Life Sciences in Space Research 10 (2016) 1–16

Contents lists available at ScienceDirect

Life Sciences in Space Research

journal homepage: www.elsevier.com/locate/lssr

Review and analysis of over 40 years of space plant growth systems

P. Zabel[a,*], M. Bamsey[a], D. Schubert[a], M. Tajmar[b]

[a] German Aerospace Center (DLR), Institute of Space Systems, Bremen, Germany
[b] Technische Universität Dresden, Institute of Aerospace Engineering, Dresden, Germany

ARTICLE INFO

Article history:
Received 30 November 2015
Revised 31 May 2016
Accepted 23 June 2016

Keywords:
Bio-regenerative life support
Space greenhouse
Controlled environment agriculture

ABSTRACT

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 systems. The paper reviews the different designs and technological solutions implemented in higher plant flight experiments. 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.

1. 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 (Halstead and Dutcher, 1984), short duration crewed missions (e.g. Shuttle, Shenzhou) (Hoehn et al., 1998, Preu and Braun, 2014) as well as those typically of longer duration conducted in Salyut, Mir and the Inter-national Space Station (ISS) (Porterfield et al., 2003). 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.

2. Plant growth chambers in space

2.1. 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 (Hoehn et al., 1998, Preu and Braun, 2014, Porterfield et al., 2003, Berkovitch, 1996, Haeuplik-Meusburger et al., 2014, Häuplik-Meusburger et al., 2011, Paul et al., 2013 a). 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 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. Fig. 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 (Floyd, 1974, Kleinknecht and Powers, 1973) and Shenzhou (Preu and Braun, 2014), they are listed in Section 2.6.

* Corresponding author. Tel.: +49 421 24420 1273.
E-mail addresses: paul.zabel@dlr.de (P. Zabel), matthew.bamsey@dlr.de (M. Bamsey), daniel.schubert@dlr.de (D. Schubert), martin.tajmar@tu-dresden.de (M. Tajmar).

http://dx.doi.org/10.1016/j.lssr.2016.06.004
2214-5524/

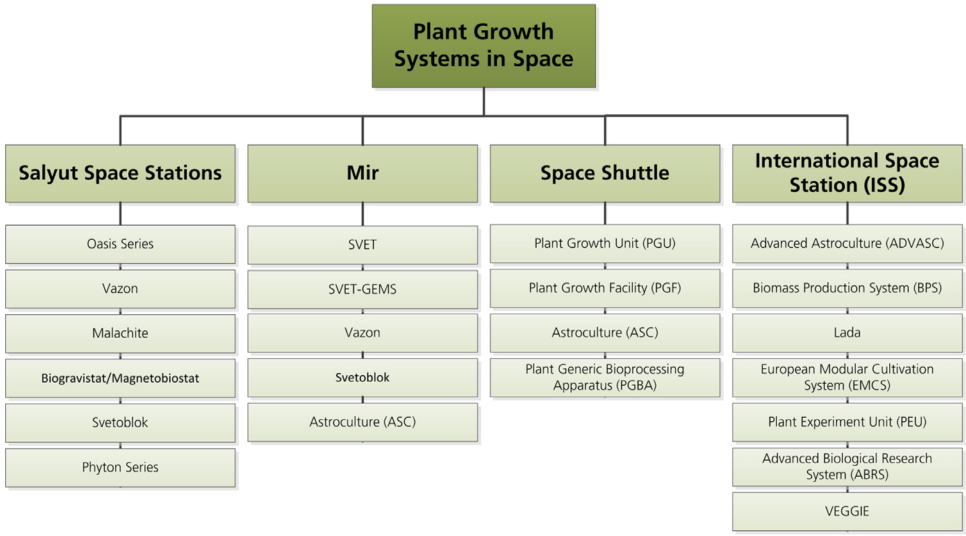

Fig. 1. Overview of plant growth chambers in space.

2.2. 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.

2.2.1. The oasis series

The first Soviet Union flight experiment was the Oasis 1 plant growth system. It was first flown on the unmanned Cosmos 368 flight to test the system in space (Harvey and Zakutnyaya, 2011). The first flight on a manned mission was on Salyut 1 in 1971. During the mission flax, leek, onion and Chinese cabbage 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 1 M, 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 (Porterfield et al., 2003). In Oasis 1 M (Figs. 2) peas and onion were grown. The experiments with peas were not successful. During the first mission only four out of 30 plants reached maturity and during the second mission the pea plants died within three weeks. Although the issues for the failure are not clear, the cosmonauts speculated, that the plants might have experienced too strong illumination burning the plants to death. The onions on the other hand did much better and grew to 20 cm height. In July 1975, the grown onions became the first space-grown vegetables ever eaten by humans (cosmonauts Klimuk and Sevastianov) (Harvey and Zakutnyaya, 2011). 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 (Figs. 2) was installed in the Salyut 7 station and was the last of the Oasis experiments. Compared to its predecessors, Oasis 1A was capable of

Fig. 2. Oasis 1 M (left) and Oasis 1A (right) as exhibited in the Memorial Museum of Astronautics in Moscow (photos taken by co-author M. Bamsey in 2014).

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 (Halstead and Dutcher, 1984, Porterfield et al., 2003, Haeuplik-Meusburger et al., 2014).

2.2.2. 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 (Porterfield et al., 2003). On Salyut 6 onions were grown and with Soyuz 34 several Vazon systems containing mature tulip plants and a Kalanchoe tree were brought up to the station to increase the mood of the crew. Cosmonauts Ryumin, who operated the plant growth system, reported that tending the stations 'garden' helped him to cope with his depression. During his mission plants were grown in the Oasis, Phyton, Biogravistat and several Vazon systems at the same time. He also convinced the Soviet mission control to bring soft artificial soil packs to the station with one of the supply flights. Ryumin could attach them to the station walls to grow

Fig. 3. Malachit plant growth system as exhibited in the Memorial Museum of Astronautics in Moscow (photo taken by co-author M. Bamsey in 2014).

plants by manually water them from time to time (Zimmerman, 2003).

2.2.3. Malachite

Malachite (Fig. 3), 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 (Porterfield et al., 2003). Malachite was brought to space by Soyuz 35 containing mature orchid plants and fresh seeds. The mature plants did not survive and wilted shortly after being brought to space. The seeds on the other hand grew and flowered. However, they wilted without producing any seeds (Harvey and Zakutnyaya, 2011).

2.2.4. Biogravistat/Magnetobiostat

Biogravistat was first flown on the eight day Soyuz 22 mission to investigate the effects of microgravity on higher plant shoots (Harvey and Zakutnyaya, 2011). It was also flown on Salyut 6 including cucumber, lettuce and parsley seeds. It was shaped like 1-foot wide starfish and could be rotated to simulate different level of gravity. The cucumber plant developed small leaves, but eventually began to wither. The improvements to the watering system made by the cosmonauts during the mission could not solve the problem that the plants were not getting enough water in the microgravity environment. Consequently, the cucumber, lettuce and parsley plants dried out and withered over time (Zimmerman, 2003).

Magnetobiostat is the upgrade installed to Biogravistat during one mission on Salyut 6. The upgrade was used to apply a magnetic field around Biogravistat. The scientists hoped to improve the growth with the system. Lettuce, barley and mushrooms were grown and at some point the cosmonauts discovered the correct rotation rate for the centrifuge inside Magnetobiostat to develop normal plants.

On Salyut 7 cosmonaut Lebedev grew lettuce in a Biogravistat system (Zimmerman, 2003).

2.2.5. Svetoblok

The first progress freighter to supply Salyut 7 delivered the Svetoblok plant growth system. It already contained tomato plants in it. However, the tomato plants did not well, growing only very slowly. They were only around 7.5 cm high after three weeks of growth (Zimmerman, 2003).

Svetoblok 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 (Haeuplik-Meusburger et al., 2014, Musgrave and Kuang, 2003).

2.2.6. Phyton series

The Phyton plant growth systems were first flown on Salyut 6. Phyton-1 had a very powerful lamp, a nutrient medium and a filter to extract air contaminants. Onions, cucumbers, tomatoes, garlic and carrots were sown. The crew also grew Arabidopsis plants and a dwarf wheat variety. The latter grew slower than expected and had to be cut down before the final development stage of the plants was reached, because the crew had to return to Earth (Harland, 2004).

Phyton-2 was another plant growth system used on Salyut 6. It consisted of three light sources and interchangeable plant pods which contained an ion-exchange nutrient. The plants were automatically watered with defined quantities. The first experiments showed that the shoots of the plants developed better, when they were exposed to sunlight near a porthole, than using solely electrical lighting. Nevertheless, the peas and wheat plants sown all died in their early development stages (Harland, 2004).

