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SPACEFLIGHT HARDWARE FOR CONDUCTING PLANT GROWTH EXPERIMENTS IN SPACE: THE EARLY YEARS 1960-2000

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ABSTRACT

The best strategy for supporting long-duration space missions is believed to be bioregenerative life support systems (BLSS). An integral part of a BLSS is a chamber supporting the growth of higher plants that would provide food, water, and atmosphere regeneration for the human crew. Such a chamber will have to be a complete plant growth system, capable of providing lighting, water, and nutrients to plants in microgravity. Other capabilities include temperature, humidity, and atmospheric gas composition controls. Many spaceflight experiments to date have utilized incomplete growth systems (typically having a hydration system but lacking lighting) to study tropic and metabolic changes in germinating seedlings and young plants. American, European, and Russian scientists have also developed a number of small complete plant growth systems for use in spaceflight research. Currently we are entering a new era of experimentation and hardware development as a result of long-term spaceflight opportunities available on the International Space Station. This is already impacting development of plant growth hardware. To take full advantage of these new opportunities and construct innovative systems, we must understand the results of past spaceflight experiments and the basic capabilities of the diverse plant growth systems that were used to conduct these experiments. The objective of this paper is to describe the most influential pieces of plant growth hardware that have been used for the purpose of conducting scientific experiments during the first 40 years of research.

INTRODUCTION

On October 4, 1957 exploration of outer space began when Sputnik was launched by the Soviet Union. Today, humans have gone to the moon and have spent extended periods of time in low earth orbit. While these endeavors are important for research and technological development, they do not fully satisfy the human thirst for exploration and discovery. This is why manned missions farther out into the solar system, and eventually to other systems, are being proposed for the 22nd century. Such long-term manned missions will present significant logistics problems and investigations are currently underway to begin to address these problems.

The BLSS approach is regarded as the best strategy for supporting long term human missions within and beyond our solar system. The Soviet Union began BLSS research in 1965 (Salisbury, 1990) and this basic research is being continued today by the Russian Federation. The National Aeronautic and Space Administration (NASA) of the United States (US) did not begin research on an equivalent level until 1985 when, at Kennedy Space Center (KSC), a large chamber, originally built and used to test the Mercury spacecraft, was modified to act as a closed system for the development of BLSS technologies (Salisbury,

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1990). Like the Soviet/Russian strategy, NASA is also highly dependent upon the growth of higher plants for success (Salisbury and Bugbee, 1988).

The development of these BLSS technologies will require a greater understanding of how spaceflight might impact plant growth. Because of this interest in developing BLSS technology, there has been a considerable investment in spaceflight plant growth studies. This research has been possible by access to extended spaceflight and by development of spaceflight plant growth hardware systems. As a result of these early efforts, we are just now beginning to learn about the limitations of plant growth in space and how to design and build systems that will overcome these limitations. For example, roots were commonly studied as a model system for understanding plant gravitropism, but very little research was conducted to analyze the overall physiological status of the root system. As a result, the development and use of nutrient delivery technologies proceeded without critical information concerning the physiological status of roots in the spaceflight environment. Because of these hardware limitations, spaceflight exposed root tissues have been subjected to hypoxic stress (Cowles *et al.*, 1984; Krikorian and O'Connor, 1984; Krikorian and Levine, 1992; Slocum *et al.*, 1984; Sytnik *et al.*, 1983) and associated metabolic limitations associated with the induction of fermentative metabolism (Porterfield *et al.*, 1997; Porterfield et al., 2000; Stout et al., 2001). It is now understood that this phenomena is caused by the disruption of gravity dependent buoyancy driven thermal convection (Musgrave *et al.*, 1988) which biophysically limits the bioavailability of oxygen under these diffusion limited conditions (Porterfield, 2002). Only now are we beginning to develop nutrient delivery systems for use in microgravity that can avoid oxygen deprivation in the rootzone caused by biophysical limitations in physiological transport associated with the microgravity environment (Porterfield, 2002).

During the formative years of plant space biology, researchers have been involved with hardware design in order to facilitate their desire to conduct spaceflight experimentation. As we have learned more about the results of these experiments, researchers and engineers have attempted to improve the hardware available to do this work. In looking back upon the results of past flight experiments, it will be important to maintain a proper perspective about the potential limitations of the flight hardware that was used by these researchers. The objective of this paper is to provide that perspective in the form of a historical review of the plant growth systems that have been used for spaceflight research by the Soviet Union/Russian Space Agency, NASA, and the European Space Agency (ESA), during the first 40 years of activity, starting in the year 1960.

