Unit (PEU) is an experiment container to be mounted within the Cell Biology Experiment Facility (CBEF) inside the Kibo laboratory module of the ISS. Each PEU is 95 mm high, 240 mm wide and 170 mm deep and consists of a LED lighting system with red and blue LEDs, a growth chamber, an automated watering system and a CCD camera. The chamber provides growth space up to 48 mm height, 56 mm width and 46 mm depth, see Figure 9. The lower part of the chamber is reserved for the growth medium (rock wool) which is fed by an integrated water line. In 2009, eight PEUs were launched with STS-128 and implemented into the CBEF. The experiment was called Space Seed and had the purpose to grow Arabidopsis from seed to seed under different conditions. The plants were grown for 62 days inside the PEU mounted in the CBEF[50].

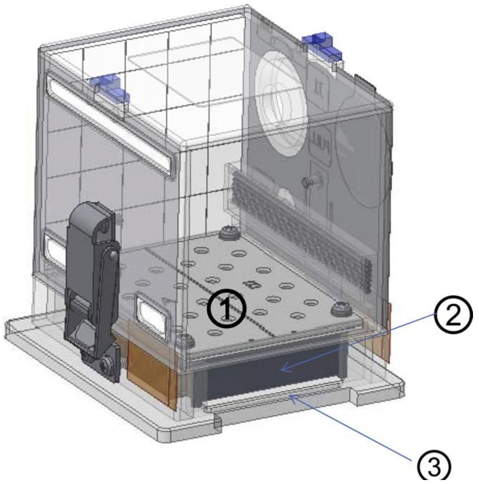

Figure 9. Onboard model of the PEU plant growth chamber. (1) Stainless steel cover plate with 24 holes; (2) IR-target plate; (3) Polyvinyl alcohol sponge[50].

6. *Advanced Biological Research System (ABRS)*

The Advanced Biological Research System (ABRS**)** was launched in 2009 on STS-129. Similar to its predecessors, ABRS was designed to fit into a single middeck locker as displayed in Figure 10. The main parts of ABRS are two Experimental Research Chambers (ERCs) that provide a controlled environment for experiments with plants, microbes and other small specimens. Each ERC has a grow area of 268 cm² with up to 5 cm height for the root zone and 19 cm for the shoot zone. The chambers are outfitted with a LED light module, which consists of 303 LEDs mainly red and blue, but also with some white and green LEDs. The spectral peaks are at 470 nm and at 660 nm. An environmental control panel is part of each ERC. The panel enables the control of temperature, relative humidity and CO_2 level. A filter system is used to clean the incoming air. Furthermore, a filtration module allows the removal of volatile organic compounds (VOCs). One of the two ERCs is outfitted with a novel Green Fluorescent Protein (GFP) Imaging System (GIS). This system is designed to investigate organisms with modified GFP reporter genes[51]. One of the first experiments conducted within the ABRS was the investigation of the Transgenic Arabidopsis Gene Expression System (TAGES)[52, 53].

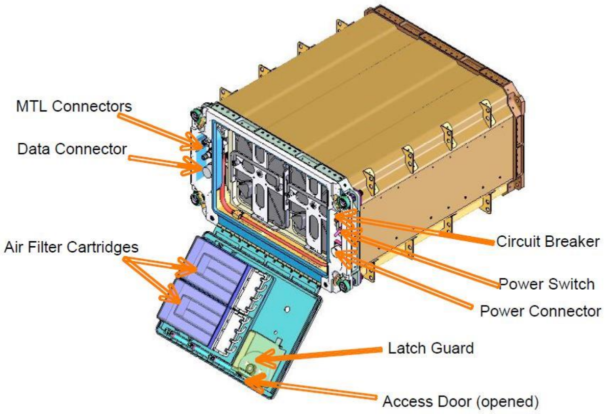

Figure 10. Advanced Biological Research System (ABRS) overview[51].