Phyton-3 was used to grow Arabidopsis plants on Salyut 6. In 1980 the plants flowered in space, four days later than their counterparts in a control experiment on Earth. This was a major step towards the first seed-to-seed experiment in space. Phyton-3 was also flown on Salyut 7. There it 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 (Porterfield et al., 2003). In 1982 the Arabidopsis plants were grown under continuous lighting for 69 days. They developed pink flowers and afterwards developed pods. The pods ripened and developed seeds. Around 200 seeds were produced in space and brought back to Earth. Half of them were immature and only 42% germinated to produce normal plants (Harland, 2004, Salisbury, 1999). This was the first time at all that plants were grown from seed to seed in space and therefore a major achievement for plant cultivation in space.

2.3. 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.

2.3.1. 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 (Ivanova et al., 1993, Ivanova et al., 1994).

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 (Ivanova et al., 1993, Ivanova et al., 1994).

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 et al. (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.

2.3.2. 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 (Bingham et al., 1996).

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 (Bingham et al., 1996, Ivanova et al., 1998, Monje et al., 2000, Ward et al., 1970).

Between 1995 and 1997 several experiments with super-dwarf wheat were conducted and the SVET greenhouse received small design updates with each subsequent experiment (Ivanova, 2010). 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 (Salisbury et al., 2003, Bingham et al., 2000). 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 (Campbell et al., 2001).

The results of the 1996/97 experiments were better than expected (Ivanova et al., 1998, Salisbury et al., 2003). 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.

2.4. 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.

2.4.1. 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 (Porterfield et al., 2003, Cowles et al., 1984). The PGU was used to perform experiments on reproduction of Arabidopsis plants on STS-51, 54 and 68 (Musgrave et al., 1997a).

2.4.2. 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/(m^2 s) to 220 μmol/(m^2 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 (Porterfield et al., 2003, Kuang et al., 2000). 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 (Musgrave et al., 1997b).

2.4.3. Astroculture (ASC)

The Astroculture series was another plant growth chamber designed for the Space Shuttle. Its first flight (ASC-1) was on STS-50

Fig. 4. ASC-8 flight hardware installed in a middeck locker (Musgrave et al., 1997a).

in 1992, followed by continuous updates and corresponding qualification flights (STS-57, -60, -63, -73, -89, -95) (Zhou et al., 2000). 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 (Morrow et al., 1993, Morrow et al., 1994). An LED lighting subsystem was added to the system for the ASC-2 experiment (Bula et al., 1994) and a temperature and humidity control subsystem for ASC-3 (Duffie et al., 1994, Duffie et al., 1995). Further subsystems (pH control subsystem, nutrient com-position 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 cm^2. 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 Fig. 4, 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 (Musgrave et al., 1997b).

2.4.4. Plant generic bioprocessing apparatus (PGBA)

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. Fig. 5 shows an exploded assembly drawing of the PGBA with all its major parts highlighted. The PGBA was operated during three Space Shuttle missions (STS-77, STS-83, STS-94) with durations of 4, 10 and 16 days respectively (Hoehn et al., 1998). In 2002 the PGBA was also used for experiments onboard ISS during Expedition 5 (Evans et al., 2009).

2.5. 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).

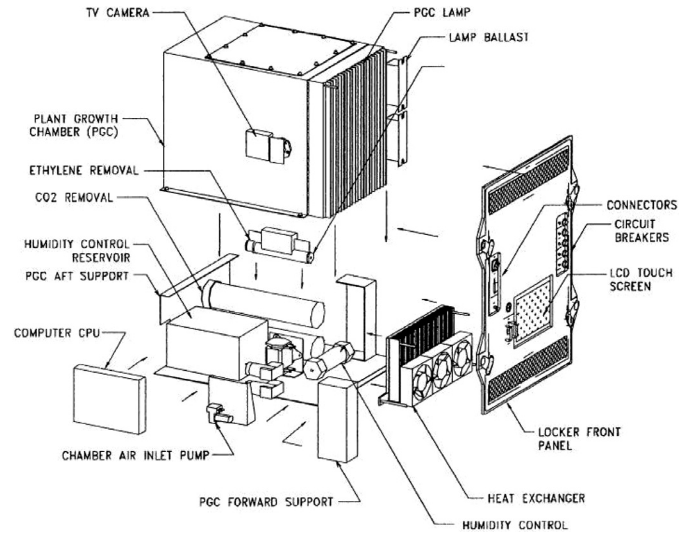

Fig. 5. Exploded assembly drawing of the PGBA (Hoehn et al., 1997).

Fig. 6. Advanced Astroculture ISS plant growth chamber (Link et al., 2003).

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.

2.5.1. 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 (Porterfield et al., 2003). 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 Fig. 6, while the other contains the plant growth chamber, top insert in Fig. 6. 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 (Zhou et al., 2002). During the ADVASC-1 experiment (2001), a seed-to-seed experiment with *Arabidopsis Thaliana* was performed. Several seeds were gathered (Link et al., 2003). These 1st generation seeds were used for the ADVASC-2 (2001/2002)

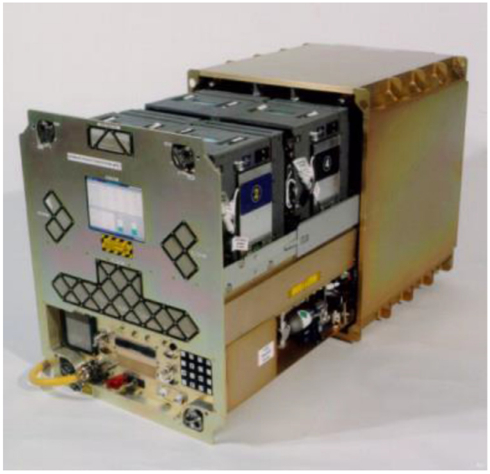

Fig. 7. BPS at NASA Johnson Space Center (NASA, 2014b).

Fig. 8. Lada; control and display module (upper center), growth modules (left and right), water tank (bottom center) (Bingham et al., 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 (Zhou, 2005).

2.5.2. Biomass production system (BPS)

The Biomass Production System (BPS) (Fig. 7) 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 (Evans et al., 2009, Morrow and Crabb, 2000, Stutte et al., 2005). 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 (Evans et al., 2009). The total grow area was 1040 cm^2 divided equally among the four chambers with each 260 cm^2. The subsystems and technologies validated with the BPS were later used within the Plant Research Unit (PRU) (Kern et al., 2001).

2.5.3. Lada

The Lada greenhouse is a plant growth system developed for the ISS and flown in 2002 (Ivanova, 2002). The system partly reused equipment from the SVET-GEMS experiment. The subsystems of Lada are spread amongst four modules: the control and display module (Fig. 8 upper center), two growth modules (Fig. 8 left and right) and a water tank (Fig. 8 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 (Bingham et al., 2002). The light bank could be outfitted either with fluorescent lamps (Bingham et al., 2003) or LEDs (Bingham et al., 2002). 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.

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 (Bingham et al., 2002). Some reactions of the ISS crew to the consumption of space-grown plants are cited by reference (Bingham et al., 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 (Sychev et al., 2007). Lada was also used to develop the hazard analysis and critical control point (HACCP) plan for vegetable production units (Hummerick et al., 2011, Hummerick et al., 2010).

2.5.4. European modular cultivation system (EMCS)

The European Modular Cultivation System (EMCS) was launched on STS-121 in July 2006 (Solheim, 2009). EMCS was installed onboard the ISS within the US Destiny module (Brinckmann, 2005). In April 2008 the experiment was moved to the European Columbus Module (ERASMUS Centre 2016). The EMCS contains two rotors to apply different levels of gravity (0.001–2.0 g) to the contained experiment containers (EC), see Fig. 9. 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 l (Brinckmann, 1999). The EMCS was used to carry out different European plant growth and plant physiology experiments (e.g. GRAVI, GENARA, MULTIGEN and TROPI) (Brinckmann, 2005). It was also utilized by the Japanese Aerospace Exploration Agency (JAXA) (Kamada et al., 2007). The EMCS was designed to conduct plant research and other biological experiments in space. The size of the EC and the whole experiment setup does not allow the growth of vegetables or other plants for food production. However, the Timescale (Norwegian University of Science and Technology 2016) project, funded by the European Union under

Fig. 9. EMCS in EXPRESS Rack-3 inside ESA Columbus Module (since April 2008) (ERASMUS Centre 2016).

Fig. 10. PEU flight model (JAXA 2014).

the Horizon 2020 research program, started in 2015 to investigate and validate possible improvements of the EMCS.

2.5.5. 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 Fig. 10. 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 (Yano et al., 2013).

