Microgravity Primer

Gravity is a dominant factor in many chemical and physical processes on Earth.

- Heat applied to the bottom of a soup pot is conducted by the metal of the pot to the soup inside. The heated soup expands and becomes less dense than the soup above. It rises because cool, dense soup is pulled down by gravity, and the warm, less dense, soup rises to the top. A circulation pattern is produced that mixes the entire soup. This is called buoyancy-driven convection.

- Liquids of unequal density which do not interact chemically, like vinegar and oil, mix only temporarily when shaken vigorously together. Their different densities cause them to separate into two distinct layers. This is called sedimentation.

- Crystals and metal alloys contain defects and have properties which are directly and indirectly attributed to gravity-related effects. Convective flows such as those described above are present in the molten form of the material from which the solids are formed. As a result, some of the atoms and molecules making up the crystalline structure may be displaced from their intended positions. Dislocations, extra or missing half planes of atoms in the crystal structure, are one example of microscopic defects which create subtle, but important, distortions in the optical and electrical properties of the crystal.

Many basic processes are strongly influenced by gravity. For the scientific researcher, buoyancy-driven convection and sedimentation are significant phenomena because they have such a profound direct effect on the processes involved. They can also mask other phenomena that may be equally important but too subtle to be easily observed. If gravity's effects were eliminated, how would liquids of unequal densities mix? Could new alloys be formed? Could large crystals with precisely controlled crystalline and chemical perfection be grown? What would happen to the flame of a candle? There are many theories and experiments which predict the answers to these questions, but the only way to answer and fully understand these questions and a host of others is to effectively eliminate gravity as a factor. Drop towers, airplanes, sounding rockets, and the Space Shuttle make this possible, as will the International Space Station in a few years.

What are the subtle phenomena that gravity masks? What research will scientists pursue in microgravity?

The Fluid State

To most of us, the word "fluid" brings to mind images of water and other liquids. But to a scientist, the word fluid means much more. A fluid is any liquid or gaseous material that flows and, in gravity, assumes the shape of the container it is in. Gases fill the whole container; liquids on Earth fill only the lower part of the container equal to the volume of the liquid.

Scientists are interested in fluids for a variety of reasons. Fluids are an important part of life processes, from the blood in our veins and arteries to the oxygen in the air. The properties of fluids make plumbing, automobiles, and even fluorescent lighting possible. Fluid mechanics describes many processes that occur within the human body and also explains the flow of sap through plants. The preparation of materials often involves a fluid state that ultimately has a strong impact on the characteristics of the final product.

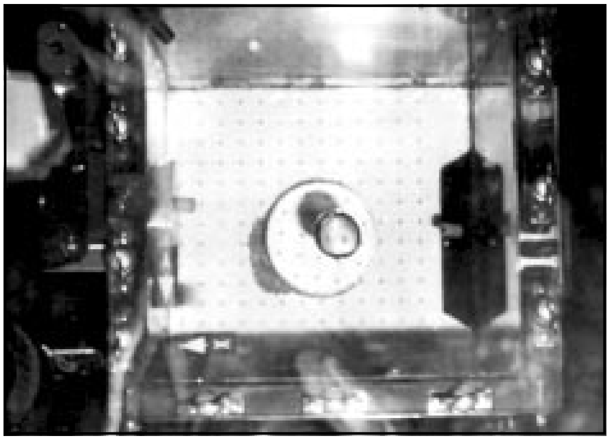


Figure 9. A liquid is manipulated by sound waves in the Drop Dynamics Module experiment on Spacelab 3. By using sound waves to position the drop, possible container wall contamination is eliminated.

Scientists gain increased insight into the properties and behavior of fluids by studying their movement or flow, the processes that occur within fluids, and the transformation between the different states of a fluid (liquid and gas) and the solid state. Studying these phenomena in microgravity allows the scientists to examine processes and conditions impossible to study when influenced by Earth's gravity. The knowledge gained can be used to improve fluid handling, materials processing, and many other areas in which fluids play a role. This knowledge can be applied not only on Earth, but also in space.

Fluid Dynamics and Transport Phenomena

Fluid dynamics and transport phenomena are central to a wide range of physical, chemical and biological processes, many of which are technologically important in both Earth- and space-based applications. In this context, the term transport phenomena refers to the different mechanisms by which energy and matter (e.g., atoms, molecules, particles, etc.) move. Gravity often introduces complexities which severely limit the fundamental understanding of a large number of these different transport mechanisms.

For example, buoyancy-driven flows, which arise from density differences in the fluid, often prevent the study of other important transport phenomena such as diffusion and surface tension-driven flows. Surface tension-driven flows are caused by differences in the temperature and/or chemical composition at the fluid surface. The fluid flows from areas where the surface tension is low to areas where it is high. Low gravity conditions can reduce by orders of magnitude the effects of buoyancy, sedimentation, and hydrostatic pressure, enabling observations and measurements which are difficult or impossible to obtain in a terrestrial laboratory. (Hydrostatic pressure is that pressure which is exerted on a portion of a column of fluid as a result of the weight of the fluid above it.)

