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LAST PLANT EXPERIMENTS IN THE "SVET" SPACE GREENHOUSE EQUIPMENT ONBOARD THE "MIR" ORBITAL STATION

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Abstract

Unique results from the plant growth research under microgravity were achieved during the last experiments in the Bulgarian SVET Space Greenhouse (SG). It was launched onboard the MIR Orbital Station (OS) in 1990 and was the only equipment for long lasting plant experiments in the world till the end of MIR OS. A total of 680 days of experiments with different plant species were carried out on international programs. In 1989-1999 two Russian crews conducted the most productive several-month experiments with a new wheat variety. This more resistant variety allowed full life cycle plant development and even producing second generation "space" seeds. So, it was proved that there were no obstacles to grow the crop that is most important for the future Biological Life Support Systems (BLSS) during long-lasting missions. The last OS MIR crew conducted experiments with different leafy vegetables in the SVET SG in 2000. Plant samples were returned to Earth for analysis while the rest were eaten with pleasure by the cosmonauts to taste their flavour qualities.

1. Introduction

The research on plant growth under microgravity is of great importance since plants are a major element of Biological Life Support Systems (BLSS) for future long-term space missions. Plants can supplement the astronaut food and scrub the carbon dioxide in cabin air through their metabolism, thus regenerating the atmosphere. Besides, taking care of a garden in such extreme conditions has a significant psychological effect on the crew's emotional status, rapidly enhancing the astronauts' psycho-physiological condition.

The SVET Space Greenhouse (SG), an automated facility for plant growth under microgravity, was designed in the Space Research Institute, Bulgarian Academy of Sciences. It was tested and launched in space under a joint project with the Institute of BioMedical Problems (IBMP), Moscow, within the *Krystall* module, docked to the MIR OS on June 10, 1990. Since those times, SVET SG has been a regular equipment onboard the MIR OS till its plunge into the Pacific and was used to accommodate a series of total 680 days plant space experiments on different scientific programs in 1990-2000 (Table 1). Unique scientific results in the field of Space Biology were obtained from these experiments.

Table 1. Main plant experiments carried out in the SVET SG onboard the MIR OS in 1990-2000.

No	Year	Start–end	Days	Plant variety	Program
1	1990	16 Jun-8 Aug	54	Radishes, Chinese Cabbage	INTERCOSMOS
2	1995	10 Aug-9 Nov	90	Wheat *Super Dwarf*	MIR-SHUTTLE
3	1996	5 Aug-6 Dec	123	Wheat *Super Dwarf*	MIR-NASA-3
4	1996-97	6 Dec-17 Jan	42	Wheat *Super Dwarf*	MIR-NASA-3
5	1997	31 May-30 Sep	115	Mustard *Brassica Rapa* (3 veg.)	MIR-NASA-5
6	1998-99	18 Nov-26 Feb.	100	Wheat *Apogee*	RUSSIAN
7	1999	9 Mar-17 Aug	130	Wheat *Apogee* (2nd generation)	RUSSIAN
8	2000	21 May-15 Jun	27	4 lattice crops-genus *Brassica*	RUSSIAN
		Total time:	**680**		

The first successful 2-month experiments with vegetable plants (radishes and Chinese Cabbage) carried out in 1990 proved the efficiency of Bulgarian hardware and technology [1,2]. In 1995, American scientists from the Utah State University (USU), USA and NASA/Ames Research Center designed the American Gas-Exchange Measurement System (GEMS) [3]. It was added to the SVET SG basic Bulgarian equipment to record more environmental factors to which plants are exposed. Three-month wheat (*Super Dwarf* variety) plant experiments were carried out in the SVET-GEMS equipment. The physiological and chemical analyses showed that the space plants, grown in these two experiments, though looking healthy, had been exposed to significant moisture and nutrient stress [4]. This made us direct our efforts to equipment optimization in order to provide more adequate environment for the plants - light intensity and spectrum and substrate (soil) moistening.

