EIR Science & Technology

The Mir space station: a technological feat

The Mir, the culmination of 25 years of Soviet and Russian space station technology and experience, has paved the way for the International Space Station. Marsha Freeman reports.

On June 6, 1985, the Soyuz T-13 spacecraft was launched to the Salyut 7 space station, with cosmonauts Vladimir Dzhanibekov, who had flown four previous missions and had visited Salyut 7 twice before, and Viktor Savinykh, who had been on the last flight to Salyut 6, onboard. As they approached and circled Salyut 7, they could see that the station was slowly tumbling in orbit. Its solar panels were not aligned with the Sun, and the cosmonauts knew that without electricity, the rotating Salyut 7, with which they would be trying to dock, would be a dead, frozen station.

They transmitted television pictures to mission control, and flight director Valery Ryumin reportedly described the pictures as "alarming."

Four months earlier, Soviet mission controllers had lost all contact with the station. Without ground contact, the solar arrays would not stay oriented to the Sun. Without electricity from the arrays, the attitude control system had become dysfunctional, allowing the station to slowly tumble. Without electricity, the thermal control system had stopped functioning, the water pipes froze, and a layer of frost covered the instrument panels, as temperatures plunged below freezing. There were reports in the Soviet press indicating that the station would be abandoned.

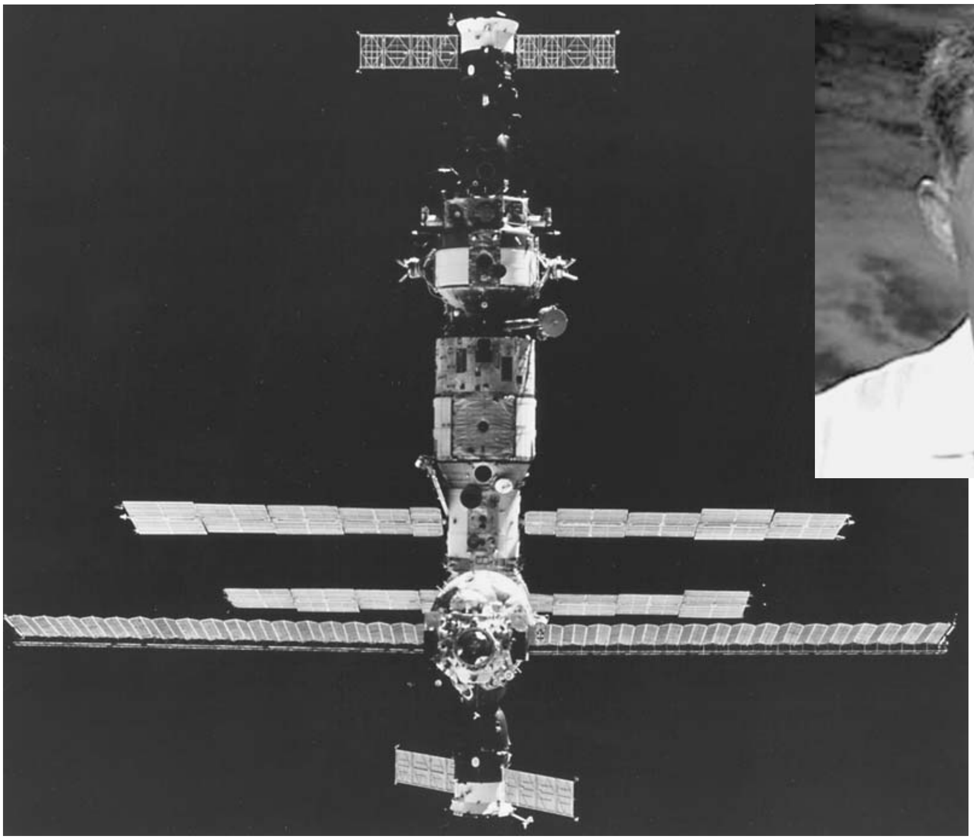
Two days after they arrived in orbit, on June 8, the cosmonauts docked manually with Salyut 7, and found the station in worse shape than they had expected. In his book, *Soviet Space Programs 1980-1985,* Nicholas Johnson explains that, "With no power at all on Salyut 7, the flight plan called for the cosmonauts to retreat to [their] Soyuz T-13 and return to Earth." But the cosmonauts were not about to give up that easily. They entered the station wearing breathing apparatuses and multiple layers of warm clothing, including wool hats.

The "rescue crew" gerry-rigged one of the solar arrays to a storage battery, using cable and objects they found in the station, and began charging it. For several days, Dzhanibekov and Savinykh patiently brought Salyut 7 back to life, charging one battery at a time and returning to the Soyuz T-13 every 40 minutes to warm themselves, according to Johnson.

The temperature in the Salyut 7 station was estimated at −10°C. Because the thermometers' lower range went down to only 0°C, mission control had one of the cosmonauts spit on the wall and time how long it took to freeze, so that they could estimate the temperature.

The crew worked in arctic attire, and reported that their feet got painfully cold. After working without ventilation, the cosmonauts reported that they would get headaches, and feel sleepy and listless from the buildup of carbon dioxide, so they set up a pipe from the Salyut to one of the ventilation systems on their Soyuz spacecraft to remove the CO_2. They were finally able to activate the life support systems in the Salyut station on June 12.

They restored electricity, after replacing cables and bypassing connections that were not working. Equipment that had been damaged in the cold was replaced. On June 16, the station's temperature finally rose above freezing.



The Mir space station, photographed in 1995 by the crew of the Space Shuttle Discovery, on Mission STS-63. David Wolf (inset), a medical doctor and engineer, has just started his four-month stay aboard the Mir, where he will continue biomedical experiments.

As the electrical system was restored, the water onboard thawed, and direct communications between Salyut and mission control center were reestablished. It took ten days to bring the Salyut 7 up to a condition in which mission planners would permit an indefinite stay in the laboratory.

The Salyut 7 mission

Anyone who thinks that Russian spacecraft designers, mission managers, and cosmonauts have never had to deal with slowly tumbling stations, life support malfunctions, misaligned solar arrays, and other serious in-orbit failures before Mir, don't know history.

Of course, the purpose of launching the Salyut 7 station was not to be able to practice dare-devil rescue missions. It was the sixth operational station built by the Soviets since Salyut 1 in 1971. It was launched on April 19, 1982, to extend the time in orbit for space explorers; to study the physiological effects of microgravity; to conduct materials science, astronomical, and Earth observation research; and to conduct the technological tests that would pave the way for a space station that could be permanently manned.