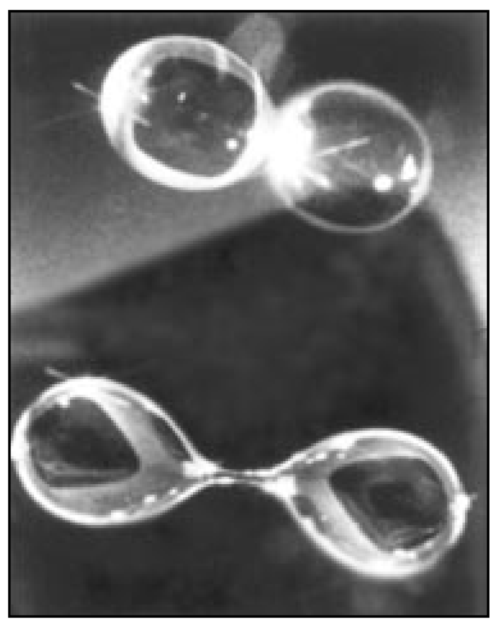


Figure 10. During an experiment on USML-1, a rotating liquid drop separates into two drops.

The systematic study of fluids under microgravity conditions holds the promise of refining existing theory or allowing the formulation of new theories to describe fluid dynamics and transport phenomena. Such research promises to improve the understanding of those aspects of fluid dynamics and transport phenomena whose fundamental behavior is limited or affected by the influence of gravity. Several research areas contain promising opportunities for significant advancements through low-gravity experiments. These research areas include: capillary phenomena, multiphase flows and heat transfer, diffusive transport, magneto/electrohydrodynamics, colloids, and solid-fluid interface dynamics. These terms will be defined in their respective sections.

Capillary Phenomena. Capillarity describes the relative attraction of a fluid for a solid surface compared with its self-attraction. A typical example of capillary action is the rise of sap in plants. Research in capillary phenomena is a particularly fertile area for low-gravity experiments because of the increased importance of capillary forces as the effects of gravity are reduced. Such circumstances are always encountered in multiphase fluid systems where there is a liquid-liquid, liquid-vapor, or liquid-solid interface. Surface tension-driven flows also become increasingly important as the effects of gravity are reduced and can dramatically affect other phenomena such as the interactions and coalescence of drops and bubbles.

Multiphase Flow and Heat Transfer. Capillary forces also play a significant role in multiphase flow and heat transfer, particularly under reduced-gravity conditions. It is important to be able to accurately predict the rate at which heat will be transported between two-phase mixtures and solid surfaces—for example, as a liquid and gas flow through a pipe. Of course, it is equally important to be able to predict the heat exchange between the two different fluid phases. Furthermore, when the rate of transferring heat to or from the multiphase fluid system reaches a sufficient level, the liquids or gases present may change phase. That is, the liquid may boil (heat entering the liquid), the liquid may freeze (heat leaving the liquid), or the gas may condense (heat leaving the gas). While the phase change processes of melting and solidification under reduced-gravity conditions have been studied extensively—due to their importance in materials processing—similar progress has not been made in understanding the process of boiling and condensation. Although these processes are broadly affected by gravity, improvements in the fundamental understanding of such effects have been hindered by the lack of experimental data.

Diffusive Transport. Diffusion is a mechanism by which atoms and molecules move through solids, liquids, and gases. The constituent atoms and molecules spread through the medium (in this case, liquids and gases) due primarily to differences in concentration, though a difference in temperature can be an important secondary effect in microgravity. Much of the important research in this area involves studies where several types of diffusion occur simultaneously.

Figure 11. Space Shuttle *Atlantis* crewmembers John E. Blaha and Shannon W. Lucid prepare liquids in a middeck experiment on polymer membrane processing.

The significant reduction in buoyancy-driven convection that occurs in a free-fall orbit may provide more accurate measurements and insights into these complicated transport processes.

Magneto/Electrohydrodynamics. The research areas of magnetohydrodynamics and electrohydrodynamics involve the study of the effects of magnetic and electric fields on mass transport (atoms, molecules, and particles) in fluids. Low velocity fluid flows, such as those found in poor electrical conductors in a magnetic field, are particularly interesting. The most promising low-gravity research in magneto/electrohydrodynamics deals with the study of effects normally obscured by buoyancy-driven convection. Under normal gravity conditions, buoyancy-driven convection can be caused by the fluid becoming heated due to its electrical resistance as it interacts with electric and magnetic fields. The heating of a material caused by the flow of electric current through it is known as Joule heating. Studies in space may improve techniques for manipulating multiphase systems such as those containing fluid globules and separation processes such as electrophoresis, which uses applied electric fields to separate biological materials.

Colloids. Colloids are suspensions of finely divided solids or liquids in gaseous or liquid fluids. Colloidal dispersions of liquids in gases are commonly called aerosols. Smoke is an example of fine solid particles dispersed in gases. Gels are colloidal mixtures of liquids and solids where the solids have linked together to form a continuous network. Research interest in the colloids area includes the study of formation and growth phenomena during phase transitions—e.g., when liquids change to solids. Research in microgravity may allow measurement of large scale aggregation or clustering phenomena without the complication of the different sedimentation rates due to size and particle distortion caused by settling and fluid flows that occur under normal gravity.

Solid-Fluid Interface Dynamics. A better understanding of solid-fluid interface dynamics, how the boundary between a solid and a fluid acquires and maintains its shape, can contribute to improved materials processing applications. The morphological (shape) stability of an advancing solid-fluid interface is a key problem in such materials processing activities as the growth of homogeneous single crystals. Experiments in low-gravity, with significant reductions in buoyancy-driven convection, could allow mass transport in the fluid phase by diffusion only. Such conditions are particularly attractive for testing existing theories for processes and for providing unique data to advance theories for chemical systems where the interface interactions strongly depend on direction and shape.