7. *VEGGIE*

The VEGGIE Food Production System is NASA's latest achievement in developing BLSS. It was launched in early 2014. VEGGIE is the first system designed for food production rather than plant experiments under microgravity. A deployable design allows VEGGIE to be stowed to 10% of its nominal deployed volume. In collapsed configuration, six VEGGIE units can be stored in a single middeck locker. Each unit consists of three major subsystems, the lighting subsystem, the bellows enclosure and the root mat and provides 0.17 m² grow area with a variable height of 5 to 45 cm. A customized LED panel with red, blue and green LEDs is used as the lighting subsystem. The panel is able to provide more than 300 µmol/(m² s) of illumination to the plants. The bellows enclosure separates the plant environment from the cabin to provide containment for the plants and to maintain elevated humidity. The enclosure is supported by a foldable structure, which allows adjustment of the distance between the lighting subsystem and the root mat while maintaining containment. The root mat serves as a passive nutrient delivery system, which requires only a small amount of crewtime to be supplied with water and nutrient solution[54]. Several different growth media have been investigated[55, 56] and in the end specially developed rooting pillows were selected. Crops produced by the VEGGIE system shall be used as supplemental food for the ISS crew. Achieving this objective is challenging and requires compliance with NASA's microbiological standards for food. The project team developed a HACCP plan, based on the plans tested with Lada, to minimize the risk of consuming produced vegetables. The selected sanitizer demonstrated functionality and applicability during a test campaign at NASA's Desert Research and Technology Studies (DRATS). For the demonstration a VEGGIE unit was installed in the Habitat Demonstration Unit (HDU) Pressurized Excursion Module (PEM), see Figure 11. After a 28 day growth cycle the harvested lettuce plants were sanitized and more than 99 % of the microbial load was removed. The microbial load of the produce was well within the NASA standards[57].

Figure 11. VEGGIE prototype during ground tests (left); NASA astronaut Steve Swanson next to VEGGIE after the deployment on-board ISS (right)[58].

F. Additional Systems and Design

Besides the aforementioned plant growth system, a number of concepts were never realized or are still in an early design and concept phase. Brief descriptions of some of these facilities are provided in the subsequent paragraphs.

The Vitacycle is a Russian plant growth chamber concept with a novel approach for the arrangement of the growth area. The design incorporates a convex growth area combined with a conveyor, which leads to a savings in occupied volume compared to a standard flat growth area. Prototypes of the chamber were built and tested in advance of a proposed utilization in the Russian compartment of the ISS[59-62]. The concept was also part of the Russian Mars500[62].

The Salad Machine concept was initially investigated by NASA's Ames Research Center[63] and further developed over the following years[64, 65]. The objective of the Salad Machine was to design and construct a salad vegetable production unit for Space Station Freedom (SSF). The production unit was planned to occupy a standard rack and provide around 5% of the total caloric intake of the crew. Later the design was adapted to match the requirements of the ISS.

The Plant Research Unit (PRU) was supposed to fly to ISS in its early years. It was the direct predecessor of the BPS. The PRU was designed as a closed system to generate a reliable plant growth environment. Although extensive effort was put into the design of the PRU[66-70], the program was canceled in 2005[71].

The Portable Astroculture Chamber (PASC) was a planned follow-on to the ADVASC. Although it did not fly, the PASC was designed for installation within an ISS EXPRESS rack. Compared to its predecessors, PASC planned to reduce complexity by utilizing ISS ambient air and included four transparent sides to permit easy viewing by the crew[72].

Astro Garden (later termed Education Payload Operations - Kit C Plant Growth Chambers) was developed as an educational tool and hobby garden for on orbit plant growth. The unsophisticated apparatus which flew to the ISS on STS-118 in 2007 required no supplemental power and utilized existing ISS light sources for growth[73].

CPBF (Commercial Plant Biotechnology Facility), although never flown was a quad middeck locker based system with a growth area of 0.2 m^2. It was being developed to provide a facility for long-term scientific and commercial plant trials onboard the ISS[2].