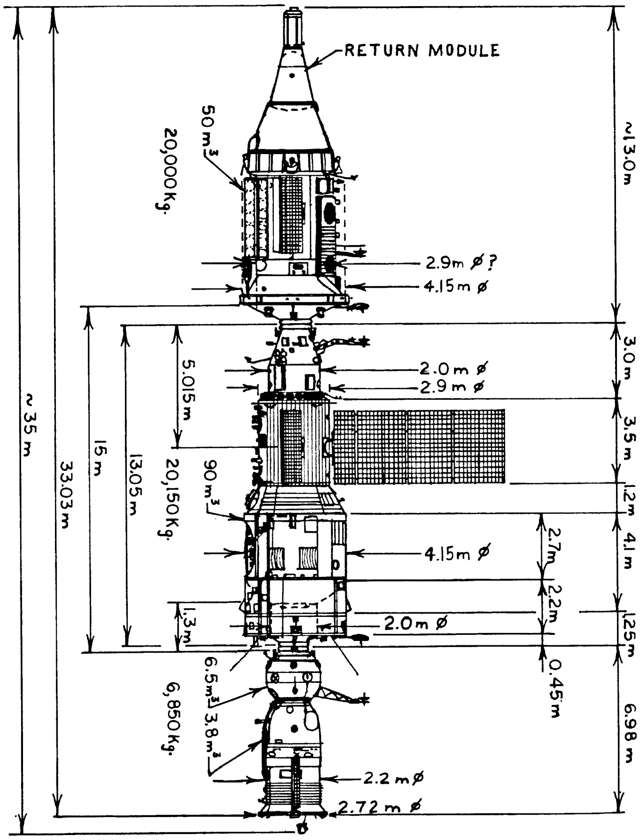
A month after Salyut 7 was launched, cosmonauts onboard activated their Oasis orbital garden, which had been tried on Salyut 6 but had had disappointing results. Growing food successfully in space has always been seen as a prerequisite for long-term space travel. Two furnaces for microgravity materials processing were delivered to Salyut 7 by an unmanned Progress supply ship, along with other scientific equipment.

In June 1982, Jean-Loup Chrétien, one of two French cosmonauts who had arrived in the Soviet Union for training in September 1980, was on the first international flight to Salyut 7. (Chrétien is a crew member on the current STS-86 Shuttle flight to Mir.)

By 1986, the Soviets made it known that they were ready to orbit a new, more advanced modular space station, named Mir. The first Mir crew, which included current mission control flight director Vladimir Solovyev, arrived at the new station in March 1986. The crew then flew to, and docked with the Salyut 7 station, becoming the first, and only, crew to visit two space stations.

The cosmonauts carried out a spacewalk outside Salyut 7 to practice assembling large structures, which would be needed for the new Mir station, and, after completing some experiments and carrying equipment back with them, they redocked with the Mir.

With the Salyut 7 missions, the Soviets had made flights to Earth orbit routine events. They developed the system of sending unmanned cargo ships to the station to allow crews to stay onboard for months at a time, and demonstrated that



The Salyut 7 space station (center) attached to a Progress supply ship (bottom), a "heavy" Cosmos 1443 mock station module (upper center), and a Soyuz return vehicle (top).

up to four spacecraft could be linked together into a stable orbital complex. It was learned that with exercise and other measures to counter the effects of microgravity, there did not seem to be any reason that people could not stay in space for many months. The Soviets also gained crucial experience in repairing and maintaining orbital stations, which cannot be brought back to Earth for repair, but must be maintained by small, well-trained teams of cosmonauts, in orbit.

Assembling the Mir

The now-completed Mir station is the largest complex of spacecraft that has ever existed in space. It was assembled in orbit from individual modules that were launched one at a time.

The core block of the Mir was launched on Feb. 20, 1986. It weighs 204 tons, and provides basic services, such as living quarters, for the crew, along with life support and power from solar arrays.

The second module, Kvant, was launched a little more than a year later, on March 31, 1987. It is an astrophysics module, which also carries equipment for attitude control and life support. After it was attached to the core module, Kvant took over as the station's aft port, which receives the Progress supply ships.

Kvant houses an international X-ray observatory called Rentgen, which includes the Pulsar X-1 hard X-ray telescope/spectrometer, a Fosvich high-energy scintillation telescope/spectrometer, and other equipment developed in cooperation with the United Kingdom, the Netherlands, West Germany, and the European Space Agency. Kvant also houses an automated electrophoresis unit for biotechnology experiments.

During Kvant's docking with the Mir, when it was at a distance of 200 meters from the complex, its thrusters failed to slow it down, and it flew right past the station. Flight controllers on the ground considered aborting the mission, but decided to make a second docking attempt, rather than abandon the laboratory. On the second try, a soft docking was effected, in which the docking unit penetrated the Mir docking unit, but then got stuck.

So, an unscheduled spacewalk was carried out from the Mir, after cosmonauts on the ground replicated the planned extra-vehicular activity (EVA) in the water-tank facility at the training center, which simulates microgravity. It turned out that there was debris attached to the docking port. The cosmonauts freed the obstruction, and ground controllers completed the hard docking. In April, when a Progress supply ship docked with the Mir, the Soviets were operating a station composed of four separate spacecraft, including the Soyuz. The Soyuz on which the crew comes to Mir, is always docked at the station. It is their transportation back to Earth.

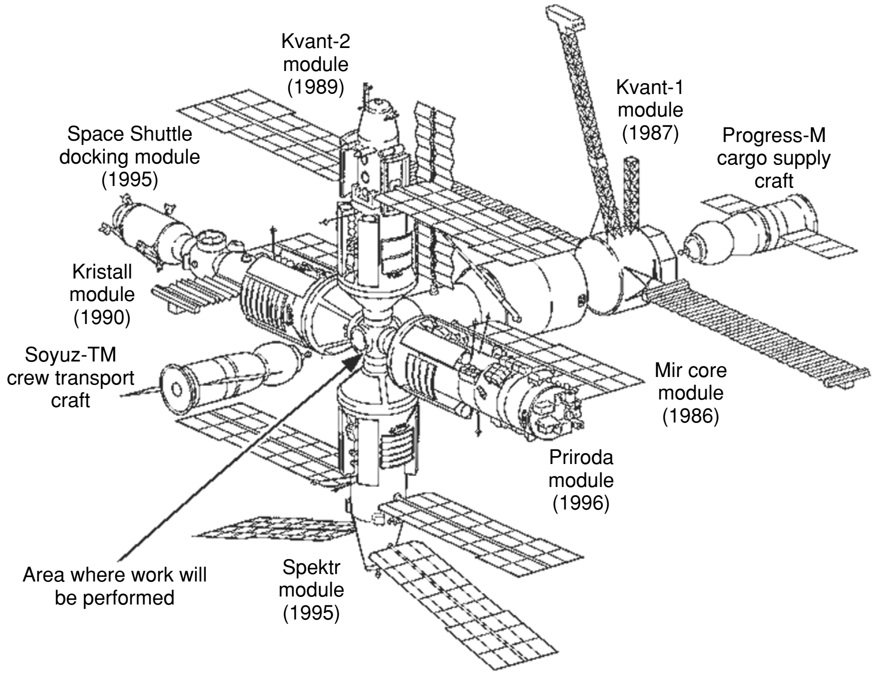
The next laboratory module that was added to the Mir was Kvant 2, launched on Nov. 26, 1989. It weighs 19.6 tons, and carries an EVA airlock, two solar arrays, and science and life support equipment. It was from the Kvant-2 airlock that Anatoly Solovyev and Michael Foale exited the Mir on Aug. 22, 1997, to perform their EVA on the damaged Spektr module.