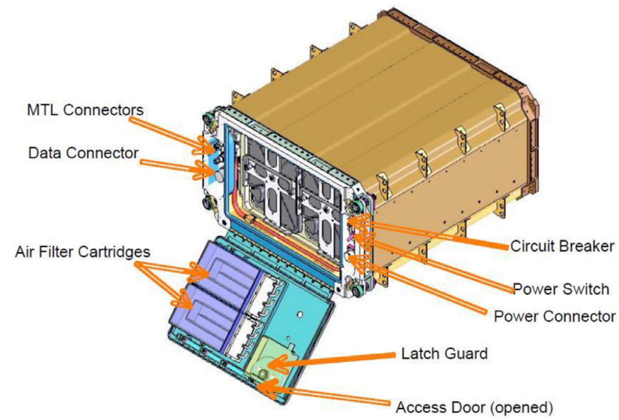

Fig. 11. Advanced Biological Research System (ABRS) overview (Levine et al., 2009).

2.5.6. 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 Fig. 11. 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 cm^2 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 (Levine et al., 2009). One of the first experiments conducted within the ABRS was the investigation of the Transgenic Arabidopsis Gene Expression System (TAGES) (Paul et al., 2012, A.-L. Paul et al., 2013b).

2.5.7. 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 m^2 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/(m^{2}*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 crew time to be supplied with water and nutrient solution (Morrow et al., 2005). Several different growth media have been investigated (Massa et al., 2013, Stutte et al., 2011 a) 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

Fig. 12. VEGGIE prototype during ground tests (left); NASA astronaut Steve Swanson next to VEGGIE after the deployment on-board ISS (right) (Stromberg, 2014).

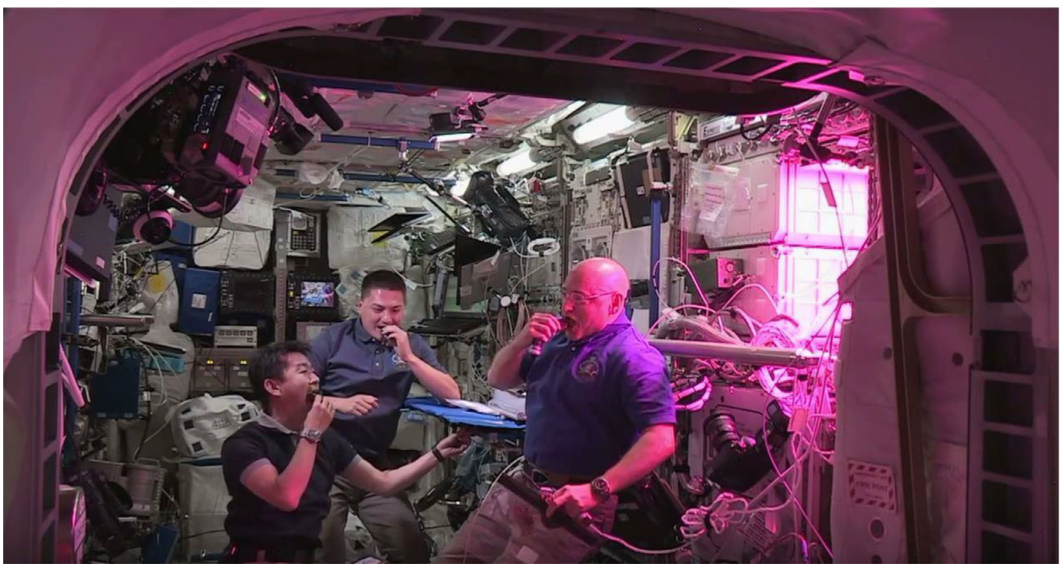

Fig. 13. A stronauts Kelly, Lindgren and Yui eating self-grown lettuce (image made by the authors from reference (NASA Kennedy Space Center 2015)).

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 Fig. 12. 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 (Stutte et al., 2011).

On August 10 in 2015 NASA astronauts were, for the first time ever, officially allowed to eat their space-grown vegetables. The astronauts Kelly, Lindgren, Yui, Kononenko and after their spacewalk Padalka und Kornijenko ate lettuce of the variety Outredgeous grown within the Veggie growth system, see Fig. 13 (NASA Kennedy Space Center 2015).

2.6. 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 (Berkovich et al., 1997, Berkovich et al., 1998, Berkovich et al., 2004, Berkovich et al., 2009). The concept was also part of the Russian Mars500 (Berkovich et al., 2009).

The Salad Machine concept was initially investigated by NASA's Ames Research Center (Kliss et al., 1990) and further developed over the following years (Kliss et al., 2000a,b). 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 (Turner et al., 1995, Crabb et al., 2001, Stadler and Brideau, 2004, Stadler et al., 2004, Heathcote et al., 1997), the program was canceled in 2005 (Forehand, 2014).

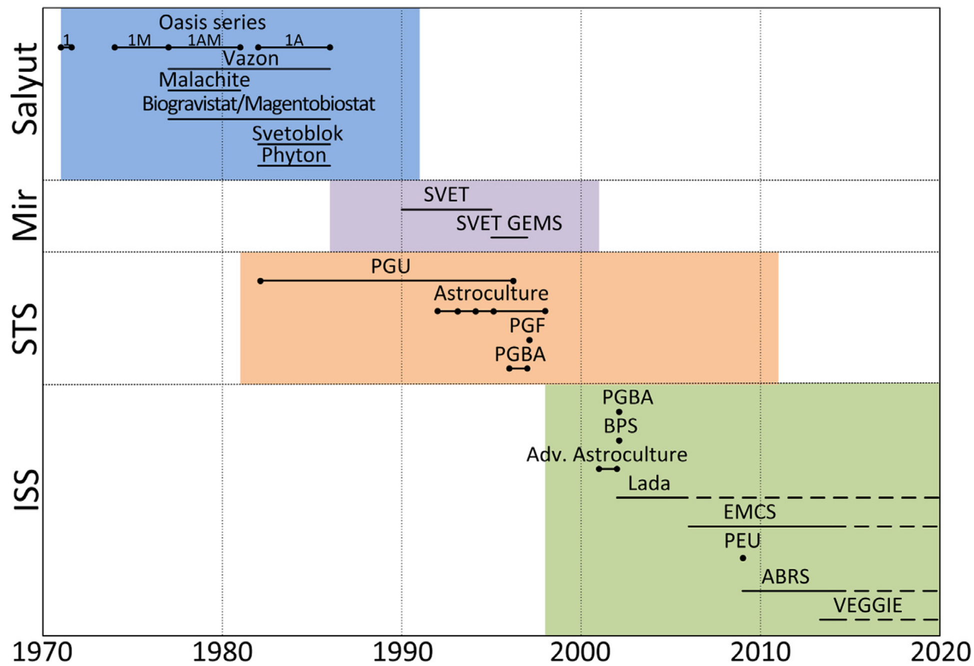

Fig. 14. Timeline of plant growth chambers flown or proposed to fly in space.

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 (NASA, 2014a).

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 (Morrow et al., 2007).

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 (Hoehn et al., 1998).

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 0.2–0.25 m^2 production area onto the ISS (Spaceref 2014, Wheeler, 2012).

During the operation of Skylab talented high school students were granted the opportunity to submit ideas for small research projects on board. Among them were also experiments which concentrated on plant growth in space. One experiment investigated the effects of microgravity on cytoplasmic streaming in elodea, an aquatic plant. Several issues delayed the execution of the experiment procedures on board and the plants died, because of two unscheduled days without illumination. Another experiment concentrated on the germination of seeds and how the seedlings would orientate themselves without gravity. The plant growth system for the experiment consisted of eight compartments with small windows on one side to allow photography of the seedlings. Three rice seeds were put into each compartment, which themselves contained an agar medium. After 22 days of growing the astronaut tending the experiment reported, that almost all plants are elongated and that the direction of growing is irregular and inconsistent (Summerlin, 1977).

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 (Preu and Braun, 2014).

3. Comparative analysis

3.1. 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. Fig. 14 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).

3.2. Comparison of growth area and volume

As evident in Fig. 15, 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

Table 1
Summary of key plant growth chamber data.

