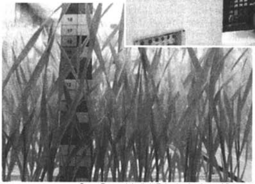
Greenhouse Aboard Mir Shows Plants Can Thrive In Space

The author studying samples of onion plants, during an Earth experiment in the SVET Space Greenhouse.



Space Research Institute/Bulgarian Academy of Sciences

Astronauts living in space could be eating fresh vegetables and "space bread," milled and harvested from an onboard greenhouse. The seeds from these plants will grow the first food crops on Mars.

by Dr. Tania Ivanova

After discovering huge deposits of frozen water on the Moon, the researchers breathed more easily: Nature itself had paved the way for future scientific stations on Earth's satellite. Future lunar stations could now be supported by an artificial, closed biological system, like the Earth's biosphere, with all the necessary plant and animal species—enough for food, and for air recycling. Settled on the Moon, the Earth inhabitants could launch spacecraft to other planets (initially to Mars), more easily and much more cheaply: Six times less power is needed to escape the Moon's gravity than to escape that of Earth.

When flight to Mars becomes a reality in the near future, a considerable part of the interplanetary spacecraft's interior will be occupied by a space greenhouse. Vegetable crops and even wheat—whose grains the astronauts will use to mill flour and to make fresh bread as on the Earth—will be grown there. At the time when trips to Mars become a reality, and the habitable bases on the Moon begin to look like settlements with their gardens and parks, the history of astronautics will record that some of the first space greenhouses were developed and produced in Bulgaria.

The SVET ("light") greenhouse, automated plant growth facility, developed as a Bulgarian-Russian Project in the 1980s, was launched in the Mir Orbital Station on June 10, 1990. The goal of the investigation was to study plant growth under microgravity, in order to include plants in future Biological Life Support Systems for long-term manned space missions.

An American-developed Gas Exchange Measurement System (GEMS) was added to the Bulgarian-developed SVET equipment in 1995, to monitor additional environmental and physiological parameters. Many long-duration plant space experiments were carried out in the SVET-GEMS complex right up to the end of the 20th Century.

Significant results in the field of fundamental gravitational biology were achieved, as second-generation wheat seeds were produced under microgravity. The new International Space Station provides a perfect opportunity for conducting

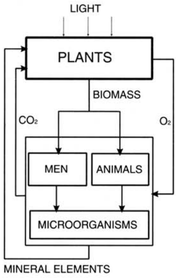


Figure 1
BLOCK DIAGRAM OF A BIOLOGICAL LIFE SUPPORT SYSTEM
Long-term travel in space, and life on the Moon and Mars, will require a closed life support system, similar to Earth's biosphere, which will rely on plants both for food, and for cleaning the air the crew must breathe.

long-term, full life-cycle plant experiments in microgravity during the 21st Century.

The team of scientists that created the first-generation SVET Space Greenhouse has developed a concept for a new generation Space Greenhouse with adaptive environmental control for optimal results during plant microgravity experiments, based on Bulgarian "know-how" and experience. Future long-duration manned flights to Mars and the scientific laboratories on the Moon and Mars, based on plant bioregenerative systems, will be a reality.

Plants and Biological Life Support Systems

The creation of a Biological Life Support System based on the recycling of chemical elements, as in the Earth's biosphere, is a fundamental and very complicated scientific task for our civilization, and is a prerequisite for future long-term manned space missions. A system that includes higher plants and animals theoretically ensures up to 90 to 95 percent of the needed substances for the crew. The effect of microgravity on growing plants is an important area of research, because plants could be a major contributor to Biological Life Support Systems.

Plants will produce food and oxygen for the space crews while eliminating carbon dioxide and excess humidity from the closed cabin environment. The functional diagram of Biological Life Support Systems by analogy with natural ecosystems includes organisms of the principal trophic levels (Figure 1).[1] The first level is the energy "gates" of the system, through which energy enters from outside. This energy (light) is the basis of the system's existence. This level is produced by photoautotrophic organisms—plants.

The next trophic levels are occupied by heterotrophic organisms, including men and animals, for which the organic matter produced on the first level (biomass) is a source of life. The last link of the trophic chain is presented by different soil microorganisms (fungi, bacteria, and so on) which complete the decomposition of organic matter and turn it into mineral elements utilized by plants.