The Kristall module was launched on May 31, 1990. It has two stowable solar arrays for additional power, science and technology equipment, and a docking port equipped with a special androgynous docking mechanism designed to receive spacecraft weighing up to about 100 tons. This docking unit was originally designed for the Soviet Buran shuttle, and was used by the Space Shuttle on the first docking mission with Atlantis. The research performed in Kristall focusses on biological and materials science.

The now-famous Spektr module was launched to Mir on March 20, 1995. It has four solar arrays attached to it, and houses scientific equipment, including 1,600 pounds of U.S. equipment. It was the research and living quarters for U.S. astronaut Michael Foale, before the collision with the Progress supply ship last June. Spektr's instruments are geared toward atmospheric research and Earth observation studies.

The final laboratory for Mir, Priroda, was launched on April 23, 1996. Equipment onboard the module is used for microgravity studies and Earth observation, and includes 2,200 pounds of U.S. equipment.

In a paper published this year in the *Journal of the British Interplanetary Society,* Andy Salmon did an extensive survey of the science experiments conducted on the space station



The fully assembled Mir space station.

between 1986 and 1994, before the start of U.S. missions to Mir, and before the Spektr and Priroda modules were added.

Experiments were conducted, with varying degrees of success, in protein crystal growth, human physiology and psychology, materials science, radiation in the space environment, Earth observation, geophysics, bioprocessing, biology, astronomy, and new technologies. Much of the equipment and instrumentation was provided by international partners.

The results of some experiments were disappointing, due to limitations of power aboard the station. Retrieving experimental results has been hampered by the small amount of product that can be returned to Earth by the crew on the Soyuz spacecraft, and the fact that there is virtually no "real-time" communication between the cosmonauts in space who are running the experiments, and the scientists on the ground who designed them.

For the Russians, these shortcomings could be improved with participation from the United States, with its sophisticated electronic and communications systems, and a Space Shuttle that can carry back to Earth tons of equipment, samples, and data on each flight.

For the Americans, collaborating with the world's only other nation that has a manned space program, could bring 25 years of space station experience to an International Space Station (ISS) that the United States and the West are planning to build.

The Shuttle-Mir partnership

The Shuttle-Mir program was initiated by President George Bush in 1992, after the fall of the Soviet Union. It called for a Russian cosmonaut to fly on the Shuttle, and for an American astronaut to visit Mir for three months. The primary reason given for the program was to extend the time during which U.S. life sciences research could be conducted in space, which was limited to a maximum of two weeks on the Space Shuttle.

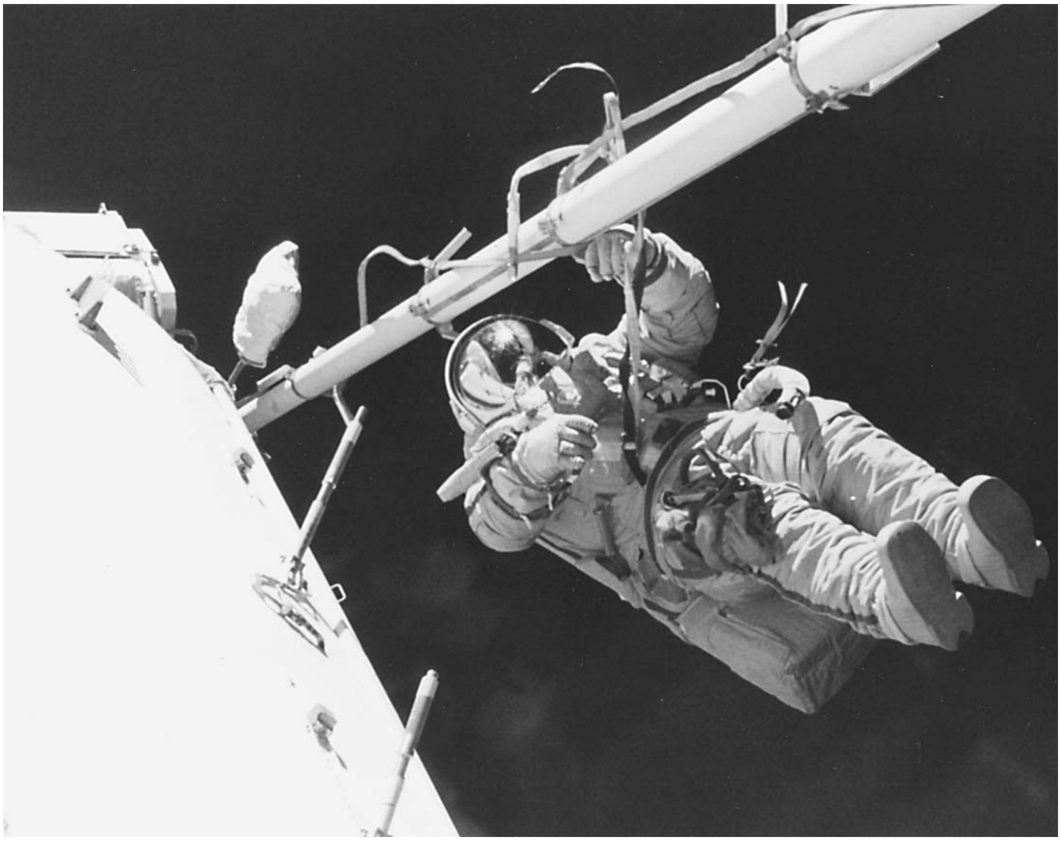
In 1993, the Clinton administration expanded the Shuttle-Mir program, as part of the President's effort to strengthen America's relationship to Russia, and to help preserve the precious capabilities of Russian science and engineering. During a meeting of the Gore-Chernomyrdin Commission that year, Shuttle-Mir became Phase I of a three-phase cooperation that would culminate in the building of the ISS.

On Sept. 2, 1993, the United States and Russia agreed to merge the U.S. and Russian space station programs; the Russians would not build their follow-on Mir 2, which they were increasingly unable to fund, and the United States would take the Russians in as a full partner in the international station.

The expanded agreement said that as many as nine Shuttle docking flights to Mir would be carried out, and an additional 21 months of U.S. astronaut time on Mir would be included, for a total of up to 24 months. On June 24, 1994, NASA Administrator Dan Goldin and Russian Space Agency Director Yuri Koptev signed a contract under which NASA committed itself to the "enhancement of Mir-1 operational capabilities; joint space flights; and joint activities leading to Russian participation in the design, development, operation, and utilization of an ISS."

By 1996, it was clear that the Russian Space Agency did not have the money to keep its hardware contributions to the ISS on schedule, or to keep Mir operational. The U.S.-Russian agreement was extended again and modified. Russia agreed that it would deliver on time two modules for the ISS, and would build a cargo spacecraft called the Logistics Transfer Vehicle. NASA agreed to pay Russia $72 million more than the original $400 million agreed to, and exercised the option for two more Shuttle-Mir docking flights, to help Russia keep Mir operational longer than originally planned. The Shuttle flights to Mir would deliver supplies that would otherwise have to be brought to the station by Progress supply ships.

