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PHASE 1 RESEARCH PROGRAM OVERVIEW

John J. Uri
Phase 1 Mission Scientist, NASA/Johnson Space Center, Houston, TX
Oleg N. Lebedev
RKK-Energiya, Korolyov, Russia

ABSTRACT

The Phase 1 research program was unprecedented in its scope and ambitious in its objectives. The National Aeronautics and Space Administration committed to conducting a multidisciplinary long-duration research program on a platform whose capabilities were not well known, not to mention belonging to another country. For the United States, it provided the first opportunity to conduct research in a long-duration space flight environment since the Skylab program in the 1970's. Multiple technical as well as cultural challenges were successfully overcome through the dedicated efforts of a relatively small cadre of individuals. The program developed processes to successfully plan, train for and execute research in a long-duration environment, with significant differences identified from short-duration space flight science operations. Between August 1994 and June 1998, thousands of kilograms of research hardware was prepared and launched to Mir, and thousands of kilograms of hardware and data products were returned to Earth.

More than 150 Principal Investigators from eight countries were involved in the program in seven major research disciplines: Advanced Technology; Earth Sciences; Fundamental Biology; Human Life Sciences; International Space Station Risk Mitigation; Microgravity; and Space Sciences. Approximately 75 long-duration investigations were completed on Mir, with additional investigations performed on the Shuttle flights that docked with Mir. The flight phase included the participation of seven US astronauts and 20 Russian cosmonauts. The successful completion of the Phase 1 research program not only resulted in high quality science return but also in numerous lessons learned to make the ISS experience more productive. The cooperation developed during the program was instrumental in its success.

INTRODUCTION

Against the backdrop of the well-publicized competition between the space programs of the United States and the former Soviet Union, there is a 37-year history of cooperation between the two countries. Many significant milestones have been accomplished during this time, such as the Apollo-Soyuz Test Project in 1975, but none has been as significant or involved as much collaboration as the joint program between the US and Russia on board the Mir space station. This program has been variously called Shuttle/Mir, NASA/Mir or Phase 1. For our purposes, it will be referred to as Phase 1, to underline its importance as a pathfinder for the International Space Station (ISS) Program, the actual construction and operation of which is referred to as Phase 2 and 3. The partnership established during Phase 1 has successfully expanded the knowledge and the capabilities of both nations. Contributions to the development of the ISS, providing a unique opportunity to learn more about how all people can better live and work on Earth and in space, and making significant advancements to the world's scientific knowledge have all been achieved during the historic Phase 1 program.

Joint programs are not new to either partner. On the US side, NASA has previously entered into partnerships with Canada, France, Germany, Italy, Japan, and the European Space Agency. Historically, Russia has collaborated with numerous nations in a variety of programs, and in the human space flight arena that included the flight of international crewmembers and their research on Salyut and Mir space stations. In several cases, both the US and Russia independently collaborated with the same international partners. NASA benefited from Russia's unique capability for and experience in long-duration human space flight. Russia benefited by adding the Space Shuttle's unique capabilities to Mir's logistical and resupply vehicle complement, as well as having a third crewmember to assist the Mir crews in their station operations. Both sides also gained an unprecedented amount of knowledge and joint development from facing the challenges that were inherent to the program.

PHASE 1 PROGRAM OVERVIEW

The origins of the Phase 1 program date to the Joint Statement on Cooperation in Space agreement signed by US President George Bush and Russian President Boris Yeltsin in June of 1992. An implementation agreement signed by NASA Administrator Daniel Goldin and Russian Space Agency (RSA) General Director Yuri Koptev in July of 1992 outlined a cooperative program of three joint space missions: a flight of a Russian cosmonaut on a US Space Shuttle; a long-duration flight of a US astronaut aboard the Russian Space Station Mir; and the docking of a Space Shuttle with Mir. The latter two missions were combined such that the Shuttle would return the entire long-duration crew (two Russians and the American) from Mir, while delivering their replacements. Cooperative science experiments were designated as a cornerstone of these missions.

In December 1993, this program was expanded to include up to nine additional Shuttle dockings with Mir, and four additional long-duration flights of US astronauts to Mir. In addition, two Russian modules awaiting launch to Mir would be outfitted with US hardware: Spektr with life sciences equipment and Priroda with microgravity equipment. Once again, research was planned to be an integral part of this expanded program. This program was eventually expanded to add a Shuttle rendezvous flight to Mir as a precursor to the first docking, and two additional long-duration flights of US astronauts aboard Mir.