A great quantity of energy is lost in the process of passing from one trophic level to another. Plants are a fundamental link of bio-regenerative Biological Life Support Systems for future use on space stations and in spacecraft making long journeys to other planets. By achieving maximum yields of edible plant products, the investigators can supplement the food, now carried from Earth, with fresh food grown onboard in space. This would save weight, which is especially important in such long space journeys.

Plants can also regenerate the atmosphere onboard by expelling oxygen through their photosynthesis, and scrubbing the carbon dioxide produced by the crew's breathing. At the same time, having in mind the complexities of living and working on long-duration flights in closed volumes, we should not underestimate the uplifting psychological effect of taking care of a garden far away from the Earth, which will contribute to mission success.

The question of the possibility of growing plants in weightlessness has excited scientists from the very beginning of space research. Since 1962, almost all the scientific programs for both piloted and automatic biological spacecraft have included plant experiments. For 20 years, biologists have almost managed to prove that the critical conditions in space were not a show stopper for growing plants through a complete life cycle.

Limited success in a seed-to-seed cycle was achieved in 1982, when *Arabidopsis thaliana* plants were grown from seed to maturity. But growth was quite retarded and generally poor.[2] The plants were grown in a Russian Phyton-3 device on the Salyut-7 Orbital Station for 69 days. About 200 seeds were formed, half of them immature, after return to Earth laboratories. Further, the plant growth was considerably less vigorous and healthy than that achieved with ground controls in the same plant-growth devices, and many of the seeds produced were empty.

After this success, which eliminated weightlessness as an obstacle, in principle, for plant development, an international team of investigators under the direction of the Institute of Biomedical Problems (now the State Scientific Center) in Moscow, took up the task of developing every single link of the space Biological Life Support Systems separately.

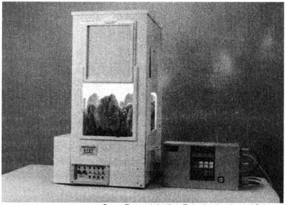
A new scientific program, "Study of the ways and means for use of higher plants, algae, and animals in biological systems for life support of space crews" was set up within the framework of the "Intercosmos" Program in 1983. This was coordinated by G.I. Meleshko and Ye. Ya. Shepelev from the Institute for Biomedical Problems in Moscow, with scientific teams from other countries joining their efforts to design and develop instrumentation and new biotechnology. The goal was to develop the main links of a future closed biological system, including plants and animals.

A team of researchers from the Space Biotechnology Department of the Space Research Institute of the Bulgarian Academy of Sciences developed the first Space Greenhouse, named SVET, for plant experiments. These researchers were included in this scientific task because their 15 years of experience in developing equipment for space physics investigations was well known. The development and production of the SVET Space Greenhouse modules was funded by the Bulgarian side (a patent has been issued), while the Russian side ensured the launch and crew training, and led the flight experiment. Another scientific team, from the Institute of Animal Biochemistry and Genetics of the Slovak Academy of Sciences developed the Incubator-2 system, created for long-term experiments with animal eggs (Japanese quail).[3]

Both pieces of equipment, for plant and animal research, were launched to the Mir Orbital Station in 1990, and the first successful experiments in microgravity were carried out. The Bulgarian research activities on the SVET Space Greenhouse project can be divided into two main periods. From 1983 to 1991, Russian-Bulgarian collaboration took place within the framework of the "Intercosmos" program, which included the launch of the SVET equipment and the first experiments. The second phase of activities, from 1994 to 2000, centered on the American-Russian-Bulgarian collaboration, characterized by the launch of the second-generation, modified SVET-2 Space Greenhouse, and many long-term experiments.

In the 1980s, the aim was to improve and optimize the equipment and biotechnology for plant growth, with the purpose of providing additional vitamins to the space crew's food. But in the 1990s, the research was directed to those experiments that would also clear the air, and even provide food for future long-term space voyages. It was of great importance to solve the problem of providing the crew with "bread" by growing a crop of wheat—a very good prospective grain crop for the future Biological Life Support Systems in weightlessness.

Some wheat experiments were being conducted in various Russian facilities onboard Mir, but again, plants were less healthy than those grown in control groups on the ground. Super-Dwarf wheat was grown in the Russian Svetoblock-M equipment for 167 days during 1991.[4] When plants were harvested at the "boot" stage (each surrounded by a leaf, the head not yet visible), they were only 13-cm high and had only one tiller. There were no seeds gathered (nor were there any in the control experiment on Earth), because of the poor light conditions. Some space plants matured under somewhat higher light, after return to Earth laboratories (28 seeds produced). However, the only head formed during the spaceflight turned out to be sterile.