As Frank Culbertson, NASA astronaut and manager of the Shuttle-Mir program, explained in testimony to the House Committee on Science on Sept. 18, 1996, "Initially, the role of the U.S. crew was patterned after that of the other foreign personnel, to fly to the Mir as guest cosmonauts." But the



Mir 18 crew member Gennady Strekalov is shown during one of five spacewalks conducted by the crew, in 1995.

United States was now entering into a partnership with the Russians.

"As the Shuttle-Mir missions progressed, it became clear that our goal of learning how to work with the Russians should include direct knowledge of the operational techniques, through involvement in the operations themselves," Culbertson explained. "The Russians quickly agreed to the principle of making our astronauts an integral part of the crew, and work was begun to modify the training program to allow for expanded duties, with some changes even made before Shannon Lucid's mission, including the change from Cosmonaut Researcher to Flight Engineer-2."

As the cooperation changed to collaboration, the goals changed from doing biology experiments, to learning how to operate a space station, in order to reduce the risks on the ISS. The goals of Phase I (the Shuttle-Mir flights), according to Culbertson, are:

1. To learn to work together with each other, both in space and in ground support activities;

2. To reduce the risks to ISS development and operations by testing hardware, refining joint procedures, and integrating the operational practices of the two nations with primary operational responsibility for ISS;

3. To gain experience in long-duration stays on a space station, and develop effective bio-medical countermeasures to the effect of extended weightlessness;

4. To conduct scientific and technological research in a long-duration environment, gaining both valuable research data, and developing effective research procedures and equipment for use in the ISS.

Note that, regardless of the constant harping by congressmen and other critics, that the Shuttle-Mir program is not producing enough science because of the mechanical problems on the station, science is the fourth priority of the program.

Lessons learned

After the first six U.S. long-duration missions to Mir, critical experience has been gained. One of the most important, and most basic accomplishments has been to learn to rendezvous and dock the Shuttle to the Mir. The Shuttle had never docked to any spacecraft before that.

The complexity of this activity was described by Shuttle pilot Charlie Precout, before the first Shuttle-Mir docking mission in June 1995, as an "eight-dimensional problem." The crew had to take into account the three axes of rotation of the Shuttle orbiter to keep it steady, the three dimensions of the Shuttle's position relative to the Mir had to be on target, the speed at which the approach was conducted had to be "glacial," and the time of the docking was constrained, because the Mir had to be over one of the Russian ground stations. Just because each Shuttle-Mir docking so far has been successful, does not mean it is easy, or risk-free.

Second, the United States is learning how to use the Shuttle for attitude control of large, flexible structures. There will be times when the Shuttle is docked to ISS where it will be necessary, or desirable, to have the Shuttle maneuver the whole complex. This has been done by placing the Mir in free drift and using the Shuttle orbiter to keep attitude orientation.

Also, by sitting alongside the Russian flight directors in Russian mission control, the United States has been able to observe "the pros and cons of Russian strategy for operation." The Russians operate non-critical hardware to failure, "as we will on ISS," Culbertson stated, "so we have a good database on what is likely to fail and what spares should be maintained on-orbit."

This operational approach has produced a great outcry among those who do not bother to try to understand how Mir functions. At a press conference on Sept. 25, the day before the STS-86 launch to Mir, retired Air Force general and former astronaut Thomas Stafford addressed a concern that has been harped on in the press, of the failure of oxygen-generating units aboard the Mir.

General Stafford reported that his independent safety review team had just concluded a ten-day stay in Russia, where "we reviewed the status of each individual system" on Mir, and "the operational procedures." The team concluded that "productive work can still be done on Mir; that the risk of going to Mir was no greater than it has been before."

Stafford explained that on Mir, you can operate even some life-support systems to failure, because "you have nearly five levels of redundancy of oxygen, and that's more than I ever had on Gemini or Apollo."

Congressmen and the press had best understand now, before the International Space Station deployment begins next year, that it will not be possible to keep spares of everything onboard. Therefore, critical systems will be changed when they reach the end of their expected lifetime, but non-critical systems, and those where there are redundancies, will be "operated to failure," and then replaced, as they are on Mir.

The United States has learned from having astronauts trained for the Mir missions, how the Russians train cosmonauts for long-duration stays aboard Mir, and what is required is very different than a ten-day Shuttle flight. The Russians train for general system skills that will be used over months, rather than for flight-specific tasks that will be used in the next few days.

As Culbertson has said, "Pre-mission training of crew members, while it still must result in crew members able to carry out the mission and the scientific experiments, must also take into account that it may be weeks or even months before certain activities trained for on the ground will actually be performed in orbit. The capability to retrain or at least provide refresher training during the mission must be built in. Preflight planning must take into account that it is virtually impossible to predict at the start of the mission, what exactly will happen in the second or third month of the flight, and this flexibility must be built in."

Although the Shuttle-Mir program is bilateral, it has involved the United States in multi-national operations, which will be required for ISS, because the Russians work with the European Space Agency, the German Space Agency, and the French Space Agency, on Mir. NASA has learned how to use interpreters, and operate with redundant responsibility between two Control Centers—in Houston and Russia. With the ISS, foreign partners will provide control of the payload in their own laboratory modules.

So far, there have been over 120 experiments conducted by the United States on Mir, some of which directly benefit the ISS:

1. Engineers have been able to estimate the contamination to Mir from the plume induced by Shuttle and Mir thruster firings, which is critical in order to avoid damage to the outside of the ISS.

2. They have validated models of the space radiation environment, which has an impact on the structural and other precautions that need to be taken to protect the crew and the station.

3. There have been evaluations done by crew members, to indicate where modifications can be made on ISS systems to meet the criteria for noise levels.

4. Measurements have been made to more accurately characterize the electromagnetic conditions at the Mir inclination, which is 56° from the equator, as opposed to 28° for most non-station Shuttle flights. This is important for the design of electronic and computer equipment aboard the ISS.

