Research on Mir advances growing plants in space

An international program to grow plants in microgravity has produced important, and sometimes surprising results. Marsha Freeman reports.

One of the techniques that will have to be mastered to accomplish long-term space missions, will be the ability to grow crops in space. On other solid bodies, such as the Moon and Mars, the task will be somewhat Earth-like, in that a soil is available, and even the partial Earth gravity on these bodies provides growing conditions quite different from those with virtually no gravity at all.

But, on space stations orbiting the Earth, Moon, or other planets, and in spacecraft making journeys considerably longer than the two days it took Apollo astronauts to travel to the Moon, supplementing the food that is carried along from Earth, with food that can be grown *in situ,* would be a great weight-saving benefit.

In addition, plants can provide a service now performed by mechanical equipment using chemical techniques, to "scrub" the carbon dioxide in the atmosphere expelled when the crew members breathe. At present, the oxygen they consume has to be replaced with on-board supplies carried from Earth. Plants, which use carbon dioxide in their metabolism and expel oxygen as a waste product, can potentially take on the task of regenerating the spacecraft's atmosphere.

And, not to be underestimated, is the up-lifting psychological effect of caring for and nurturing a garden, so far away from the greenery of Earth.

With the goal of long-term space flight in mind, in 1984, scientific work was begun under the auspices of the Soviet-led Intercosmos program, coordinated by the Institute for Biomedical Problems in Moscow, for the "study of the ways and means for use of higher plants, algae, and animals in biological systems for life support of space crews." The Soviet programs and their successors have placed great emphasis on developing closed-cycle life support systems, where the water can be recycled, and plants can substitute for, or at least complement, the chemical regeneration of the atmosphere.

As Dr. Tania Ivanova from the Space Research Institute of the Bulgarian Academy of Sciences explains, during the 1980s, a number of scientists from several East bloc countries contributed to the design and development of various experimental facilities to study the growth of plants in the microgravity of space.

In 1985, the first preliminary experiments took place aboard the Soviet Salyut 7 space station, to test the hydrodynamic characteristics in space of a zeolite material called Balkanin, for use as a nutritive medium for future plant-growth experiments. Zeolites are three-dimensional aluminosilicate crystal structures that can lose and gain water reversibly. Balkanin was used because it is a natural zeolite, which might also be found on the Moon and Mars. It is "dressed" or doped with mineral salts to provide nutrition for the plants.

At the same time, greenhouse modules were designed and tested on Earth. A major advance was made in June 1990, when the SVET ("light") greenhouse, developed by Dr. Ivanova and her colleagues in Bulgaria, was launched to the Mir space station inside the Kristall laboratory module. On June 15, the first experiments with the SVET, termed Greenhouse 1, were begun.

In 1996, under the Shuttle-Mir joint program, a Gas Exchange Measurement System (GEMS) from the United States was added to the SVET greenhouse. It enhanced the ability

Dr. Shannon Lucid, aboard Mir, looks in on the wheat crop she has planted in the SVET greenhouse.

to precisely measure the critical environmental parameters affecting plant growth, particularly the up-take of carbon dioxide and the substrate moisture.

During the Shuttle-Mir joint science program, Greenhouse 2 and 3 experiments were performed, growing Super Dwarf wheat, and then a plant in the mustard family. Because not all of the experiments have been successful, scientists are learning how growing crops in microgravity differs from agriculture on Earth, and are developing ways to solve the problems that the space environment presents.

Early experiments in SVET

The SVET greenhouse is a small facility, with a plant-growing area of about one square foot. The root modules, where the seeds are planted, are arranged in four rows side by side. The root module is mounted on rails and fits like a drawer into the bottom of the structure of the greenhouse. There is room for plants to grow to a height of about 16 inches.

Water is injected into the Balkanin substrate from tubes through a foam, which is surrounded by a chloride-impregnated fabric, or wick. This wick prevents particulate matter from the substrate from escaping into the cabin of the spacecraft, and increases the surface area for the water to move into the substrate. From the start of the experiments, plant physiologists working on the project recognized that the major challenge to growing plants in microgravity was going to be the even distribution of water to the roots of the plants.

The transpiration rate of the plants bears a linear relationship to the amount of water that the plants can extract from the root zone; too little or too much water disturbs the "breathing" of the plant. In turn, the transpiration rate, or gas exchange of the plants (taking up carbon dioxide and expelling oxygen), determines the rate of accumulation of dry plant matter, or the growth rate. Water is also important for cooling the plants, especially under the intense light of an artificial growing environment. Doubling the light level for the plants, to increase their growth rate, will also double the amount of water the plants must extract through their roots.