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The SVET Space Greenhouse, with lettuce growing in the plant chamber and the control box at right.

First 'Space' Vegetables Grown in the SVET

The first SVET Space Greenhouse was created in order to grow plants under the long-term spaceflight conditions of the Mir environment (see photo, this page). The equipment was mounted inside the Krystal module, docked to the Mir, on June 10, 1990. In the same year, the first successful two-month vegetable plant space experiment was conducted. SVET was the only automated facility for such experiments onboard the Mir, and was used until Mir's plunge into the Pacific Ocean in March 2001. It was used to accommodate a series of plant space experiments (a total of 680 days) named "Greenhouse" during different scientific programs in the period 1990-2000 (see table, this page).

The SVET Space Greenhouse has a 1,000 square-centimeter growing area, and can accommodate mature plants up to 40 cm.[5] The plant chamber is well lit by fluorescent lamps and has two wide windows (the front one is transparent) for seed sowing, observation, and sample taking by the crew.

The root module is divided into two equal sections and is filled with the substrate balkanine, which is a natural zeolite that is enriched with mineral salts in order to sustain several consecutive crop cycles. (This is an original Bulgarian technology.) This module is changeable, mounted on rails like a drawer. The substrate moisture is controlled precise-

MAIN PLANT EXPERIMENTS CARRIED OUT IN THE SVET SPACE GREENHOUSE ONBOARD THE MIR ORBITAL STATION (1990-2000)

Experiment	Year	Start-End	Days	Plant variety
1. **GH 1**	1990	June 16 - Aug.8	54	Radishes, chinese cabbage
2. **GH 2a**	1995	Aug. 10 - Nov. 9	90	Wheat, super dwarf
3. **GH 2b-I**	1996	Aug. 5 - Dec. 6	123	Wheat, super dwarf
4. **GH 2b-II**	1996-1997	Dec. 6 - Jan. 17	42	Wheat, super dwarf
5. **GH 3**	1997	May 31 - Sept. 30	115	Mustard (*Brassica rapa*) *(3 experiments)*
6. **GH 4**	1998-1999	Nov. 18 - Feb. 26	100	Wheat, *Apogee*
7. **GH 5**	1999	March 9 - Aug. 17	130	Wheat, *Apogee* (2nd generation)
8. **GH 6**	2000	May 15 - June 26	4	Lettuce crops *(genus Brassica)*
			Total days: 680	

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Radish plant sampling in the SVET Space Greenhouse.

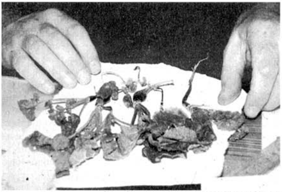
ly at a desirable level by sensors, valves, and a water pump, and the necessary oxygen is supplied to the root area.

The controller collects the environmental data from both the shoot and root zone and provides automatic control using actuators (lamps, ventilator, pump, and compressor). On June 16, 1990, Russian cosmonauts Alexander Balandin and Anatoli Solovyov, started the first long-term, 54-day plant experiments called "Greenhouse 1" with vegetables—white-topped red radishes and chinese cabbage (*Khibinskaya*). They were carried out in the SVET Space Greenhouse during the Russian-Bulgarian biological program, June-August 1990.

When fresh plant samples were returned to Earth for investigation, they were normally developed, although small sized. For the first time, we had grown a radish root crop under microgravity, but they were three times smaller than the control group grown on the ground. The considerably large difference (4 to 8 times) in biomass for plants grown under space and Earth conditions showed that the space plants were exposed to significant moisture and nutrient stress. The balance between the optimal air and water content in the plant root media was disturbed; obviously, it was necessary to work on this problem for future experiments.

In any case, this first experiment was an indisputable success and proved the efficiency of the Bulgarian research equipment and biotechnology in space. Unfortunately, after this hopeful experiment, experiments in the SVET Space Greenhouse came to a standstill for almost five years. It turned out that Russia did not have enough funds to use all of the capacity of its orbital laboratory, and a number of important programs were simply given up.