Over a span of about four years, the Phase 1 program brought the Mir and the Space Shuttle together 10 times (9 of those were dockings). These were supplemented by Soyuz vehicles for cosmonaut launch and landing, and Progress vehicles for station resupply. Seven US astronauts and 17 Russian cosmonauts (three of the cosmonauts flew to Mir twice during Phase 1) participated in the long duration research program. In addition, 52 crewmembers flew on Space Shuttle missions as part of Phase 1, seven traveling to Mir twice, and one crewmember visiting Mir three times. Of this total, 45 were Americans, 5 Russians, one French, and one representative of the European Space Agency. The Shuttle crewmembers supported the long duration mission by transferring the vital resupply and return equipment, as well as conducting stand alone research on the Shuttle. Significant statistics of the Phase 1 program are summarized in Table 1.

The program provided both sides unique opportunities to collectively share much information about space travel and extended duration stays. One US crewmember traveled to Mir on a Russian provided Soyuz vehicle, and several Russian cosmonauts made the trip from Earth to Mir on the Space Shuttle.

Three US astronauts performed ExtraVehicular Activities (EVA's) during their long-duration stays, including activities to support the research program, and two additional EVA's were performed while the Shuttle was docked to Mir.

All US crews trained at the Gagarin Cosmonaut Training Center outside Moscow, while Russian crews spent time training at Johnson Space Center in Houston. American and Russian investigators were able to share results of previous space flight experiences, as well as laboratory knowledge, and design and execute joint investigations on both the Shuttle and Mir.

PHASE 1 RESEARCH PROGRAM

At the start of the Phase 1 program, four major research goals were established:

Table 1. Phase 1 Programmatic Accomplishments

Number of Long-Duration Crewmembers:
- 7 Americans
- 17 Russians

Time on Mir:
- 808 days of continuous US presence on Mir
- 947 days of US astronaut time aboard Mir
- 981 days of long-duration stay time
- 2356 crew hours spent on Mir US program

Number of EVA's:
- Total: 21
- Mir Standalone: 19
- With Shuttle docked: 2
- Science Payload installation and/or retrieval: 8

US Science Hardware Launched (via Shuttle, Priroda, Spektr, Soyuz, and Progress): 5789.76 kg
US Science Hardware Returned (via Shuttle): 4479.72 kg

- Obtain engineering and operational experience with a research program on a long-duration space platform.
- Learn more about the Mir space station and its environment as a platform for conducting a multi-disciplinary research program.
- Use the Mir space station as a test-bed for space technologies, processes and operations planned or proposed for ISS.
- Gain experience conducting Extra Vehicular Activities (EVA) from a long-duration platform.

Despite the difficulties and challenges described below, all four goals were met or exceeded. During the Phase 1 program investigations were conducted on Mir and also on the Shuttle during its resupply missions. Approximately 100 investigations were conducted during this program, several spanning multiple missions. These investigations represented investigators from many different countries, sharing information and data with scientific communities from around the world. The research program was divided into seven major disciplines. The major objectives of each discipline were as follows:

Advanced Technology

- Identify appropriate future technology needs through testing, demonstration, calibration, and prototyping.
- Facilitate the timely development of key enabling technologies in support of other NASA and US space programs.
- Facilitate the application of completed technology developments to industrial needs.

Earth Sciences

- Continue and expand existing cooperation between the US and Russia in Earth observation through joint field experiments and research use of satellite data.

Fundamental Biology

- Study the long-term effects of microgravity on the growth and development of organisms.
- Determine the role gravity plays in molecular mechanisms at the cellular level and in regulatory and sensory mechanisms in an integrated system.

Human Life Sciences

- Identify changes in human physiology during long-duration space flight, specifically for the metabolic, neurological, musculoskeletal, and cardiopulmonary systems, and where feasible, identify mitigating procedures.
- Determine the time course, extent, and underlying mechanisms of physiological changes.
- Determine if and how these physiological changes as well as long-term exposure to microgravity affects crew behavior and performance.
- Characterization of the Mir habitable environment and life support systems in support of science research.

ISS Risk Mitigation

- Use flight system investigations to provide test data that will reduce technical risks for ISS construction and operation.

