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

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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.

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

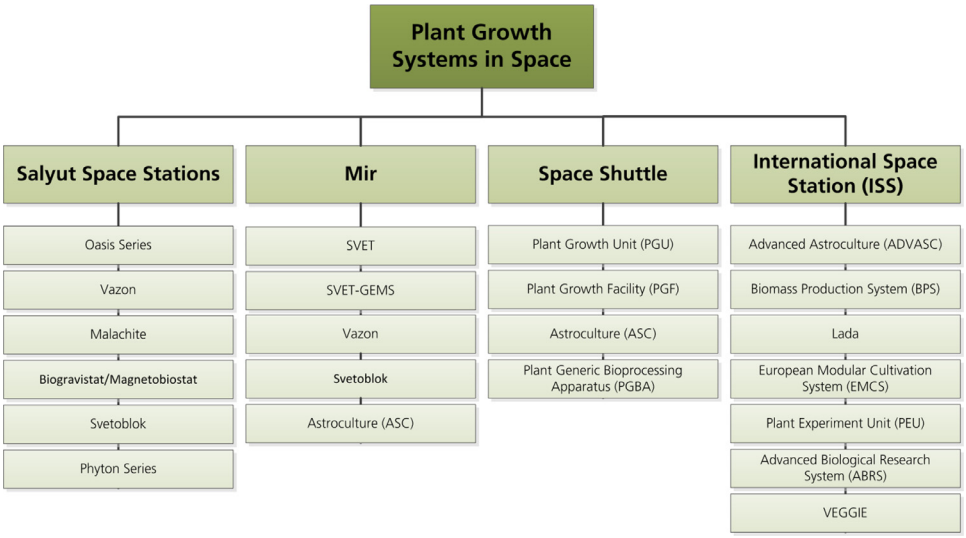

Fig. 1. Overview of plant growth chambers in space.

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 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).

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).

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