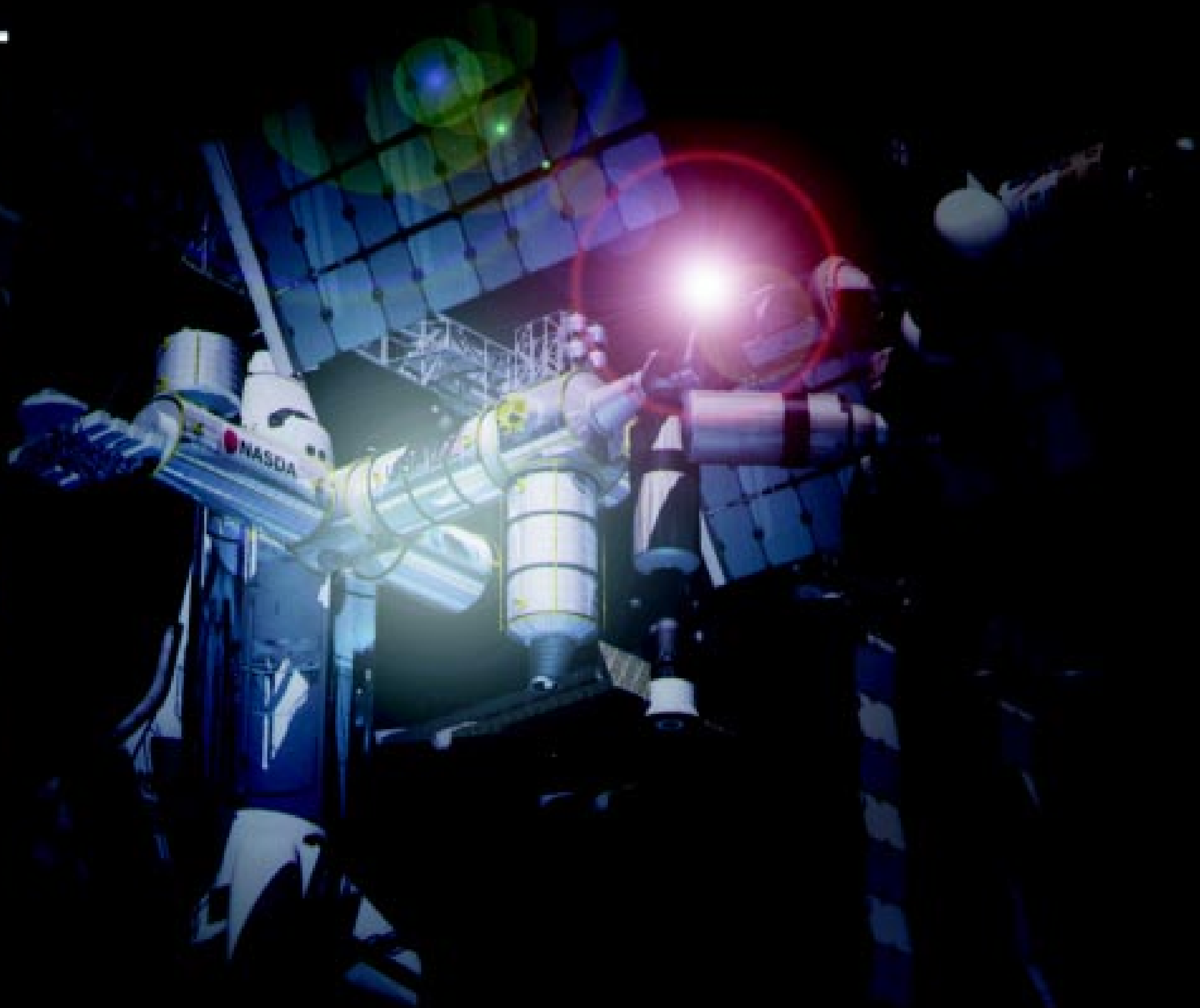
The International Space Station

Improving Life on Earth and in Space

The NASA Research Plan, an Overview



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Foreword

Daniel S. Goldin

Gravity is a force of attraction between all matter in the universe, affecting virtually every physical, chemical, and biological process that surrounds us. Only recently has humankind been able to manipulate gravity in scientific experiments, uncovering nuances of our world never before imagined. Missions conducted on Skylab, the Space Shuttles, *Mir,* and robotic platforms have provided important but limited opportunities to understand nature in the absence of gravity's effects. Access to a permanently crewed space laboratory is a critical opportunity to focus research on the behavior of matter without the masking influence of Earth's pull.

As we perform ground-breaking research in the unique environment of Earth orbit, we will be learning how to live and work in space as part of an international crew. This aspect of the International Space Station (ISS)—its human experiment—will serve as a springboard for our next great leap in space exploration and development, as we send our astronauts to explore Earth's neighborhood.

The ISS is an unprecedented undertaking in scientific, technological, and international experimentation. Whether the research improves our industrial processes, increases fundamental knowledge, helps us to look after our health, or enables us to take the next steps in the exploration and development of space, research on board the ISS should bring enduring benefits for life on Earth and in space. Collaboration among our international, industrial, and academic partners will ensure that the benefits from ISS work are felt across the global spectrum of public and private interests.

Women and men will perform work on the ISS that will cover the gamut from fundamental scientific inquiry to advanced technology and commercial product development. Indeed, the synergy between scientific research and product development will be an important aspect of ISS work, since an understanding of fundamental physical, chemical, and biological processes is a critical step in the development of new commercial products. Efforts over the next few years may well provide the foundation for a 21st century "boom in space," as investigators research tomorrow's products today on board the ISS.

