leagues 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 produced a very luxuriant growth in their experiment, but did not produce viable seeds. As I understand it, they did do a pollination, so there was some flowering and there was some pollination. But, they did not produce viable seeds.

So, the goal of the investigators for my experiment, from Louisiana State University, and from the Institute for Biomedical Problems in Moscow, and from the University of Utah, was to grow *Brassica rapa,* which is, as far as I know, a form of broccoli, and to take that from the seed, all the way through flowering, and through pollination, and to seeds in a pod, and then to harvest the seeds, and then replant them.

That cycle was expected to take about a month. And so, the hope was that in my time on Mir, which would be four and a half months, I would do this three times, and produce two space generations of seed, from which, in turn, would be produced plants in space. The goal was, specifically, to attack the problem of not just germination, but pollination and then the production of seeds. And then fruition and harvesting, and then repeated plantings of those space-produced seed.

Basically, we were successful. The way we carried out this experiment was, we had root modules prepared. And a root module allowed four rows of plants watered in pairs, to grow about 13 seeds per row. So, we could do about 52 plants at a shot. That was the plan: 52 seeds planted.

The root module was a box that contained zeolite powder, but is not a uniform powder. It has small grain sizes and large soil sizes. And this is very critical, they have found, in space research, in getting the water to not flood the root or totally dry the root. You want the water to form patches, but not to totally flood the zeolite when you feed the water in. There's no gravity to differentially separate the water from the root.

On Earth, in soils, when the water goes in, it's more dense as you go down, and it's drier as you go up. So, the root can find places where there's air, and places where there's water, and pick or choose the environment.

In space, for many, many years with the SVET module, they had very little success, because the soil material didn't work out. It was always a fine powder of one particular size, 70 microns. And that would either totally wet and flood the root, or totally dry out the root. But either way, they couldn't get viable plants. They kind of solved that problem, and I think much of the credit goes to the University of Utah, for coming up with a system that allowed this wetting to be done in a more root-friendly way.

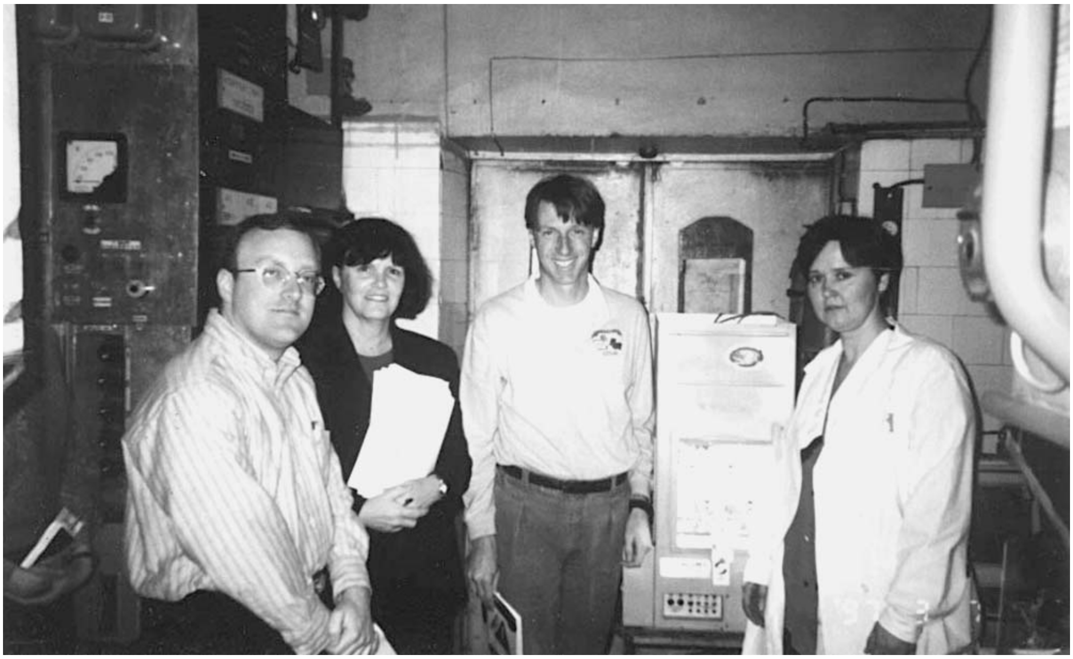
On top of the soil material, there are wicks placed, that spread out down into the zeolite material. And I would place this root module, which is roughly a half-meter by a half-meter, into the greenhouse, and connect up water tubes and electrical sensors. I would measure the temperature, along the strips, at different depths in the soil, as well as free water. The whole point of this was to measure the humidity, the water-level content, at different points in the root module, near the plants, so that the machine itself could control the wetting, and it didn't flood the roots, or dry them out.