	Spacecraft	First Launch	Platform (e.g. MDL)	Growth Area (m^2)	Notable Information
Oasis 1	Salyut 1	1971	Wall mounted	0.001	first plant growth system in a crewed spacecraft
Oasis 1M	Salyut 4	1974	Wall mounted	0.010	produced first space grown crops (onions) eaten by humans
Oasis 1AM	Salyut 6	1977	Wall mounted	0.010	
Oasis 1A	Salyut 7	1982	Wall mounted	0.010	
Vazon	Salyut 6/ 7; Mir	1973	Wall mounted	n.a.	first ornamental plants
Malachite	Salyut 6	1973	Wall mounted	n.a.	first psychological investigations of human-plant interactions
Biogravistat/ Magnetobiostat	Soyuz 22; Salyut 6/7	1976	Wall mounted	n.a.	centrifuge to simulate different gravity levels; application of magnetic fields to plants
Svetoblok	Salyut 7; Mir	1982	Wall mounted	n.a.	first flowering of plants in space
Phyton	Salyut 7	1982	Wall mounted	n.a.	first successful seed-to-seed experiment
SVET	Mir	1990	Wall mounted	0.100	
SVET-GEMS	Mir	1995	Wall mounted	0.100	
PGU	STS	1982	MDL	0.050	
PGF	STS	1997	MDL	0.055	
ASC	STS	1992	MDL	0.021	
PGBA	STS	1996	2x MDL	0.075	
ADVASC	ISS	2001	2x MDL	0.052	
BPS	ISS	2002	EXPRESS	0.104	
Lada	ISS	2002	n.a.	0.050	first hazard analysis and critical control point (HACCP) plan for vegetable production units in space
EMCS	ISS	2006	4x MDL	0.077	
PEU	ISS	2009	n.a.	0.027	
ABRS	ISS	2009	MDL	0.053	Green Fluorescent Protein Imaging System
VEGGIE	ISS	2014	MDL	0.170	first plant growth system purposed for investigating food production in space

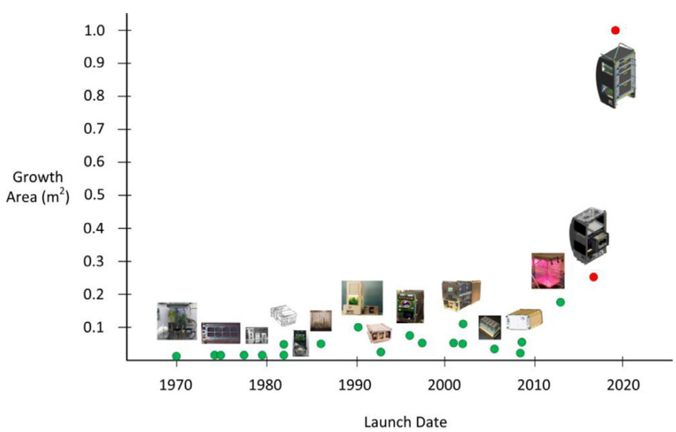

Fig. 15. Comparison of space plant growth chamber growth area between 1970 and 2020. Green dots represent flown systems while red dots represent currently planned systems. The right-most data point represents the expected plant growth area of a full ISS rack-based plant growth system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

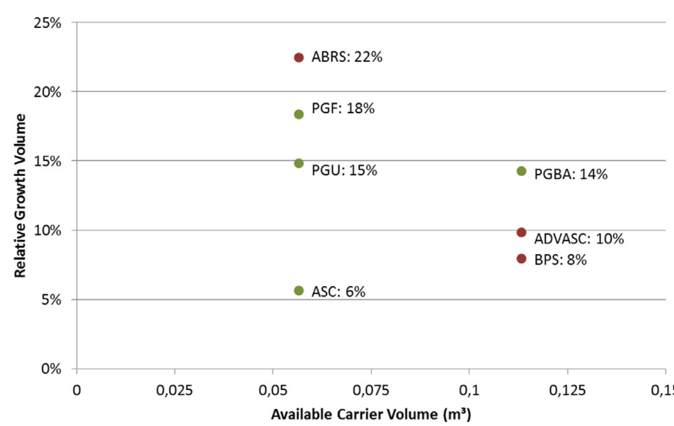

Fig. 16. Comparison of relative growth volume for plant growth systems on-board STS (green dots) and ISS (red dots). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 Fig. 15, 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. Fig. 16 shows a comparison of the relative growth volume for a number of plant growth chambers. Note that Fig. 16 only shows flown plant growth chambers designed to fit into standardized experiment carriers (e.g. MDL, double-MDL). As evident from Fig. 16, 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.

3.3. Nutrient delivery system analysis

Plant growth system irrigation and reliable root zone moisture control has been and continues to be a challenge for microgravity-based systems. Unlike terrestrial or future planetary surface systems, where gravity can be used to help drain irrigation water and thus aid in water recovery, controlling water movement/distribution in microgravity is more challenging and in many systems has resulted in flooding and anoxia (Hoehn et al., 2000). As water transport in microgravity also changes significantly with

Table 2
Detailed information on the nutrient delivery systems used in flown plant growth chambers.

	Nutrient delivery subsystem
Oasis 1	Two compartment system (water and ion exchange resin)
Oasis 1M	Fibrous ion exchange medium
Oasis 1AM	Cloth ion exchange medium
Oasis 1A	Included root zone aeration system
Vazon	Cloth sack filled with ion exchange resin
Malachite	Ion exchange resin, water supply
Biogravistat/ Magnetobiostat	n.a.
Svetoblok	Agar based, later also used other media
Phyton	1.5% agar nutrient medium
SVET	Polyvinyl formal foam surrounded perforated tubing wrapped in a wick within zeolite based substrate enriched with nutrients
SVET-GEMS	Similar to SVET but with additional sensors
PGU	Passive system capable of containing varied substrates/materials
PGF	Passive system capable of containing varied substrates/materials
ASC	Porous tubes in matrix
PGBA	Agar, soil or growth substrate in gas permeable polypropylene bags with option to connect bags to water supply
ADVASC	Porous tubes in matrix
BPS	Porous tubes in matrix
Lada	Perforated tubing wrapped in a wick within a matrix
EMCS	Water reservoir providing water to experiment unique nutrient delivery equipment
PEU	Rock wool fed by integrated water line
ABRS	Experiment specific
VEGGIE	Passive NDS, rooting pillows, manual water and nutrient supply

the grain size and packing density of plant growth substrates Earth-based testing is further complicated. Payload developers have considered various types of substrates, alone or in combination with various types of irrigation systems. As illustrated in Table 2 on-orbit plant growth chambers have incorporated systems ranging from completely passive systems, such as solidified agar (Petri plates or bags/packs) to active nutrient delivery systems such as perforated tubing wrapped in a wick (e.g. SVET, SVET-GEMS, LADA) or porous tubes (e.g. ASC, ADVASC, BPS and the planned APH). Several growth chambers such as ABRS, EMCS have relied on experiments themselves to carry ‘experiment unique equipment’ to provide irrigation/nutrient delivery while other growth chambers have included fixed hardware. Although passive on-orbit nutrient delivery systems will continue to have their merit in smaller scale systems, future systems will continue to build upon experience gained with active systems to further improve reliable irrigation and nutrient provision. Even though there remain challenges to overcome, porous tubes (and porous plates) with their heritage have particular promise to serve as the baseline nutrient delivery system in future on-orbit nutrient delivery systems.

3.4. Illumination system analysis

The development of the illumination system for plant growth chambers can be divided into two eras, the pre-LED era and the LED era. Successful experiments on new materials in the 1990s sped up the development of LEDs significantly. At the beginning of the 2000s more and more LED types were commercially available and their efficiency was improved. The advantages of LEDs such as high efficiency, small size, controllability and variable spectrum over lamp types used in the pre-LED era (fluorescent, high-pressure sodium) are the reasons why all growth systems of the recent past illuminate their plants with LEDs, see Table 3.

Table 3 also provides detailed information on the illumination systems integrated in past plant growth chambers. The light intensity varies between the cultivation systems. However, most of chambers (except the early Oasis systems and the PGU) provide more than 200 μmol/(m^{2*}s) which is sufficient for most of the crops typically grown in space. The SVET-GEMS system with a capability of up to 500 μmol/(m^{2*}s) allowed extensive experiments on wheat, as described earlier.

3.5. Atmosphere management system analysis

The early systems relied on ventilation with cabin air to remove excess heat produced by the fluorescent lamps (Table 4). Two systems, Vazon and Oasis 1A, did not even have closed vegetation boxes. Their plants were growing directly in the cabin atmosphere. Beginning with the American PGF system, almost all growth chambers had an independent atmosphere management system which includes temperature and humidity control and to some degree carbon dioxide regulation. The ASC was the first system to have active trace gas control in form of an ethylene scrubber. The same technology was used again in other plant growth chambers.

3.6. Crop analysis

A broad variety of crops were grown in space utilizing the aforementioned plant cultivation systems. Table 5 shows several plant species and in which system they were grown. Table 5 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.

Please note, that the crops listed in the table were grown with different success depending on the experiment, the growth system setup and the mission schedule. Not all of them reached a mature state in their respective experiments.