Combustion Science

There is ample practical motivation for advancing combustion science. It plays a key role in energy transformation, air pollution, surface-based transportation, spacecraft and aircraft propulsion, global environmental heating, materials processing, and hazardous waste disposal through incineration. These and many other applications of combustion science have great importance in national economic, social, political, and military issues. While the combustion process is clearly beneficial, it is also extremely dangerous when not controlled. Enormous numbers of lives and valuable property are destroyed each year by fires and explosions. Two accidents involving U.S. spacecraft in the Apollo program were attributed to gaps in the available knowledge of combustion fundamentals under special circumstances. Planning for a permanent human presence in space demands the development of fundamental combustion science in reduced gravity to either eliminate spacecraft fires as a practical possibility or to develop powerful strategies to detect and extinguish incipient spacecraft fires. Advances in understanding the combustion process will also benefit fire safety in aircraft, industry, and the home.

The recently developed capability to perform experiments in microgravity may prove to be a vital tool in completing our understanding of combustion processes. From a fundamental viewpoint, the most prominent feature that distinguishes combustion processes from processes involving fluid flow is the large temperature variations which invariably exist in a reacting flow. These large temperature variations are caused by highly-localized, highly-exothermic heat release from the chemical reactions characteristic of combustion processes. For example, the temperature of a reactive mixture can increase from the unreacted, ambient state of about 25°C (around room temperature) to the totally reacted state of over 2750°C. These large temperature differences lead to correspondingly large density differences and hence, to the potential existence of strong buoyancy-driven fluid flows. These flows can modify, mask, or even dominate the convective-diffusive transport processes that mix and heat the fuel and oxidant reactants before chemical reactions can be initiated. For combustion in two-phase flows, the presence of gravity introduces additional complications. Here particles and droplets can settle, causing stratification in the mixture. The effects of surface tension on the shape and motion of the surface of a large body of liquid fuel can also be modified due to the presence of buoyancy-driven flows.

Gravity can introduce a degree of asymmetry in an otherwise symmetrical phenomenon. For example, combustion of a gaseous jet injected horizontally quickly loses its symmetry along its long axis as the hot flame plume gradually tilts ‘upward.’ The fluid transport processes in these situations are inherently multi-dimensional and highly complex.

Important as it is, buoyancy is frequently neglected in the mathematical analysis of combustion phenomena either for mathematical simplicity or to facilitate identification of the characteristics of those controlling processes which do not depend on gravity. Such implications, however, can render direct comparison between theory and experiment either difficult or meaningless. It also weakens the feedback process between theoretical and experimental developments which is so essential in the advancement of science.

Materials Science

The current materials science program is characterized by a balance of fundamental research and applications-oriented investigations. The goal of the materials science program is to utilize the unique characteristics of the space environment to further our understanding of the processes by which materials are produced, and to further our understanding of their properties, some of which may be produced only in the space environment. The program attempts to advance the fundamental understanding of the physics associated with phase changes. This includes solidification, crystal growth, condensation from the vapor, etc. Materials science also seeks explanations for previous space-based research results for which no clear explanations exist. Research activities are supported which investigate materials processing techniques unique to the microgravity environment, or which, when studied in microgravity, may yield unique information with terrestrial applications.

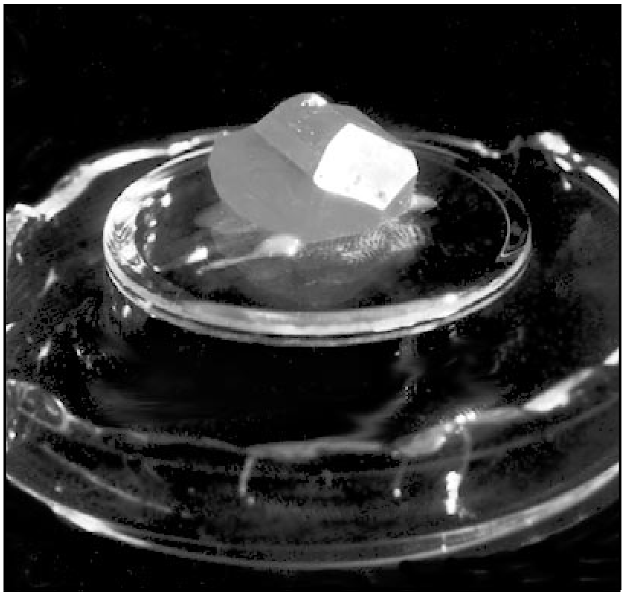


Figure 12. Crystal of mercuric iodide grown by physical vapor transport during a Spacelab experiment.

Microgravity Materials Science Background

The orbital space environment offers the researcher two unique features which are attainable on Earth to only a very limited extent. These are 'free fall' with the attendant reduced gravity environment and a high quality vacuum of vast extent. Suborbital conditions of free fall are limited to less than 10 seconds in drop towers, less than 25 seconds during aircraft maneuvers, and less than 15 minutes during rocket flights. The quality of the microgravity environment of these various ground-based options ranges from 10^{-2} g to 10^{-5} g. With the Space Shuttle, this duration has been extended to days and weeks—with Space Station and free flyers, to months and years.

