Microgravity Science Space Flights

Until the mid-20th century, gravity was an unavoidable aspect of research and technology. During the latter half of the century, the use of drop towers to reduce the effects of gravity became more prevalent, although the extremely short periods of time they provided (<6 seconds) severely restricted the type of research that could be performed.

Initial microgravity research centered around solving space flight problems created by the reduction in gravity's effects experienced on orbit. How do you get the proper amount of fuel to a rocket engine in space or water to an astronaut on a spacewalk? The brief periods of microgravity available in drop towers at the Lewis Research Center and the Marshall Space Flight Center were sufficient to answer these basic questions and to develop the pressurized systems and other new technologies needed to cope with this new environment. But, they still were not sufficient to investigate the host of other questions that were raised by having gravity as an experimental variable.

Skylab, America's first space station.

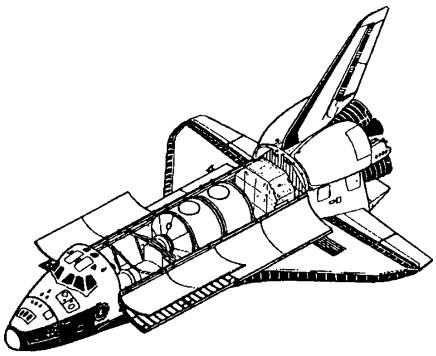
The first long-term opportunities to explore microgravity and conduct research relatively free of the effects of gravity came during the latter stages of NASA's first great era of discovery. The Apollo program presented scientists with the chance to test ideas for using the space environment for research in materials, fluid, and life sciences. The current NASA microgravity program had its beginning in experiments conducted in the later flights of Apollo, the Apollo-Soyuz Test Project, and onboard Skylab, America's first space station.

Preliminary microgravity experiments conducted during the 1970's were severely constrained, either by the relatively low power levels and space available on the Apollo spacecraft, or by the low number of flight opportunities provided to Skylab. These experiments, as simple as they were, provided new insights into the roles of fluid and heat flows in materials processing Much of our understanding of the physics underlying semiconductor crystal growth, for example, can be traced back to research initiated on Skylab.

Since the early 1980's, NASA has sent crews and payloads into orbit on board the Space Shuttle. The Space Shuttle has given microgravity scientists an opportunity to bring their experiments to low-Earth orbit on a more regular basis. The Shuttle introduced significant new capabilities for microgravity research: larger, scientifically trained crews; a major increase in payload volume and mass and available power; and the return to Earth of all instruments, samples, and data. The Spacelab module, developed for the Shuttle by the European Space Agency, gives researchers a laboratory with enough power and volume to conduct a limited range of sophisticated microgravity experiments in space.

Use of the Shuttle for microgravity research began in 1982, on its third flight, and continues today on many missions. In fact, most Shuttle missions that aren't dedicated to microgravity research do carry microgravity experiments as secondary payloads.

The Spacelab-1 mission was launched in November 1983. The primary purpose of the mission was to test the operations of the complex Spacelab and its subsystems. The 71 microgravity experiments, conducted using instruments from the European Space Agency, produced many interesting and provocative results. One investigator used the travelling heater method to grow a crystal of gallium antimonide doped with tellurium (a compound useful for



The Spacelab module in the Orbiter Cargo Bay.

making electronic devices). Due to the absence of gravity-driven convection, the space-grown crystal had a far more uniform distribution of tellurium than could be achieved on Earth. A second investigator used molten tin to study diffusion in low gravity- research that can improve our understanding of the solidification of molten metals.

The first Spacelab mission dedicated to United States microgravity science on USML-I. The coast of Florida appears in the background.

Another Shuttle mission using the Spacelab module was Spacelab-3, which flew in April 1985. SL-3 was the first mission to include U.S. developed microgravity research instruments in the Spacelab. One of these instruments supported an experiment to study the growth of crystals of mercury iodide-a material of significant interest for use as a sensitive detector of X-rays and gamma rays. Grown at a high rate for a relatively short time, the resulting crystal was as good as the best crystal grown in the Earth-based laboratory. Another U.S. experiment consisted of a series of tests on fluid behavior using a spherical test cell. The microgravity environment allowed the researcher to use the test cell to mimic the behavior of the atmosphere over a large part of Earth's surface. Results from this experiment were used to improve mathematical models of our atmosphere.

In October 1985, NASA launched a Spacelab mission sponsored by the Federal Republic of Germany, designated Spacelab-D1. American and German scientists conducted experiments to synthesize high quality semiconductor crystals useful in infrared detectors and lasers. These crystals had improved properties and were more uniform in composition than their Earth-grown counterparts. Researchers also successfully measured critical properties of molten alloys.

International Microgravity Laboratory-1, January 1992

More than 220 scientists from the United States and 14 other countries contributed to the experiments flown on the first International Microgravity Laboratory (IML-1) in January 1992. Several biotechnology experiments concerned with protein crystal growth enabled NASA scientists to successfully test and compare two different crystal-growing devices.

A German device called the Cryostat produced superior-quality crystals of proteins from several microorganisms including the satellite tobacco mosaic virus (STMV), which has roles in diseases affecting more than 150 crop plants. As a result of this experiment, scientists now have a much clearer understanding of the overall structure of STMV. This information is useful in efforts to develop strategies for combating viral damage to crops.

Payload Commander Bonnie J. Dunbar and Payload Specialist Lawrence J. DeLucas working in the module on USML-1.

IML-1 also carried experiments designed to probe how microgravity affects the internal structure of metal alloys as they solidify. The growth characteristics, determined from one of the experiments, matched the predictions of existing models, providing experimental evidence that current hypotheses about alloy formation are correct.

United States Microgravity Laboratory-1, June 1992

In June 1992 the first United States Microgravity Laboratory (USML-1) flew aboard a 14-day shuttle mission, the longest up to that time. This Spacelab-based mission was an important step in a long-term commitment to build a microgravity program involving government, academic, and industrial researchers.

The payload included 31 microgravity experiments using some facilities and instruments from previous flights, including the Protein Crystal Growth facility, a Space

Acceleration Measurement System, and the Solid Surface Combustion Experiment. New experiment facilities, all designed to be reusable on future missions, included the Crystal Growth Furnace (CGF), a Glovebox provided by the European Space Agency, the Surface Tension Driven Convection Experiment apparatus (STDCE), and the Drop Physics Module.