In this critical situation, the question was whether this space



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Freshly gathered radish plant samples, wrapped in wet filter paper, were delivered to Earth by the crew in August 1990.

station itself would be given up as well. NASA's interest in this long-standing, habitable space object saved the Mir Orbital Station. The Americans did not have their own space station, in which to conduct long-term experiments. After U.S. Presidents George Bush and Bill Clinton reduced the budget for space research and for the Freedom Space Station, the American scientists directed their attention to the Russian capabilities.

In 1993, Vice President Al Gore and Russian Premier Viktor Chernomyrdin signed an agreement to conduct joint space research using the hardware complex available onboard the Mir. An American-Russian-Bulgarian agreement was signed in Moscow in April 1994 to carry out long-term experiments within the framework of the Mir-NASA program in the SVET Space Greenhouse during 1995-1997. The fundamental biological task was to grow wheat through a complete seed-to-seed life cycle onboard the Mir, with the participation of American astronauts and by the good offices of the repeated flights and capabilities of the Space Shuttle and the Russian cargo missions.

The Struggle for 'Space'-Produced Seeds

According to the agreements, an American Gas Exchange Measurement System (GEMS) was developed for additional environment monitoring, at the Space Dynamic Laboratory of Utah State University, under the leadership of Gail Bingham. GEMS was added to the existing SVET Space Greenhouse in 1995.[6]

Two separate transparent bags were placed above the plants, one over each of the two root module sections, enclosing the plant chamber volume, so as to allow local gas exchange and leaf environment measurement. GEMS provided four infrared, high-precision gas analyzers measuring the absolute and differential carbon dioxide and water vapor levels in the air entering and exiting each bag, as well as the absolute and differential pressures of the measured gases. These were necessary to evaluate the photosynthesis, respiration, and transpiration of the plants. Cabin pressure and oxygen levels were also measured. A laptop computer collected all the environment data on a disk, and brought these data to Earth at the end of the mission.

The SVET system provides one substrate moisture sensor per each root module section, which is enough for the measurement and control of the substrate moisture levels. GEMS supplements these with 16 additional substrate moisture level sensors (8 per module), to monitor the water distribution in the whole substrate volume. The additional sensors were designed to be integrated in the existing Bulgarian root module in flight.

A series of long-duration plant experiments was conducted in the SVET-GEMS complex during 1995-1997. The first attempt to grow Super Dwarf wheat in this complex was made in 1995 as a part of the Mir-Shuttle program. The Principal Investigator was Frank Salisbury, from Utah State University.[7]

In the 90-day experiment "Greenhouse 2a," low light intensity and other technical problems strongly disturbed the ontogenetic cycle of the wheat plants; they stayed alive but were mostly vegetative.[8] A new, modified piece of equipment—SVET-2, with optimized units, developed by Bulgarian scientists, was launched to Mir in 1996, (supported by NASA). The new light unit with 2.5 times higher lamp intensity, and all the other units, functioned well, and no hardware problems were encountered until 2000.

The Super Dwarf wheat experiment "Greenhouse 2b" was repeated by the same investigators in the new SVET-2-GEMS complex in 1996.[9] The Greenhouse 2b" experiment was conducted in two stages, of 123 days and 42 days. During the first stage, the aim was to grow wheat during a full seed-to-seed life cycle. Although 297 perfect looking wheat heads developed in the growing area, all the heads were sterile, with development stopped at the pollen development stage. Ground studies proved that ethylene, which was measured as 1 to 2 ppm in Mir's cabin atmosphere, induced male sterility in the wheat plants.[10]

New wheat seeds were planted during the second experiment stage. The leaf bags were installed and for the first time, successful transpiration and photosynthesis measurements were carried out for 12 days using the GEMS equipment.[11] GEMS demonstrated that open gas exchange measurements are possible in space. The green plants were frozen and returned to Earth for biochemical analysis.

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A discussion of the American-Russian-Bulgarian agreement for utilization of the SVET Space Greenhouse in April 1993, in Moscow. From left: the author; Dr. G. Meleshko, from the Institute for Biomedical Problems in Moscow; and Dr. Gail Bingham, from the Space Dynamics Lab of Utah State University.