In a reduced gravity environment, relative motion is slowed in direct proportion to the reduction in net acceleration. At 10^{-6} g, particles suspended in a fluid will sediment a million times more slowly than they do on Earth. Thermal and solutal convection is much less vigorous in microgravity than it is on Earth, and in some cases seems to become a secondary transport mechanism.

Both thermal and solutal convection are examples of buoyancy-driven convection. In the first case, the difference in density is caused by a difference in temperature; in the second case, the density difference is caused by the changing chemical composition of the liquid. As indicated previously, buoyancy-induced convection can be suppressed in a low-gravity environment. For many materials science investigations, this experimental condition is extremely interesting because it allows us to study purely diffusive behavior in systems for which conditions of constant density are difficult or impossible to create or for which experiments in 'convection-free' capillaries lead to ambiguous results.

To date, much of the space-based research has focused on this unique condition with respect to processing materials which are particularly susceptible to compositional nonuniformities resulting from convective or sedimentation effects. The process by which compositionally nonuniform material is produced is referred to as segregation. Some of the first microgravity experiments in metallurgy were attempts to form fine dispersions of metal particles in another metal when the two liquid metals are immiscible. Unexpected separation of the two metals seen in several low gravity experiments in this area has given us new insight into the mechanisms behind dispersion formation (fine droplets of one metal dispersed in another metal), but a complete model including the role of critical wetting, droplet migration, and particle pushing has yet to be formulated.

There is no dispute that gravity-driven convective flows in crystal growth processes affect mass transport. This has been demonstrated for crystals growing from the melt as well as from the vapor. The distribution of components in a multicomponent system has a marked influence on the resultant properties of a material (for example, the distribution of selenium atoms in the important electronic material, GaAs). Consequently, space processing of materials has always carried with it the hope of reducing convective flows during crystal growth to such a degree that crystallization would proceed in a purely diffusive environment for mass transport, to result in crystals with uniform composition. However, the expectation of space-processed, perfectly homogeneous materials with improved properties has yet to be realized. Future experiments on crystal growth will be directed at a wide variety of electronic materials such as GaAs, triglycine sulfate, HgI_2, HgCdTe (from the vapor), CdTe, HgZnTe, $PbBr_2$ and PbSnTe. In addition, the research of our international collaborators will include InGaAs, InSb, SiAsTe, Si, GaInSb, InP, and Ge.

In order to understand crystal growth processes in microgravity, it is essential that many aspects of these phase transformations (e.g., liquid to solid, vapor to solid) be understood. This includes a thorough knowledge of the behavior of fluids (gases and liquids), a fundamental understanding of the crystallization process, and a sufficient data base of thermophysical information (e.g., thermal conductivities, diffusion coefficients, etc.) with which various theories can be tested. It may be necessary to measure some of these quantities in microgravity, as ground-based data may be either subject to error or even impossible to generate.

The flight research focussing on fundamental problems in solidification reflects this broad scope of activity, ranging from studies of morphological stability in transparent organic systems (which serve as excellent experimental models of metallic systems) to studies of metals solidifying without the confinement of a container.

Microgravity Materials Science Research

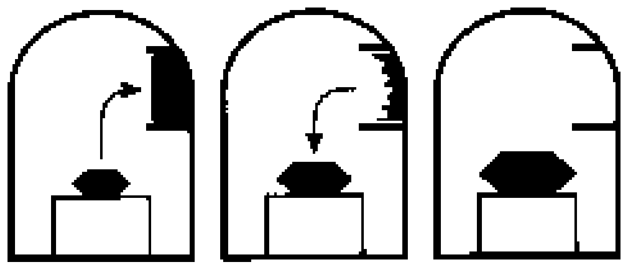
The field of materials science is extremely broad. It encompasses essentially all materials, concerns itself with the synthesis, production, and further processing of these materials, and deals with matter both on an atomistic level and on a bulk level. Although materials science addresses a myriad of problems, there are fundamental scientific issues common to all of its subdisciplines. These include evolution of the microscopic structure of the materials, transport phenomena, and the determination of relevant thermophysical properties. Interface morphology and stability, and macro- and micro-segregation (the distribution of a component on the microscopic and macroscopic scales) represent ongoing challenges.

Historically, the materials science community has segmented itself on the basis of materials (composites, steels, polymers), on the basis of specific processes (casting, solidification, welding), and on the basis of fundamental physical phenomena (property measurements, diffusion studies, study of morphological stability).

<u>Materials</u>. The materials of interest to the microgravity materials science discipline have traditionally been categorized as electronic, metallic, glass, and ceramic. However, recent space experiments have broadened this traditional categorization to include polymeric materials as well. Additional classes of materials which may benefit greatly from being studied in a low gravity environment are: advanced composites, electronic and opto-electronic crystals, high performance metal alloys, and superconductors (high temperature and low temperature, metallic, ceramic, and organic). For their scientific and technological significance, there is also strong interest in composites, fibers, foams, and films, whatever their

constitution, when the requirement for experiments in low gravity can be clearly defined.

Processes. Because the manifestation of gravitational effects is greatest in the presence of a fluid, the following processes are of considerable importance: solidification, crystallization from solution, and condensation from the vapor. These processes have been the subject of numerous low-gravity investigations for many years. Scientifically interesting, and potentially important technologically, are the processes of welding and electrodeposition. Unique welding experiments in Skylab and recent low-gravity electrodeposition experiments in sounding rockets have produced unexplained results. The ultra-high vacuum and nearly infinite pumping rate of space offer researchers the possibility of pursuing ultra-high vacuum processing of materials and, perhaps, ultra-purification.