Science Standards

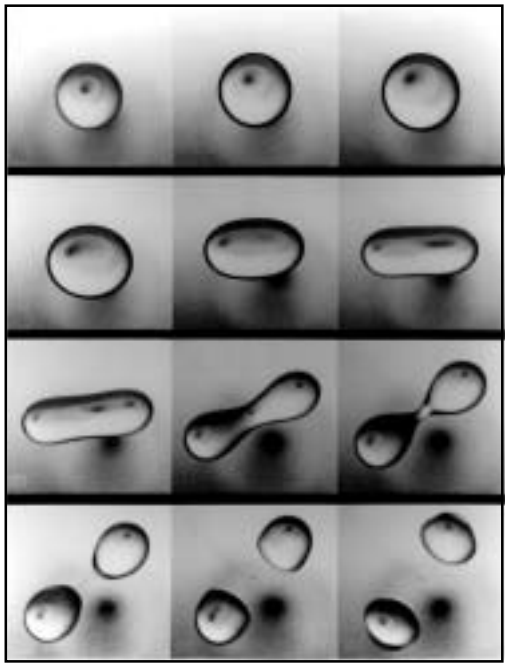
Δ ❑ Earth and Space Science
Δ ❑ History and Nature Of Science
Δ ❑ Physical Science
Δ ❑ Unifying Concepts and Processes

Questions for Discussion
- What are Cd, Hg, Te, Zn?
- What do these elements have in common?

Hint: Look at their position on the periodic table of the elements.

Investigators used the CGF to grow crystals of four different semiconductor materials at temperatures as high as 1260°C. One space-grown **CdZnTe** crystal developed far fewer imperfections than even the best Earth-grown crystals, results that far exceeded pre-flight expectations. Thin crystals of **HgCdTe** grown from the vapor phase had mirror-smooth surfaces even at high magnifications. This type of surface was not observed on Earth-grown crystals.

Researchers used the STDCE apparatus to explore how internal movements of a liquid are created when there are spatial differences in temperature on the liquid's surface. The results are in close agreement with advanced theories and models that the experiment researchers developed.



Fission sequence of a rotating levitated drop.

In the Drop Physics Module, sound waves were used to position and manipulate liquid droplets. Surface tension controlled the shape of the droplets in ways that confirmed theoretical predictions. The dynamics of rotating drops of silicone oil also conformed to theoretical predictions. Experimental and theoretical results of this kind are significant because they illustrate an important part of the scientific method: hypotheses are formed and carefully planned experiments are conducted to test them.

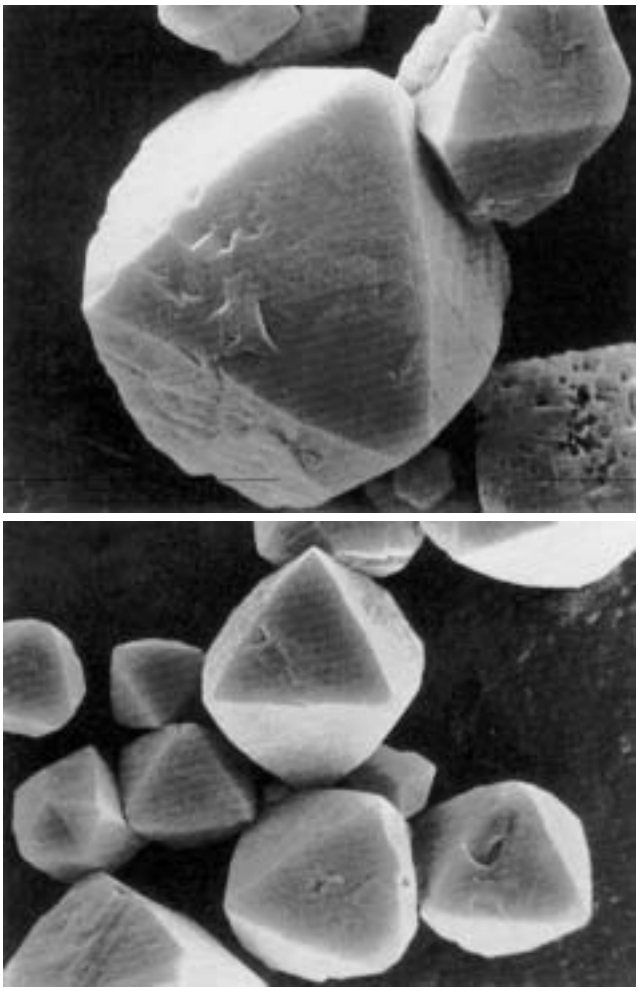
Sixteen different investigations run by NASA researchers used the Glovebox, which provided a safe enclosed working area; it also was equipped with photographic equipment to provide a visual record of investigation operations. The Glovebox allowed crew members to perform protein crystallization studies as they would on Earth, including procedures that require

hands-on manipulation. Among other results, use of the Glovebox provided the best-ever crystals of malic enzyme that may be useful in developing anti-parasitic drugs.

The burning of small candles in the Glovebox provided new insights into how flames can exist in an environment in which there is no air flow. The results were similar (though much longer lived) to what can be seen by conducting similar experiments in freefall here on Earth. (See Candle Flames in Microgravity, in the Activities section of this guide.) The candles burned for about 45 to 60 seconds in the Glovebox experiments.

Another Glovebox investigation tested how wire insulation burns under different conditions, including in perfectly still air (no air flow) and in air flowing through the chamber from different directions. This research has yielded extremely important fundamental information and also has practical applications, including methods for further increasing fire safety aboard spacecraft.

The crew of scientist astronauts in the Spacelab played an important role in maximizing the science return from this mission. For instance, they attached a flexible type of glovebox, which provided an extra level of safety, to the Crystal Growth Furnace. The furnace was then opened, previously processed samples were removed and an additional sample was inserted. This enabled another three experiments to be conducted. Two other unprocessed samples were already in the furnace.

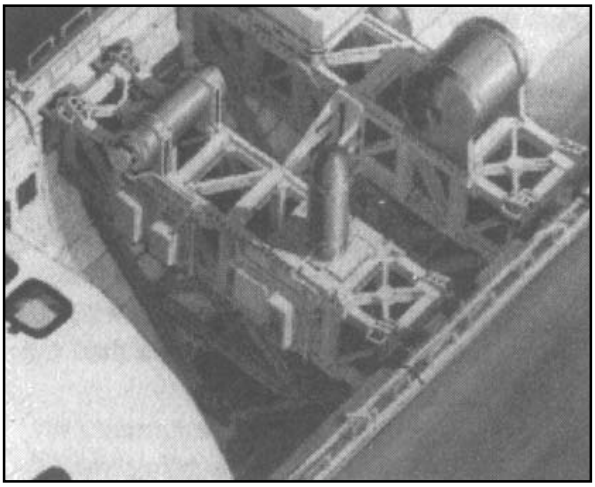


Zeolite crystals can be grown in the Glovebox Facility. Shown here are photos (at the same scale) of zeolite crystals grown on USML-I (top) and on Earth (bottom).