SOVIET/RUSSIAN SPACE AGENCY HARDWARE

The first plant materials carried into space were launched in 1960 on Sputnik 4 and included *Triticum aestivum*, *Pisum sativum*, *Zea mays*, *Allium cepa*, and *Nigella damascena* seeds (Halstead and Dutcher, 1984). Early Soviet researchers classified the development of complete plant growth systems into three generations. These are based on the goals of the vegetative system, lifetime of operation, and energy consumption (Mashinski *et al.*, 1983). The ultimate goal of first generation hardware was to determine the potential limitations on plant growth in the spaceflight environment and to provide psychological comfort to the crew. Such systems were first utilized on the Salyut stations, which had an operational time of a few years and a total power output in the range of a few kilowatts. Therefore, the first generation hardware was limited to power consumption in the tens of watts range and to maximum weight up to a few kilograms. Second generation systems were actually intended to be prototypes for the development of BLSS technologies. These systems would have operational lifetimes of months to years, power consumption in the hundreds of watts, and weights up to a hundred kilograms. The last space station, Mir, had the capacity to support such a system but none was installed or reportedly developed. Third generation systems are to be functional as a BLSS and would constitute an integral part of a spacecraft or station. The system would have an operational lifetime equal to that of the spacecraft and would be designed to facilitate regular maintenance and possible upgrades. Estimates of its energy consumption would be a few kilowatts, with a weight of up to one ton (Neichitailo and Mashinski, 1993). All of the hardware that was developed and used in space falls within the first generation of hardware development.

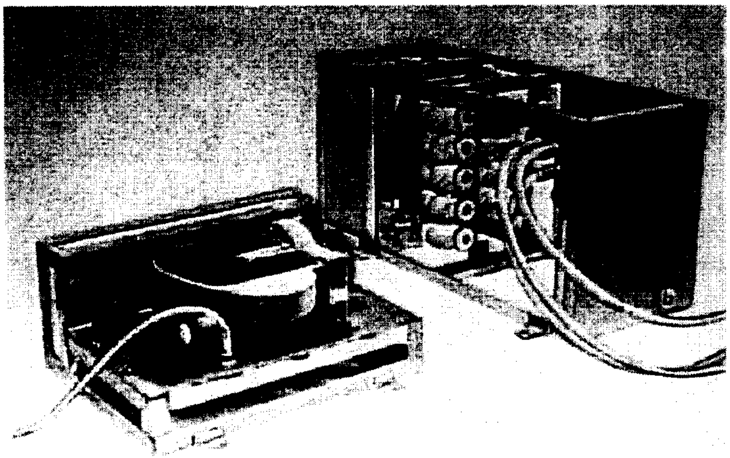

Fig. 1. The Oasis 1 plant growth system used aboard Salyut 1, pictured with the cinematic recording system (Neichitailo and Mashinski, 1993).

Russia's first complete system for the cultivation of higher plants was the Oasis 1 system (Figure 1). The workers who designed this hardware named the system based on the idea of creating an oasis for man in the harshness of space. This system was incorporated into the first Soviet space station, Salyut 1, and was used to cultivate *Brassica capitata*, *Linum usitatissimum*, and *Allium porrum* (Smolders, 1973). Illumination was provided by three fluorescent lamps, supplying approximately 50-68 $\mu mol\ m^{-2}\ s^{-1}$. Temperature recording was included and capable of measuring temperatures in the $0°$-$50°$ C +/- $1°C$ range. The system was equipped with eight nutrient delivery vessels, each made of an elastic material and connected to a common water reservoir. Air was separated from water in the main reservoir by an elastic diaphragm and water was delivered to the vegetative vessels by increasing the volume of air within the reservoir. The vegetative vessels comprised a bi-compartment nutrient delivery system, with the two compartments separated by a hydrophilic elastic membrane. The lower compartment served as a metering water reservoir and the upper compartment was filled with an ion exchange resin that was attached to a cloth and contacted the hydrophilic membrane. The ion exchange resin served as a storage medium for the plant nutrients and as a support system for the roots. Oasis 1 was also equipped with a cinematic film system for recording the progress of the plant growth (Neichitailo and Mashinski, 1993). Although the general capability of Oasis 1 was demonstrated by the crew (Dobrovolsky, Volkov, and Patsaev) during the Salyut 1 mission, the status of any returned plant material may be questionable since the Soyuz spacecraft experienced rapid decompression of the crew compartment, resulting in the deaths of the three cosmonauts (Smolders, 1973).