A set of the SVET-2 SG equipment (a greenhouse of a new generation) with considerably improved technical characteristics was designed by Bulgarian scientists on NASA's order and launched on board the MIR OS in early 1996. A succession of plant experiments on the "Greenhouse" Project were planned by the USU and IMBP and carried out in the SVET-2 SG equipment on the MIR-NASA program in 1996-97 [5]. The specific goals of these experiments were to grow plants through a complete life cycle in space "from seed to seed". Healthy plants of *Super-dwarf* wheat were grown through a complete life cycle during the "Greenhouse 2b" experiments conducted on MIR-NASA-3 program from August 1996 to January 1997 by the U.S. astronauts Shannon Lucid and John Blaha. Unfortunately, in these experiments wheat seeds were not produced in space. All 297 heads harvested on December 6, 1996 were sterile - not a single seed was detected. It was found that the ethylene gas in the cabin atmosphere of MIR OS had caused the sterility of the heads.

Another plant species - mustard plants (*Brassica Rapa*) with a very short life cycle were used in the next "Greenhouse 3" experiments. They were planned by the Louisiana State University, USU and IBMP and conducted by the astronaut Michael Foale on the MIR OS in 1997 under the MIR-NASA-5 program [6]. For the first time, a full plant life cycle "from seed to seed" was completed and seeds produced in space were planted, germinated and developed. A total of three successive generations of *Brassica Rapa* plants were grown and harvested.

Notwithstanding the indisputable success of these experiments - a complete life cycle "from seed to seed" achieved under microgravity - the problem of producing wheat seeds in space was still left open. Scientists directed their attention to wheat plants again as more important for the future BLSS and crew food during long-term space missions.

Experiments "Greenhouse 4 and 5" were performed on the MIR OS under the Russian national space research program in 1998-99. The main purpos of these experiments was to continue the studies of wheat reproductive function in microgravity and to grow crops of several wheat generations. The last experiment "Greenhouse 6" with leafy crops was carried out by the crew of the last MIR OS in 2000.

2. Results from the Last SVET-2 SG Experiments on the MIR OS

The plant experiments in the SVET-2 SG were continued in 1998-99 with another wheat variety *Apogee*. This variety was designed by scientists from the USU under the direction of Prof. B. Bagbee especially for greenhouses and has the ability to form seeds in the conditions of high ethylene concentrations. The *Apogee* wheat reaches average height, which is important for the conditions of a space flight. The **"Greenhouse 4"** wheat plant experiment was carried out between November 1998 and February

1999 by the 26th Russian crew. On November 18, 1998, the space "farmers" Genadiy Padalka and Sergey Avdeev planted 50 wheat seeds, but only 8 of them germinated due to insufficient initial substrate moistening. New seeds were sown again on November 30. In the beginning of December, they started to germinate and grew good sprouts. Later, about January 27, plants started to form heads, which seemed full with seeds. The scientists were excited. For the first time wheat seeds appeared to be obtained in space. The crew confirmed this at the time of video observations on February 2 (Fig.1).

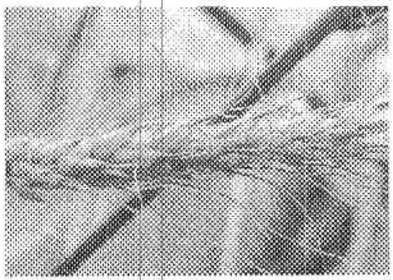

Fig. 1. A photograph of the Apogee wheat plants grown during the "Greenhouse 4" experiment in the SVET-2 SG on the MIR Orbital Station taken in February 1999.