Spacelab-J, September 1992

The Spacelab-J (SL-J) mission flew in September 1992. SL-J was the first Space Shuttle mission shared by NASA and Japan's National Space Development Agency (NASDA). NASA microgravity experiments focused on protein crystal growth and collecting acceleration data in support of the microgravity experiments.

NASDA's science payload consisted of 22 experiments focused on materials science and the behavior of fluids, and 12 human biology experiments. NASDA also contributed two experiment facilities. One of these, the Large Isothermal Furnace, was used to explore how various aspects of processing affect the structure and properties of materials. The second apparatus was a Free-Flow Electrophoresis Unit used to separate different types of molecules in a fluid.



USMP experiments are mounted on Mission Peculiar Equipment Support Structures in the Shuttle Cay.rgo Bay.

United States Microgravity Payload-1, October 1992

The first United States Microgravity Payload (USMP-1) flew on a 10-day Space Shuttle mission launched on October 22, 1992. The mission was the first in an ongoing effort that employs telescience to conduct experiments on a carrier in the Space Shuttle Cargo Bay. Telescience refers to how microgravity experiments can be conducted by scientists on the ground using remote control.

The carrier in the Cargo Bay consisted of two Mission Peculiar Equipment Support Structures. On-board, the two Space Acceleration Measurement Systems measured how crew movements, equipment operation, and thruster firings affected the microgravity environment during the experiments. This information was relayed to scientists on the ground, who then correlated it with incoming experiment data.

A high point of USMP-1 was the first flight of MEPHISTO, a multi-mission collaboration between NASA-supported scientists and French researchers. MEPHISTO (designed and built by the French Space Agency, Centre National d'Etudes Spatiales or CNES) is designed to study the solidification process of molten metals and other substances. Three identical samples of one alloy (a combination of tin and bismuth) were solidified, melted, and resolidified more than 40 times, under slightly different conditions each time. As each cycle ended, data were transmitted

from the Space Shuttle to Marshall Space Flight Center. There, researchers analyzed the information in combination with data from the Space Acceleration Measurement System and sent back commands for adjustments. In all, the investigators relayed more than 5000 commands directly to their instruments on orbit. Researchers compared experiment data with the predictions of theoretical models and showed that mathematical models can predict important aspects of the experiment behavior. This first MEPHISTO effort proved that telescience projects can be carried out efficiently, with successful results.

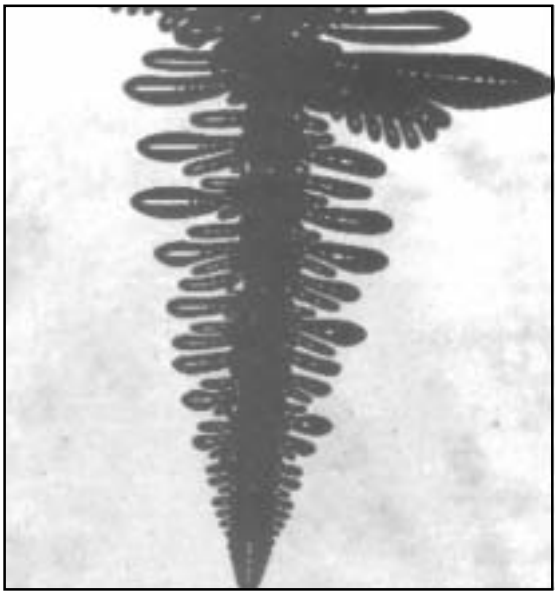
The lambda point for liquid helium is the combination of temperature and pressure at which normal liquid helium changes to a superfluid. On Earth, effects of gravity make it virtually impossible to measure properties of substances very close to this point. On USMP-1, the Lambda Point Experiment cooled liquid helium to an extremely low temperature—-a little more than 2 K above absolute zero. Investigators measured changes in its properties immediately before it changed from a normal fluid to a superfluid. Performing the test in microgravity yielded temperature measurements accurate to within a fraction of one billionth of a degree—several hundred times more accurate than would have been possible in normal gravity. Overall the new data were five times more accurate than in any previous experiment.

United States Microgravity Payload-2, March 1994

The second United States Microgravity Payload (USMP-2) flew aboard the Space Shuttle Columbia for 14 days from March 4 to March 18, 1994. Building on the success of telescience in USMP-1, the Shuttle Cargo Bay carried four primary experiments which were controlled by approximately 10,000 commands relayed by scientists at Marshall Space Flight Center. USMP-2 also included two Space Acceleration Measurement Systems, which provided scientists

Science and mission management teams monitor and control experiments from operations centers worldwide.

on the ground with nearly instant feedback on how various kinds of motion-including crew exercise and vibrations from thruster engines-affected mission experiments. The Orbital Acceleration Research Experiment in the Cargo Bay collected supplemental data on acceleration, providing an indication of the quasi-steady acceleration levels experienced by the experiments.



A dendrite grown in the Isothermal Dendritic Growth Experiment aboard the USMP-2. This is an example of how most metals solidify.

Throughout the mission, the Critical Fluid Light Scattering Experiment—-nicknamed Zeno—analyzed the behavior of the element xenon as it fluctuated between two different states, liquid and gas. First, a chamber containing liquid xenon was heated. Then, laser beams were passed through the chamber as the xenon reached temperatures near this transition point. A series of measurements were taken of how the laser beams were scattered (deflected) as the xenon shifted from one state to another. Researchers expected that performing the experiment on orbit would provide more detailed information about how a substance changes phase than could be obtained on Earth. In fact, the results produced observations more than 100 times more precise than the best measurement on the ground.

The Isothermal Dendritic Growth Experiment (IDGE) examined the solidification of a material that is a well-established model for metals. This material is especially useful as a model because it is transparent, so a camera can actually record what happens inside a sample as it freezes. In 59 experiments conducted during 9 days, over 100 television images of growing **dendrites** were sent to the ground and examined by the research team. Dendritic growth velocities and tip radii of curvature were measured. Results obtained under certain experiment conditions were not consistent with current theory. This inconsistency was the subject of subsequent research on USMP-3. In another successful demonstration of telescience, the team relayed more than 200 commands to the IDGE, fine-tuning its operations.