Seed warmed; atoms go from seed to source.

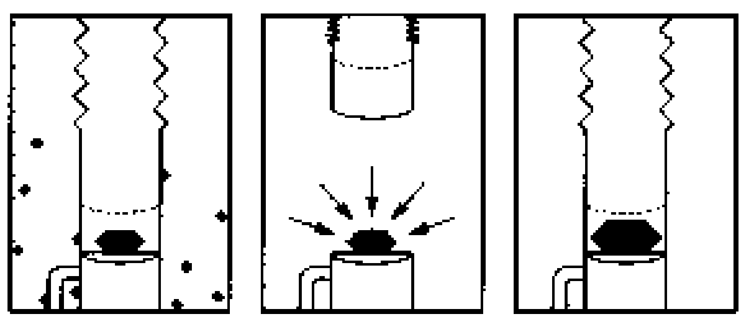
Seed cooled; crystal growth begins.

Source depleted; growth complete.

Figure 13. Vapor Crystal Growth System

Of primary importance is the utility of the space environment in helping an investigator understand the process of interest. Can a low-gravity environment be used to our advantage in elucidating important scientific information concerning these processes? Are there processes that are truly unique to the microgravity environment?

Phenomena. On a macroscale, convective motion, induced by residual accelerations or other effects, persists in the liquid or gaseous fluid from which a material is either solidifying, crystallizing, or condensing. On a microscale, the arrangement of atoms or molecules in a solid occurs at a boundary between the ‘frozen’ solid and the convecting fluid. The interaction between these convective flows and the resultant solid formation needs much greater understanding. A critical issue facing space-based materials science research is the response of experiments to more or less random acceleration environments within a manned spacecraft. Are compositional inhomogeneities and other major defects results of such random accelerations? What is the tolerable acceleration level for a given experiment? Are there ways of increasing experimental tolerance to a given level of acceleration? The answers to these questions will not only enhance our understanding of fundamental phenomena but also provide the foundations upon which useful space-based laboratories for materials science can be designed.



Seed crystal protected from solution; crystallites dissolving.

Crystal growth from solution initiated.

Growth completed; crystal protected.

Figure 14. Solution Crystal Growth Process

Shot Towers
The idea of using “free fall” or microgravity for research and materials processing is not a new one. American colonists used free fall to produce lead shot for their weapons. This process, patented by British merchant William Watts in 1782, involved pouring molten lead through a sieve at the top of a 15- to 30-meter-tall tower. As the lead fell, the drops became nearly perfect solid spheres that were quenched upon landing in a pool of water at the foot of the tower. Free fall produced shot superior to that produced by other methods. Scientists now explore both the phenomenon of microgravity and the use of microgravity for materials research.

Since the pioneering diffusion experiments conducted on Spacelab D-1 concerning self-diffusion in tin, there has been a heightened awareness of the need to measure the appropriate thermophysical parameters of the material under investigation. It hardly suffices, in many instances, to conduct an experiment in a diffusion-controlled environment, if the analysis of the experiment uses ground-based thermophysical data which may be in error. To avoid ambiguity in the interpretation of space experiments, it may be necessary to generate data on selected materials parameters from actual low-gravity experiments. This area of research is particularly important to the entire materials science field.

Biotechnology

The biotechnology program is comprised of three areas of research: protein crystal growth, mammalian cell culture, and fundamentals of biotechnology.

Protein Crystal Growth

The protein crystal growth program is directed to: (1) contribute to the advance in knowledge of biological molecular structures through the utilization of the space environment to help overcome a principal obstacle in the determination of molecular structures—the growth of crystals suitable for analysis by X-ray diffraction; and (2) advance the understanding of the fundamental mechanisms by which large biological molecules form crystals. The program seeks to develop these objectives through a coordinated effort of space- and ground-based research, whereby ground-based research attempts to use and explain the results of flight research, and flight research incorporates the knowledge gained from ground-based research and prior flight experience to develop refined techniques and objectives for subsequent experiments.

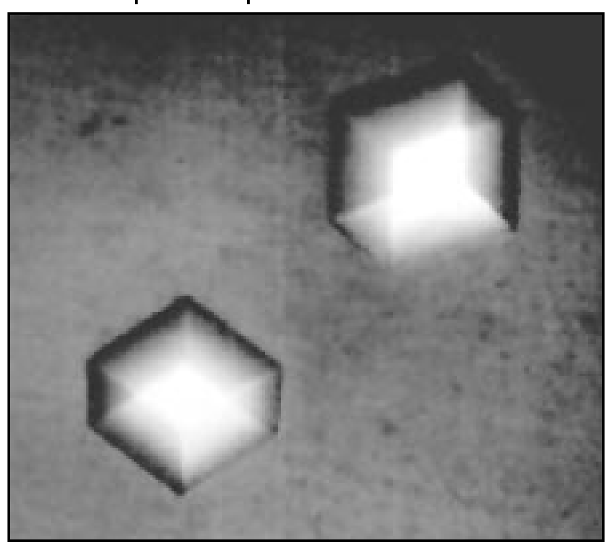


Figure 15. Canavalin protein crystals grown in microgravity.