The Greenhouse 1 experiments were performed in SVET after it arrived at Mir in 1990. Dr. Ivanova reported, in a paper presented in 1992, that the first fresh root-vegetables were produced in space during these experiments, consisting of white-ended red radishes and Chinese cabbage plants. It was observed that the vegetables accumulated biomass in direct proportion to the duration of the light period, and that it was not indispensable to simulate "night" and "day." But, the duration of the light period for the plants during Greenhouse 1 experiments was limited by the on-board power supply, to 16 hours per day.

The scientists report observing a delay in the stages of development of the space plants, due to difficulties in substrate moistening. In addition, when fresh 23- and 54-day, and dried 29-day roots were returned by the crew for study by scientists, it was observed that the SVET plants were half the size of the ground-control plants that had been grown under the same lighting conditions as aboard Mir. For example, the Chinese cabbage and radish plants in space on the 23rd growth day corresponded to the ground vegetation on the 10th or 11th day of growth.

From these characteristics, Dr. Ivanova and her colleagues concluded that photosynthesis had been reduced fourfold in the space greenhouse. Dr. Ivanova reported at a conference last October in Italy that physiological and chemical analyses showed that the space plants were "exposed to significant moisture and nutrient stress." It was clear that better real-time monitoring of environmental conditions would aid in altering watering procedures more rapidly, thus reducing stress on the plants.

The wheat grown in the SVET appeared to be mature and normal. Note the numerous heads on the the tops of the wheat plants, that scientists believed contained seeds.

Greenhouse 2 experiments

In 1994, NASA, the U.S. space agency, and the Russian Space Agency signed an agreement to conduct a number of joint Shuttle-Mir missions, which would deliver U.S. astronauts for long-duration stays on the Russian Mir station. Along with a crew member, scientific equipment developed in the United States would be delivered on each mission to Mir, in order to augment the capabilities already on the station, for a joint science program.

In May 1995, the new Spektr module was launched to Mir, and on June 30 the Space Shuttle *Atlantis* docked with the station, carrying a new vegetation module developed in Bulgaria, and the Gas Exchange Measurement System (GEMS), designed and built by Utah State University. GEMS was designed to monitor the environment in the SVET greenhouse and in the Kristall module of Mir.

GEMS includes a set of 16 moisture sensors that monitor the water distribution in the substrate of the greenhouse. The unit measures and records data every three seconds, on substrate moisture; light, leaf, and air temperatures; oxygen; and cabin air pressure and temperature.

The Greenhouse 2 experiments were conducted on Mir between Aug. 10, 1996 and Jan. 17, 1997. On Aug. 10, 1996, astronaut Shannon Lucid planted Super Dwarf wheat seeds in the SVET, with the goal of completing the first "seed to seed" full plant cycle. All of the active components of the SVET were replaced for the experiment, including a new fluorescent light.

In the May 1998 issue of *Scientific American,* Lucid described the experiment, explaining that "every day we photographed the wheat stalks and monitored their growth. At selected times, we harvested a few plants and preserved them in a fixative solution for later analysis on the ground. . . . One evening, after the plants had been growing for about 40 days, I noticed seed heads on the tips of the stalks. I shouted excitedly to my crewmates, who floated by to take a look."

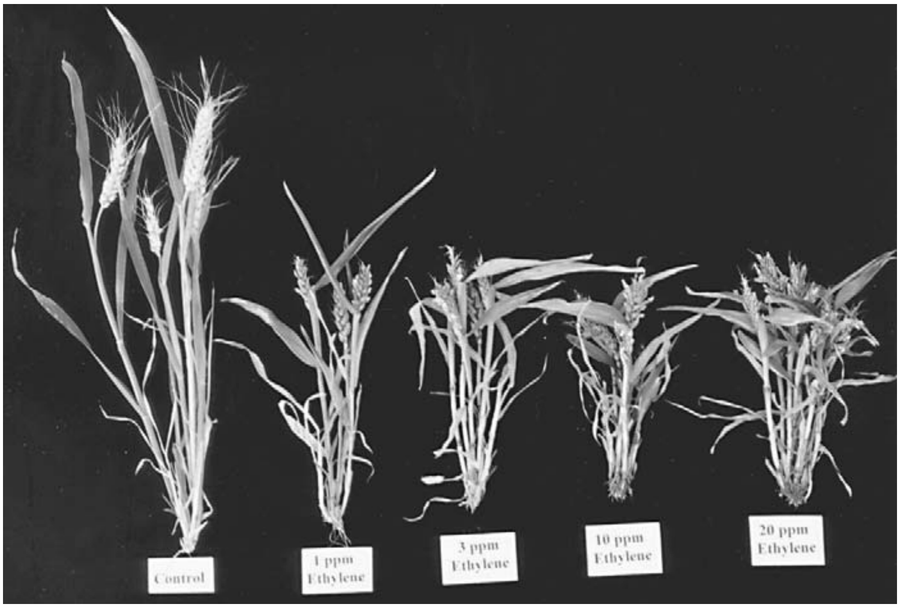
Lucid was replaced by astronaut John Blaha on the Mir on Sept. 16, to whom fell the responsibility of harvesting the dwarf wheat crop.