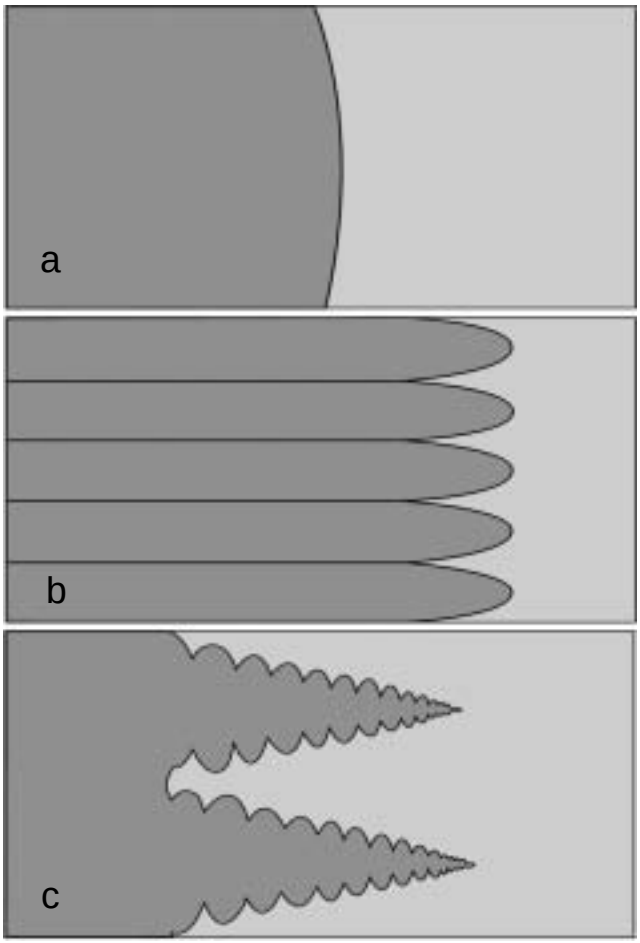
Science Standards

Δ ❑ Physical Science
Δ ❑ Unifying Concepts and Processes

Dendrites are branching structures that develop as a molten metal solidifies under certain conditions. The root of this word is the (Greek dendron, meaning tree. Branching structures in biology (nerve cells) and geology (drainage systems) are also referred to as being dendritic.

USMP-2 also included a MEPHISTO experiment. On this mission, the MEPHISTO apparatus was used for U.S. experiments to test how gravity affects the formation of crystals from an alloy of bismuth and tin that behaves much like a semiconductor during crystal growth. Metallurgical analysis of the samples has shown that interactions between the molten and solid alloy during crystallization play a key role in controlling the final morphological stability of the alloy.

Another USMP-2 materials science experiment used the Advanced Automated Directional Solidification Furnace (AADSF). An eleven day experiment using the AADSF yielded a large, well-controlled sample of the alloy semiconductor, HgCdTe. The results of various analysis techniques performed on the crystal indicate that variations in the acceleration environment had a marked effect (due to changing residual fluid flow) on the final distribution of the alloy's components in the crystal.



Representations of different .shapes of the liquid-solid interface in a solidifying material: a) planar, b) cellular; and c) dendritic. More information about interface morphology is provided in the Metals and Alloys discussion in the Materials Science section of this publication.

International Microgravity Laboratory-2, July 1994

The second International Microgravity Laboratory (IML-2), with a payload of 82 major experiments, flew in July 1994 on the longest Space Shuttle flight to that time. IML-2 truly was a world class venture, representing the work of scientists from the U.S. and 12 other countries.

Materials science experiments focused on various types of metals processing. One was sintering, a process that can combine different metals by applying heat and pressure to them. A series of three sintering experiments expanded the use in space of the Japanese built Large Isothermal Furnace, first flown on SL-J. It successfully sintered alloys of nickel, iron, and tungsten.

Other experiments explored the capabilities of a German-built facility called TEMPUS. It was designed to position molten metal experiment

samples (molten drops) away from the surfaces of a container in order to eliminate processing side effects of containers. Experiments of four U.S. scientists were successfully completed, and the research team developed improved procedures for managing multi-user facilities.

One of the experiments used a clever approach to measure two important thermophysical properties of molten metals. While a spherical drop of molten metal was positioned in a containerless manner it was momentarily distorted by using electromagnetic forces to squeeze it. When the squeezing was released, the droplet began to oscillate. The surface tension of the molten metal was determined from the frequency of the oscillation. The oscillation gradually decayed. The rate at which the decay occurred was used to determine the viscosity of the molten material.

Biotechnology experiments were performed using the Advanced Protein Crystallization Facility, developed by the European Space Agency. The facility's 48 growth chambers operated unattended throughout the flight, producing high-quality crystals of nine proteins. High-resolution video cameras monitored critical crystal growth experiments, providing the research team with a visual record of the processes. U.S. investigators used the Bubble, Drop, and Particle Unit to study how temperature **gradients** in the liquids influence the movement and shape of gas bubbles and liquid drops. The Critical Point Facility enabled researchers to study how a fluid behaves at its critical point. Research using the Critical Point Facility is applicable to a broad range of scientific questions, including how various characteristics of solids change under different experimental conditions.

Mathematics Standards

- ❑ Conceptual Underpinnings of Calculus
- ❑ Functions
- Δ ❑ Mathematical Connections
- Δ Patterns and Functions

Science Standards

- Δ ❑ Earth and Space Science
- Δ ❑ Physical Science
- Δ ❑ Science and Technology
- Δ ❑ Science in Personal and Social Perspectives
- Δ ❑ Unifying Concepts and Processes

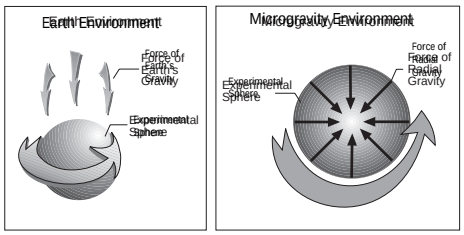
A **gradient** is the variation of a quantity such as temperature, pressure, or concentration with respect to a given parameter, typically distance. A temperature gradient can have dimensions of temperature per length, for example, °C/cm.

United States Microgravity Laboratory-2, October 1995

The second United States Microgravity Laboratory (USML-2) launched on October 20, 1995 for a mission with more than 16 days on orbit. During that time microgravity research was conducted around-the-clock in the areas of biotechnology, combustion science, fluid physics, and materials science. It was a perfect example of interactive science in a unique laboratory environment.

Along with investigations that previously flew on USML-1, several additional experiment facilities flew on USML-2. Fourteen protein crystal growth experiments in the Advanced Protein Crystallization Facility had varied results that provided more insight into the structures of some of the proteins and into optimal experiment conditions. The goal of the Geophysical Fluid Flow Cell experiment was to study how fluids move in microgravity as a means of understanding fluid flow in oceans, atmospheres, planets, and stars. The results of the studies of fluid movement and velocity are still being analyzed.