The NASA Advanced Plant Habitat (APH) is a planned four middeck locker plant growth system being developed at the Kennedy Space Center in cooperation with ORBITEC. The APH is based upon some of the design heritage of the CPBF. The project is divided into several phases with the final goal to deploy an EXPRESS rack based plant growth chamber with 0.2 to 0.25 m^2 production area onto the ISS[74, 75].

Small-scale plant growth hardware has also flown on Shenzhou. In particular, the DLR developed Science in Microgravity Box (SIMBOX) flew on a late 2011 Shenzhou flight and within it contained 17 different bio-medical experiments in collaboration between German and Chinese researchers. Included were a number of plant seedlings under LED illumination[3].

III. Comparative Analysis

A. Overview

Analyses and comparisons of the plant growth chambers described in the previous chapter are presented in the following section. Over the last few decades the size and shape of space plant growth chambers have changed and the technologies implemented into the different subsystems were developed further. Since 1970, 21 plant growth chamber designs were used to perform over 50 different plant cultivation experiments. Figure 12 shows a timeline indicating the timeframe in which each of the systems were utilized.

Table 1 summarizes the key data of flown plant growth chambers described above. They are sorted chronologically. The key data includes the spacecraft on which the chamber was operated, the platform for the experiment design (e.g. Middeck Locker (MDL)), the growth area, and details about the nutrient delivery system (NDS), the illumination system (ILS) and the atmosphere management system (AMS).