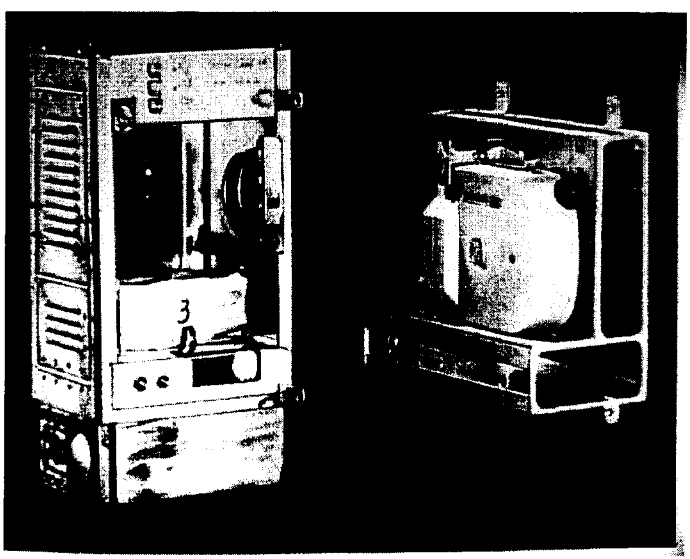

Fig. 2. The Oasis 1M plant growth system used for long term plant cultivation aboard Salyut 4 (Neichitailo and Mashinski, 1993).

The Oasis 1 system did have some problems with the water metering system which were addressed in the design of Oasis 1M (Figure 2). Intermediate designs may have existed but, due to major problems with Salyut 2 and Salyut 3, no experiments were conducted until Salyut 4 carried the Oasis 1M system, which was used for two orbital science missions (Merkys *et al.*, 1976). This system had a completely redesigned nutrient delivery system. The vegetative vessels were square (plant growth area = 100 cm^2) and made of glass with a myplast plate in the bottom that contacted a water input port. The vessels were filled with a fibrous ion exchange medium that was pre-charged with nutrients. The medium was designed to have a high moisture capacity, while allowing for maximum air permeability (Soldatov and Peryshkina, 1985). The main water reservoir contained a mixture of water and silver ions, presumably to prolong water storage. This solution was delivered to the bottom of the vessel through the myplast plate by the action of a hand pump and a metering valve.

The next version in the Oasis series was Oasis 1AM (Figure 3) which was designed for prolonged use aboard Salyut 6. Modifications included modularization of the illumination system to allow maintenance, changes in the vegetative vessels and a modified water delivery system. The vegetative vessel was equipped with a cloth ion exchange insert mounted to a stiff frame. This modification was made to address problems encountered with water distribution in the Oasis 1M vessels. The water delivery system worked in a manner analogous to the Oasis 1M system but was based on a removable Kolos 5D inboard drinking vessel (Neichitailo and Mashinski, 1993).

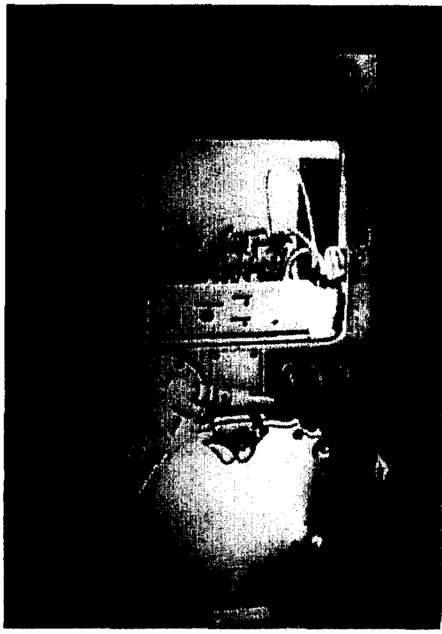

Fig. 3. The Oasis 1AM plant growth system flown on Salyut 6 (Neichitailo and Mashinski, 1993).