On Dec. 12, 1996, NASA announced that Blaha had harvested the first crop of healthy plants grown in the SVET that had completed their life cycle of going from seed to seed. The press release from NASA stated that project scientists were optimistic that the plants "appeared to have matured fully to produce the desired seed-containing heads."

But on Feb. 21, 1997, scientists reported that when the Space Shuttle STS-81 mission brought back the dwarf wheat plants (and Blaha) from the Mir, they found that the wheat heads lacked seeds. All of the 296 heads that formed on the plants were sterile, and had stopped developing at the pollen development stage, while the rest of the plant parts were normal.

Some in the press immediately branded the experiment a "failure," but co-investigator Dr. David Bubenheim from the NASA Ames Research Center said, "These conclusions are not justified by the results of the Mir experiments. The potential failure of the wheat plants to set seeds in space was anticipated in advance, since it is known that head sterility can be induced on the ground by several environmental stresses." The job now was to find out what had caused the problem.

Ground studies were initiated at Utah State University and the NASA Ames Center to replicate the conditions on Mir to try to isolate the cause of the sterility of the plants. In a presentation that Dr. William Campbell from Utah



After the SVET wheat plants were returned to Earth and found to be sterile, ground control tests simulating the Mir's atmosphere, including high levels of ethylene gas, demonstrated the impact on plants of high levels of this contaminant.

State University will make in November, at the third Phase I [Shuttle-Mir] Results Symposium, he will report that scientists conclude, that the exposure of the wheat plants to 1-2 parts per million of ethylene gas had led to small and shriveled pollen grains and sterility. Dr. Campbell reports that the scientific "literature is replete with the use of ethylene to induce male sterility in cereals," which makes a strong case for their conclusions regarding the data from Mir.

This led to the question: What would happen to the mustard plants that were being planted on Mir by astronaut Mike Foale, in the follow-on Greenhouse 3 experiment?

New plants from space seeds

When Foale launched on the Space Shuttle to Mir on May 15, 1997, he had no idea what an eventful four months it was going to be on the Russian station, in more ways than one.

Along with Foale aboard *Atlantis,* were *Brassica rapa* seeds to be planted in the SVET greenhouse. Dr. Mary Musgrave, of the Louisiana State University Agricultural Center, the principal investigator for Foale's experiment, along with Dr. Margarita Levniskikh from the Institute for Biomedical Problems in Moscow, describes *Brassica rapa* as derived from the economically important mustard family.

Prior to Foale's launch to Mir, Dr. Musgrave explained that the goal of the experiment was to study "a plant's entire life cycle in microgravity and better understand the effects of microgravity on plant reproduction." The plan was for three successive seed plantings in the SVET, "starting with dry seeds grown on Earth, planting them in space to get a second generation, and using the resulting seeds to get a third generation of plants," Musgrave explains.

The plants take about 14 days to flower after planting, and the plan was for Foale to then spend seven days using a bee stick to transfer pollen from one plant to another. A bee stick is a small stick with the body of a honey bee attached at the end. After 45 days, the plants were to be harvested, and the seeds from the first generation would be planted. In the accompanying interview, astronaut Foale describes the SVET experiment during his four-and-a-half-month increment aboard Mir. Prior to launch, Foale remarked, "I never was a farmer in my childhood, but I'm ready to be one now. I'm a physicist, in fact, by training, but this idea of growing seeds from a seed to a fully flowering plant . . . pollinating first, and then collecting the seeds, kind of excites me. I'm looking forward to that."

In the midst of his farming, on June 25, an unmanned Progress supply ship collided with the Mir space station, decompressing and rendering useless the Spektr module, which housed Foale's personal effects and scientific equipment. The consequences of that accident led to problems that stressed both the crew and Musgrave's mustard plants, including changes in the atmospheric pressure and composition, and three days of darkness for the tiny plants.

Dr. Musgrave reports that both Foale and the plants rose to the occasion. As Musgrave reported on Aug. 1, 1997, for the first time, seeds that were produced in space had been planted and germinated. "This is really a historic time for us," she said. "This seems like a real milestone in plant space biology. My first reaction was feeling really good for the whole group of people who have been involved in this project, and especially good for astronaut Mike Foale."