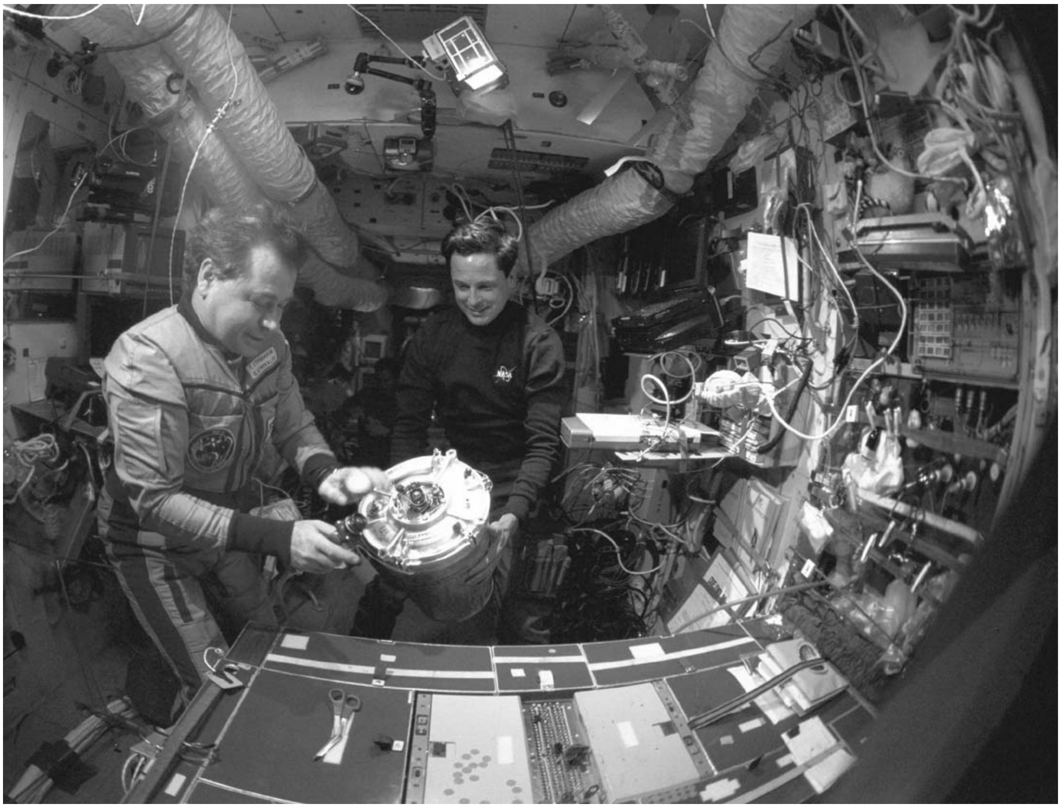
5. Photographic and video images from the Micrometeoroid/Debris Photo Survey will aid our understanding of the external environment and provide information for protective mechanisms for the ISS. Contamination deposition observed on some Mir surfaces, for example, has prompted changes to purge and venting port orientations on ISS in order to avoid deposition on solar arrays and radiators.

6. NASA has been able to test systems for water microbiology monitoring. The crew medical restraint system was tested, along with other aspects of providing crew health care.

7. NASA astronauts have had the experience of participating in EVAs, or spacewalks, from Mir, and have already validated some assembly and maintenance tasks, upon which the construction and long life of ISS will depend.

When Wernher von Braun and his team of rocket specialists came to the United States after World War II, with their tons of technical documents and their decade of experience, it was estimated that this country saved ten years in the development of rocket systems. While the United States has not saved a decade in deploying the International Space Station, which begins in 1998, it *has* had the opportunity to test systems, procedures, emergency procedures, crew training, EVAs, and working relationships with its most important international partner.

This has lowered the risks to the crew and the hardware involved in ISS, and means that when that huge and complex multi-national facility becomes operational, in many ways it



Astronaut Greg Harbaugh (right) and Mir 18 crew member Gennady Strekalov transfer water from the Shuttle to the Mir during the joint flight in 1995.

will be able to "hit the ground running," rather than duplicate the testing that has already been conducted on Mir.

Thus, if there had been *no* scientific experiments conducted on Mir during the joint NASA missions, what would have been learned would already be invaluable.

But it is the case that some of the research that astronauts have been able to perform on Mir will have long-term benefits for people in space, and on Earth.

Long-term research in space

In eloquent testimony before the House Committee on Science, Space, and Technology, Subcommittee on Space, on June 22, 1993, concerning health benefits of space station research, Dr. Michael DeBakey, chancellor and chairman of the Department of Surgery, Baylor College of Medicine, stated: "The Space Station is not a luxury any more than a medical research center at Baylor College of Medicine is a luxury.

"Present technology on the Shuttle allows for stays in space of only about two weeks. . . . We do not limit medical researchers to only a few hours in the laboratory and expect cures for cancer. We need much longer missions in space—months to years—to obtain research results that may lead to the development of knowledge and breakthroughs.

"Our leaders should not see programs as Medicare and a space station as a choice. Rather, the goal should be to use the unique microgravity laboratory of a space station to research ways to treat or prevent the deteriorating physical conditions that affect the elderly and disabled."

One new field of inquiry developed from microgravity research that Dr. DeBakey pointed to, was that of producing replicas of human tissues, or tissue culturing, which he described as "a relatively new field that promises important insights for cancer research, organ transplant research, and human virus research."

"But on Earth," he explained, "we have only a two-dimensional understanding of how human cells work and replicate in the body. A tissue modeling device, called a rotating wall vessel, recently developed by NASA . . . imitates certain microgravity properties. . . . This device has grown the largest three-dimensional cultures of normal and cancerous tissues ever developed outside the body."

He continued, "The new technology provides an impressive research tool that may greatly advance cancer research and may even allow for the development of transplantable human tissues. Demonstrations on the Space Shuttle have shown great promise for this culture system. But, quite literally, its full potential won't get off the ground until there is a space station where it can be researched for long periods."

The rotating wall vessel to which Dr. DeBakey referred was developed by a team of inventors from NASA's Johnson Space Center, including David Wolf, the current Mir astronaut and medical doctor, and people in industry. The original purpose of the device was to protect delicate cell cultures from the high shear forces generated during the launch and landing of the Shuttle.

The cells on their way to space in the Shuttle, are to be used in a bioreactor for the culturing of human tissue in three dimensions. On Earth, where cells are typically cultured in a dish or matrix in only two dimensions, they do not replicate all of the complex functions and attributes of real, *in vivo,* human tissue.

The problem to be solved is how to suspend cells in a nutritional fluid to provide sustenance, while removing waste, without damaging or killing the cells or inhibiting their growth. In order to learn how to solve this problem, experiments have been conducted on the ground, in which the cells are kept suspended in the fluid by rotating them constantly. The rotation, which simulates a microgravity "free fall," keeps the cells in the center of the fluid in which they are growing.

This technology, which NASA was developing for use in space, was found to be applicable also to growing three-dimensional tissue on the ground. Fifteen hand-made rotating wall vessels were initially made available to biomedical researchers, and now there are about 75 in use in Earth-based laboratories.

The rotating wall vessel used on Earth, like the bioreactor designed for space, has a cylindrical growth chamber that contains an inner co-rotating cylinder with a gas-exchange membrane. The suspended cells rotate as a solid body, with minimal disruptive shear. In space, where there is no natural mixing from convection, the two cylinders rotate at different speeds, producing a gentle flow between them, allowing mixing to take place, keeping the cells nourished and removing waste coming off the surface of the cells.