Fig. 4. The Oasis 1A system used aboard Salyut 7 (Neichitailo and Mashinski, 1993).

Salyut 7 was equipped with the last of the Oasis series to be used in space. This system was designated Oasis 1A (Figure 4) and reportedly included root zone aeration capabilities, removable vessels which could be moved closer and farther from the lights in response to plant growth, and ventilation to remove excessive heat and provide for better gas exchange. The Oasis series was used to grow numerous types of plants on the Salyut space stations. The current Oasis system has a lighting system capable of providing approximately 170-350 μmol m^{-2} s^{-1} (Neichitailo and Mashinski, 1993).

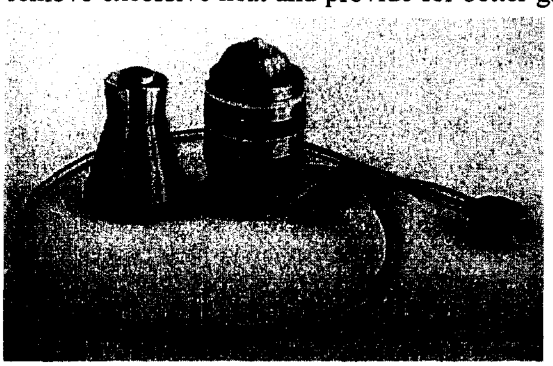

Fig. 5. The Vazon system disassembled with a bulb (Neichitailo and Mashinski, 1993).

Vazon (Figure 5), a system designed for cultivation of bulbous plants, was first carried on Soyuz 12. Vazon is basically a nutrient delivery system and illumination was presumably obtained from onboard light sources. This system consisted of an upper part designed to contain the bulb through the action of a sliding hub and a system of springs, and a lower part which contained a cloth sack filled with an ion exchange substrate. The roots were allowed to grow into the substrate through a fibrous material that occupied a hole in the sack. Water was delivered by an on/off switch operated by a cosmonaut, and was obtained from the spacecraft's water regeneration system. The Vazon system was also equipped with a drain valve for removing excess water. Updated versions of Vazon were flown aboard Salyut 6, Salyut 7, and Mir (Neichitailo and Mashinski, 1993).

Fig. 6. A cosmonaut working with a crop of ornamental plants in the Malachite device (Neichitailo and Mashinski, 1993).

Another system to fly aboard Salyut 6 was the Malachite device (Figure 6). This system was designed for the sole purpose of ornamental plant culture to provide psychological comfort to the cosmonauts in the interior of the space station. This system was equipped with four planting boxes containing an ion exchange resin, a water supply system, and an illumination source. Orchids in blossom were taken to the station in this system but the blossoms fell off before flowering (Neichitailo and Mashinski, 1993).

Svetoblok (Figure 7) is a small cultivation system originally designed to be mounted under illumination sources of the Salyut 7 space station. A cylindrical clear plastic growing chamber, equipped with an agar based nutrient delivery system, could be removed from the mounting bracket and returned to earth, usually by riding on the lap of a cosmonaut in the Soyuz spacecraft. Updated versions of the Svetoblok were equipped with an independent fluorescent light source and with other nutrient substrates, which were watered through the action of the Oasis water delivery system. The sterile cultivation of plants in the Svetoblok is considered to be its strong point, and is attributed to the success of the system in producing flowers for the first time in space during a 65-day experiment aboard Salyut 7. A 1.5% agar medium was used for this experiment but no viable seed production was achieved in the experiment due to the "degenerative nature" of the flowers resulting from the spaceflight exposure (Kordyum *et al.*, 1983).

Fig. 7. The Svetoblok shown with optional independent illumination source (Neichitailo and Mashinski, 1993).

In response to the Svetoblok experiments, the Phyton system (Figure 8) was designed to perform seed to seed experiments. This device was equipped with five removable glass cylinders which contained a 1.5% agar nutrient medium. An automatic seed sowing apparatus allowed seed planting to occur while in orbit. Ventilation of the vegetative chamber occurred through a system of openings that were covered with a bacterial filter (Laurinavichyus *et al.*, 1984) and a separate illumination source was mounted on top of the chamber (Merkys and Laurinavichyus, 1990). A complete seed to seed experimental cycle was reported to have been achieved aboard Salyut 7 using this system.