A mustard plant species, *Brassica rapa,* with a very short life cycle, was used in the next seed-to-seed experiment, Greenhouse 3, carried out in SVET-2-GEMS equipment in 1997. The Principle Investigator was Mary Musgrave, from Louisiana State University.[12]

The collision of Mir with the Progress supply ship on June 25, 1997, caused a loss of power to the SVET-2 Space Greenhouse, as well as a lowering of the temperatures and changing of the atmospheric pressure and composition on Mir. American astronaut Michael Foale saved the experiments, by supplying them with power from the main core module of Mir to SVET by a cord. The first successful seed-to-seed full plant cycle in space was completed. For the first time, "space" seeds (produced in space), were planted again, germinated, and one normal plant was developed. A series of three experiments was completed during the 122-day opportunity on the Mir.

But the struggle of the scientists was to grow wheat seeds, and they knew that only one step was left for success. American scientist Bruce Bugbee, also from Utah State University, proposed using another wheat variety, called Apogee, because it is resistant to high ethylene concentrations.

The wheat plant experiments continued in 1998-1999. The "Greenhouse 4 and 5" experiments were carried out by Russian cosmonauts (mostly by Sergei Avdeev), in the Russian Scientific Program. In the "Greenhouse 4" experiment, 12 Apogee plants produced a total of 508 seeds. Dry-matter samples were taken, and most of the seeds were returned to Earth.

In the "Greenhouse 5" experiment, 10 of the space-produced seeds were planted, and one of them produced second generation space seeds. All the seeds developed during the Greenhouse 4 and 5 experiments were normal. They were planted on Earth, germinated, and produced healthy green plants.[13]

The last experiment in the SVET-2, "Greenhouse 6," was carried out in May-June 2000. Seeds of four different species of lettuce crops, genus *Brassica,* were planted by the last Mir space crew and grew normally. The plants were chosen for their short vegetation cycle. Samples of each plant were brought back to Earth, while, for the first time, the rest were tasted with pleasure by cosmonauts Sergei Zalyotin and Alexander Kalery "to evaluate the flavor qualities of the received plant production."

Basic Scientific Results on the Mir

There were more than 400 experiments on Mir during its 15 years in orbit, and the "Greenhouse" experiments are considered to be among the most important and successful. Unique results were obtained during the biological flight experiments in the SVET-GEMS complex in the field of fundamental gravitational biology. Reiteration of the seed-to-seed cycle was achieved, and the environmental variables in a human space habitat that have an impact on plant growth and development under microgravity were determined.

The successful *Brassica rapa* and Apogee wheat experiments proved that the lack of gravity was not an obstacle for normal plant development in space. The impact of microgravity as a stress operator on the second- and third-generation space-produced seeds, in respect to normal plant sizes and yields, can be seen on a cellular level. The scientific results obtained during the experiments answered a number of questions concerning plant growth under microgravity:

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Russian cosmonaut S. Avdeev enjoys his job, monitoring the maturation of wheat plants in the SVET Space Greenhouse aboard the Mir, in 1999.

• Light completely replaces the gravity vector and plants turn towards the light as they sprout. The plants which are in the middle of the sowing area turn upwards while the others turn to the side, because of the reflecting surface (mylar) put on the walls inside of the chamber.

• Seeds must be preliminarily oriented before sowing, because if the root begins to grow towards the light, the plant will die.

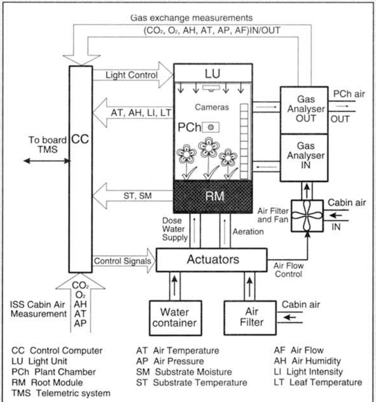
• The roots fill up the entire substrate volume and they are oriented not to the gravity vector but to substrate areas containing more nutrients and moisture.

• The nutrients flow towards the tuber, not because of gravity, but because of capillary osmosis (seen in radishes grown in 1990).

• The space plants take the same time to flower and produce seeds in microgravity as they do under normal gravity conditions.

The researches conducted in this facility brought the scientists nearer to the possibility of growing plants for food in space. They proved the feasibility of Biological Life Support Systems development, if appropriate equipment is designed. The biological results obtained during the "Greenhouse" experiments

The Proposed SVET-3 Greenhouse for ISS



CONCEPTUAL DIAGRAM OF THE PROPOSED SVET-3 SPACE GREENHOUSE

The main units of the new Space Greenhouse concept, are the light unit (LU), plant chamber (PU), root module (RM), gas analyzers, actuators and control computer (CC).* The plant chamber has a plant growing area of at least 1,000 square centimeters. The environment within the Plant Chamber is partitioned off from the ISS cabin atmosphere.