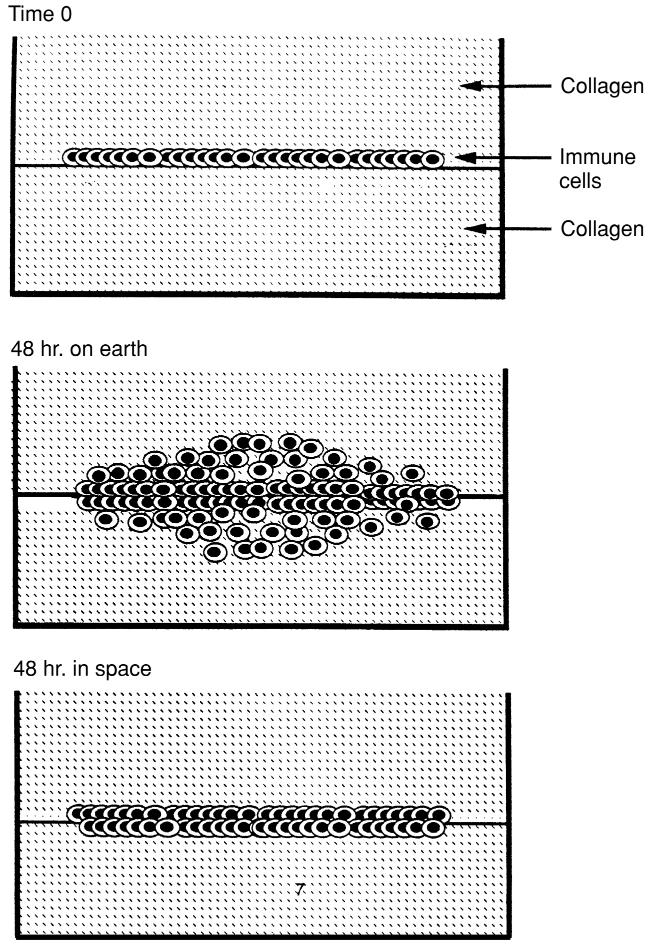
The limitations of simulated microgravity on Earth become apparent, however, when the cells grow to a mass such that centrifugal force pushes them to the outside of the fluid (when the weight equals the mass), or they settle despite the rotation. The cells are usually damaged or destroyed by the impact with the bioreactor wall or with each other. Generally, cells can be grown under simulated microgravity conditions on Earth for only three months.

According to Dr. Neal Pellis, Program Director for Biotechnology Cell Science at the Johnson Space Center (JCS), tissue grown in the Earth-bound rotating wall vessel has a limit of about one-half inch of tissue. But great advancements in increasing our understanding of the complex functioning of normal and pathological tissue has already been gained, using the rotating wall vessel and bioreactor technology on Earth.

Tissue engineering in three dimensions

In testimony before the House Committee on Science, Space, and Technology, Subcommittee on Space, on June 22, 1993, Dr. John M. Jessup, currently Professor of Surgery, University of Pittsburgh Medical Center, described his research on colon and pancreatic cancers, using simulated, and actual microgravity technology. "The space bioreactor by NASA JSC has provided a new tool for addressing the development and treatment of these tumors," he said.

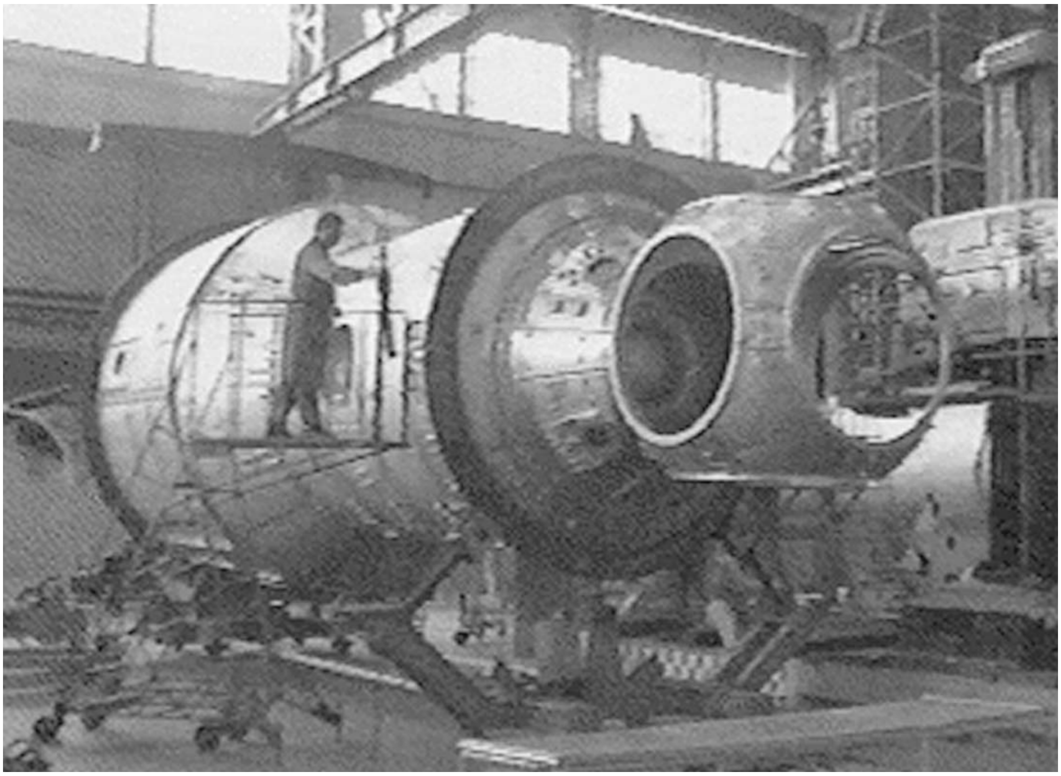
Locomotion assay using Nunc chamber slide wells



Scientists have found that in space, immune system cells do not "walk" as they do on Earth. Here, the locomotion of lymphocytes is compared on Earth and in space.

In the past, researchers tested new drugs against cancer cells that were grown on the ground in two dimensions on plastic, or in mice, he said, and both are "poor representatives of the human system. . . . Drugs that kill cells on plastic may not kill cancer cells in the patient."

Using NASA's rotating wall vessel that simulates the microgravity of space, Dr. Jessup found that cancer cells grown in the laboratory produce substances that many colon, breast, stomach, and other cancers produce *in vivo,* but not when replicated in two dimensions. Because these substances may bear on the way cancers spread throughout the body, such a high-fidelity re-creation of a cancer tumor is critical for research. Dr. Jessup found that cancer cells grown on plastic



The Functional Cargo Block will be the first element of the International Space Station, to be launched next June. Here, it is seen under construction at the Krunichiev manufacturing plant in Russia.

never reach a density high enough to form tissue, and, therefore, do not produce some of the celluar by-products needed for study.

Dr. Jessup's cancer tissue experiments flew on the Space Shuttle STS-70 mission in July 1995, which was the first flight of the bioreactor with human cells. The four-day mission was to test an engineering design unit. He found that the microgravity cultures are more viable than the ground-based cultures; there is less cell death, and better morphology. Dr. Jessup believes the knowledge gained with cancer cell growth will also have applications for fast-growing normal cells.

Dr. Pellis has done research using the rotating wall vessel, and has flown experiments on the Space Shuttle to investigate the performance of lymphocytes in microgravity. It had been observed that after long stays in space, astronauts exhibit a diminished immune response, which can be deleterious to their health. Learning more about the mechanisms that produce this effect could also aid our understanding of immune deficient, auto-immune, and other pathologies in general.