Mammalian Cell Culture

The mammalian cell culture program seeks to develop an understanding sufficient to assess the scientific value of mammalian cells and tissues cultured under low-gravity conditions, where mechanical stresses on growing tissues and cells can be held to very low levels. Preliminary evidence from the culture of a variety of suspended cells in rotating vessels has shown indications of increased viability and tissue differentiation. These results suggest that better control of the stresses exerted on cells or tissues can play an important role in the culture of *in vitro* tumor models, normal tissues, and other challenging problems.

Fundamentals of Biotechnology

This area of research is concerned with the identification and understanding of biotechnological processes and biophysical phenomena which can be advantageously studied in the space environment. Potential research areas include molecular and cellular aggregation, the behavior of electrically-driven flows, and capillary and surface phenomena, as applied uniquely to biological systems.

Background of Protein Crystal Growth Flight Experiments

The first protein crystal growth experiments in space were conducted on the Spacelab-1 mission in 1983 where crystals of hen egg white lysozyme and beta-galactosidase were grown. In the mid-1980's, a hand-held device for protein crystal growth experiments was developed and flown on four Shuttle missions as a precursor to the Vapor Diffusion Apparatus (VDA) - Refrigerator/ Incubator Module experiments later flown in the Shuttle middeck. Despite having encountered a number of minor technical difficulties on several flights, the project has enjoyed significant success. These include the growth of crystals to sizes and degrees of perfection beyond any ground-based efforts, and the formation of crystals in scientifically useful forms which had not been previously encountered in similar ground-based experiments. Though the physics of protein crystal growth are understood in broad terms, there is currently no agreement on a detailed mechanistic explanation for these phenomena.

Microgravity and Space Flight

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

Initial research centered around solving space flight problems created by microgravity. 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 NASA Lewis Research Center and NASA 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.

The first long-term opportunities to explore the microgravity environment 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 the 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 volume available on the Apollo spacecraft, or by the low number of flight opportunities provided by Skylab. These experiments, as simple as they were, often stimulated new insights in 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 with Skylab.

Figure 16. 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, 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 scientists 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 carry microgravity experiments as secondary payloads.

Spacelab-1, November 1983

The Spacelab-1 mission was launched in November 1983. Over ten days, the seven crewmembers carried out a broad variety of space science experiments, including research in microgravity sciences, astrophysics, space plasma physics, and Earth observations.

Although 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 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 behavior of molten metals. A German investigator grew protein crystals that were significantly better than those grown from the same starting materials on the ground. These crystals were analyzed using X-rays to determine the structure of the protein that was grown.

Spacelab-3, April 1985

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. The experiment produced a crystal of mercury iodide grown at a rate much higher than that achievable on the ground. Despite the high rate of growth and relatively short growth time available, 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 have been used to improve numerical models of our atmosphere.

Spacelab D-1, October 1985

In October 1985, six months after the flight of SL-3, NASA launched a Spacelab mission sponsored by the Federal Republic of Germany, designated Spacelab-D1. This mission included a significant number of sophisticated microgravity materials and fluid science experiments. 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. On Earth, convection-induced disturbances make such measurements impossible.

Spacelab Life Sciences-1, June 1991

The Spacelab Life Sciences-1 mission, flown in June 1991, was the first Spacelab mission dedicated to life sciences research. Mission experiments were aimed at trying to answer many important questions regarding the functioning of the human body in microgravity and its readaptation to the normal environment on Earth. Ten major investigations probed autonomic cardiovascular controls, cardiovascular adaptation to microgravity, vestibular functions, pulmonary function, protein metabolism, mineral loss, and fluid-electrolyte regulation.

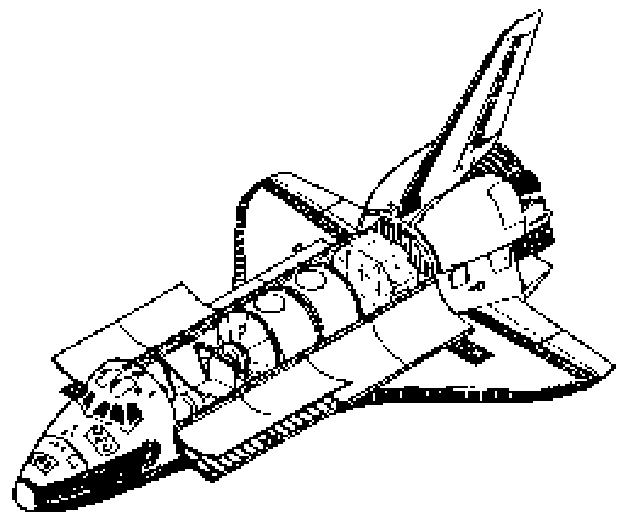


Figure 17. Spacelab long module in Orbiter payload bay.

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. Since IML-1 researchers have reported impressive results for mission experiments. Several biotechnology experiments concerned with protein crystal growth enabled NASA scientists to successfully test and compare two different crystal-growing devices. For example, U.S. researchers used a Protein Crystal Growth apparatus to obtain unusually high quality crystals of human serum albumin (HSA), which is the most abundant protein in human blood. Because the space crystals were of much better quality than had been obtained on Earth, it has since been possible to use X-ray methods to determine important details of atom positions within the crystal structure. This work may have major medical applications, especially in the development of methods for attaching therapeutic drugs to HSA, which could then transport a drug in the bloodstream to body sites where it is needed.