Microgravity

- Determine structures and their relationship to function to understand and control protein activity.
- Measure and analyze the microgravity acceleration environment on board the Mir in support of microgravity science research.
- Use microgravity to study how physical, chemical, and biological processes are affected outside the influence of sedimentation and buoyancy caused by Earth's gravity.
- Use the microgravity environment to study the underlying principles necessary to predict the relationships of synthesis and materials processing to their resulting structures and properties.
- Use the microgravity environment to study combustion phenomena such as soot formation and flame structures.

Space Sciences

- Use the Mir platform for sampling interstellar and interplanetary materials, namely cosmic dust particles.

The international cooperative spirit is not new to either partner, but its breadth and depth is unique in Phase 1, as these scientists developed working relationships and data sharing agreements with their counterparts. These relationships are essential to continue to perform research on the International Space Station. The complexity of the ISS will require investigators around the world to work together for common goals in an unprecedented fashion. Teams must be established and organized to deliver quick responses to ensure their research goals are met.

MIR AS A LABORATORY

The Mir space station complex is modular in design, with seven permanent elements launched between 1986 and 1996 and assembled in orbit (figure 1). The complex, with a total habitable volume of approximately 380 m^3, is designed to be multifunctional, with research being one of its capabilities. To facilitate research for the Phase 1 program, hardware (US and Canadian) was installed in the Spektr and Priroda modules and integrated into the complex in 1995 and 1996. Use was also of already esxisting hardware on Mir, some of which had been provided through Russia's collaborative efforts with its partners (e.g., Slovakia, Bulgaria). Regular resupply to Mir by unmanned Progress cargo vehicles was greatly expanded during the Phase 1 program by using the US Space Shuttle both to resupply the station with science hardware and consumables, as well as to return samples and data products from completed experiments. Typically, Soyuz vehicles launched and returned Russian cosmonauts, while US astronauts used the Space Shuttle for transportation. The mix of vehicles provided added flexibility that proved critical at some of the more challenging moments of the program.

The modules in Mir contained the scientific apparatus for conducting a wide variety of experiments in a shirt-sleeve environment. Power for the facilities was provided by a number of solar arrays that converted

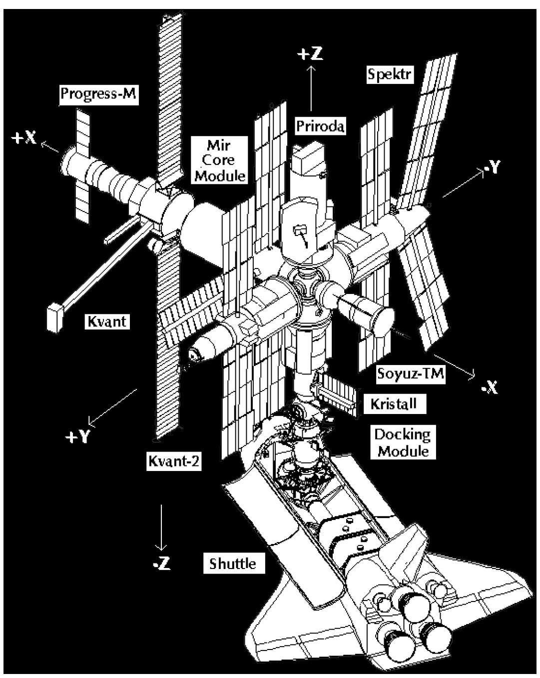

Figure 1. The Space Shuttle docked with the Mir Space Station complex.

solar energy to electricity. The station also provided other services to the experiments, including cooling, data recording, and limited capacity for downlinking data to the ground. Experiments requiring exposure to the space environment were typically deployed and retrieved by crewmembers during EVAs.

CHALLENGES

As one would expect, many technical and other challenges were faced and overcome during the implementation of this historic program. Some were of a newsworthy nature, such as a collision in space, and others were not so unexpected, but just as complex. The cultural differences between those involved in this program are inherent in such an international endeavor, and were perhaps just as difficult as other obstacles encountered in space travel. These cultural differences were sometimes subtle, and other times pronounced. They forced individuals to take into account how other people live and work, and to respect differences in cultural expectations, language, religion, philosophy, and society. Performing research in space is a difficult task in itself, but these societal differences added difficulties that could not be resolved strictly on a technical basis.

The ability to effectively communicate directly or through translators developed over time, as did the level of trust between the two sides. Language is deeply rooted in culture, and many found that verbal translations of words sometimes did not convey exact meanings.