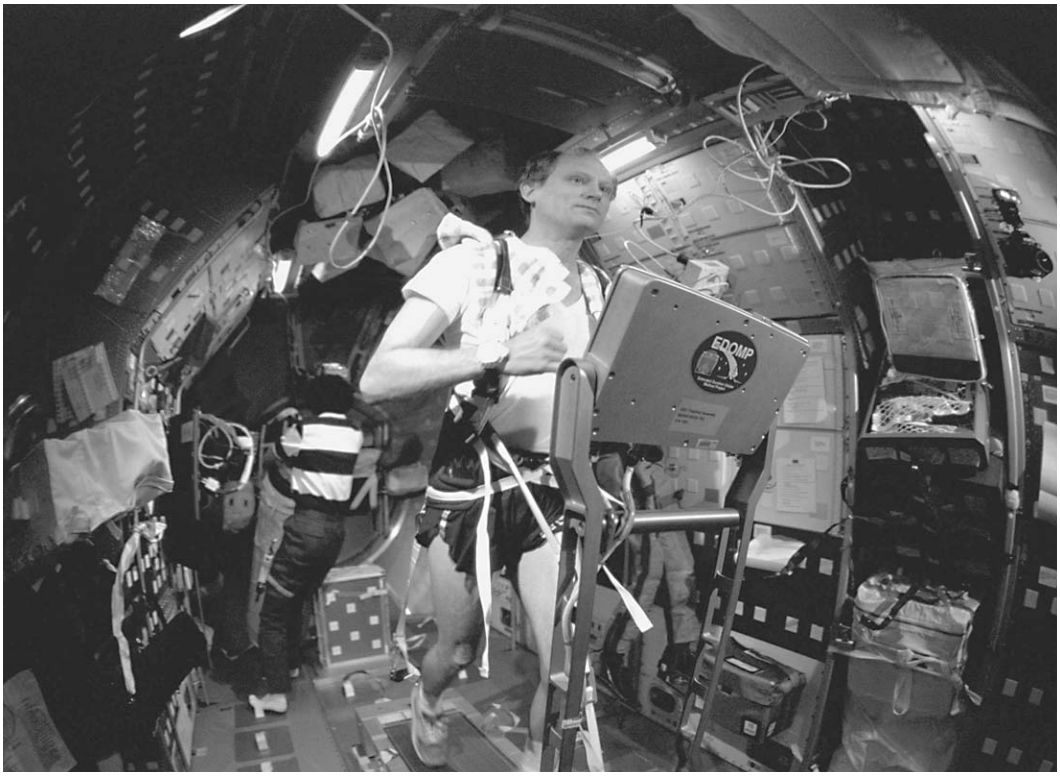
Dr. Pellis found that while researchers thought that failed lymphocyte performance, and the arrest of lymphocyte movement into tissue in cancer patients, was unique, the same phenomenon was found in the bioreactor simulation of microgravity. From his experiments on the Space Shuttle, Pellis found that immune cells do not "walk" well in space. Research to test ways of increasing the mobility of immune cells, will be done in the space station.

The first long-duration test of the bioreactor came on the NASA-3 mission to Mir in September 1996, when John Blaha replaced Shannon Lucid on the station and brought up to Mir a Biotechnology Systems (BTS) experiment, in which a bioreactor on Mir was used to grow bovine cartilage cells. Cell cultures were transported to Mir in temperature-controlled vessels and placed in the experiment module. Dr. Lisa Freed of MIT is using the bioreactor system to study cartilage cells that may be engineered for replacement and transplantation.

The BTS facility was launched to Mir earlier in 1979 aboard the Priroda module. The facility has six modules, four of which are contiguous and house the main facility. The other two are for storage. The Cartilage in Space experiment was designed to investigate the cell attachment patterns and interactions among singular-cell-type cultures and varied-cell-type cultures, the cellular role in forming functional tissue, cellular growth, and morphogenesis of mammalian cells.

One of the questions that Mir can help answer, according to Dr. Pellis, is, can we operate the bioreactor for long periods of time? The crew found during its four months on Mir, that the bioreactor had problems with bubbles forming, but the researchers had chosen cartilage cells, which are very durable, with slow metabolism. Dr. Pellis reports that Dr. Freed and colleagues continue to analyze the tissue, but have already had some surprising results.

On the ground, the cartilage developed in a rotating wall



Astronaut Norm Thagard aboard the Mir space station during his three-month long-duration flight. A medical doctor, Thagard tested an exercise regimen to counter the effects of weightlessness.

vessel was able to use a molecular scaffold to give it shape. But in space, while there was good replication, the cells did not grow around the scaffold, but into balls, with a diameter about the size of the scaffold. The researchers believe this may be due to the fact that in the absence of gravity in space, the compressibility of the cells is different.

The tissue grown in space had a larger volume than the ground sample, but the mass was only one-third; it was more loosely packed. The nature of cartilage, like bone, is that it is related to load, which is missing in microgravity. The scientists want to determine if there is a difference in the synthesis of components in space, or if the difference is simply that the tissue is connected more loosely.

There is also great interest in knowing if re-synthesis can be promoted, and how that could be done. The research has implications for the recovery from injury in space, and for the recovery from the effects seen in the "normal" adaptation to weightlessness. The difference in cellular packing could also bear on the progression and, possibly, reversal, of similar conditions on Earth, such as osteoporosis.

The next experiments on Mir

During astronaut David Wolf's four-month stay on Mir, he will be testing the Biotechnology Specimen Temperature Controller that he has taken onboard with him. The BSTC is an incubator, built with culture modules that are a repository of cells for future bioreactor experiments in space. Wolf will take cells from one culture module and transfer them to other modules as they replicate. It is important to investigate whether microgravity exerts a selective pressure on replicating cells, Dr. Pellis explains. This means, for example, that after 100 replications, are the cells the same as the ones that you started out with? This is a critically important experiment that will answer many questions, including, do organisms in space become pathogenic over long periods of time?

On Wolf's flight, three kinds of cells will be studied. The first type is leukemia cells from stem cells, to see if they differentiate when biochemically induced and if they differentiate spontaneously in microgravity. Second, will be neuroendocrine cells from the adrenal gland, to see if they produce different substances in microgravity than are produced by normal cells under conditions on Earth. Scientists are investigating whether normal cell products, complex signal transmission, and other characteristics of healthy tissue function are exhibited in cultured tissue. If so, such engineered tissue could have applications in nerve regeneration and pain control.

Third, Dr. Tim Hammond at Tulane University has been studying kidney tubular cells, and they will be flown on the Mir. There are some antibiotics that bind to one of the two proteins that are produced by healthy kidney cells, which kill the cells. But these proteins are not expressed in two-dimensional tissue cultures grown on Earth, making them difficult to study. It is hoped that three-dimensional tissue from the bioreactor may express the proteins in an appropriate way, so that the mechanism by which drugs affect the cells can be researched.

Assuming Wolf's experiments with the space incubator on the Mir are successful, the Shuttle astronaut who arrives on Mir in January 1998 as the next long-duration crew member will be involved in the next step in the research. According to Dr. Pellis, on that flight there will be an attempt to induce the development of blood vessel formation, or angiogenesis, in the tissue that is grown in the bioreactor.