A German device called the Cryostat also produced superior-quality crystals of proteins from several microorganisms. One experiment yielded unusually large crystals of the satellite tobacco mosaic virus (STMV), which has roles in diseases affecting more than 150 crop plants. Using the large crystals, researchers were then able to decipher the overall structure of STMV's genetic material, which is located deep within the tiny virus. Principal Investigator Dr. Alexander McPherson reported that the STMV space crystals produced "the best resolution data obtained on any virus crystal, by any method, anywhere." As a result, 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.

IML-1 also carried experiments designed to probe how microgravity affects the internal structure of metal alloys as they solidify. When an alloy solidifies, tiny crystal branches called "dendrites" form in the cooling liquid. On Earth, gravity-driven fluid flow (convection) in the liquid influences forming dendrites. Among other effects, convection can produce flaws that undermine key properties of the alloy, such as its mechanical strength and ability to resist corrosion. However, by processing alloys in a low gravity environment, it may be possible to understand the role gravity plays in determining alloy properties. In the Casting and Solidification Technology (CAST) experiment, a simple alloy was solidified under controlled conditions. Investigators are still interpreting data from the tests, but preliminary results indicate that the alloy solidified about 50 percent faster than on Earth, and far fewer structural flaws developed. These growth characteristics 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. This mission marked the beginning of a new era in microgravity research.

The payload included 31 experiments in biotechnology, combustion science, fluid physics, materials science, and technology demonstrations. Several investigations used facilities or instruments from previous flights, including the Protein Crystal Growth (PCG) facility, a Space Acceleration Measurement System (SAMS), and the Solid Surface Combustion Experiment (SSCE). New experiment facilities, all designed to be reusable on future missions, included: the Crystal Growth Furnace, a Glovebox provided by the European Space Agency, the Surface Tension Driven Convection Experiment apparatus (STDCE), and the Drop Physics Module. The mission was an unqualified operational success in all of the areas listed above, with the crew conducting what became known as a "dress rehearsal" for the International Space Station.

Figure 18. The first Spacelab mission dedicated to United States microgravity science on USML-1. The coast of Florida appears in the background.

USML-1 included the first use in space of the Crystal Growth Furnace (CGF), a device that permitted investigators to grow crystals of four different semiconductor materials at temperatures as high as 1260ºC. 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. Semiconductors (The most widely used one is silicon.) are used in computer chips and other electronics.

Other USML-1 experiments also contributed to NASA's protein crystal growth program. Sixteen different investigations run by NASA researchers used the Glovebox (GBX), which provided a safe enclosed working area; it also was equipped with photographic equipment to provide a visual record of investigation operations. The GBX 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 GBX provided the best-ever crystals of malic enzyme that may be useful in developing anti-parasitic drugs.

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.

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. Preliminary results indicate that the dynamics of rotating drops of silicone oil also conformed to theoretical predictions. Results of this kind are significant in that they illustrate an important part of the scientific method: hypotheses are formed, and experiments are conducted to test them.

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. Astronauts burned small candles in the Glovebox, an enclosed, safe environment. The results were similar (though much longer lived) to what can be seen by conducting the experiment in free fall, here on Earth. (See *Activity 8, Candle Drop*, in the Activities section of this teacher's guide.) The candles burned for about 45-60 seconds in the microgravity of continuous free fall aboard the Space Shuttle *Columbia*.

Another GBX 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 theoretical information. It 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.)

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). It also was the most ambitious scientific venture between the two countries to date.
NASA microgravity experiments focused on protein crystal growth and evaluating the SAMS (Space Acceleration Measurement System) that flew on IML-1.

NASDA's science payload consisted of 22 experiments focused on materials science and the behavior of fluids, and 12 human biology experiments. Researchers are currently analyzing data from these investigations. NASDA also contributed two devices that could be used on future missions. One of these, the Large Isothermal Furnace, is used to explore how various aspects of processing affect the structure and properties of materials. The second apparatus was a Free-Flow Electrophoresis Unit, which can be used to separate different types of molecules in a fluid. In microgravity, the unit may produce purer samples of certain substances than can be obtained on Earth.

Figure 19. Astronaut Bonnie J. Dunbar, USM-1 payload commander, is about to load a sample in the Crystal Growth Furnace as payload specialist Lawrence J. DeLucas, at the multipurpose glovebox, confers with her.

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 microgravity experiments that scientists on the ground can supervise by remote control.

The carrier in the Cargo Bay consisted of two Mission Peculiar Equipment Support Structures (MPESS). The on-board Space Acceleration Measurement System (SAMS) 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 beginning of MEPHISTO, a multi-mission collaboration between NASA scientists and French researchers. MEPHISTO is designed to study changes in molten metals and some other substances as they solidify. 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 was transmitted from the Space Shuttle to NASA's Marshall Space Flight Center in Huntsville, Alabama. There, researchers analyzed the information and sent back commands for adjustments. In all, the investigators relayed more than 5000 commands directly to their instruments on orbit. Researchers are comparing mission data with the predictions of theoretical models. Conducting the experiments in microgravity enabled the researchers to obtain conditions during solidification that more closely agree with those assumed by the models. On Earth, gravity effects skew the conditions that develop during solidification. This first MEPHISTO effort proved that telescience projects can be carried out efficiently, with successful results.