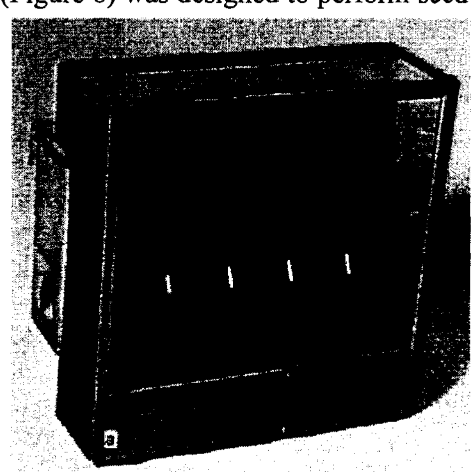

Fig. 8. The Phyton device with four tubes of the seed sowing apparatus shown (Neichitailo and Mashinski, 1993).

The research greenhouse Svet (Figure 9) was used aboard the Mir space station and was upgraded as a part of a Russian-US cooperative experiment. This cooperation primarily involved scientists from the Institute of Medical-Biological Problems in Moscow and Utah State University. This upgrade included an improved fluorescent lighting system which doubled the original light output levels to approximately 500 μmol m^{-2} s^{-1} PAR. The system was also modified by the addition of the Gas Exchange Monitoring System (GEMS). The GEMS system added gas analysis and data storage capabilities to the Svet system, as well as advanced environmental controls (Bingham *et al.*, 1995). The Svet unit had a cultivation area of 0.1 m^2. The system maintained static air temperatures in the vegetative chamber and controlled rootzone substrate moisture levels through a system of water and humidity sensors. Moisture was delivered to the rootzone ion exchange substrate through a porous polyethylene tube embedded in a zeolite based ion exchange matrix. During the time of these joint Russian/US investigations aboard Mir using Svet in the late 1990s, this system came under close scrutiny by NASA. In fact, a replica of the Svet unit had been built and studied at the Kennedy Space Center Plant Space Biology Laboratory (Chetirkin *et al.*, 1994).

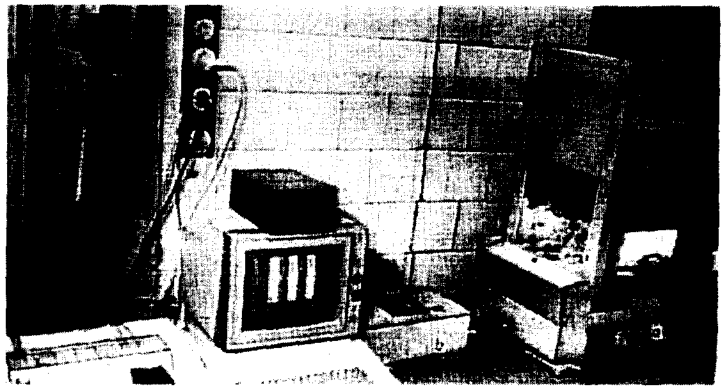

Fig. 9. The Russian Svet greenhouse shown with computer control system (Neichitailo and Mashinski, 1993).

During the latter part of the 1990's, progress in the way of new developments in plant growth hardware in the Russian space program was very slow. This is most likely due to the economic conditions in the Russian Federation that has lead to a crippling lack of resources in the space program. Despite these limitations, there has been work on two new pieces of hardware named Lada and Vitacycle. Lada has been developed jointly by the Institute of Biomedical problems (Moscow, Russia) and the Space Dynamics Lab/Utah State University (Logan, UT, USA) as a replacement for the SVET unit. This hardware will be will be installed in the Zvezda module of the ISS (Bingham et al., 2002). Vitacycle is not a research system, but instead is a "salad machine" for the production of edible plants for consumption in space (Bercovich, et al., 1997). While a prototype system has been developed, there are currently no plans to fly the Vitacycle system.

UNITED STATES / NASA HARDWARE

In 1967, Biosatellite II carried the first complete plant growth system used during spaceflight. This system was designed to perform a gravitropism experiment in the pepper plant *Capsicum annuum*. Four plants were grown in a non-toxic hydrocarbon polymer derived foam which was inserted into plastic cylinders equipped with lids that were sealed in place. Distilled water, sufficient for 10 days of growth, was added to the substrate prior to loading aboard the Delta rocket which carried the satellite into low earth orbit. During the flight experiment the plants were photographed and illuminated through a series of mirrors.