Shuttle and Mir astronaut Michael Foale. The logo (inset) is of the joint U.S.-Russian program in fundamental biology research in space.

The first day of the experiment, I set up the equipment, which took a lot of time, finding all the pieces that were left over from the expedition before mine. Finding things was hard. I set up all of the electronic monitoring of the temperatures of the soil, and then took out long cellophane strips on sticky tape of the seeds. The seeds were about a millimeter in size, these little round holes. And I would place them, by hand, with tweezers, into this wick, about 13 per row.

Then my job was to wet the zeolite and the root module enough, but not too much. And initially, on the first try, I think we overshot. We weren't getting any measurements of humidity in the first 12 hours or so, so I and the investigators agreed that we'd put more water in. And lo and behold, suddenly, we saw the humidity levels going way past 50%, and we were afraid we were going to flood the root module.

This happened in the first day, and we got better at it the second and the third time around. At the same time, we left the light bank on continuously, in a cycle of 23 hours on, and one hour off.



Before his flight to Mir, Mike Foale posed at the Institute for Biomedical Problems in Moscow with a ground duplicate of the SVET unit in which are growing Brassica rapa *plants. With Foale are Keith Zimmerman and Sally Greenwalt from the United States, and on the right is Dr. Margarita Levinskikh, a Principal Investigator with Dr. Mary Musgrave on Foale's experiment on Mir.*

Q: How did the plants respond?

Foale: In weightless conditions, there is no up or down. And as the seeds started to germinate, about 50% of them will put a little root shoot—the up-growing shoot on Earth—would just burrow down into the wick, and the root would start popping up. It would be completely confused. About another 50%, would go heads up and tail down, which is the right way we wanted them. And others would just grow along the wick. This was especially true on the first planting, because I had placed the seeds fairly deep down into the wicks, so there wasn't much light getting down to them. The wicks were made of a whitish material, so some light got down.

When they finally popped their heads up above the wick—or I teased them up with tweezers, so they could sort of see the light—then the light, through phototropic action, drew the plants upwards in the right direction, toward the light, and the roots, in the opposite direction, went down toward the wick.

Overall, about 50 to 80% of each of the rows, germinated. In fact, I think almost all of the seeds germinated. I'm not an expert; "germination" to me meant they'd burst their little shoot out. Beyond that, some of them failed. And only about 80% would actually carry on—again, with me helping them in the right direction—to go up toward the light, and reach down.

In a matter of a week or so, two weeks, they would start to grow one or two primary leaves, and then flower buds. And only after about four weeks did the flower buds—now the plants would be about five centimeters, six centimeters high—suddenly produce a plethora of yellow flowers, which had pollen on the stamens.

I would write down every day the stage of the plants: how they looked, how many had buds, how many didn't. And I would write down the average highs, and then the minimum high and the maximum high for each row. And, of course, at the same time, we'd carefully monitor the temperature and the humidity level in the root module.

Now, there's air being blown across this greenhouse as well. And in the first experiment, before the collision of the Progress module and Spektr, the seeds would start to germinate. After the plants had grown about three or four centimeters, we placed what we called leaf bags—just basically polyethylene bags that were sealed—over the plant. The gas that would go in from the cabin, into the greenhouse, would be passed over the plants, and then passed out through a gas analyzer. And a measurement was made of the carbon dioxide intake and outtake, the respiration rate of the plants during most of the growing phase.

It was only when I was going to pollinate, that I would take the leaf bags off. And I would then take a bee stick—pieces of bees on sticks. This is actually a common technique. I didn't know this. In schools—most schools know about this, teaching high school kids how to pollinate plants.