Trust is often understated in its importance - many tend to place less importance in personal relations in the professional world of NASA, where people are interchangeable within a group, and anyone representing a position is given benefit of the doubt that they speak for the group. This is not the case as we found in Phase 1. We soon learned that trust was one of the more important qualities that developed as the program evolved. At first, people found themselves questioning motives, explanations, and rationale - something they wouldn't do inside their own organizations. Once trust was established and relationships were forged, the cornerstone of joint cooperation was laid in place. These relationships will carry us into the era of the International Space Station, with multiple groups working for the same common goal.

Numerous technical difficulties were faced and overcome by engineers on both sides, from differing power supply voltages and connectors (in laboratories and space vehicles), different concepts of redundancy vs. complexity in hardware design, and even differing views on levels of containment for biohazards. Both agencies' highest priority was safety, but the philosophy behind this priority often differed. These technical difficulties were minor, but often frustrating, barriers that eventually were resolved through compromise. This compromise was key, as each program gained new respect and insight into an approach that was effective, but different from its own "tried and true" approaches.

During actual operations on Mir, support personnel from Houston living in Moscow were expected to request information from the Russian ground controllers concerning completion of a crew activity. Communication with the Mir, approximately only 10 minutes out of every 90 minutes is dramatically less than Shuttle communication; therefore the Russians operated on "negative reporting". Only if a planned activity was not completed would it be reported. Again, a philosophical difference that was based upon the constraints of the system. Both sides had to understand each other's mode of operation, and what was expected from their partner.

Another difficulty that showed a dramatic shift in the NASA way of doing business involved the planning of the missions. For short-duration Shuttle flights, NASA had a history of planning missions in great detail, and planning for any contingency situation. Long duration space flights, such as those on Mir, showed us how this type of planning is not suitable for such missions. Multiple events throughout the Phase 1 program necessitated frequent and often significant replanning of the implementation of the research program. Examples of the events are: delays in the launch of research modules, with obvious impacts to the research depending on hardware in those modules; delay of Shuttle and Soyuz launches, causing unexpected extensions of long-duration missions; replacement of prime crews with back-up crews, who were not fully trained, within days or weeks of launch; loss of a research module, power and crewtime resulting from the Progress collision with Mir; and numerous vehicle-related incidents such as loss of attitude control, replanning and addition of EVA's, and changes in the scheduling of Progress resupply vehicles. The lesson from this exercise forced planners to do business a smarter way only reworking immediate impact days leaving days further out alone until the situation stabilized. Through theses efforts, virtually all planned research was completed. It should be anticipated that over the course of its lifetime, ISS will encounter similar episodes requiring replanning of the research program.

Through compromise, both sides gained understanding of how their partner operated, and the partnership was solidified. Throughout the program these compromises brought the two sides together to work to the common goal of mission success.

The Phase 1 program fulfilled its goal as a precursor to operations on the International Space Station.

RESEARCH ACCOMPLISHMENTS

The Phase 1 program provided many investigators with their first experience with a long-duration platform. Table 2 summarizes the total number of investigations from the seven disciplines completed on

Table 2. Long Duration Research on Mir
Number of Investigations in Specific Disciplines per Research Increment

		Long-Duration Increment						
Discipline	Total*	1	2	3	4	5	6	7
Advanced Technology	6		1	2			1	3
Earth Sciences	3		2	2	2	3	3	3
Fundamental Biology	10	1	3	2	4	5	1	
Human Life Sciences	44	26	11	12	8	6	5	6
ISS Risk Mitigation	11		5	7	8	7	6	2
Microgravity	24	1	12	10	11	9	9	8
Space Sciences	2		2	2	2			
Total	100	28	36	37	35	30	25	22

* The number reflected in the Total column reflects total unique experiments, therefore is not a summation of experiments performed through the program, as some were repeated to gain higher sample sizes.

each research increment; this number does not represent unique investigations, since some were conducted on multiple missions. Approximately 150 investigators from the United States, Russia, Canada, the United Kingdom, Japan, Germany, France, and Hungary participated in conducting research during Phase 1.