The plant chamber provides a growing volume sufficient for economically important plant species. It can accommodate plants up to a height of at least 35 cm, and provides on-orbit access to the plant material for taking samples at different stages of development. A semi-transparent front window allows visual observation of the plants' status.

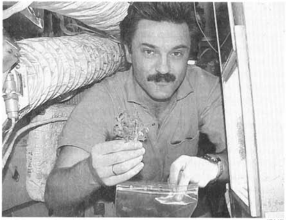
Two digital cameras photograph the plants from above and from the side, in order to evaluate the total leaf area. The cameras record the process of plant growth and development and downlink data via the telemetry system. Processing the data, scientists will obtain qualitative information about the state of the plants so as to understand and evaluate the experiment.

The light unit (LU) provides white light using fluorescent lamps with a spectrum concentrated in the red and blue spectral regions, as required for normal plant growth. The lamps are enclosed in prosuggest that the space biotechnology used is suitable for microgravity conditions and should be developed in the future.

Future Space Greenhouse Concept for The International Space Station

The International Space Station (ISS) will provide a perfect opportunity for conducting full life-cycle plant experiments in microgravity during the next 15 to 20 years. A number of plant growth facilities for scientific research, some of them based on the SVET Space Greenhouse's functional principles, are being developed by almost all advanced space countries.

Most of these facilities provide a fair level of environmental control to maintain defined environmental parameters considered adequate for normal plant growth. The first plant growth facility to support commercial plant experiments, already launched onboard the ISS in 2001, is called Advanced Astroculture (ADVASC), developed at the Wisconsin Center for Space Automation and Robotics.[14] It is configured as a double Mid-deck Locker; it has a closed plant chamber with approximately half the SVET Space Greenhouse growing area, and a height of 34 cm.



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Russian cosmonaut A. Kalery takes a plant sample during the "Greenhouse 6" experiment, carried out in the SVET-2 Space Greenhouse in 2000.

tective hermetic bodies. They are mounted outside of the Plant Chamber, in order to provide separate cooling. The light intensity level can be regulated from 0 to 500 $\mu mol/m^2/sec$ photosynthetic photon flux (PPF) in steps, and the light period can vary from 0 to 24 hours with increments of 1 hour.

The root module uses a substrate matrix of about 1 to 1.5-millimeter particle size as a medium for plant root development. The substrate moisture level in the nutrient matrix is measured by three sensors, located near the water source, in the most distant region, and in the middle. The dose water supply control system maintains the moisture automatically in the range of 5 percent to 95 percent by actuators—a pump injecting water portions through valves, and porous tubes into the substrate.

Aeration by a compressor ensures effective gas exchange (oxygen) in the root zone. The environmental parameters within the plant chamber, air temperature (AT), and humidity (AH), light intensity (LI), carbon dioxide and oxygen concentrations, are measured and registered. A fan maintains the air humidity and carbon dioxide concentrations, by controlling the rate of airflow entering the plant chamber from the cabin. An air filter removes the gaseous contaminants (including ethylene) from the ISS cabin air.

Two high-precision infrared gas analyzers (GA) are connected to the plant chamber inlet and outlet. The cabin airflow passes through a filter and is delivered to the GA inlet by a fan. Carbon dioxide, oxygen, water, humidity, temperature, air pressure, and air flow-rate parameters are measured in real time in the gas analyzer. The ISS cabin air parameters are currently measured by a different sensor system.

The airflow entering the chamber is distributed in the plant leaf area. After gas exchange caused by the plants' physiological processes, the air leaves the chamber, and enters the GA outlet, where the same parameters are measured. The water recovery system and ethylene scrubber (not shown in the figure) are available to clean the air outflow before entering the cabin.

The well-known method for photosynthesis evaluation by carbon dioxide assimilation measurement is described above, but we are working on the question of how another one could be used. Different pigments, the most important of which is chlorophyll, absorb light—the energy that drives photosynthetic reactions. However, not all of the light absorbed is used in photosynthesis. Part of it is converted into heat, and another part is re-emitted as light—fluorescence—with a higher wavelength than the absorbed light. Most of the fluorescence is emitted by chlorophyll.