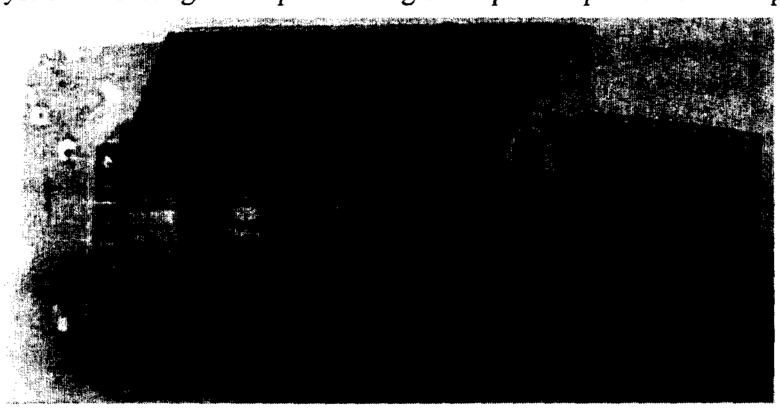

Fig. 10. The Plant Growth Unit shown with a Plant Growth Chamber.

Lighting was provided by four 15 watt incandescent lamps which produced 36 μmol m^{-2} s^{-1} of light in 5-second bursts that occurred every 10 minutes. The hardware was designed for a 10-day flight but the satellite only flew for 45 hours due to technical problems. Temperature and humidity were recorded during flight and downloaded to earth telemetrically (Johnson and Tibbitts, 1968). This system was primarily designed to maintain plants for the study of tropic responses and not to support full photosynthetic growth. Sadly, the United States' Biosatellite program was canceled and further development of complete spaceflight systems would have to wait until the 1980's and the Space Shuttle program.

In 1982, the third Space Shuttle flight (STS-3) was the maiden voyage of the Plant Growth Unit (PGU) which was used to perform an experiment that examined seedling growth and lignification in microgravity (Cowles *et al.*, 1984). The PGU subsequently served as the workhorse for American spaceflight plant growth studies for over 15 years. This system (Figure 10) was designed and built to fit into a mid-deck locker by Lockheed and NASA-Ames Research Center. The overall dimensions of the PGU are 51 x 36 x 27 cm (L x W x H), and it consists of support components and an open area designed to accommodate up to six Plant Growth Chambers (PGC). Each PGC (Figure 11) contains an approximate 2-liter air-tight volume, and is composed of an anodized aluminum alloy base and a Lexan top fitted together by screws and a rubber gasket. Lighting is supplied by three 15 watt fluorescent light bulbs (Vita-Lite spectrum) providing a light intensity of approximately 75-50 μmol m^{-2} s^{-1} to the middle four chambers and approximately 48-30 μmol m^{-2} s^{-1} to the outer two PGCs. In addition, the PGU could be equipped with an Air Exchange System (AES) at the expense of one PGC. In this configuration, four of the PGCs are also equipped with a gas inlet and outlet port while the fifth remains closed (Kuang *et al.*, 1996). When configured without the AES, each PGC could be equipped with a thermistor probe and two gas sampling ports. The PGU is also equipped with a timer for the lighting system, temperature sensors, electronically controlled fans, a heater, a data acquisition system, and internal batteries (Cowles *et al.*, 1984). The PGC bases have been equipped with various different types of nutrient delivery systems including systems composed of sandwiched urethane foam and Miracloth over an agar slab (Cowles *et al.*, 1984), phenolic horticultural foam equipped with Nitex envelopes (Levine and Krikorian, 1992), and agar (Porterfield *et al.*, 1997).

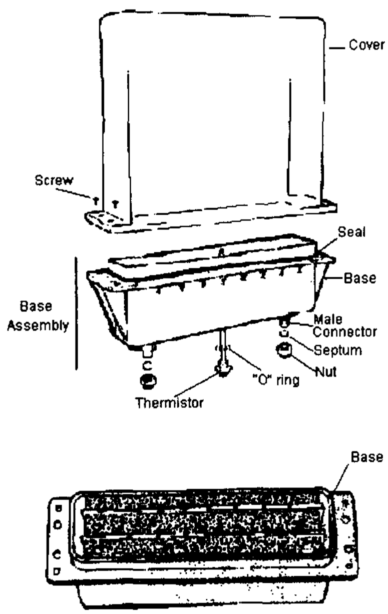

Fig. 11. The PGC shown disassembled with sandwiched urethane foam and miracloth nutrient delivery system (Cowles *et al.*, 1984).