There are a number of other crops from the Salyut era which are mentioned in several references, but which could not be certainly assigned to one of the growth systems. The crops are: Coriander (Zimmerman, 2003), Dill (Bluth and Helppie, 1987), Peppers (Bluth and Helppie, 1987), Strawberries (Bluth and Helppie, 1987), Oats (Bluth and Helppie, 1987), Kale (Bluth and Helppie, 1987) and Herbs (Bluth and Helppie, 1987).

Most of the candidate crops recommended for plant cultivation on future human space exploration missions (Wheeler, 2004) have been cultivated in space plant growth chambers with different degree of success, see Table 6.

4. Discussion

Within this section different aspects of plant growth chamber design are discussed based on the knowledge gained from the review of flown cultivation system.

4.1. Chamber purpose

The early plant growth chambers focused on purely on enabling plant cultivation, flowering and fruiting of plants in space. Once this milestone was achieved, plant growth chambers were designed to enable basic plant science. Among others, plant orientation, root formation, germination, seed production under different conditions and different crops were studied and are still under investigation. Basic plant science is required to better understand plant development in general and especially plant cultivation in space. Here, experimenters continue to supplement this work by not only focusing on model organisms such as Arabidopsis but placing direct focus on growing food crops.

Table 3
Detailed information on the illumination systems used in flown plant growth chambers.

	Lamp type[a]	Light intensity [μmol/(m²∗s)]	Additional information
Oasis 1	F	50–68	
Oasis 1M	F	50–68	
Oasis 1AM	F	50–68	
Oasis 1A	F	170–350	Separate illumination and root module allowed adjustments of distance between lamps and plant canopy.
Vazon	no lamps	n.a.	Cabin light was used for plant illumination.
Malachite	type not specified, presumably F	no information	
Biogravistat/ Magnetobiostat	no lamps	n.a.	Closed compartment to study germination and early root development.
Svetoblok	F	no information	
Phyton	no information	no information	First cabin light, later separate illumination system added.
SVET	F	~216 (12.000 lx)	LED (RGB) illumination system tested during an experiment on ground (Ilieva et al., 2010).
SVET-GEMS	F	500	
PGU	F	30–75	
PGF	F	>220	
ASC	LED (RB)[b]	red: 0–450 blue: 0–50	
PGBA	F	>350	
ADVASC	LED (RB)	red: 0–550 blue: 0–70	
BPS	F	50–350	Controllable in 5 μmol/(m²∗s) increments.
Lada	F	250	
EMCS	LED (IRW)	no information	
PEU	LED (RB)	110	Red to blue ratio is 3:1.
ABRS	LED (RGBW)	300	
VEGGIE	LED (RGB)	>300	

[a] F=fluorescent lamp; LED=Light Emitting Diode; R=red; B=blue; W=white; G=green; IR=infrared.
[b] First integrated for ASC-2 mission.

Table 4
Detailed information on the atmosphere management systems used in flown plant growth chambers.

	Temperature and humidity control	CO_2 control	Trace gas control	Additional information
Oasis 1	no	no	no	Closed vegetation boxes.
Oasis 1M	no	no	no	Closed vegetation boxes.
Oasis 1AM	no	no	no	Closed vegetation boxes.
Oasis 1A	n.a.	n.a.	n.a.	Ventilation fan to remove excessive heat generated by lamps. Plants grew in cabin atmosphere.
Vazon	n.a.	n.a.	n.a.	Plants grew in cabin atmosphere.
Malachite	no	no	no	Closed vegetation box.
Biogravistat/ Magnetobiostat	no	no	no	Closed vegetation box.
Svetoblok	no	no	no	Closed vegetation box. Sterile environment.
Phyton	partly	no	no	Ventilation including bacterial filters.
SVET	partly	no	no	Ventilation fan to remove excessive heat generated by lamps. Oxygen supply to the root module. Environmental condition sensor package including temperature, humidity, substrate moisture.
SVET-GEMS	only temperature	no	no	Two separate air streams (one for plants one for cooling lamps). Large environmental sensor package, including: photosynthesis and transpiration measurements, CO_2 and O_2 sensors, temperature, humidity, substrate moisture.
PGU	only temperature	no	no	Could be equipped with an air exchange system, when sacrificing 1/5 of the cultivation area.
PGF	yes	yes	yes	Ethylene filter.
ASC	yes[a]	yes[b]	yes[c]	Ethylene scrubber unit to fully oxidize ethylene to CO_2 and water.
PGBA	yes	yes	yes	Ventilation with cabin air. Absorption beds to keep CO_2 level within requirements. Same ethylene scrubber technology as ASC.
ADVASC	yes	yes	yes	Same equipment as in ASC.
BPS	yes	yes	yes	Injection of pure CO_2. Ethylene scrubber and particulate filter. Photosynthesis and transpiration measurements.
Lada	yes	no	no	
EMCS	yes	yes	yes	Gas supply unit, pressure control unit, ethylene removal unit.
PEU	yes	yes	no	
ABRS	yes	yes	yes	VOC removal with potassium permanganate ($KMnO_4$).
VEGGIE	only temperature	no	no	Cabin air to control temperature and CO_2 level.

[a] First integrated for ASC-3 mission.
[b] First integrated for ASC-6 mission.

Table 5
Plants grown in space using plant growth chambers, with a focus on edible crops.

	Barley	Cabbage	Carrots	Chinese Cabbage	Corn	Cress	Cucumber	Dwarf pea	Flax	Garlic	Leek	Lentil	Lettuce	Mizuna	Mustard	Onion	Parsley	Pea	Radish	Rice	Soybean	Spinach	Swiss chard	Tomato	Wheat	Non-edible plants
Oasis		×		×					×		×					×		×							×	×
Vazon																×										×
Malachite																										×
Svetoblok																								×		×
Phyton			×				×			×						×								×	×	
Biogravistat / Magnetobiostat	×						×						×				×									×
SVET				×															×							
SVET-GEMS													×	×	×										×	
Skylab																				×						
PGU																										×
PGF														×												
ASC																										×
PGBA																						×				×
BPS														×											×	
ADVASC																					×					×
Lada	×							×						×				×	×							
EMCS						×						×														×
PEU																										×
ABRS																										×
VEGGIE													×													

However, as future human space exploration missions require sustainable bio-regenerative life support systems and especially food production, future plant growth chamber developers should also have that goal in mind. There are differences between basic plant science and food production growth chamber design requirements. While systems dedicated to plant studies can be rather small, food production systems require a certain size to contribute to the crew's diet. Furthermore, the larger size of food production systems has a significantly higher impact on the overall life support system architecture than small chambers. Scientific chambers require a high amount of sensors, data acquisition and imaging systems while production chambers only require those necessary for the control of the chamber subsystems. Scientific experiments usually require higher precision environmental control than do food production systems.

Both the basic plant science and production greenhouses pathways are complementary to each other and should always be seen in the larger context of bio-regenerative life support system development. As in the near future the possibility to install plant cultivation systems in space is limited to the International Space Station and its restricted resources, the size of the next generation of growth chambers will most likely not exceed the size of past chambers by a large margin. Therefore, it is even more important to focus all experiments on the overall goal of sustainable food production in space.

4.2. Effects of different light mixtures

Recent advancements in LED technology allow for a wavelength specific control of plant illumination. Past plant growth chambers mainly relied on red (~660 nm) and blue (~450 nm) LEDs, because of the high photosynthetic efficiency of plants under that spectrum. However, the effects of additional wavelengths (e.g. far-red) and different combination of wavelengths on plant growth in space needs to be studied. LED systems also enable time dependent control of plant illumination to e.g. simulate dusk and dawn in the plant growth chamber. Besides maximizing plant growth and dry mass production, the effects of the light spectrum on the production of secondary ingredients such as vitamins and antioxidants need to be studied.

4.3. Energy efficiency

Although the advancements in LED technology increased the efficiency of plant illumination in recent years and will increase it even more in the following years, plant cultivation has high energy demands. While past plant growth chambers typically required only a few hundred Watt, because of their limited size, future food production greenhouses in space will need a substantial part of the total energy budget of a spacecraft or planetary base. Means to reduce the energy demand are therefore a high priority for future plant cultivation technology development.

4.4. Automation

As plant cultivation systems in space get larger, means of automation need to be investigated to reduce the required crew time to maintain the system. While atmospheric and illumination systems are already widely automated, the watering of the plants (especially under microgravity) and the adjustments of the nutrient solution are still mostly performed by the crew. Plant health monitoring is another important area to improve automation. Until today, such tasks have been primarily performed by the crew, which rarely comprises a horticulturist, and communicated to the plant cultivation experts on Earth for evaluation. Systems to automati-

Table 6
Candidate crop lists according to Wheeler (Wheeler, 2004), crops grown in space until now highlighted in green.