If conditions are unfavorable, leaf chlorophyll content will begin to decrease. By measuring leaf chlorophyll content, the photosynthetic rate can be evaluated, and from that, the physiological status of plants.

Leaf temperature, leaf area, and plant height are also measured. Having all these data, the computer calculates transpiration and photosynthesis, evaluates the state of the plants, and carries out adaptive control of both the root and shoot environments. The control computer collects and records sensor data, calculates plant parameters, and, as needed, changes adaptively the main controlling procedures in order to operate the actuators to provide the environment that the plants need. The control computer is connected to the ISS telemetry system, which downlinks data and carries out feedback control from Earth.

An LCD display and a keyboard give the crew the possibility of communicating with the greenhouse. An autonomous (manual) mode for control of each actuator is also provided for the experiment. The basic system is open for further modifications and extensions, depending on the experimental requirements. The proposed concept is feasible and can be used in the Brazilian Space Greenhouse project for ISS, if financial support is provided.

Notes

* P. Kostov, T. Ivanova, I. Dandolov, S. Sapunova, and I. Ilieva, 2001. "Adaptive Environmental Control for Optimal Results during Plant Microgravity Experiments." 52nd International Astronautical Congress, 1-5 Oct. 2001, Toulouse, France, Rep. IAF/IAA-01-G.4.04.

The principal ADVASC systems maintain constant parameters of the plant chamber environment, and full substrate wetting, ethylene removal, and water recovery. Light in the red and blue spectrum is provided using light emitting diodes (LEDs). Seed pods grown in this facility in the first 8-week plant experiment with *Arabidopsis thaliana,* conducted during May-July in 2001, were returned to Earth with seeds.

Our former partners in the Russian Institute for Biomedical Problems, and Utah State University in America, developed the LADA plant growth facility, with the same infrastructure, and based on the same functional principles as the SVET, for the Russian Service Module onboard the ISS. LADA has two growth chambers with a smaller volume, one quarter the size of SVET.[15]

The achievements reached during the SVET Greenhouse experiments, as well as the photosynthesis and transpiration measurements made by the American GEMS equipment, encouraged the Bulgarian researchers to continue working on the SVET Space Greenhouse project. The next step is to create a fully automatic space greenhouse that can measure plant growth-physiological parameters during the entire plant life cycle, and can change the period of lighting, the water content in the root module, and the rate of gas-exchange between the plant chamber and the cabin air, depending on the requirements for these parameters. The goal is to maintain "non-stop" optimal conditions for plant growth, because plants are very sensitive to any change in the environment.

Plants do not have a developed nervous system and thus adapt to the extreme space conditions with much more difficulty than can man and animals. They react to unfavorable environmental conditions with "stress," stoppage of growth, and even death. Early signs of stress are invisible to the naked eye, and by the time these signs become visible, plants may already be too damaged to be saved. Crops need to be monitored to determine if they are healthy.

On Earth, crops can be monitored frequently to ascertain how they are growing, but in space, astronauts have too many different duties to be able to do this, and the crops must be monitored automatically. Photosynthesis and transpiration are important plant processes whose normal rate can be affected by unfavorable environmental conditions. By measuring these processes as well as the environmental variables, and by knowing how they affect plant physiological parameters, researchers will receive the feedback to provide a "stressless" growth environment for the plants.

Photosynthesis is the most important process in green plants, and is, therefore, an excellent indicator of the physiological state of plants. Photosynthesis is the process in which plants absorb carbon dioxide and water, and by aid of light, convert them into organic compounds, with oxygen as a waste product. A classical method to evaluate photosynthesis is to measure the carbon dioxide assimilation of plants, which requires a partial enclosure of the system.

Plants regulate their temperature by evaporation of water from the plant shoot zone, a process called transpiration. Rates of transpiration increase with temperature. Leaf temperature could be measured to take account of water stress in plant. The correlation between leaf temperature and water stress is based on the assumption that as a crop transpires, the water evaporated cools the leaves below the air temperature.