Four separate studies were performed in the Crystal Growth Furnace (CGF). The goals of the experiments were to investigate quantitatively the gravitational influences on the growth and quality of the compound semiconductor, CdZnTe, using the seeded, modified Bridgman-Stockbarger crystal growth technique; to investigate techniques for uniformly distributing a **dopant**, selenium, during the growth of GaAs crystals; to understand the initial phase of the process of vapor crystal growth of complex, alloy-type semiconductors (HgCdTe); and to test the integration of a current induced interface demarcation capability into the CGF system and to assess the influences of a change in Shuttle attitude on a steady-state growth system using the demonstrated capabilities of the interface demarcation technique.



Gravitational force acting on spherical planetary models on Earth and in a microgravity environment

In the Geophysical Fluid Flow Cell, electric charges, electrostatic force, and heaters are used to simulate buoyancy forces, radial gravity, and heating patterns in planetary atmospheres. As shown in the diagram, attempts to use spherical models on Earth are hampered by the force of Earth's gravity acting perpendicular to the sphere's rotation (indicated by the large curving arrow around the sphere's equator). In microgravity, this problem is removed.

Science Standards

Δ ❑ Physical Science
Δ ❑ Science and Technology
Δ ❑ Science in Personal and Social Perspectives
Δ ❑ Unifying Concepts and Processes

A **dopant** is an impurity intentionally added to a pure semiconductor to alter its electronic or optical properties.

Science Standards

Δ ❑ Physical Science
Δ ❑ Science and Technology
Δ ❑ Science in Personal and Social Perspectives
Δ ❑ Unifying Concepts and Processes

A **surfactant** is a substance added to a liquid to change its surface tension. Surfactants are used in experiments where a liquid must wet its container in a particular way. A common use of surfactants is dishwashing detergent. The surfactant properties of the detergent is what causes food grease and oil to separate from most household dishware.

Two investigators had experiments conducted in the Drop Physics Module. The Science and Technology of Surface-Controlled Phenomena Experiments had three major goals: to determine the surface properties of liquids in the presence of **surfactants**; to investigate the dynamic behavior and the coalescence of droplets coated with surfactant materials; and to study the interactions between droplets and acoustic waves. The shapes of oscillating drops recorded on videotape were analyzed frame by frame, revealing the variations of the oscillation amplitude with time. The frequency and damping constant of the droplet shape oscillations were calculated. Analysis of the results is ongoing.

The goals of the Drop Dynamics Experiment were to gather high-quality data on the dynamics of liquid drops in microgravity for comparison with theoretical predictions and to provide scientific and technical information needed for the development of new fields, such as containerless processing of materials and polymer encapsulation of living cells. The experiments on the USML-2 mission included breaking one drop into two drops (bifurcation) and positioning a drop of one liquid at the center of a drop of a different liquid. Preliminary results show that the acoustic levitation technique has a strong influence on the drop bifurcation process.

Seven investigations were performed in the Glovebox on USML-2. These studies examined various aspects of fluid behavior, combustion, and crystal growth. Two separate devices were used for protein crystal growth experiments.

The Surface Tension Driven Convection Experiment investigated the basic fluid mechanics and heat transfer of thermocapillary flows generated by temperature variations along free surfaces of liquids in microgravity. It determined when and how oscillating flows were created. Preliminary analysis indicates that current theoretical models used to predict the onset of oscillations are consistent with the experiment results.

The USML-2 Zeolite Crystal Growth experiment attempted to establish a quantitative understanding of **zeolite** crystallization to allow control of both crystal defect concentration and crystallite size. The preliminary conclusions indicate that, with few exceptions, the crystals from USML-2 are larger in size than their Earth-grown counterparts and are twice as large as those grown on previous Shuttle flights. Analysis will continue to determine the effect of space processing on crystal defect concentration.

The projects that measured the microgravity environment added to the success of the mission by providing a complete picture of the Shuttle's environment and its disturbances. The Orbital Acceleration Research Experiment (OARE) provided real-time quasi-steady acceleration data to the science teams. The Microgravity Analysis Workstation (MAWS) operated closely with the OARE instrument, comparing the environment models produced by the MAWS with the actual data gathered by the OARE. Two other instruments, the Space Acceleration Measurement System and the Three Dimensional Microgravity Accelerometer, took g-jitter measurements throughout the mission. The Suppression of Transient Events by Levitation demonstrated a vibration isolation technology that may be suitable for experiments that are sensitive to variations in the microgravity environment.

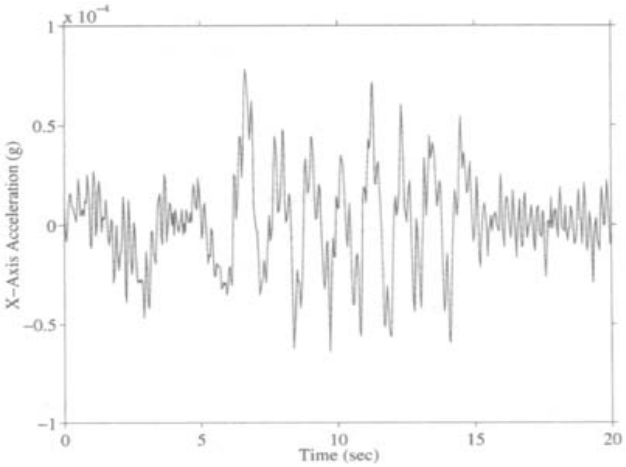
United States Microgravity Payload-3, February 1996

The third United States Microgravity Payload mission launched on February 22 for 16 days of research on orbit. During that time, microgravity research was conducted in the areas of combustion science, fluid physics, and materials science. The ultimate benefit of USMP-3 research will be improvements in products manufactured on Earth. During the eight and one-half days dedicated to microgravity science, researchers used telescience to control materials processing and thermodynamic experiments in the Cargo Bay

Science Standards

Δ ❑ Physical Science
Δ ❑ Science and Technology
Δ ❑ Scienee in Personal and Social Perspectives
Δ ❑ Unifying Concepts and Processes

Zeolites are hydrous aluminum silicate minerals which also contain cations of sodium, potassium, calcium, strontium, barium, or a synthetic compound. They are commonly used as molecular filters. For example, they are used to make every drop of gasoline sold in the United States.



The change in acceleration character seen in the middle of this plot is due to a crew member swinging an experiment container around to mix its contents. Examination of the plot indicates that the crew member swung his arm around seven to eight times in ten seconds.