The body nourishes and removes waste from cells through capillaries. In the bioreactor, this is done through the design of the co-rotating cylinders. But for the study and replication of tissues and, perhaps eventually, organs, a true vascular system will be required.

Dr. Jessup explains that capillary beds in the circulatory system, and also neural networks, are three-dimensional structures and need a gentle, undisturbed growth. This is hard to do in gravity or in the rotating wall vessel bioreactor on Earth, where it needs a supporting matrix. The space bioreactor will be better for complex patterns and structures.

Scientists see many applications for engineered tissue in the future. One, is their use in transplantation for replacement of injured or diseased tissue. Second, such three-dimensional tissue can be used to create models for human disease. For example, Joshua Zimmerberg and Leonid Margolis at the National Institutes of Health have been able to culture viable lymph nodes to see how the human immuno-deficiency virus (HIV) traverses from cell to cell.

And, there will be biopharmaceutical applications, where drugs can be tested, and biological pharmaceuticals can be produced. Dr. Pellis reports that researchers at the U.S. Army Medical Research Institute of Infectious Diseases at Fort Detrick, Maryland are using human liver, spleen, and lymph-node cultures from a rotating wall vessel to find new compounds that could be used to treat patients with the Ebola virus.

While it is not certain now that entire organs can be grown in space for human transplant, Dr. Jessup proposes that a nearer-term step may be the growth of tissue to make a liver-assist device. Such devices would be similar to dialysis machines, by taking up the functions of a damaged or nonfunctional organ, but rather than machines, they would be living tissue that could temporarily take on the functions of the liver.

During a press briefing on Sept. 24, the day before the launch of the Space Shuttle to Mir, NASA Administrator Goldin said, "We have heard the calls of some who would say it's time to abandon Mir. We at NASA, especially Michael Foale, who's in space today, are deeply touched by the outpouring of emotion.

"However, we know that the decision to continue our joint participation aboard Mir should not be based on emotion or politics; it should not be based on fear. Our decision should be based, and is based, on scientific and technical assessment of the mission safety and the agency's ability to gain additional experience and knowledge that cannot be gained elsewhere."

Leave space decisions to the experts

For the past eight months, the press has turned every failure on the Mir into a soap opera of impending catastrophe, implying that NASA has downplayed the seriousness of each event because of the political importance to the White House of saving U.S.-Russian cooperation. It is, therefore, interesting to hear a report from a Western astronaut, who is *not* from the United States, who spent time on Mir.

On Dec. 20, 1994, ESA astronaut Ulf Merbold gave a briefing at the Johnson Space Center, where he was helping the United States plan for work with the Russians on Mir. He was on the Euromir 94 mission, which was launched on Oct. 3, 1994, and he was onboard Mir for 30 days.

According to the notes of one of the attendees at the briefing, Merbold related that on day nine of his mission, there was a complete loss of power. The whole station started to precess and the solar panels became misaligned. This was likely the result of the activities the day before, including a press conference with Germany's Chancellor Helmut Kohl, which stressed the power system past its limit.

For the next two days, Merbold reported, they lost power intermittently, but after two days, power was restored to normal. He said that he was impressed with the Russians, who fixed things quickly and calmly. He said that he never thought his safety was in danger, and he trusted his commander to make the right decision. He said that the two cosmonauts who worked on the hardware "saved the day."

The Russians have a history of bringing candidates in to be cosmonauts who have a technical background and have worked in the aerospace field. The best, who have had the experience of participating in space missions, are brought into management responsibilities for the overall manned space program.

The way the Russian space program is discussed in the U.S. media, the impression is given that the director of mission control, or the head of the enterprise that built the Mir, are more concerned about their reputations and careers than the safety of their crews. But, who are these "bureaucrats"?

Vladimir Solovyev, the director of mission control near Moscow, was born on Nov. 11, 1946. He is a trained engineer, who worked in the Korolev design bureau, which built most of the spacecraft for the Soviet space program. He is an expert on space propulsion systems.

Solovyev was selected as a cosmonaut in 1978. In 1984, he flew to the Salyut 7 space station, and stayed onboard eight months, breaking the previous record. During his stay, he performed six space walks, totaling 22 hours, and was an "orbital repairman" for Salyut's main rocket engines, which were badly damaged in an accident the year before. He had helped design the Salyut propulsion system.

One of the greatest benefits for the International Space Station from the Shuttle-Mir missions is joint training. In this photo, taken on May 23, 1995, cosmonaut Anatoly Solovyev (in drivers' seat) trains with the STS-71 crew for his trip on the Shuttle.

Two years later, Solovyev was on the mission to activate the new Mir station. He flew from Mir to Salyut 7, in order to finish experiments, and performed an EVA to practice building structures in space. He then helped close out the Salyut station.

In his career, Solovyev has logged almost 352 days in space and 31 hours of EVAs. In between his two flights, he was an assistant flight director, and was involved in the repairs to the derelict Salyut 7 in the summer of 1985, reviewed in the opening of this article.

Valery Ryumin, director of the Phase 1 Shuttle-Mir program for RSC Energia (the successor to the Korolev design bureau) which built the Mir, was born on Aug. 16, 1939. When he was selected as a cosmonaut in 1973, he had worked at the Korolev design bureau for seven years, and played a major role in the development of the Salyut space station. He was involved in the design of astronomical experiments for the Salyut 4 missions, and in the design of Salyut 7. He was the chief flight director for all of the missions to the Salyut 7 space station.

Ryumin was a member of the first crew that flew to Salyut 6 in 1977. But after at least three attempts, they were unable to hard dock, and returned to Earth after 49 hours in space. Two years later, he completed a record-breaking 175 days in space aboard Salyut 6. He was also on the Salyut when a Soyuz spacecraft with a visiting crew was unable to dock, and had to return to Earth.

The failure to dock left Ryumin and his crewmate with a Soyuz attached that would be too old for them to use to return to Earth, either when planned or in an emergency. Had the crew been able to visit, they would have taken the old Soyuz home, and left the new one for the long-duration team. In order for the crew to continue their long-duration mission, for the first time an unmanned Soyuz was sent up to the station.

During Ryumin's stay, the crew made repairs while on an EVA, conducted astronomical observations using a radio telescope, carried out space manufacturing, made repairs to equipment aboard the Salyut 6 that had outlived the original 18-month design life, and, near the end of the mission, carried out a daring spacewalk to cut away the radio telscope which had snagged as it was jettisoned from the outside of the station.

Less than a year later, Ryumin was back in space again, when there had to be a last-minute crew change. He spent an additional 185 days in space. On Aug. 28, 1997, Energia announced that NASA has invited him to train for a U.S. Shuttle mission.

The Mir is a technological achievement that has been kept functioning beyond its projected lifespan by the competence, dedication, and courage of the cosmonauts and mission managers who work on the program. Mir benefitted from a quarter-century of Soviet and Russian experience in the design, construction, and operation of space stations. Now, the International Space Station will gain the benefit of 11 years of experience with Mir.