Early in the career of the PGU it became evident to researchers that this system was not adequate to achieve the level of plant growth support desired. The Plant Growth Facility (PGF), developed by A. D. Little Inc. and the Bionetics Corporation, was built to address some of the weaknesses of the PGU (Chapman *et al.*, 1995). Being a middeck locker housed system, the PGF has the exact same dimensions as the PGU and can accommodate six PGCs, but has improved lighting and atmospheric control systems. The lighting system was designed to supply a minimum of 220 μmol m^{-2} s^{-1} of illumination. The atmospheric systems control humidity, CO_2, and temperature, and include filters for removing ethylene. The PGF was flight certified by NASA and was used to grow *Brassica rapa* (Stout et al., 2001) as part of the Collaborative Ukrainian Experiment flown on Space Shuttle Mission STS-87.

The Astroculture system, designed and built by the Wisconsin Center for Space Automation and Robotics (WCSAR), has a nutrient delivery system that is conceptually similar to the Svet system. It is composed of a series of porous stainless steel tubes embedded in a matrix of nutrient charged zeolite granules. Water is held in the tubes under a slight negative pressure (-490 Pa) and is delivered to the plant roots in the zeoponic matrix by capillary action. This system also includes capabilities for controlling the plant chamber humidity by regulating the temperature of water circulating under negative pressure inside a porous tube. This tube is exposed to the plant growth chamber air and can measure the recovered plant transpirant. In addition, the lighting system of the Astroculture system represents a departure from traditional techniques. Recently developed high intensity light emitting diode (LED) technology has allowed this system to achieve some of the highest light intensities to power consumption ratios seen in a system used during spaceflight application (Morrow, 1993). The Astroculture system was used to grow plants for the first time in spaceflight in February, 1995 on board the Space Shuttle mission STS-63 (Morrow *et al.*, 1995; Porterfield et al., 2002). It was later used in three other shuttle flight experiments and an experiment aboard Mir in the late 1990's. The lessons that were learned in the development and use of the Astroculture system led to the development of a larger system named the Advanced Astroculture system. This system has the same basic capabilities as the original system but is twice as large as the original Astroculture. The Advanced Astroculture system has the distinction of being the first system to be utilized on the International Space Station (ISS) in an experiment to grow *Arabidopsis*. Subsequently, the Advanced Astroculture system has flown two more times on the ISS. WCSAR is also currently developing an even larger system equivalent in size to four mid-deck lockers, which is called the Commercial Plant Biotechnology Facility (CPBF). If this system is fully developed and flown, it will be the largest such system to be constructed and used in space.

The Plant Generic Bioprocessing Apparatus (PGBA) was developed in the 1990's by Bioserve Space Technologies (University of Colorado). To date, the system has flown on three shuttle missions. The hardware is double mid-deck size and includes fluorescent lighting, CO_2 and humidity level controls, and ethylene removal systems. The system does deviate from the other newer American systems in the use of an agar gel based nutrient delivery system. The shuttle based tests of the PGBA system have resulted in hardware system improvements that will be implemented in tests to be conducted during ISS Expedition Five in the later part of 2002. The PGBA is also being fitted with a Porous Tube Insert Module (PTIM) in support of the Water Offset Nutrient Delivery Experiment (WONDER) (Burtness et al., 2002). This experiment will allow for a side-by-side comparison of the porous tube nutrient delivery system (Dreschel and Sager , 1989) with the substate base nutrient delivery system that has been used in other systems like the SVET, Astroculture, and the BPS.