Vibration Frequencies Commonly Seen in Orbiter Accelerometer Data

Freq. (Hz)	*Disturbance Source*
0.43	cargo bay doors
3.5	Orbiter fuselage torsion
3.66	structural frequency of Orbiter
4.64	structural frequency of Orbiter
5.2	Orbiter fuselage normal bending
7.4	Orbiter fuselage lateral bending
17	Ku band antenna dither
20	experiment air circulation fan
22	refrigerator freezer compressor
38	experiment air circulation fan
39.8	experiment centrifuge rotation speed
43	experiment air circulation fan
48	experiment air circulation fan
53	experiment air circulation fan
60	refrigerator piston compressor
80	experiment water pump
166.7	Orbiter hydraulic circulation pump

and astronauts performed combustion studies in the Middeck Glovebox.

The MEPHISTO science team used flight-proven equipment to learn how the chemical composition of solidifying Sn-Bi alloys changes, and can be controlled, during solidification. Such knowledge applies to ground-based materials processing. For the first time, the changes in the microgravity environment caused by carefully planned Shuttle thruster firings were correlated with the effects of fluid flows in a growing crystal. With the help of data from the Space Acceleration Measurement System, the experiment data showed that with thruster accelerations parallel to the crystal-melt interface a large effect was noted, whereas when thruster accelerations were perpendicular to the interface there was little impact. Also, the MEPHISTO team successfully monitored the point at which their sample's crystal interface underwent a key change-from flat to cellular (like three dimensional ripples)-as it solidified. Measurements from the MEPHISTO facility will now be analyzed, along with the final metallic samples, in order to increase our understanding of subtle changes that occurred during the samples' solidification and subsequent cooling.

In the Advanced Automated Directional Solidification Furnace, three lead tin telluride (PbSnTe) crystals were grown while Columbia orbited in three different attitudes, to determine how these orientations affect crystal growth. This knowledge is expected to help researchers develop processes, and semiconductor materials that perform better and cost less to produce.

The Isothermal Dendritic Growth Experiment (IDGE) on USMP-3 achieved its mission objectives. After collecting data to answer some of the questions opened by the USMP-2 results, research has shown that the small variations in dendritic growth rates (how fast the tree-like solid pattern in a molten metal forms) measured in microgravity on the Space Shuttle are not due to variations in the microgravity environment on

orbit. The investigators are currently completing measurements on the three-dimensional shape of these dendritic tips, which will further advance the empirical basis from which more accurate solidification models are being developed and tested. This is an early step in what will ultimately be solidification models that could be used to make less expensive and more reliable cast or welded metal and alloy products.

The IDGE team also participated in an important technology demonstration by commanding a microgravity space instrument from a remote site located at the Rensselaer Polytechnic Institute. This first-ever remote commanding to the Shuttle from a U.S. university campus foreshadows operations aboard the International Space Station.

As we move toward the era of the International Space Station, more experiment monitoring and control is being performed from NASA centers and university laboratories "remote" from Marshall Space Flight Center and Johnson Space Center.

Investigators for the Critical Fluid Light Scattering Experiment were successful in observing, with unprecedented clarity, xenon's critical point behavior-the precise temperature and pressure at which it exists as both a gas and a liquid. The transparent xenon sample displayed the unusual critical point condition, with maximum light scattering followed by a sudden increase in cloudiness. This effect was much more distinctive than observed during the USMP-2 mission and happened at a lower temperature than expected. Knowledge gained from this experiment will prove valuable for applications from liquid crystals to superconductors.

Glovebox Investigation Module hardware.

This mission was the first flight of a Glovebox facility in the Middeck section of the Shuttle. Three combustion science investigations were conducted by the crew. The Forced Flow Flamespreading Test burned 16 paper samples, both flat and cylindrical. Video of the cylindrical samples showed significant differences in flame size, growth rate, and color with variations in air flow speed and fuel temperature. The Comparative Soot Diagnostics investigation completed 25 combustion experiment runs. The

team obtained excellent results, testing the effectiveness of two different smoke-sensing techniques, for detecting fires aboard the Shuttle and the International Space Station. The Radiative Ignition and Transition to Spread Investigation team observed new combustion phenomena, such as tunneling flames which move along a narrow path instead of fanning out from the burn site. Also, for the first time, these investigators studied the effects of sample edges and corners on fire spreading in microgravity.

The Space Shuttle Columbia, carrying the Life and Microgravity Spacelab, launched from Kennedy Space Center June 20, 1996.

Life and Microgravity Spacelab, June 1996

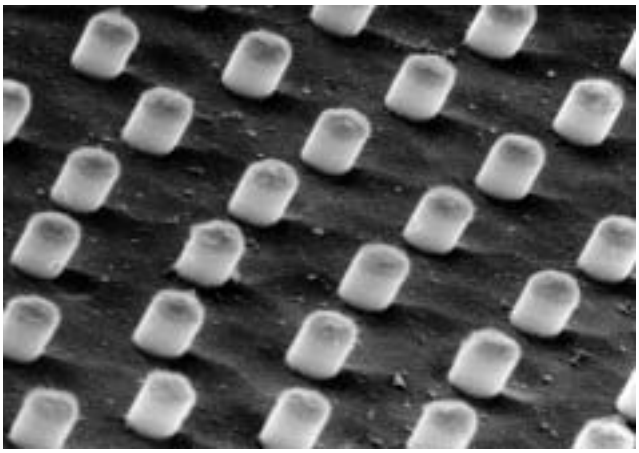
The Life and Microgravity Spacelab mission successfully completed a 17 day flight on July 6, 1996. For this mission there was an unprecedented distribution of teams monitoring their experiments around the world, with experiment commanding performed from three sites.

A number of researchers conducted experiments using the Advanced Gradient Heating Facility (AGHF) from the European Space Agency. Three aluminum-indium alloys were directionally solidified to study the physics of solidification processes in immiscible alloys called monotectics. The three samples, which differed only in indium content, were processed at the same growth rate to permit a comparison of microstructures, how the indium was distributed in the aluminum matrix. Two of these samples were of compositions which cannot be processed under steady state conditions on Earth due to gravitationally-driven convective instabilities and subsequent sedimentation of the liquid indium.

Another AGHF experiment used commercial Al-based samples to obtain insight into the mechanism of particle redistribution during solidification. Additional studies were geared toward enhancement of the fundamental understanding of the dynamics of insoluble particles at solid/liquid interfaces. The physics of the problem is of direct relevance to such areas as solidification of metal matrix composites,

management of defects such as inclusions and porosity in metal castings, development of high temperature superconductor crystals with superior current carrying capacity, and the solidification of monotectics.