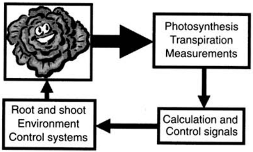

Figure 2
A CONCEPT FOR SVET-3 SPACE GREENHOUSE FOR THE INTERNATIONAL SPACE STATION

As the crop becomes water stressed, transpiration will decrease, and the leaf temperature will increase. The American GEMS equipment was designed to use both methods, and its effectiveness was proven during the 12-day measurements in the SVET-GEMS complex in 1997. But the measurement data obtained were stored for further analysis on Earth, and not used at the time for evaluation of the photosynthesis rate, which would have enabled the researchers to change the growth conditions in real time through feedback.

The new concept for an advanced SVET-3 Space Greenhouse for the ISS, based on the Bulgarian experience and know-how, as well as international experience, is shown in Figure 2. The absolute and differential air plant chamber parameters and some plant physiological parameters are measured and processed in real time. On the bases of the photosynthesis and transpiration measurement data, the necessary calculations are made and the plant status is evaluated.

As a result, adequate controlling signals are applied to the root and shoot environment control systems in order to provide the most favorable conditions for plant growth at every stage of plant development. The plant chamber parameters, optimized autonomously, provide "stressless" plant growth, in order to obtain optimal results from the microgravity experiments. This feedback concept for adaptive environmental control is new; it differs from the SVET-GEMS on Mir (only passive parameters were monitored) and ADVASC on ISS (constant parameters are maintained).

Food for Thought and Action

In developing space greenhouses for the ISS, scientists suffer the contradiction between their wish to enlarge the growing area so as to allow more effective experiments, and the almost non-stop reduction of funds for space research, with a view to the strained international situation and economic crises.

ADVASC, the first ISS greenhouse, does not allow observation of the plants growing in the chamber. There is only a miniature video camera, which records, in shadowy violet color (a combination of the red and blue LEDs), what is going on inside with the plants. Because the systems that maintain the environmental parameters at fixed levels fill the limited chamber volume, only a very small space is left for the plants. The plant air volume could be enlarged, but only at the expense of the other systems.

The astronauts like the experiments very much, and take real pleasure in taking care of the growing plants. During our Greenhouse series of experiments on Mir, instead of watching over the plants once every five days, as prescribed in the instructions, astronauts "floated" to the greenhouse at least five times a day to enjoy the growing plants.

In an interview with astronaut Michael Foale, who worked with the SVET Space Greenhouse in 1997, *21st Century* Associate Editor Marsha Freeman asked him if he "would consider taking plants on long duration missions just to take care of them, and not as subjects for experiments."[16] The answer was categorical:

> Yes, very much so. I think, just like we have house plants for no reason but for their being there, I think exactly the same—in fact, more so—would we value having Earth plants in space, for no reason but that they're pretty, or that they're a reminder of Earth. It's something to follow. They grow, they flower.

The chamber of a future ISS greenhouse should be large enough to accommodate more experimental plants and should be well illuminated, using white light with characteristics similar to normal sunlight. It should also be visually open, allowing easy access by the astronauts attending on the plants; there should be a large window, as the psychological effect of viewing the plants should not be underestimated.

Plant species resistant to the extreme ISS conditions have to be selected in advance, based on Earth investigations. For example, if the Apogee variety of wheat used in 1998-1999, which is resistant to the high ethylene concentrations in the Mir environment, had been chosen earlier for the 1996-1997 plant experiments, the failure of the months-long, high-cost Super Dwarf wheat experiments could have been avoided.

We recommend using leaf crops with rich biomass and a short vegetation cycle, which grow well in high cabin temperatures (25 to 28°C), and low lighting (because of the limits on energy available). Their rich biomass may meet the crew's needs for fresh food, and they could be used to clear the cabin air by absorbing carbon dioxide. And, not least of all, their luxuriant green mass would delight the astronauts' eyes through the transparent chamber wall as "a reminder of Earth."

The possibilities of long-term manned missions have been continuously increased in recent years. Astronauts from all over the world have stayed for long times in space on board the Mir and International Space Station. A fifth Expedition crew is working successfully on the ISS now, and new crews will stay on the station an average of three months. The experience of these station missions will serve the long-term purpose of mankind—expeditions to Mars and the other planets. That is why providing crews with food is a central problem at present.

As a result of the international experiments in the Bulgarian SVET Space Greenhouse facility, half the way from growing wheat seeds to making "space" bread has already been travelled. The experience gained will help to improve the technology for growing plants in space in the future. But there is still much to be done before habitable bases on the Moon, still in our dreams, become a reality.

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