All 12 plants with 29 ears had seeds [7]. On February 26, the life cycle was completed and the plants were harvested. All 29 ears were put in a bag and sent to Earth. On Earth, each ear with the seeds was packed separately and sent for detailed analysis. A total of 508 space-produced seeds were counted although the investigators anticipated getting no more than 100. The preliminary report said that the "space" seeds had similar structures to "earth" seeds and that they looked viable. Only 10 seeds were kept onboard for further sawing in order to produce second generation space seeds. 45 of the seeds that slipped out of the ears were packed and put aside to be planted on Earth. Fresh seeds usually require a long rest period (of several months) before planting. The scientists used another way in order to save time. On April 1, they soaked these 45 seeds for a day. 40 of them germinated and were put into a freezer. On April 5, the seeds were taken out and, on the next day, all 40 seeds were planted and further sprouted.

The same procedure was applied onboard the MIR OS. On March 3, 1999, the next **"Greenhouse 5"** wheat plant experiment was started by the 27th Russian space crew. The cosmonauts soaked 40 seeds (10 space-produced and 30 earth-produced). All the seeds germinated and, on the next day, they were put into a freezer for several days. On March 9, the seeds were planted in the SVET-2 SG. Unfortunately, at this time the temperature in the MIR OS was about 29°C while the wheat plants required an optimal soil temperature of 12-17°C. For that reason, only two out of the ten space seeds sprouted. Further, one of them died and the only remaining wheat plant developed and produced seeds. Nevertheless, this was a unique result. For the first time second-generation space seeds were produced in microgravity. In April, the new "space" seeds were returned to the MIR OS. They endured the landing and launch loading well and were planted in the vacant places in order to use the sowing area more effectively. The experiments were completed on June 7, 1999, but the plants were not harvested because of the risk of rotting. The equipment continued operating till August 17, when the plant samples were collected and returned to Earth for further detailed analysis. All the 5 second-generation space seeds were planted on Earth, germinated and produced healthy green plants. The experiments gave further evidence that wheat growth and development in microgravity follow the same pattern as on Earth. The period of vegetation as a whole was not extended. Neither were the individual phases of wheat development. Experiments "Greenhouse 4 and 5" yielded a total of more than 1000 "space" seeds and second-generation "space" seeds were obtained in the "Greenhouse 5" experiment. Table 2 presents data for the comparative analysis of two space generations wheat plants [8]. On the whole, the only second-generation space plant was not morphologically different from the first-generation ones and the ground experimental samples (control).

Table 2. Characteristics of *Apogee* wheat in experiments "Greenhouse 4 and 5"

Parameter	Flight experiment "Greenhouse 4"	Flight experiment "Greenhouse 5"		Control without ethylene	Control with ethylene 1.1 mg/m^3
		I generation	II generation		
Period of the full cycle of vegetation, *days*	70-82	83-90	83-90	80-83	75-80
Dry mass of one plant, *g*	3.64	2.29	1.21	3.05±0.86	1.70±0.28
Number of shoots with heads per plant	2.4	2.1	2.0	2.8±0.4	3.0±1.0
Plant height, *cm*	35.3±3.1	33.9±5.9	27.0	44.8±2.8	27.7±1.1
Stem length, *cm*	26.2±2.0	27.1±3.1	22.0	36.2±3.1	18.9±4.2
Number of seeds per plant	42.3	20.7	5	68.3	13.2

This experiment was a great scientific success. A plant with a long life cycle was grown "from seed to seed" in space. Moreover, this was a wheat plant - a plant of great agricultural importance. Before the results of the "Greenhouse 4 and 5" experiments were received the retarding effect of microgravity on plant development was debatable. Now biologists drew the conclusion that retarding of plant development in space is caused not only by the lack of gravitational force, but also by the conditions existing in a closed space where there are many environmental pollutants whose concentration, though admissible for man, is harmful to plants.

The MIR OS was renewed after it had been empty for 223 days and the next **"Greenhouse 6"** plant experiment was carried out in the year 2000 under the Russian national space program. Seeds of 4 different species of lattice crops - genus *Brassica* were planted in the SVET-2 SG on May 21 by the 28th space crew (cosmonauts Sergey Zalyotin and Alexander Kalery) which grew normal biomass (Fig. 2).