A series of experiments was performed in the Advanced Protein Crystallization Facility. The experiments were generally successful in terms of yielding crystals. Those crystals which showed particular promise, based on early microscopic examination, were ferritin, satellite tobacco mosaic virus, satellite panicum mosaic virus, lysozyme, and canavalin.



Magnification of a sample of an aluminum-indium alloy. When the sample is melted then controllably solidifies in the AGHF; the indium forms in cylindrical fibers within a solid aluminum matrix.

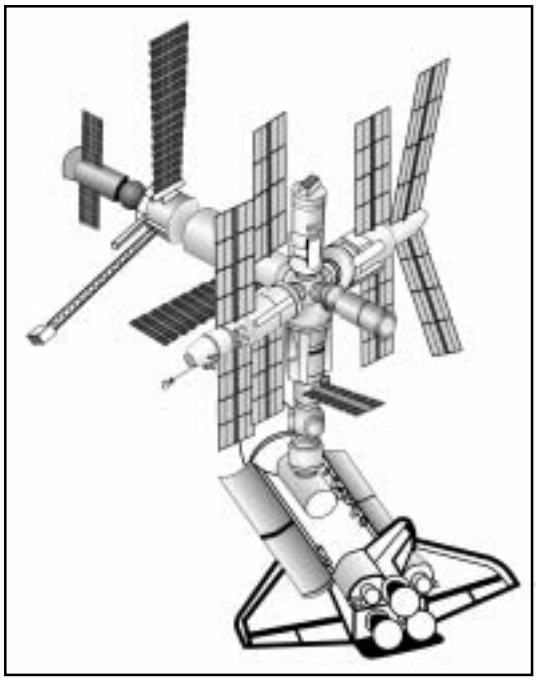
Several experiments were conducted using the Bubble, Drop and Particle Unit (BDPU) from the European Space Agency. In one experiment, the transition to periodic and chaotic convection was detected. The results of this experiment will trigger ground based research on the nonlinear dynamics of convecto-diffusive systems. In another experiment, thermocapillary flows in two and three layer systems were observed for five temperature gradients. The results of this experiment will improve our understanding of heat and mass transfer in other fluid physics research.

An additional experiment studied the interaction between pre-formed gas bubbles inside a solid and a moving solid/liquid interface, obtained by heating an initially solid sample. Early results concerning the release of bubbles from the melting front indicate that once a hole has been made and the gas inside the bubble contacts the liquid then the liquid enters the cavity (by wetting the solid walls) and pushes out the gas inside the bubble.

The scientific results of one set of BDPU experiments provide us with new insights into bubble dynamics and into evaporation. This will lead to a better understanding and modeling of steam generation and boiling. Initial findings of another experiment showed that, under

microgravity conditions, boiling heat transfer is still as efficient as under normal Earth gravity. In contrast to the existing theory the findings show that the influence of Earth gravity is less than predicted. The heat transfer in a microgravity environment is still as efficient, sometimes even more efficient than, at normal gravity.

Real-time Orbital Acceleration Research Experiment data were used by the science teams to monitor the microgravity environment during their experiment operations. The effects of mission activities, such as venting of unneeded water and Orbiter orientation changes, were presented to help the science teams understand the environment in which their experiments operated. The Microgravity Measurement Assembly (MMA) used this mission to verify a new system, augmented by a newly developed accelerometer for measuring the quasi-steady range. MMA provided real-time quasi-steady and g-jitter data to the science teams during the mission.



Schematic diagram of Space Shuttle Orbiter docked to Mir.

Shuttle/Mir Science Program, March 1995 to May 1998

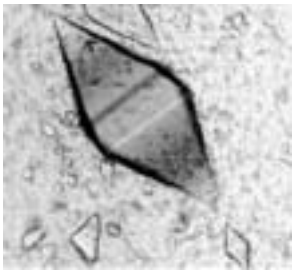
Although competition in the space program has existed between the United States and Russia for some time, there has also been a rich history of cooperation that has grown into the highly successful joint science program that it is today. One part of that program is geared towards microgravity research.

Many of the investigations from that program are configured to run in a Glovebox facility that has been installed in the Priroda research module of the Mir Space Station. The Microgravity Isolation Mount (MIM) is also located in Priroda. The MIM was developed by the Canadian Space Agency to isolate experiments attached to it from ongoing g-jitter. The MIM is also able to induce defined vibrations so that the effects of specific disturbances on experiments can be studied. Additional experiments are being performed in individual experiment facilities that have been placed in the Priroda and other Mir modules.

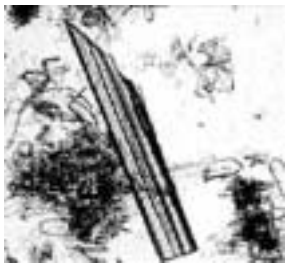
Various protein crystal growth experiments use the Gaseous Nitrogen Dewar (GN2 Dewar). Samples are placed in the GN2 Dewar and it is charged with liquid nitrogen, freezing them. The system is designed so that the life of the nitrogen charge lasts long enough to get the payload launched and into orbit. As the system absorbs heat, the nitrogen boils away and the chamber approaches ambient temperature. As the samples thaw, crystals start growing in the Dewar. The crystals are allowed to form throughout the long duration mission and are returned to Earth for analysis. Initial investigations using the Dewar served as a proof of concept for the experiment facility. Successive experiment runs using different samples will continue to improve our knowledge of protein crystal structures.

The Diffusion-Controled Crystallization Apparatus for Microgravity experiment is designed primarily for the growth of protein crystals in a microgravity environment. It uses the liquid/liquid and dialysis methods in which a precipitant solution diffuses into a bulk solution. In the experiment, a small protein sample is covered by a semipermeable membrane that allows the precipitant solution to pass into the protein solution to initiate the crystallization process. Diffusion starts on Earth as soon as the chambers are filled. However, the rate is so slow that no appreciable change occurs before the samples reach orbit one or two days later. Such an apparatus is ideally suited for the long duration Mir missions.

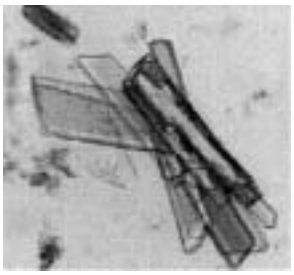
The Cartilage in Space—Biotechnology System experiment began with cell cultures being transported to Mir by the Shuttle in September 1996 on mission STS-79. The investigation is a test bed for the growth, maintenance, and study of long-term on-orbit cell growth in microgravity. The experiment investigates cell attachment patterns and interactions among cell cultures as well as cellular growth and the cellular role in forming functional tissue.