They find bees, and they chop the tails off, and stick them on sticks, on little toothpicks. And you basically go along with your toothpick, with the bee on the end of it—your bee stick (bzzz, bzzz, bzzz)—you go up and down the rows.

I practiced some of this on the Earth, and I did it pretty well in space, it turns out. You collect pollen first from the stamens, and then you put the pollen onto the pistils. And after collecting pollen in one pass up and down the row, like a bee would, you then go into two passes, trying to take the pollen you've collected, and put it onto the female part of the plant.

And, lo and behold, within two or three days—There's only a day's window, or two days' window, in this plant's very rapid growth cycle, when any one flower is ripe to be pollinated. And, it's not quite the same time as when it's ripe to give pollen. So, we do the pollination over a period of about a week, about four weeks into any one planting.

And then, after that, you put the leaf bags back on so you can measure the CO_2 over the plants again. And another two weeks went by, which was already two weeks longer than we expected. We thought the cycle would be four weeks. It is on Earth. It takes longer in space. Also, by this time, the conditions were harder on Mir. The temperature wasn't quite so constant, it got cold a lot in that module. So, it slowed down things.

After six weeks, some pretty long seed pods—just like pea pods—grew in the place where the flowers were. And it was pretty clear that they were full of seeds. They seemed to be full of seeds. And when I was told finally to harvest, I just took down the whole experiment, and collected the plants in a glove box. This was invaluable stuff.

This is in a spacecraft where your whole life is dependent on air flow moving around, blowing the carbon dioxide away. And yet, when you pull out these flimsy little plants that are so light and drying now, they'll blow away in a heartbeat. And so, I had to be very careful in collecting these, especially the seed pods, and popping them into little vials with a desiccant. At the same time, I took the rest of the plants, and put them into a general container bag, so I could then put them into formaldehyde to fix them, so the product could be studied on Earth.

That was a very laborious process. It took me three days or so to do that. But then, having taken the seed pods and dried them after about 50 days, I then set up a whole sort of sticky tape, across the base block [section of the Mir], and started, very carefully, taking these crispy, crispy seed pods between tape again, and breaking the tape, wiggling it, so that the dry, husky material would fall apart, and just the seeds would be exposed.

And then, I'd peel apart the tape. These were tiny seeds, half a millimeter. These were *smaller seeds than Earth seeds*. They were not as strong. Some of them would float away very, very quickly. And I'd try and catch them, and then stick them down on the tape that I had for collecting them.

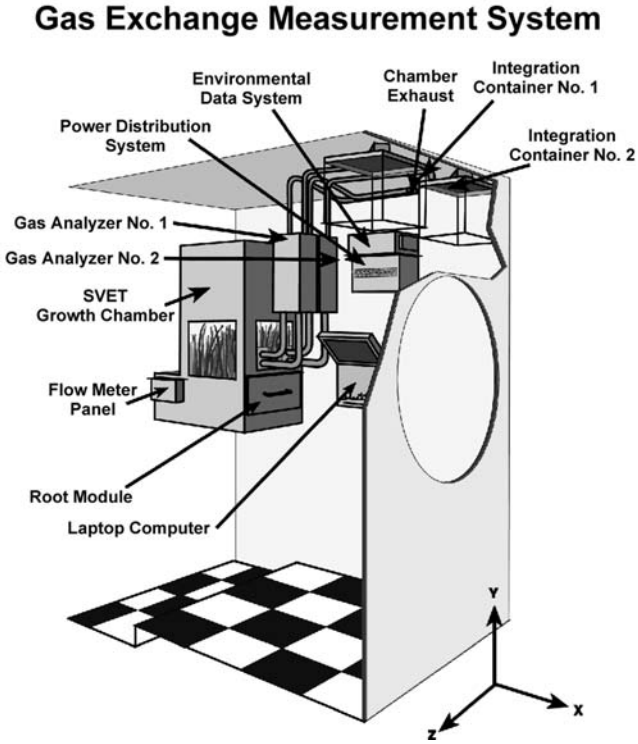
Having loaded up all my space-produced seeds, I would then replant half of them in the next module wicks. And at the same time, in each row, I would have half space seeds, and then the other half, original Earth seeds, which I had a supply of, also on sticky tape.

The fifth NASA astronaut to live on the Mir was Michael Foale, seen here exercising on the treadmill onboard the Russian station, on Sept. 30, 1997, at the end of his eventful Mir mission.