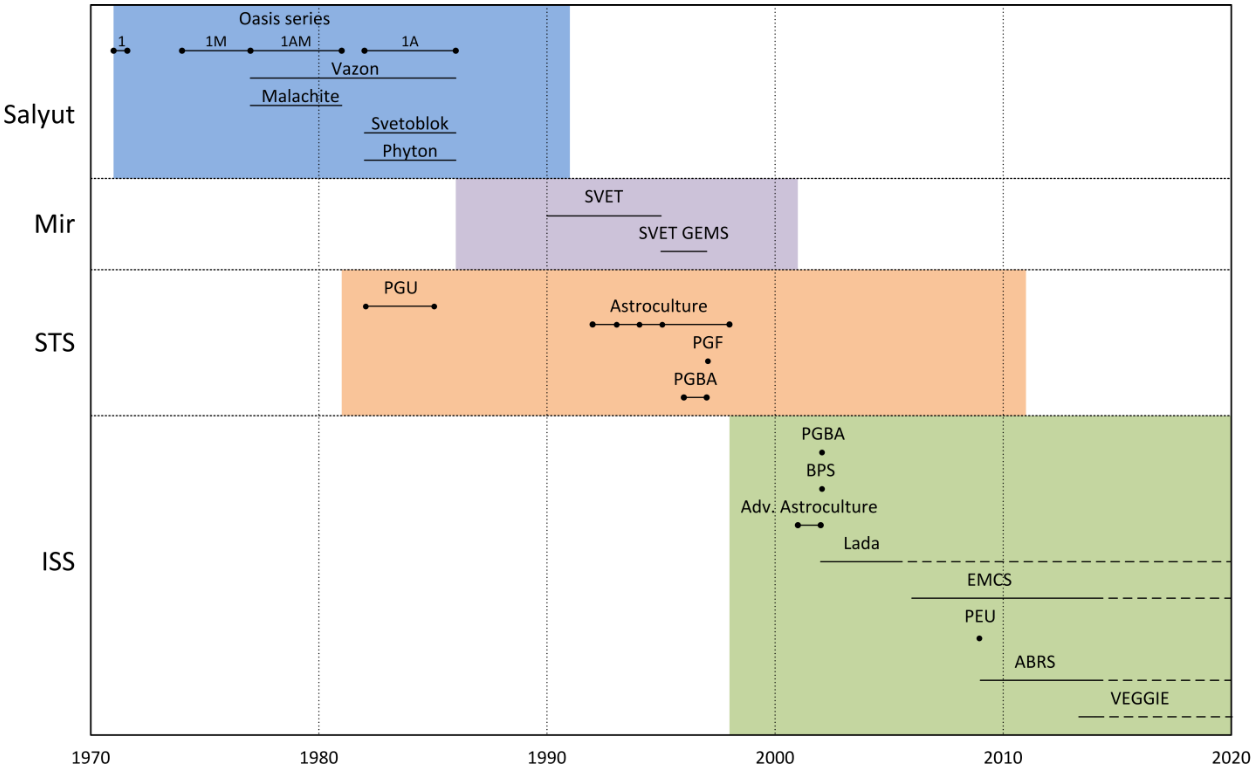

Figure 12. Timeline of plant growth chambers flown or proposed to fly in space.

Table 1. Summary of key plant growth chamber data.

	Space-craft	**First Launch**	**Platform (e.g. MDL)**	**Growth Area (m²)**	**NDS**	**ILS**	**AMS**
Oasis 1	Salyut 1	1971	Wall mounted	0.001	Two compartment NDS (Water and ion exchange resin)	Fluorescent lamps, 50-68 μmol/(m² s)	n.a.
Oasis 1M	Salyut 4	1974	Wall mounted	0.010	Fibrous ion exchange medium	Fluorescent lamps, 50-68 μmol/(m² s)	n.a.

	Space-craft	**First Launch**	**Platform (e.g. MDL)**	**Growth Area (m^2)**	**NDS**	**ILS**	**AMS**
Oasis 1AM	Salyut 6	1977	Wall mounted	0.010	Cloth ion exchange medium	n.a.	n.a.
Oasis 1A	Salyut 7	1982	Wall mounted	0.010	Included root zone aeration system	170-350 µmol/(m^2 s)	Ventilation
Vazon	Salyut 6, 7; Mir	1973	Wall mounted	n.a.	Cloth sack filled with ion exchange resin	Cabin light	Cabin air
Malachite	Salyut 6	1973	Wall mounted	n.a.	Ion exchange resin, water supply	Separate lighting system	n.a.
Svetoblok	Salyut 7	1982	Wall mounted	n.a.	Agar based NDS, later also other media	Cabin light, later fluorescent lamps	Sterile environment
Phyton	Salyut 7	1982	Wall mounted	n.a.	1.5 % agar nutrient medium	Separate lighting system	Ventilation incl. Bacterial filters
SVET	Mir	1990	Wall mounted	0.100	Zeolite based Balkanin substrate	12x fluorescent lamps	Ventilation
SVET-GEMS	Mir	1995	Wall mounted	0.100	Zeolite based ion exchange medium, root zone moisture controllable	Fluorescent lamps, 300 µmol/(m^2 s)	Controlled environment, photosynthesis and transpiration measurements
PGU	STS	1982	MDL	0.050	Various NDS used	3x 15 W fluorescent lamps, 50-75 µmol/(m^2 s)	Optional active air exchange system
PGF	STS	1997	MDL	0.055	Saturated foam or agar	Fluorescent lamps, > 220 µmol/(m^2 s)	Humidity, CO_2 and temperature control; ethylene filter
ASC	STS	1992	MDL	0.021	Porous tubes with matrix	LED (RB); 300 µmol/(m^2 s)	Humidity, CO_2, temperature and trace gas control
PGBA	STS	1996	2x MDL	0.075	Agar or aggregate that provide nutrients	Fluorescent lamps: > 350 µmol/(m^2 s)	Humidity, CO_2, temperature and trace gas control, photosynthesis and transpiration measurements
ADVASC	ISS	2001	2x MDL	0.052	Porous tube-based NDS	LED (RB); 410 µmol/(m^2 s)	Humidity, CO_2, temperature and trace gas control
BPS	ISS	2002	EXPRESS	0.104	Particulate matrix with porous tubes	Fluorescent lamps, 350 µmol/(m^2 s)	Humidity, CO_2, temperature and trace gas control,