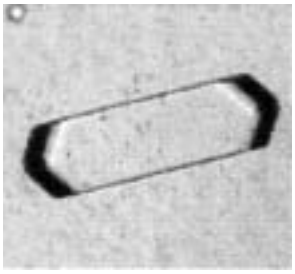
Thaumatin



Alpha Amylase

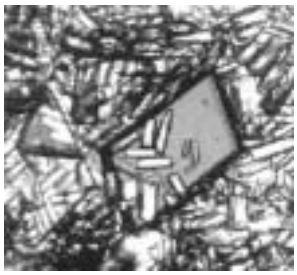


Creatine Kinase

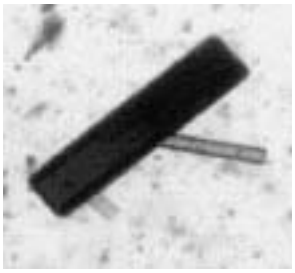


STMV

Ribonuclease



Rhombohedral Canavalin



Myoglobin

Hemoglobin

Protein and virus crystals grown in the GN2 Dewar on Mir.

The Biotechnology System-Cartilage in Space Experiment in orbit. Top: Astronauts Carl Walz (left) and Jay Apt prepare the experiment for transfer frorn the middeck of the Space Shuttle Atlantis to the Priroda module of Mir Bottom: Walz and Apt test the bioreactor media for pH, carbon dioxide, and oxygen levels.

The Candle Flames in Microgravity investigation conducted 79 candle tests in the Glovebox in July 1996. The experiments explored whether wick flames (candles) can be sustained in a purely diffusive environment or in the presence of a very slow, sub-buoyant convective flow. An associated goal was to determine the effect of wick size and candle size on burning rate, flame shape and color, and to study interactions between two closely spaced diffusion flames. Preliminary data indicate long-term survivability with evidence of spontaneous and prolonged flame oscillations near extinction (when the candle goes out).

The Forced Flow Flame Spreading Tests ran in the Glovebox in early August 1996. The investigations studied flames spreading over solid fuels in low-speed air flows in microgravity. The effects of varying fuel thickness and flow velocity of flames spreading in a miniature low-speed wind tunnel were observed. The data are currently being analyzed and compared to theoretical predictions of flame spreading. The numerical model predicted that the flame would spread at a steady rate and would not experience changes in speed, shape, size, or temperature.

The Interface Configuration Experiment Glovebox investigation studied how a liquid with a free surface in contact with a container behaves in microgravity. This provides a basis for predicting the locations and configurations of fluids with the use of mathematical models. The data are currently being analyzed.

The Technological Evaluation of the MIM (TEM) was a technology demonstration to determine the capabilities of the MIM. Through observations of liquid surface oscillations, TEM evaluated the ability of the MIM to impart controlled motions. The data are still being analyzed. A follow-on technology demonstration (TEM-2) was transferred to Mir in September 1996.

The Binary Colloidal Alloy Test Glovebox investigation was also launched to Mir on STS-79 in September 1996. The objective is to conduct fundamental studies of the formation of gels and crystals from binary colloid mixtures.

The Angular Liquid Bridge and Opposed Flow Flame Spread Glovebox investigations were carried to Mir by the Shuttle on mission STS-81 in early 1997. The former is an extension of previous fluid physics investigations conducted on the Shuttle and Mir and studies the behavior and shape of liquid bridges, liquid that spans the distance between two solid surfaces. The objective of the latter is to extend the understanding of the mechanisms by which flames spread, or fail to spread, over solid fuel surfaces in the presence of an opposing oxidizer flow.

A Space Acceleration Measurement System (SAMS) unit was launched to Mir on a Progress rocket in August 1994. Starting in October 1994, the SAMS was used to measure and characterize the microgravity environment of various Mir modules in support of microgravity experiments. Between October 1994 and September 1996, SAMS collected about sixty gigabytes of acceleration data. The data have been used to identify common vibration sources, as has been done with the Shuttles. This information has helped experimenters plan the timing and location of their experiments. The Passive Accelerometer System is a simple tool that is being used to estimate the quasi-steady microgravity environment of Mir during the increment between STS-79 and STS-81. The motion of a steel ball in a water-filled glass tube is tracked and the distance travelled over time is used to estimate accelerations caused by atmospheric drag and the location of the tube with respect to Mir's center of gravity.

Vibration Frequencies Commonly Seen in Mir Accelerometer Data

Freq. (Hz)	*Disturbance Source*
0.6	Kristall structural mode
1.0	Kristall structural mode
1.1	structural mode
1.2	structural mode
1.3	Kristall structural mode
1.9	Kristall structural mode
2.75	structural mode
3.75	structural mode
15	air quality system
24.1	humidifier/dehumidifier
30	air quality system harmonic
41	fan
43.5	fan
45	air quality system harmonic
90	air quality system harmonic
166.6	gyrodyne (system used to maintain Mir orientation)

This illustration depicts the International Space Station in its completed and fully operational state with elements from the United States, Europe, Canada, Japan, and Russia.

Future Directions

Microgravity science has come a long way since the early days of space flight when researchers realized that they might be able to take advantage of the reduced gravity environment of orbiting spacecraft to study different phenomena. Shuttle and Mir based experiments that study biotechnology, combustion science, fluid physics, fundamental physics, and materials science have opened the doors to a better understanding of many of the basic scientific principles that drive much of what we do on Earth and in space.

To reach the next level of understanding about phenomena in a microgravity environment, we need to perform experiments for longer periods of time, to be able to conduct a series of experiments as is done on Earth, and to have improved environmental conditions. The International Space Station is being developed as a microgravity research platform. Considerable attention has been given to the design of the station and experiment facility components so that experiments can be performed under high-quality microgravity conditions. The International Space Station will provide researchers with continuous, controlled microgravity conditions for up to thirty days at a time. (The time in between these thirty day increments is used for vibration-intensive activities such as Shuttle dockings, station reconfiguration, and upkeep.) This is almost twice as long as the microgravity periods available on the Space Shuttle and there will be a better environment than that provided by Mir. This increase in experiment time and improvement in conditions will be conducive to improved understanding of microgravity phenomena.

Continued microgravity research on the Shuttles, Mir, and on the International Space Station will lead to, among other things, the design of

improved drugs, fire protection and detection systems, spacecraft systems, high-precision clocks, and semiconductor materials. In addition, this research will allow us to create outposts on the Moon where we can build habitats and research facilities. The end result of research in microgravity and on the Moon will be the increased knowledge base necessary for our trips to and exploration of Mars.