The plants were chosen for their short vegetation cycle (leaves mature in 2-4 weeks after sowing). The experiment was completed on June 15. A sample of each plant was brought back to Earth, while the cosmonauts tested the rest.

In the 2000 experiment, four leafy vegetables were raised for 26 days, including Chinese cabbage (*Brassica rapa var. pekinensis*), Mizuna (*B. rapa var. nipposinica*), broccoli (*B. rapa var. utilis*), and mustard (*B. juncea*). The growth and development characteristics of the space-grown plants did not differ from their ground analogues. The comparison between the Chinese cabbage crop dry mass grown in the 1990 and 2000 space experiments demonstrated that productivity in the latter was 5 times higher.

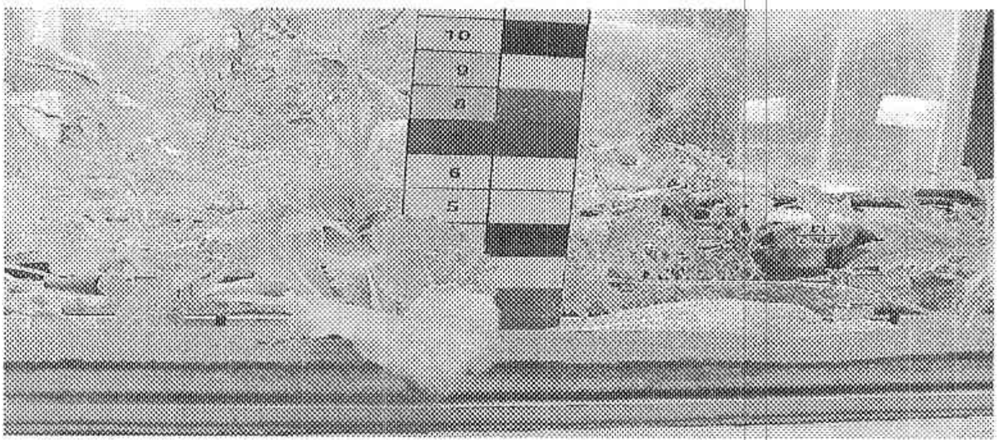

Fig. 2. A view on the green plants (4 lattice crops) grown in the SVET-2 SG in June 2000.

In the 2000 experiment, cosmonauts tested the flavour qualities of the received leaf vegetables and concluded that any of the four varieties would be a significant enhancement to their diet, and a worthy crop for a space production greenhouse, as they gave preference to Mizuna and mustard.

3. Major scientific results

More than 400 experiments were conducted on the MIR OS during its 14 years in orbit. And the "Greenhouse" experiments are considered to rank among the most important and successful ones.

The scientific results obtained during the SVET and SVET-2 SG experiments answered a number of questions concerning plant growth under microgravity [9]:

- 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 aside because of the reflecting surface (mailar) put on the walls within the chamber.
- Seeds must be orientated before sawing 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 orientated not to the gravity vector but to the areas with more nutrients and moisture.
- The nutrients flow away towards the tuber and this is not because of gravity but due to the capillary osmose (in 1990, radishes were grown).
- The space plants take the same time to flower and produce seeds in microgravity as they do under normal gravity conditions.

The results obtained during the biological flight experiments are fundamental. Reiteration of the "seed-to-seed" cycle was achieved and the environmental variables in a human space habitat (MIR OS) having an impact on plant growth and development under microgravity were determined.

The main result from the series of experiments in the SVET and SVET-2 SG on the MIR OS is that there is no "show-stopper" for plant growth in microgravity. The research conducted in this facility brought the scientists nearer to the possibility to grow plants for food in space. They proved the feasibility of BLSS development if appropriate equipment was designed.

The successful *Brassica Rapa* and *Appogee* wheat experiments showed that the lack of gravity is 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 case of normal plant size and yields is possible to be found on a cellular level.