A lambda point is the combination of temperature and pressure at which a normal liquid changes to a superfluid. On Earth, effects of gravity make it impossible to measure properties of substances very close to this point. On USMP-1, a Lambda Point Experiment took advantage of reduced gravity in Earth orbit. As liquid helium was cooled to an extremely low temperature—a little more than 2ºK 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 was 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

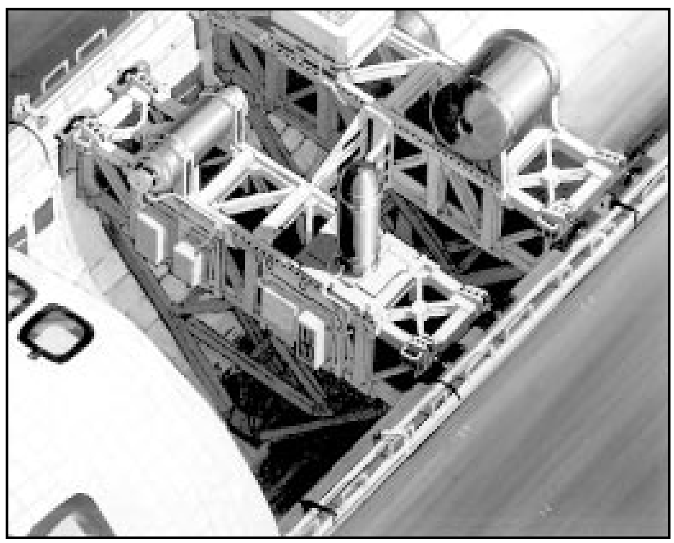


Figure 20. USMP-2 experiments mounted in the forward section of the open payload bay of the Space Shuttle.

10,000 commands relayed by scientists at NASA Marshall Space Flight Center. USMP-2 also included two Space Acceleration Measurement Systems (SAMS), which provided scientists on the ground with nearly instant feedback on how various kinds of motion—including crew exercise and vibrations from thruster engines—affected mission experiments. An Orbital

Acceleration Research Experiment (OARE) in the Cargo Bay collected additional data on acceleration and served as a test run for a United States Microgravity Laboratory mission currently slated for September, 1995.

Throughout the mission, the Critical Fluid Light Scattering Experiment (CFLSE)—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, and a series of measurements were taken of how the laser beams were deflected (scattered) 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.

An 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 that 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 (branching structures that develop as a molten metal solidifies) were sent to the ground and examined by the research team. In another successful demonstration of telescience, the team relayed back more than 100 commands to the IDGE, fine-tuning its operations. Initial findings have already identified a major role gravity that plays as a metal changes from a liquid to a solid on Earth. Space Acceleration Measurement System data obtained during IDGE operations provided insight on how small accelerations during space experiments can influence the processes.

Figure 21. A dendrite grown in the Isothermal Dendritic Growth Experiment (IDGE) aboard the USMP-2. This is an example of how most metals solidify.

USMP-2 also included a second MEPHISTO experiment, following up the first in this joint U.S./French effort that was part of USMP-1. On this mission, the MEPHISTO apparatus was used for U.S. experiments to test how gravity affects the formation of crystals in an alloy that behaves much like a semiconductor during crystal growth. Another USMP-2 experiment, using the Advanced Automated Directional Solidification Furnace (AADSF), will also help shed new light on how such crystals grow. A 10-day experiment using the AADSF yielded a large, well-controlled sample of an alloy semiconductor. As this sample is analyzed, researchers should be able to verify or refute theories related to how such crystals form. That information in turn may eventually be used to produce improved semiconductors here on the ground.

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 date. IML-2 truly was a world class venture, representing the work of scientists from the U.S. and 12 other countries. The mission recorded an impressive list of "firsts." Experiments from NASA's Microgravity Science and Applications Program included investigations in materials science, biotechnology, and fluid physics.

Materials science experiments focused on various types of metal 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 Large Isothermal Furnace first flown on the SL-J mission in 1992. It successfully sintered alloys of nickel, iron, and tungsten.

Other experiments explored the capabilities of a German-built facility called TEMPUS. Designed to position experiment samples away from the surfaces of a container, in theory TEMPUS could 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.

Biotechnology experiments expanded research use of 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 9 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 changing temperature influences the movement and shape of gas bubbles and liquid drops. A newly developed Critical Point Facility worked flawlessly. This device enables a researcher to study how a fluid behaves at its critical point. This point occurs at the highest temperature where liquid and vapor phases can coexist. Research using the Critical Point Facility will be applicable to a broad range of scientific questions, including how various characteristics of solids change under different experimental conditions.

Secondary Objectives

In addition to Spacelab flights, NASA frequently flies microgravity experiments in the Space Shuttle middeck, in the cargo bay, and in the Get-Away-Special (GAS) canisters. Since 1988, NASA has built on the results of the first Spacelab mission by growing crystals of many different kinds of proteins on the Shuttle middeck, including several sets of space-grown protein crystals that are substantially better than Earth-grown crystals of the same materials. Medical and agricultural researchers hope to use information from these protein crystals to improve their understanding of how the proteins function.

Research conducted in the Shuttle middeck has also led to the first space product: tiny spheres of latex that are significantly more uniform in size than those produced on the ground. These precision latex spheres are so uniform that they are sold by the National Institute of Standards and Technology (NIST) as a reference standard for calibrating devices such as electron microscopes and particle counters.