	Space-craft	First Launch	Platform (e.g. MDL)	Growth Area (m^2)	NDS	ILS	AMS
							photosynthesis and transpiration measurements
Lada	ISS	2002	n.a.	0.050	Similar to SVET	Fluorescent lamps; 250 µmol/(m^2 s)	Humidity, CO_2, temperature and trace gas control
EMCS	ISS	2006	4x MDL	0.077 (8 chambers)	Customizable	LED (RW)	Gas supply unit, pressure control unit, ethylene removal unit
PEU	ISS	2009	n.a.	0.027 (10 chambers)	Rock wool	LED (RB): 110 µmol/(m^2 s)	Humidity and temperature control
ABRS	ISS	2009	MDL	0.053	Customizable	LED (RGBW): 300 µmol/(m^2 s)	Humidity, CO_2, temperature and trace gas control
VEGGIE	ISS	2014	MDL	0.170	Passive NDS, rooting pillows, manual water and nutrient supply	LED (RGB), > 300 µmol/(m^2 s)	none; cabin AMS

B. Comparison of growth area and volume

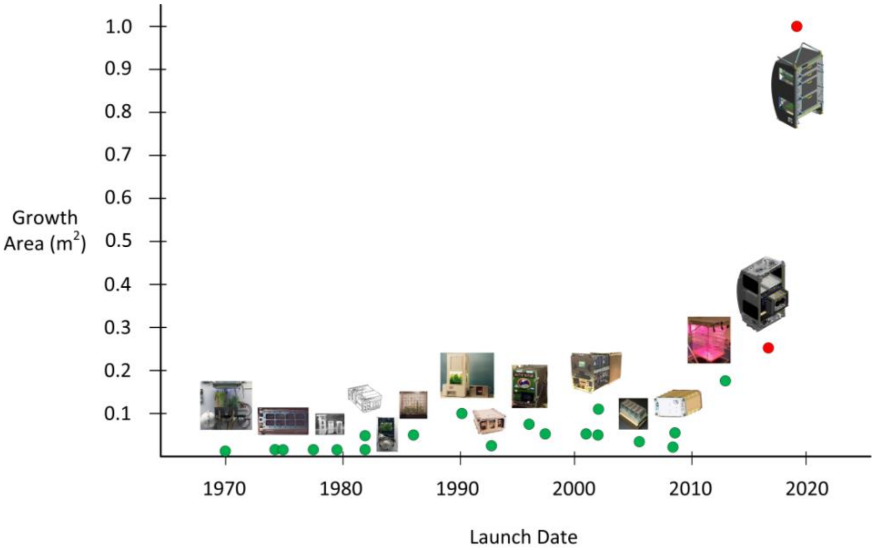

Figure 13. Comparison of space plant growth chamber growth area between 1970 and 2020. Green dots represent flown systems while red dots represent currently planned systems. The right-most data point represents the expected plant growth area of a full ISS rack-based plant growth system.

As evident in Figure 13, the total available growth area per cultivation system has constantly increased with time. Space-based plant production systems have been considerably volume constrained. Although larger scale production would be preferred, small-scale systems have been suitable to date; as focus has rested more on fundamental science related to the effect of the spaceflight environment on plant physiological functions and on the development of reliable on-orbit controlled environment facilities. Although much remains to be determined, sufficient understanding now exists in both these areas that a shift to the credible goal of non-negligible fresh food supplementation on orbit. The launch of VEGGIE and later the APH will start to provide more relevant biomass outputs but a marked increase in output would be possible with the development of a full ISS rack based system. Such a production system/salad machine would be possible of providing approximately 1 m^2 of production area which, as demonstrated in Figure 13, would provide a significant increase in capability and an initial step towards a relevant BLSS.