Pilgrim and Johnson (1962) (Pilgrim and Johnson, 1962)	Tibbits and Alford (1982) (Tibbits and Alford, 1982)	Hoff et al. (1982) (Hoff et al., 1982)	Waters et al. (2002) (Waters et al., 2002)	NASA (1998) (NASA 1998)	Salisbury and Clark (1996) (Salisbury and Clark, 1996)	Gitelson et al. (1989) (Gitelson et al., 1989)
Sweet potato	Wheat	Wheat	Wheat	Lettuce	Wheat	Wheat
Tambala	Soybean	Soybean	Soybean	Spinach	Soybean	Salad Species
Chinese Cabbage	Lettuce	Potato	Lettuce	Radish	Lettuce	Potato
Cabbage	Sweet potato	Carrot	Sweet potato	Cabbage	Sweet potato	Radish
Cauliflower	Peanut	Peanut	Rice	Green onion	Kale	Beet
Kale	Rice	Rice	Bean	Carrot	Broccoli	Nut Sedge
Collards	Sugar beet	Tomato	Beet	Tomato	Carrot	Onion
Turnip	Taro	Dry bean	Cabbage	Pepper	Canola	Cabbage
Swiss Chard	Winged bean	Chard	Broccoli	Strawberry	Rice	Tomato
Endive	Broccoli	Cabbage	Cauliflower	Different Herbs	Peanut	Pea
Dandelion	Onion		Carrot		Chickpea	Dill
Radish	Strawberry		Kale		Lentil	Cucumber
New Zealand			Spinach		Tomato	Carrot
Spinach			Potato		Onion	
			Onion		Chili pepper	

cally detect plant stress and other issues, such as thermal and fluorescent imaging should be considered for future chamber designs.

4.5. Psychological benefits of crew-plant interactions

Some references and anecdotes about the Soviet/Russian plant growth chambers in particular describe the psychological benefits of working and living with plants in space. However, a thorough scientific investigation still needs to be conducted to better understand the crew-plant interaction and the effect of growing your own food on the psychological well-being and performance of the crew. As future space missions to Mars will take more time than most astronauts have continuously spent in space, understanding the psychological benefits of cultivating plants in confined areas is required.

5. Summary

In the past 40 years more than 20 plant growth systems were utilized to grow over 40 different plant species in space. More than 50 different plant experiments were conducted in space. The paper reviews on-orbit plant growth systems and describes their characteristics. The list of facilities gives an overview about the development of plant cultivation systems in space over the last 40 years. 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 plant species grown in space.

However, to grow enough plants for supplying a crew with a substantial amount of fresh food more research and development is necessary. Especially the available grow area in space has to be significantly increased to address research related to large-scale food production (e.g. procedures, automation). As shown in this paper, there is a large discrepancy between the plants recommended for space greenhouses and the plant species actually grown in space. Plant experiments in space have to be focused on food crops rather than model plants. Until there is enough cultivation area available in space, researcher and engineers can rely on space analogue field campaigns to test integrated systems capable of cultivating food crops in a controlled closed environment.

Acknowledgments

Paul Zabel thanks the ESA MELiSSA research group and in particular Christel Paille for supporting his application to ESA's Networking/Partnering Initiative. The financial support through the program allows Mr. Zabel to work on his PhD topic of which this publication is part. M. Bamsey's participation was supported by a Marie Curie International Incoming Fellowship within the 7th European Community Framework Programme. The authors also want to thank Ray Wheeler (NASA) and Paul Zamprelli (ORBITEC) for their feedback on the content of the paper and for sharing inside knowledge related to some of the grow chambers described in the paper.

References

Berkovich, J.A., Krivobok, N.M., Siniak, J.E., Zaitsev, E.R., Monakhov, B.N., 1997. Perspectives of developing a space greenhouse for the International Space Station. In: Proceedings of the 6th European Symposium on Space Environmental Control Systems. Noordwijk, The Netherlands, ESA.
Berkovich, Y., Krivobok, N.M., Sinyak, Y., 1998. Project of conveyer-type space greenhouse for cosmonauts' supply with vitamin greenery. Adv. Space Res. 22, 1401–1405.