In the area of Advanced Technology, hardware originally designed for short-duration (less than 18 days) space flight was adapted for long duration (4-6 months) flights and successfully tested. Experiments in biotechnology, microbiology, and pharmacology were successfully conducted on two long duration missions, validating the technology for future use on ISS. An experiment using a Russian furnace examined liquid-phase sintering processes in microgravity. Qualitative improvements made possible by using this process in microgravity may ultimately lead to metal products with fewer defects and therefore longer useful lifetimes.

The three-year near continuous observations of Earth phenomena by trained crewmembers during Phase 1 has added nearly 20,000 images to the existing database of approximately 300,000 photographs of the Earth which have been collected during US manned space flight. Crewmembers were able to observe and document long-term climatic changes, alterations in land use patterns, and for the first time documented global baseline conditions leading up to and through the 1997-1998 El Nino weather phenomena. Many ephemeral events such as volcanic events and widespread forest fires were observed and documented by the crewmembers prior to their discovery by ground based researchers.

Comparison of Mir based radiation measurements with similar data obtained during the Skylab program in 1973-1974 documented for the first time not only the northward but also the westward drift of the South Atlantic Anomaly (SAA), an area where the inner Van Allen belts dip closer to Earth, leading to higher trapped radiation levels. Precise knowledge of the location of the SAA is important for monitoring the radiation doses crewmembers receive as they pass through the area, and is critical for scheduling EVAs, where spacecraft shielding of crewmembers is eliminated.

Investigations in Fundamental Biology focused on plant and avian development in microgravity, circadian rhythm changes in beetles, as well as studying the internal and external radiation environment on Mir. The plant experiments yielded the largest plant biomass ever produced in space, as well as the first plants developed from seeds produced and harvested in space, completing an entire seed-to-seed cycle in microgravity. The avian investigation was the most successful to date, providing significant insight into avian embryology and development in space. Above and beyond advancing our understanding of basic biological processes, these experiments are also significant milestones toward developing space based ecosystems.

The Human Life Sciences investigations studied the effects of long-duration space flight on the crewmembers themselves. Changes in the immune system, cardiovascular function, neurovestibular function, musculoskeletal system, regulatory physiology, the risk of developing kidney stones, and the psychology of crew interactions were investigated. Most of these studies expanded on similar research conducted on short-duration Shuttle flights, and are precursors to the types of investigations likely to be performed on ISS.

The Mir space station was an ideal test bed for hardware, materials, processes, and operations proposed or planned for ISS. The structural dynamics and micrometeoroid impact experiments, part of the ISS Risk Mitigation discipline, are two examples of demonstrations of crew and vehicle microgravity disturbances and interactions and investigating how materials and structures respond to long exposures to the low Earth orbit environment. Results from these studies were in many cases applied to design or operations of ISS.

Investigations in the Microgravity Sciences were performed in fluid physics, materials processing, combustion science, biotechnology and microaccelerations. A Canadian-built system was successfully used to isolate sensitive experiments from microaccelerations using magnetic levitation. In the biotechnology area, the duration of space-based tissue culture experiments was extended from 10 days to four months, developing 3-dimensional spherical tissue constructs difficult to produce on Earth. New techniques for growing protein and other crystals in space were established with qualitative and quantitative improvements over ground-based products. Analysis of these high quality crystals by X-ray diffraction and other methods may lead to advances in pharmacology and molecular biology.

Experiments in the Space Science discipline were externally mounted on Mir and were designed to collect both extraterrestrial natural particulates as well as artificial particulates resulting from spacecraft offgassing, and vented propellants from expended rocket stages. Aerogel, aluminum panels and other materials were used to collect the particles. New information about the relationship between particle concentration and size was gained, with importance to understanding the orbital debris environment in low Earth orbit.

As alluded to earlier, many of the investigations performed on Mir relied on past experience for their success. In some cases, hardware that had flown short-duration missions was redesigned and certified for long-duration flight. With the experience gained on Mir, many are now targeted for flight aboard ISS, implementing improvements learned in the course of the Phase 1 program.

CONCLUSIONS

The Phase 1 Research Program was the largest and most complex international research effort ever attempted in space to date. As a pathfinder and trailblazer for the even larger and more complex research program being planned for the International Space Station, it was highly successful and rewarding. Many of the challenges of conducting a multinational research program in space were met and overcome. Both sides learned to work together to achieve common goals and overcome significant obstacles. The US side in particular gained valuable experience in conducting a long duration research program in space. And finally, the dozens of experiments conducted in the various research disciplines provided a wealth of important and significant results to benefit future space programs as well as people here on Earth.