In a recent preliminary report on her experiment, Musgrave explains that it had been observed on previous short-duration Space Shuttle flights that "identical gaseous environments have very different consequences for plants growing in them on the Earth and in space." For one, in space there is no convective air movement, and, in the absence of active ventilation, stagnant air layers can form around plants.

But during Foale's stay on Mir, he was able to complete two entire growth cycles, Musgrave reports. At the time of the collision in June, the plants experienced 72 hours of darkness, and to assess the effect on the plants, and "advise astronaut Foale on future operations," Musgrave and colleagues created the same conditions for their control plants growing on Earth. The ground-based laboratory plants did exhibit diminished seed weight and had a higher percentage of undeveloped seeds than plants that continued in the light.

There were also temperature fluctuations on the Mir as the cosmonauts worked to repair some of the damage from the collision, and carbon dioxide concentrations ranged 15-20 times above normal levels on Earth. Plus, the previous Greenhouse 2 experiment with wheat had indicated problems with elevated levels of ethylene gas. But, Foale did succeed in growing plants from seeds grown in space.

At the end of August, Dr. Musgrave reported that her team had just completed a 4.5-month ground-control experiment, which replicated the day-to-day conditions on Mir that her plants experienced in SVET. Similar to the SVET plants, the ground-control plants were smaller than normal.

The Russian scientists from the Institute for Biomedical Problems are planning soon to begin a Greenhouse 4 experiment on Mir, using a variety of wheat developed at Utah State University. Whether this experiment can proceed will depend on the ability of the Russian government to adequately service the Mir station, which has been in doubt due to the financial crisis.

The Russians are also continuing a series of ground-based experiments which will help evaluate what role plants can play in moving toward a closed-cycle life support system. According to wire service reports, specialists from the Institute for Biomedical Problems are seeking volunteers to spend 240 days, starting in June 1999, in an isolation chamber similar to the Russian laboratory module that will be part of the International Space Station. Previously, such isolation experiments have been carried out with European and Russian volunteers for up to 120 days.

According to Dr. Musgrave, in her discussion with a crew member of a previous isolation experiment in Moscow, she learned that the psychological impact of caring for and observing plants while simulating a space mission, was as important, or perhaps more important, than the contribution the plants made to regenerating the atmosphere or potentially providing nutrition.

The "crew" in the upcoming experiment is to simulate the activity of a space station crew, and one requirement is fluency in English, which will be the principal language of the International Space Station. The Russians hope to have the participation of the other nations in the ground experiment that will be building and using the ISS.

All of the scientists from different nations who have participated in the SVET experiments, await the facilities that will be available on the International Space Station. As Musgrave states, "Long-duration access to orbital platforms and the dedicated time of well-trained astronauts will be necessary to develop the database needed to implement the technological goal of a plant-based life support system."

Interview: C. Michael Foale

First seed-to-seed plants grown in space

Dr. C. Michael Foale was the fifth NASA astronaut to live on the Mir station. In June 1983 he joined NASA, and four years later was selected as an astronaut candidate. Before his stay on Mir, Foale had been a crew member on three Space Shuttle missions. Currently, he serves as Assistant Director (Technical) at the NASA Johnson Space Center, and is also assigned to the third mission that will service the Hubble Space Telescope. Marsha Freeman of 21st Century Science & Technology *met with Dr. Foale in his office on May 13 and discussed his SVET experiments, and his future plans in space exploration.*

Q: One of the important aspects of the space program that does not get covered in the press very much, if at all, is the science that has been done on Mir. Your flight on Mir was very eventful in unexpected ways, but you also accomplished very important scientific and technical goals. I am particularly interested in the work that you have done with the greenhouse. I have been to the Kennedy Space Center and seen the controlled environment agriculture work they are doing. But working in microgravity must be very different. Could you describe the work that you did with the SVET greenhouse, and what you were able to accomplish?

Foale: Basically, the greenhouse experiment was a joint project between the Russians and the Americans. It was building on a lot of previous work over many years, using a facility that's been on board the Mir in the Kristall module, since it was launched.

The experiment is called the "SVET" module. And *svet,* in Russian, means light. And they call it the "SVET oranzhereza." *Oranzhereza* means a greenhouse.

It was originally built in Bulgaria, and is basically a box which has an array of bright fluorescent lights that radiate in the wavelengths that plants use most effectively, and a system of tubes that provide water in measured amounts, to what we call root modules that would hold the plants that we were trying to grow. It was sort of a generic facility, for just exploring the growth of different types of plants, from the seed up.

Shannon Lucid had done a lot of work, and that was carried on by John Blaha, who harvested wheat. And they