And then the whole experiment repeated.

I think it was about the time I'd repeated the experiment, that we had the collision. And unfortunately, the leaf modules—the plastic bags that would go over each root module to measure the carbon dioxide intake and outtake—I had stored those in Spektr. So, they weren't usable. But actually, for me, it ended up being an easier process, because then I could have access to the plants every day. I didn't have to peer through some kind of crinkly material to figure out what was going on. And if a plant was kind of going crooked, I could redirect it more easily.

Now, in the second planting, I developed a number of techniques that were more efficient than the first time. Certainly, I figured out how to set the seed with tweezers into the wick, so that it didn't float away. The first time I put the tweezers in, opening up the wick with the tweezers, to drop the seed in, but then the seed would just fly out. So, I had to figure out a way to put the seed in, so that it would stay. I basically ended up being able to put the seed in, a little more shallow. And as a result, the seeds saw the light quicker, and more of them found their way up than on the previous planting.



The Utah State University-built Gas Exchange Measurement System allowed Mike Foale to keep a constant watch on the state of his plants aboard Mir, and respond to problems quickly.

However, only three or four of the space-produced seeds germinated, out of the six or so I planted. We produced about 15 or 20 seeds total—space seeds. But they were so weak and flimsy, only two or three of them were worth even planting. I planted a total of six or seven. And I think only two of those actually ended up producing a viable plant that grew up.

Q: Was the second-generation plant as healthy as the first, or was it smaller?
Foale: No, it wasn't. It was smaller. I think the uncertainty of how the seed gets the nutrient through the wick, is enough to always favor the seed that's bigger, to do better. It really matters how big the seed is. How much built-in carbohydrate material that seed has, determines how far it gets going, before it has to stop pulling from the wick. If you had a very a nutritious soil and environment, then it wouldn't really matter too much, how strong the seed was.

Q: What were the major problems? The Russians have been trying to do experiments with this for quite a while. What were the major technical problems that they had?
Foale: The major technical problem is controlling the moisture content. That has always been the biggest problem. And I think the biggest breakthrough is the soil, this zeolite.

The University of Utah also came up with a much more sophisticated system of measuring the humidity, both at the surface and at depth in the soil. But even though that was sophisticated, and corroborated the rather simpler measurements that the Bulgarian-built SVET measured in the soil, nonetheless, those simpler measurements were the ones that were used to control the humidity level. They confirmed that just having one or two sensors, as they originally planned with the SVET module, is good enough. It was what level to control to, that they didn't know.

In the early days, people always tended to over-wet the root module. And I think now, on the third planting, I remember I got distracted, and I ended up leaving it on high wetting, for about four or five hours longer than I should have. And when I came back, I thought, "Oh, no, overshoot!" If I wanted to, I could have told the ground that everything was okay. But I knew that pretty soon, we'd have an overshoot, and then even though I would have turned off the water, the humidity level would slowly increase over a day or two. So I discussed it with the ground, and we just agreed to keep the lights on a bit longer, because that also warms, and it tends to dry out the soil. The lights are what determines the major water loss of the soil.

Q: It is my understanding that in a lot of the research on controlled-environment agriculture on Earth, in addition to finding out what the optimal number of hours of light and the wavelength should be, there's been a lot of work in controlling, or increasing and decreasing, the amount of carbon dioxide. In this case, it sounds like it is not controlled.
Foale: No, it's not. I'm afraid that's the problem the investigator has to deal with, because, in this experiment especially on Mir, the carbon dioxide level does vary quite dramatically.

Q: So it's not controlled in the greenhouse—
Foale: Nor is it controlled in the station.

Q: And the atmospheres are the same?
Foale: Well, it's the same atmosphere [in the greenhouse] as what we're breathing, and the carbon dioxide [levels] went through a large range, so you wouldn't be able to pick out, I think, the effect of carbon dioxide on the plants.

Also, the temperature variations in that module were very great. After the collision, in that timeframe and afterwards, the temperatures were down even in the 5° Celsius range, really cold in that module, when we really wanted to be running at about 20-25° Celsius.