Currently, work is being conducted in the development of the Plant Research Unit (PRU) to support long-duration plant growth experiments for up to 135 days aboard the ISS. This system is intended to be the primary research system for the ISS and will be permanently housed there. The NASA contract for this system was recently awarded to the Orbitec Corporation (Madison, WI) and is to be based on the Biomass Production System (BPS) plant growth hardware that was built in the late 1990's. The BPS system is a double mid-deck locker system that includes, fluorescent lighting, advanced atmospheric and environmental controls, and a nutrient delivery system like the Astroculture system. The BPS was recently used in 2002 to grow *Brassica rapa* and dwarf wheat in the PESTO experiment over a period of 72 days (Monje et al., in press). The adaptation of the BPS into the PRU will be limited by size constraints that will allow the PRU to be placed in the centrifuge system on board the ISS. This will provide in-flight 1 g controls for future flight experiments. The availability of a 1 g in-flight control may be one of the most important developments in experimental capabilities available for plant space biology research.

EUROPEAN SPACE AGENCY HARDWARE

As of this writing, no complete system originating from ESA has been used in a spaceflight experiment, although the Botany Facility (BF) was built for such a purpose. The BF system was originally scheduled to fly aboard the first European Retrievable Carrier (EURECA) mission but was canceled. EURECA was to be a Space Shuttle launched and retrieved satellite operational at a 525 km orbit for up to 6 months. The BF is an oil-drum sized system capable of performing an inflight 1g control. The basic plant growth module is referred to as a cuvette (Figure 13). Each cuvette (50 x 50 x 150 mm) has its own independent environment in which nutrients, water, temperature, carbon dioxide, oxygen, humidity, and ethylene levels are controlled. Each cuvette is also equipped with a fluorescent lamp delivering 34 μmol m^{-2} s^{-1} PAR to the base of the cuvette. Two basic designs of the cuvette were constructed originating from different contractors and accomplishing environmental control by different approaches. Both designs do allow the grouping of 18 cuvettes for microgravity exposure and 6 cuvettes for 1 g controls (Briarty, 1989). The system was never flown and is not being developed further.

ESA is now developing a complete plant growth system for the ISS. This is the European Modular Cultivation System (EMCS). This system is unique because it will have a centrifuge control built into the single hardware system. In addition, it has advanced lighting with white, red and blue LEDs, as well as complete environmental control systems that have become standard in systems such as the Astroculture and BPS systems.

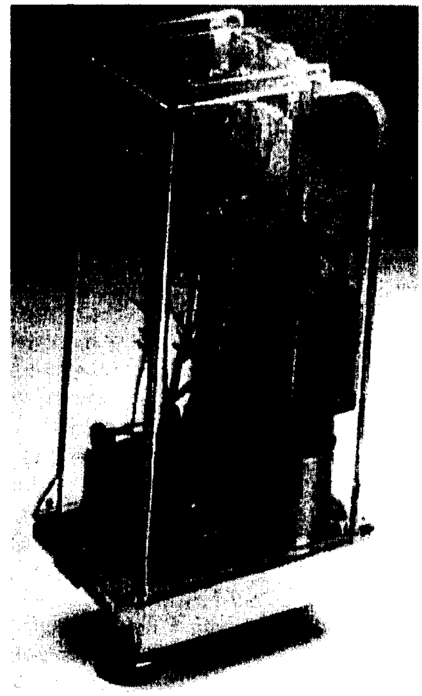

Fig. 13. ESA Botany facility cuvette designed and built by Dornier (Briarty, 1989).

CONCLUSION

A great deal of spaceflight plant growth hardware research was conducted by the former Soviet Union and this research is being continued by the modern Russian Federation. This effort has resulted in the development of many plant growth systems, like the Svet, which was used for long term plant growth studies on board Mir. Through the 1980s and the early 1990s most of NASA's Space Shuttle based research program had relied on a single piece of hardware, the PGU. The lessons learned from experimentation that utilized the PGU have lead to innovative use of new advanced technologies applied to the problem of developing spaceflight plant growth systems. There are now several new hardware systems available for use to support long term plant growth experiments on the ISS. ESA has invested a great deal of effort in the design of plant growth systems, and this is likely to come to fruition when the European Modular Cultivation System (EMCS) is flown on the ISS.

There are two major obstacles standing in the way of the development of any plant growth system. These are the power and space limitations imposed by the spaceflight platform and our limited knowledge of the requirements of plants within this unique environment. Future collaborations between ESA, the Russian Federation, Ukraine, Japan, and the US promise to issue forth a new era of global cooperation in space exploration and the development of plant growth systems for BLSS application. Indeed in the future it may become evident that such an alliance of the world community is what is needed to adapt to the challenges of the new century.

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