The vegetable plants grown onboard the MIR OS during the "Greenhouse 1" (1990) and "Greenhouse 6" (2000) experiments are of another important plant group that deserves special attention. Both experiments were conducted under severe water stress no matter that it was caused by different reasons. A few months before the MIR OS plunge into the Pacific (in March 2001), the crew tasted the green salads grown in the SVET SG for the first time.

4. Prospects for the ISS

The new International Space Station (ISS) will provide a perfect opportunity for conducting full life cycle plant experiments in microgravity, including measurement of more vital plant parameters during the next 15-20 years. Now, many countries (Russia, USA, Italy, Japan, etc.) are designing plant growth facilities for scientific research based on the SVET SG operational principles, scheduled for the ISS.

The designed biotechnological and technical equipment and the conduction of so many successful experiments make Bulgarian scientists preferred partners for future international collaboration to design facilities for plant microgravity research on the ISS. The universality of the equipment allows different international teams of biologists to use it for experiments planned on their own programs. There are different proposals for joint projects, but the most perspective is the Brazilian one.

In October, 1999, a Memorandum of Understanding was signed between the SRI and BRAZSAT (Brazilian Company in the area of space research and commercial space services). According to it, both parties will work together on the development of Equipment for Agricultural Research in Microgravity (EPAM) using Bulgarian space greenhouse experience. Two governmental institutions were involved in the Project: the Brazilian Space Research Institute (INPE) and the Brazilian Agricultural Research Company (EMBRAPA). In 2000, a Feasibility Study Contract was signed and now we are waiting for financial support for the next stages of the Project's development.

A new Concept for a new Space Greenhouse, based on the Bulgarian experience and "know-how" is being developed [10]. The absolute and differential plant chamber air parameters and some plant physiological parameters will be measured and processed on-line. Using transpiration and photosynthesis measurement data the controller will evaluate the plant status and perform adaptive environmental control in order to provide most favorable conditions for plant growth at every stage of plant development in autonomous mode during plant microgravity experiments.

The Bulgarian and Brazilian Governments support the negotiations - a bilateral agreement was signed in 2000 during the visit of the Bulgarian Foreign Minister in Brazil. The EPAM launch into space is scheduled for 2003-04 and will be probably connected with the flight of the first Brazilian astronaut. The aim of the experiments will be to test the effectiveness of the methods for fighting plant diseases and to grow more productive plant species in the conditions of microgravity. EPAM will be mounted in the ISS Brazilian allocation and will be accommodated in a double middeck locker in the upper half of the NASA developed EXPRESS Rack.

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ПОСЛЕДНИ ЕКСПЕРИМЕНТИ С РАСТЕНИЯ В КОСМИЧЕСКАТА ОРАНЖЕРИЯ "СВЕТ" НА БОРДА НА ОРБИТАЛНА СТАНЦИЯ "МИР"

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Резюме

Уникални резултати в изследванията, свързани с развитието на растенията в условия на безтегловност, са постигнати по време на последните експерименти в българската Космическа оранжерия (КО) СВЕТ. Тя е изстреляна на борда на Орбитална станция (ОС) МИР през 1990 г. и беше единствената апаратура за дългосрочни изследвания с растения в света до края на съществуването на ОС МИР. В нея са проведени общо 680 дни експерименти с различни видове растения по международни програми. В периода 1998-1999 г. двата руски екипажа на ОС МИР осъществиха най-резултатните няколко-месечни експерименти с нов сорт пшеница. Този по-устойчив сорт позволи осъществяването на пълен цикъл на развитие на растенията и дори получаването на второ поколение "космически" семена. Така бе доказано, че няма пречки да бъде отглеждана в условие на безтегловност и най-важната култура за биологичните системи за осигуряване на живота на космонавтите при бъдещите им дълготрайни полети. Последният екипаж на ОС МИР проведе експерименти с различни видове салатени култури в КО СВЕТ през 2000 г. Образци от растенията бяха върнати на Земята за изследвания, а останалите бяха изядени с удоволствие от космонавтите за да се тестват вкусовите им качества.