That second planting was a very slow planting, because that was when we were having our most trouble recovering from the collision, and that module was totally unpowered. The only thing in the whole of the Kristall module that had anything on, was the SVET, because I was running the power to the SVET, all the way with a long extension cord, from the base block. So, it was a pretty hard environment for that experiment.

It's great we actually got the results we did, because I think overall, they were very pleased with what they learned from it.

Q: What was the analysis of the seeds that you brought back?
Foale: Apparently, they're viable. I don't know much more than that. The preliminary report says that the seeds have similar structures to Earth seeds. I just read the preliminary report that came out and took a quick look after bringing this stuff back, and all that was said was the seeds look good, and they look viable, we have good products to analyze. It didn't say what the analysis was.

Q: Do you have any idea what the prospect would be for continuing these kinds of experiments on the International Space Station?
Foale: The Russians for sure will, and I think our groups are excited by the collaboration. So, I think the collaborative work will continue, which is a rather amicable arrangement, between the Institute for Biomedical Problems in Moscow, and the universities of Utah and Louisiana.

Q: Psychologically, one of the things I think would be important in space is to have something that is growing and changing, as opposed to the other hardware that surrounds you. Did this provide for you some relief?
Foale: I don't want to overstate it, because I believe my time on Mir would have gone pretty much the same, but especially when I had almost nothing else to do for a month or so after the collision, the greenhouse experiment really provided me a lot of peace of mind.

This whole business of being a gardener, and getting used to your plants, and getting into their condition, and developing some kind of connection with them, though romantic, actually has a little application in space, because it provides a very different visual scene and activity from the normal, extremely technical kind of bare and artificial existence that you have in space. It's a connection with the Earth, I guess, that you've brought with you, that gives you some comfort.

So, I very much enjoyed doing my morning status check in the greenhouse. It would only take me about 20 minutes each day, but I'd sit there, and I'd just savor that time. And, I think, on a long-duration flight, or on any space station, not only to provide scientific research, but also to provide psychological support, experiments that grow things can be well utilized—and I mean visible things, like plants. I expect animals would be just as rewarding, but they're more complicated.

Q: Do you think it would make any sense, or have people ever thought of bringing a plant just to have—not a scientific experiment, but just to take care of it?
Foale: Yes, very much so. I think, just like we have house plants for no reason but for them 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.

I think the pragmatic value, of course, is, in the long term, self-sufficiency away from the Earth in your food production. And the only way you can achieve that, is through some of these pretty aggressive technological programs to grow biological material in space, or on the surface of Mars. So, these are essential to feature in the exploration of space. Because in the end, it becomes too difficult to supply all that food from the Earth. It would be a terribly burdensome logistics problem just to keep supplying food, because you can't make it *in situ*.

As you probably know, we have a chamber here [at the Johnson Space Center], a 60-day chamber, where they put three or four people inside for, I think it was 60 days, and then 90 days. And they lived there. It was a totally closed system. I think 25% of their CO_2 was scrubbed by the plants that they grew. Pretty significant. And I think they ate most of their plants. So, they did pretty well.

And I think it was 25% of the O_2 was produced by the plants, which is pretty dramatic. Certainly, my plants weren't producing any significant O_2.

Q: What are your plans for the future?
Foale: My plans are to keep doing what I've been doing, which is enjoy my family, bring up my children responsibly, and continue to get people into space—and, if possible, myself. And, I would like very much to go back into space, do space walks, which I love doing. I got to do one on the Mir, as well as once on the Shuttle. And then, after that, in maybe two years, I would like to go to the International Space Station, and do another long-duration flight. And I choose that timeframe, because that's when my son is going to be six or seven. He'll be well on his way to having his own character, without any regard to my influence. I feel I can kind of excuse myself, even if my children don't excuse me, for going away for six months,

So, for me, it's a pretty exciting period of time. I think we've got some really big problems ahead of us, that we haven't even thought about. And I don't mean programmatic ones. I mean that there are going to be some things that just don't work out the way we expect them to. And it's going to test our ingenuity, our ability to work with the Russians, and just our general good humor to put these right. But I think we will.

And right now, my job is to apply the lessons I've learned in the last two years of my life, learning Russian and working with the Russians, and being on the Mir, to some of the problems that we're addressing now for the International Space Station, and the new astronauts that we might be picking in the very near future.