Berkovich, Y., Smolyanina, S.O., Krivobok, N.M., Erokhin, A.N., Agureev, A.N., Shanturin, N.A., 2009. Vegetable production facility as a part of a closed life support system in a Russian Martian space flight scenario. Adv. Space Res. 44, 170–176.
Berkovich, Y.A., Krivobok, N.M., Sinyak, Y., Smolyanina, S.O., Grigoriev, Y., Romanov, S., Guissenberg, A.S., 2004. Developing a vitamin greenhouse for the life support system of the international space station and for future interplanetary missions. Adv. Space Res. 34, 1552–1557.
Berkovitch, Y.A., 1996. Instrumentation for plant health and growth in space. Adv. Space Res. 18, 157–162.
Bingham, G., Jones, S., Or, D., Podolski, I., Levinskikh, M., Sytchov, V., Ivanova, T., Kostov, P., Sapunova, S., Dandolov, I., Bubenheim, D., Jahns, G., 2000. Microgravity effects on water supply and substrate properties in porous matrix root support system. Acta Astronaut. 47, 839–848.
Bingham, G.E., Salisbury, F.B., Campbell, W.F., Carman, J.G., Bubenheim, D.L., Yendler, B., Sytchev, V.N., Berkovitch, Y., Levinskikh, M.A., Podolsky, I.G., 1996. The Spacelab-Mir-1 “Greenhouse-2” experiment. Adv. Space Res. 18, 225–232.
Bingham, G.E., Topham, T.S., Mulholland, J.M., Podolsky, I.G., 2002. Lada: the ISS plant substrate microgravity testbed. In: Proceedings of the 32nd International Conference on Environmental Systems. San Antonio, Texas.
Bingham, G.E., Topham, T.S., Taylor, A., Podolsky, I.G., Levinskikh, M.A., Sychev, V.N., 2003. Lada: ISS plant growth technology checkout. In: Proceedings of the 33rd International Conference on Environmental Systems. Vancouver, Canada.
Bluth, B.J., Helppie, M., 1987. Soviet Space Stations as Analogs, 2nd ed. NASA.
Brinckmann, E., 1999. Spaceflight opportunities on the ISS for plant research — The ESA perspective. Adv. Space Res. 24, 779–788.
Brinckmann, E., 2005. ESA hardware for plant research on the International Space Station. Adv. Space Res. 36, 1162–1166.
Bula, R.J., Tennessen, D.J., Morrow, R.C., Tibbitts, T.W., 1994. Light emitting diodes as a plant lighting source. In: International Lighting in Controlled Environments Workshop. Un i versity of Wisconsin, NASA.
Campbell, W.F., Salisbury, F.B., Bugbee, B., Klassen, S., Naegle, E., Strickland, D.T., Bingham, G.E., Levinskikh, M., Iljina, G.M., Veselova, T.D., Sytchev, V.N., Podolsky, I., McManus, W.R., Bubenheim, D.L., Stieber, J., Jahns, G., 2001. Comparative floral development of Mir-grown and ethylene-treated, earth-grown Super Dwarf wheat. J. Plant Physiol. 158, 1051–1060.
Cowles, J.R., Scheld, H.W., Lemay, R., Peterson, C., 1984. Growth and lignification in seedlings exposed to eight days of microgravity. Ann. Botany 54, 33–48.
Crabb, T.M., Morrow, R.C., Frank, J.G., 2001. Plant Research unit â€“ program overview. In: Proceedings of the 31st International Conference on Environmental Systems. Orlando, Florida.
Duffie, N.A., Bula, R.J., Morrow, R.C., Quirin, P.E., Macaulay, P.D., Wranovsky, S.R., Vignali, J.C., Tibbits, T.W., 1994. Humidity and temperature control in the ASTROCULTURE™ flight experiment. In: Proceedings of the 24th International Conference on Environmental Systems. Fri e drichshafen, Germany.
Duffie, N.A., Zhou, W., Morrow, R.C., Bula, R.J., Tibbitts, T.W., Wranovsky, S.R., Macaulay, P.D., 1995. Control and monitoring of environmental parameters in the ASTROCULTURE™ flight experiment. In: Proceedings of the 25th International Conference on Environmental Systems. San Di e go, California.
ERASMUS Centre - Directorate of Human Spaceflight and Operations, European Modular Cultivation System (EMCS). 2016
Evans, C.A., Robinson, J.A., Tate-Brown, J., Thumm, T., Crespo-Richey, J., Baumann, D., Rhatigan, J., 2009. International space station science research accomplishments during the assembly years: an analysis of results from 2000-2008. In: NASA available at http://www.nasa.gov/pdf/389388main_ISS%20Science%20Report_20090030907.pdf.
Floyd, H., 1974. Student experiments on Skylab, in: scientific investigations on the Skylab satellite. In: Conference. American Institute of Aeronautics and Astronautics.
L. Forehand, NASA office of legislative affairs memo: NASA plans for plant and animal research, available at http://www.spaceref.ca/news/viewsr.html?pid=17716 (accessed on March 3, 2014) 2014.
Gitelson, I.I., Terskov, I.A., Kovrov, B.G., Lisovskii, G.M., Okladnikov, Y., Sid’ko, F., Trubachev, I.N., Shilenko, M.P., Alekseev, S.S., Pan’kova, I.M., Tirranen, L.S., 1989. Long-term experiments on man’s stay in biological life-support system. Adv. Space Res. 9, 65–71.
Haeuplik-Meusburger, S., Paterson, C., Schubert, D., Zabel, P., 2014. Greenhouses and their humanizing synergies. Acta Astronaut. 96, 138–150.
Halstead, T.W., Dutcher, F.R., 1984. Experiments on plants grown in space. Status and prospects. Ann. Botany 54, 3–18.
Harland, D., 2004. The Story of the MIR Space Station. Springer, Dordrecht.
Harvey, B., Zakutnyaya, O., 2011. Russian Space Probes: Scientific Discoveries and Future Missions. Springer, New York.
Häuplik-Meusburger, S., Peldszus, R., Holzgethan, V., 2011. Greenhouse design integration benefits for extended spaceflight. Acta Astronaut. 68, 85–90.
Heathcote, D.G., Brown, C.S., Goins, G.D., Kliss, M., Levine, H., Lomax, P.A., Porter, R.L., Wheeler, R.M., 1997. The plant research unit: long-term plant growth support for space station. In: Proceedings of the 6th European Symposium on Space Environmental Control Systems. Noordwijk, The Netherlands, ESA.
Hoehn, A., Chamberlain, D.J., Forsyth, S.W., Gifford, K., Hanna, D.S., Horner, M.B., Scovazzo, P., Smith, J., Stodieck, L.S., Todd, P.W., 1997. Plant generic bioprocessing apparatus: a plant growth facility for spaceflight biotechnology research. In: Proceedings of the 6th European Symposium on Space Environmental Control Systems. Noordwijk, The Netherlands, ESA.
Hoehn, A., Clawson, J., Heyenga, A.G., Scovazzo, P., Sterrett, K.S., Stodieck, L.S., Todd, P.W., Kliss, M.H., 1998. Mass transport in a spaceflight plant growth chamber. In: Proceedings of the 28th International Conference on Environmental Systems. Danvers, Massachusetts.
Hoehn, A., Scovazzo, P., Stodieck, L.S., Clawson, J., Kalinowski, W., Rakow, A., Simmons, D., Heyenga, A.G., Kliss, M.H., 2000. Microgravity root zone hydration systems. In: Proceedings of the 30th International Conference on Environmental Systems. Toulouse, France.
Hoff, J.E., Howe, J.M., Mitchell, C.A., 1982. Development of selection criteria and their application in evaluation of CELSS candidate species. In: NASA.
Hummerick, M., Garland, J., Bingham, G., Sychev, V., Podolsky, I., 2010. Microbiological analysis of Lada Vegetable Production Units (VPU) to define critical control points and procedures to ensure the safety of space grown vegetables. In: Proceedings of the 40th International Conference on Environmental Systems. Barcelona, Spain.
Hummerick, M., Garland, J., Bingham, G., Wheeler, R., Topham, S., Sychev, V., Podolsky, I., 2011. A hazard analysis critical control point plan applied to the Lada vegetable production units (VPU) to ensure the safety of space grown vegetables. In: Proceedings of the 41st International Conference on Environmental Systems. Portland, Oregon.
Ilieva, I., Ivanova, T., Naydenov, Y., Dandolov, I., Stefanov, D., 2010. Plant experiments with light-emitting diode module in Svet space greenhouse. Adv. Space Res. 46, 840–845.
T. Ivanova, Greenhouse aboard Mir shows plants can survive in space, 21st Century (2002) 41–49.
Ivanova, T., 2010. Plant biology under space factors: microgravity. In: Proceedings of the 4th International AgroSpace Workshop. Sperlonga, Italy.
Ivanova, T., Sapunova, S., Dandolov, I., Ivanov, Y., Meleshko, G., Mashinsky, A., Berkovich, Y., 1994. ‘SVET’ space greenhouse onboard experiment data received from ‘MIR’ station and future prospects. Adv. Space Res. 14, 343–346.
Ivanova, T.N., Bercovich, Y., Mashinskiy, A.L., Meleshko, G.I., 1993. The first “space” vegetables have been grown in the “SVET” greenhouse using controlled environmental conditions. Acta Astronaut. 29, 639–644.
Ivanova, T.N., Kostov, P.T., Sapunova, S.M., Dandolov, I.W., Salisbury, F.B., Bingham, G.E., Sytchov, V.N., Levinskikh, M.A., Podolski, I.G., Bubenheim, D.B., Jahns, G., 1998. Six-month space greenhouse experiments — A step to creation of future biological life support systems. Acta Astronaut. 42, 11–23.
JAXA, Biological Experiment Unit (BEU): PEU description, available at http://iss.jaxa.jp/en/kiboexp/pm/beu/ (accessed on 13.08.14) 2014.
Kamada, M., Omori, K., Nishitani, K., Hoson, T., Shimazu, T., Ishioka, N., 2007. JAXA space plant research on the ISS with European modular cultivation system. Biol. Sci. Space 21, 62–66.
Kern, V.D., Bhattacharya, S., Bowman, R.N., Donovan, F.M., Elland, C., Fahlen, T.F., Girten, B., Kirven-Brooks, M., Lagel, K., Meeker, G.B., Santos, O., 2001. Life sciences flight hardware development for the international space station. Adv. Space Res. 27, 1023–1030.
Kleinknecht, K.S., Powers, J.E., 1973. Skylab student project. In: Napolitano, L.G., Contensou, P., Hilton, W.F. (Eds.), Astronautical Research 1972. Springer, Netherlands, Dordrecht, pp. 309–317.
Kliss, M., Heyenga, A.G., Hoehn, A., Stodieck, L.S., 2000a. Recent advances in technologies required for a “Salad Machine”. Adv. Space Res. 26, 263–269.
Kliss, M., Heyenga, G., Hoehn, A., Stodieck, L., 2000b. Toward the development of a “Salad Machine”. In: Proceedings of the 30th International Conference on Environmental Systems. Toulouse, France.
Kliss, M., MacElroy, R.D., Machine, Salad, 1990. A Vegetable production unit for long duration space missions. In: Proceedings of the 20th International Conference on Environmental Systems. Williamsburg, Virginia.
Kuang, A., Popova, A., Xiao, Y., Musgrave, M.E., 2000. Pollination and embryo development in Brassica rapa L. in microgravity. Int. J Plant Sci. 161, 203–211.
Levine, H., Cox, D., Reed, D., Mortenson, T., Shellack, J., Wells, H., Murdoch, T., Regan, M., Albino, S., Cohen, J., 2009. The advanced biological research system (ABRS): a single middeck payload for conducting biological experimentation on the international space station.. In: Proceedings of the 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition. Orlando, Florida.
Link, B.M., Durst, S.J., Zhou, W., Stankovic, B., 2003. Seed-to-seed growth of Arabidopsis Thaliana on the international space station. Adv. Space Res. 31, 2237–2243.
Massa, G.D., Newsham, G., Hummerick, M.E., Caro, J.L., Stutte, G.W., Morrow, R.C., Wheeler, R.M., 2013. Preliminary species and media selection for the VEGGIE space hardware. Gravit. Space Res. 1, 95–106.
Monje, O., Bingham, G.E., Carman, J.G., Campbell, W.F., Salisbury, F.B., Eames, B.K., Sytchev, V., Levinskikh, M.A., Podolsky, I., 2000. Canopy photosynthesis and transpiration in micro-gravity: gas exchange measurements aboard Mir. Adv. Space Res. 26, 303–306.
Morrow, R.C., Bula, R.J., Tibbitts, T.W., Dinauer, W.R., 1994. The ASTROCULTURE flight experiment series, validating technologies for growing plants in space. Adv. Space Res. 14, 29–37.
Morrow, R.C., Crabb, T.M., 2000. Biomass Production System (BPS) plant growth unit. Adv. Space Res. 26, 289–298.
Morrow, R.C., Dinauer, W.R., Bula, R.J., Tibbitts, T.W., 1993. The astroculture™-1 flight experiment: pressure control of the WCSAR porous tube nutrient delivery system. In: Proceedings of the 23rd International Conference on Environmental Systems. Colorado Springs, Colorado.