Not only is the overall size of the growth area inside space plant growth chambers increasing by building larger systems, but so is the relative growth volume. Figure 14 shows a comparison of the relative growth volume for a number of plant growth chambers. Note that Figure 14 only shows flown plant growth chambers designed to fit into standardized experiment carriers (e.g. MDL, double-MDL). As evident from Figure 14, ABRS has the highest efficiency in terms of usable volume of the growth chamber compared to the volume of the carrier, which was enabled by on-going technology improvements (e.g. LED systems) and miniaturization.

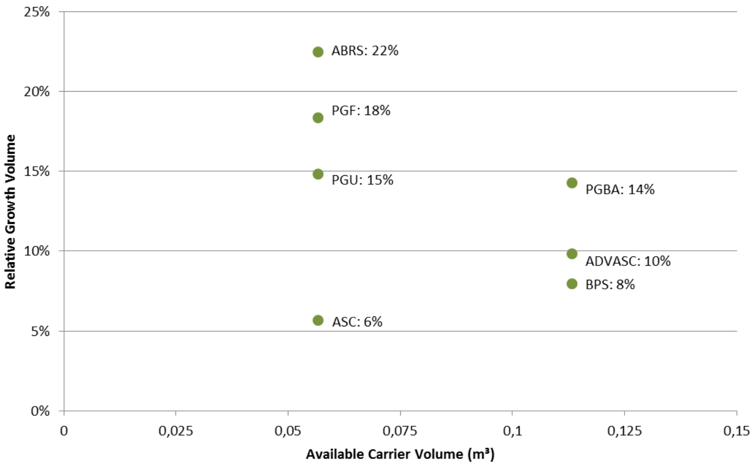

Figure 14. Comparison of relative growth volume.

C. Crop analysis

A broad variety of crops were grown in space utilizing the aforementioned plant cultivation systems. Table 2 shows several plant species and in which system they were grown. Table 2 focuses on edible crops. The total number of cultivated plant species is higher. The last column (other non-edible plants) represents plants like *Arabidopsis Thaliana*, roses, etc. Most of the candidate crops recommended for plant cultivation on future human space exploration missions[76] have still not been cultivated in space plant growth chambers. There are various reasons (e.g. plant requirements, chamber dimensions).

Table 2: Plants grown in space using plant growth chambers, with a focus on edible crops

	Allium porrum	**Barley**	**Brassica capitala**	**Brassica rapa**	**Chinese Cabbage**	**Corn**	**Dwarf pea**	**Lactuca sativa**	**Lentil**	**Lepidium**	**Linum usitatissimum**	**Pea**	**Radish**	**Snow pea**	**Soybean**	**Spinach**	**Sweet Wormwood**	**Swiss chard**	**Wheat (Triticum aestivum)**	**Other non-edible plants**
Oasis	x		x								x									
Vazon																				
Malachite																				x
Svetoblok																				x
Phyton																				
SVET					x								x							
SVET-GEMS				x															x	
PGU																				
PGF				x																
ASC																				x
PGBA																x	x			x

	Allium porrum	**Barley**	**Brassica capitala**	**Brassica rapa**	**Chinese Cabbage**	**Corn**	**Dwarf pea**	**Lactuca sativa**	**Lentil**	**Lepidium**	**Linum usitatissimum**	**Pea**	**Radish**	**Snow pea**	**Soybean**	**Spinach**	**Sweet Wormwood**	**Swiss chard**	**Wheat (Triticum aestivum)**	**Other non-edible plants**
BPS				x															x	
ADVASC															x					x
Lada		x		x			x					x	x							
EMCS									x	x										x
PEU																				x
ABRS																				x
VEGGIE								x												

IV. Summary

The paper reviews on-orbit plant growth chambers and numerous of their relevant characteristics. The list of facilities gives an overview about the development of plant cultivation systems in space over the last 40 years. It also shows concepts and designs of growth systems never operated in space and of systems currently under development. The evolution of available growth area per system is presented together with an analysis of relative growth volumes. The paper also gives an extensive summary of technologies used for the illumination subsystem, the atmosphere management and the nutrient delivery system together with an overview of crop plants grown in space.

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