Morrow, R.C., Iverson, J.T., Manzke, R.C., Tuominen, L.K., Neubaer, J.D., 2007. Education payload operation Kit C: a miniature, low ESM hobby garden for space-based educational activities.. In: Proceedings of the 37th International Conference on Environmental Systems. Chicago, Illinois.

Morrow, R.C., Remiker, R.W., Mischnick, M.J., Tuominen, L.K., Lee, M.C., Crabb, T.M., 2005. A low equivalent system mass plant growth unit for space exploration. In: Proceedings of the 35th International Conference on Environmental Systems. Rome, Italy.

Musgrave, M.E., Kuang, A., 2003. Plant reproductive development during spaceflight. Developmental Biology Research in Space. Elsevier, pp. 1–23.

Musgrave, M.E., Kuang, A., Porterfield, D.M., 1997a. Plant reproduction in spaceflight environments. Gravit. Space Biol. Bull 10, 83–90.

Musgrave, M.E., Kuang, A., Porterfield, D.M., 1997b. Plant reproduction in spaceflight environments. Gravit. Space Biol. Bull 10, 83–90.

NASA Kennedy Space Center, Veggies in space: astronauts sample freshly grown lettuce, available at https://www.youtube.com/watch?v=D_723qwjULM (accessed on 11.08.15). 2015

NASA, NASA advanced life support program memorandum, NASA, 1998.

NASA, Portable astroculture chamber (PASC), available at http://www.nasa.gov/mission_pages/station/research/experiments/372.html (accessed on 05.02.14) 2014a.

NASA, Biomass Production System (BPS), available at http://www.nasa.gov/centers/marshall/news/background/facts/bps.html (accessed on 13.08.14) 2014b.

Norwegian University of Science and Technology - Centre for Interdisciplinary Research in Space, Timescale, available at http://www.timescale.eu/ (accessed on 15.05.16). 2016

Paul, A.-L., Amalfitano, C.E., Ferl, R.J., 2012. Plant growth strategies are remodeled by spaceflight. BMC Plant Biol. 12, 232.

Paul, A.-L., Wheeler, R.M., Levine, H.G., Ferl, R.J., 2013a. Fundamental plant biology enabled by the space shuttle. Am. J. Botany 100, 226–234.

Paul, A.-L., Zupanska, A.K., Schultz, E.R., Ferl, R.J., 2013b. Organ-specific remodeling of the Arabidopsis transcriptome in response to spaceflight. BMC Plant Biol. 13, 112.

A.J. Pilgrim, S.P. Johnson, Investigation of selected higher plants as ags exchange mechanisms for closed eco-logical systems, 1962 (accessed on http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=AD0296950).

Porterfield, D.M., Neichitailo, G.S., Mashinski, A.L., Musgrave, M.E., 2003. Spaceflight hardware for conducting plant growth experiments in space: the early years 1960–2000. Adv. Space Res. 31, 183–193.

Preu, P., Braun, M., 2014. German SIMBOX on Chinese mission Shenzhou-8: Europe's first bilateral cooperation utilizing China's Shenzhou programme. Acta Astronaut. 94, 584–591.

Salisbury, F.B., 1999. Chapter 5 growing crops for space explorers on the Moon, Mars, or in Space. In: Bontinc, S.L. (Ed.), Advances in Space Biology and Medicine. Elsevier, pp. 131–162.

Salisbury, F.B., Campbell, W.F., Carman, J.G., Bingham, G.E., Bubenheim, D.L., Yendler, B., Sytchev, V., Levinskikh, M.A., Ivanova, I., Chernova, L., Podolsky, I., 2003. Plant growth during the greenhouse II experiment on the Mir orbital station. Adv. Space Res. 31, 221–227.

Salisbury, F.B., Clark, M.A., 1996. Choosing plants to be grown in a Controlled Environment Life Support System (CELSS) based upon attractive vegetarian diets. Life Support Biosph. Sci. 2, 169–179.

Solheim, B., 2009. 3D information from 2D images recorded in the European modular cultivation system on the ISS. Adv. Space Res. 44, 1382–1391.

Spaceref, NASA KSC Award: Payload Integration and Operational Support Services Advanced Plant Habitat, available at http://www.spaceref.com/news/viewsr.html?pid=40076 (accessed on February 1, 2014).

Stadler, J.J., Brideau, L.D., 2004. Human factors and maintainability in the plant research unit (PRU). In: Proceedings of the 34th International Conference on Environmental Systems, Colorado Springs. Colorado.

Stadler, J.J., Brideau, L.D., Emmerich, J.C., Varma, N.N., 2004. Integrating reliability principles in the design of the plant research unit (PRU).. In: Proceedings of the 34th International Conference on Environmental Systems. Colorado Springs, Colorado.

J. Stromberg, NASA is about to harvest lettuce on the International Space Station, available at http://www.vox.com/2014/6/3/5772628/nasa-is-about-to-harvest-lettuce-on-the-international-space-station (accessed on 04.06.14) 2014.

Stutte, G., Wheeler, R., Morrow, R., Newsham, G., 2011a. Operational evaluation of VEGGIE food production system in the habitat demonstration unit.. In: Proceedings of the 41st International Conference on Environmental Systems. Portland, Oregon.

Stutte, G., Wheeler, R., Morrow, R., Newsham, G., 2011b. Concept for sustained plant production on ISS using VEGGIE capillary mat rooting system. In: Proceedings of the 41st International Conference on Environmental Systems. Portland, Oregon.

Stutte, G.W., Monje, O., Goins, G.D., Tripathy, B.C., 2005. Microgravity effects on thylakoid, single leaf, and whole canopy photosynthesis of dwarf wheat. Planta 223, 46–56.

Summerlin, L.B., 1977. Skylab, classroom in space. In: NASA.

Sychev, V.N., Levinskikh, M.A., Gostimsky, S.A., Bingham, G.E., Podolsky, I.G., 2007. Spaceflight effects on consecutive generations of peas grown onboard the Russian segment of the international space station. Acta Astronaut. 60, 426–432.

Tibbits, T.W., Alford, D.K., 1982. Controlled ecological life support system: use of higher plants. In: NASA.

Turner, M., Lomax, P., Kelly, A., Porter, R., Cobb, M., Heathcote, D., 1995. Development of the plant research unit for use on space station.. In: Proceedings of the 25th International Conference on Environmental Systems. San Diego, California.

Ward, C.H., Wilkes, S.S., Craft, H.L., 1970. Effetcs of prolonged near weightlessness on growth and gas exchange of photosynthetic plants. Dev. Ind Microbiol 276–295.

Waters, G.C., Olabi, A., Hunter, J.B., Dixon, M., Lasseur, C., 2002. Bioregenerative food system cost based on optimized menus for advanced life support. Life Support Biosph. Sci. 8, 199–210.

Wheeler, R.M., 2004. Horticulture for Mars. Acta Horticult. (ISHS) 642, 201–215.

Wheeler, R.M., 2012. NASA advanced life support technology testing and development. In: Proceedings of the AgroSpace Conference. Sperlonga, Italy.

Yano, S., Kasahara, H., Masuda, D., Tanigaki, F., Shimazu, T., Suzuki, H., Karahara, I., Soga, K., Hoson, T., Tayama, I., Tsuchiya, Y., Kamisaka, S., 2013. Improvements in and actual performance of the plant experiment unit onboard Kibo, the Japanese experiment module on the international space station. Adv. Space Res. 51, 780–788.

Zhou, W., 2005. Advanced ASTROCULTURE™ Plant growth unit: capabilities and performances. In: Proceedings of the 35th International Conference on Environmental Systems. Rome, Italy.

Zhou, W., Duffie, N.A., Mookherjee, B., 2000. Performance of the ASTROCULTURE™ plant growth unit (ASC-8) during the STS-95 mission. In: Proceedings of the 30th International Conference on Environmental Systems. Toulouse, France.

Zhou, W., Durst, S.J., Demars, M., Stankovic, B., Link, B.M., Tellez, G., Meyers, R.A., Sandstrom, P.W., Abba, J.R., 2002. Performance of the advanced ASTROCULTURE™ plant growth unit during ISS-6A/7A mission.. In: Proceedings of the 32nd International Conference on Environmental Systems. San Antonio, Texas.

Zimmerman, R., 2003. Leaving Earth: Space Stations, Rival Superpowers, and the Quest for Interplanetary Travel. J. Henry Press, Washington, D.C..