Soon we will begin laying the foundation for a multinational, permanent human presence in space. In doing so, we will truly open the space frontier, replete with its tremendous challenge for the human spirit and its promise of intellectual and material riches. The ISS will be a world community living and working together in space, improving life on Earth and expanding humanity's horizons for the 21st century.

Daniel S. Goldin
NASA Administrator

NASA pursues a three-part mission in space and aviation encompassing scientific research, exploration, and technology transfer and development. The NASA Strategic Enterprise for the Human Exploration and Development of Space (HEDS) supports this mission in its quest to bring the frontier of space fully within the sphere of human activity to build a better future for all humankind. The goals of NASA and HEDS are guided by the following six fundamental questions of science and research. The ISS will play a central role in helping us answer these questions:

- How did the universe, galaxies, stars, and planets form and evolve? How can our exploration of the universe and the solar system revolutionize our understanding of physics, chemistry, and biology?

- Does life in any form, however simple or complex, carbon-based or other, exist elsewhere than on planet Earth? Are there Earth-like planets beyond our solar system?

- How can we utilize the knowledge of the Sun, Earth, and other planetary bodies to develop predictive environmental, climate, natural disaster, and natural resource models to help ensure sustainable development and improve the quality of life on Earth?

- What is the fundamental role of gravity and cosmic radiation in vital biological, physical, and chemical systems in space, on other planetary bodies, and on Earth, and how do we apply this fundamental knowledge to the establishment of permanent human presence in space to improve life on Earth?

- How can we enable revolutionary technological advances to provide air and space travel for anyone, anytime, anywhere more safely, more affordably, and with less impact on the environment and improve business opportunities and global security?

- What cutting-edge technologies, processes, and techniques and engineering capabilities must we develop to enable our research agenda in the most productive, economical, and timely manner? How can we most effectively transfer the knowledge we gain from our research and discoveries to commercial ventures in the air, in space, and on Earth?

This ISS Research Plan overview is a NASA Implementation Plan for the ISS Program, and it describes how NASA will utilize the ISS platform. This document, when coupled with the technical version of the ISS Research Plan (to be published in 1998), will be a component of the NASA Strategic Management System and provide a basis for accountability in the ISS Program.

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Part I

Putting Space to Work the World Over

Introducing the International Space Station

In the world of human endeavor, the International Space Station (ISS) will break new ground. With its first elements scheduled for launch in 1998, the ISS will afford scientists, engineers, and entrepreneurs an unprecedented platform on which to perform complex, long-duration, and replicable experiments in the unique environment of space. The Station will maximize its particular assets: prolonged exposure to microgravity and the presence of human experimenters in the research process. Yet the ISS is much more than just a world-class laboratory in a novel environment; it is an international human experiment—an exciting "city in space"—a place where we will learn how to live and work "off planet" alongside our international partners.

As an international crew of astronauts lives and works in space, the ISS community will expand here on Earth as researchers use the technologies of "telescience" to control and manipulate experiments from the ground. Advancing communications and information technologies will allow Earth-bound investigators to enjoy a "virtual presence" on board the ISS as they take their place in a world community that will use and benefit from an orbiting laboratory. Our city in space will include as its citizens the international cadre of astronauts and the researchers whose virtual presence will make the incredible breadth of ISS research possible.

This ambitious human experiment in our city in space will play out as the ISS executes its concurrent roles as:

- An advanced testbed for technology and human exploration
- A world-class research facility
- A commercial platform for space research and development

The governments of the United States, Canada, Europe,[1] Japan, and Russia are collaborating with their commercial, academic, and other international affiliates in the design, operation, and utilization of the ISS. As our astronauts and Earth-bound researchers act as space operators and investigators, they will generate a wealth of knowledge that we will apply in the fields of commerce, science, engineering, education, and space exploration.

NASA is committed to using the ISS program to enhance math and science education in our Nation's classrooms. Student projects will fly on the ISS, while interactive videoconferencing and telescience technologies will involve students and teachers in ISS experiments from the ground. The ISS will be a virtual classroom in space, as the excitement of space research and development is used to engage the interest of our next generation of scientists, engineers, and space entrepreneurs.

Future missions of human exploration will require crew members to live and work productively for extended periods in space and on other planets. Key biomedical, life support, and human-factor questions must be answered to ensure crew health, well-being, and productivity.

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[1] European states are represented through membership in the European Space Agency (ESA). Current ESA members cooperating on the ISS are Belgium, Denmark, France, Germany, Great Britain, Italy, The Netherlands, Norway, Spain, Sweden, and Switzerland.

How the ISS Will Be Used

- As a means to foster private-sector contribution to and utilization of space, both developing products in orbit and using knowledge gained from the unique environment of space for applications on Earth
- As a testbed for new technologies for the next step in the human exploration of the solar system
- As the only experimental laboratory where fundamental physical, chemical, and biological processes can be explored in the absence of gravity's effects
- As a long-duration platform to perform observations of Earth and space
- As a means to study the long-term effects of weightlessness on the human body and to apply that knowledge to further the exploration of space and to better the health and well-being of humans on Earth
- As a unique facility that uses the space environment to develop new processes and products to benefit life on Earth
- As a vehicle to bring together the world community through governmental, academic, and industrial cooperation

To address these challenges, NASA will work with its industrial partners to apply innovative technology to the challenges of human space exploration, ranging from advances in telemedicine, robotic control, and life support to onsite raw material utilization, miniaturized technology, and bionics. In the coming decades on board the ISS, fundamental and applied research on gravity's effects will build the necessary knowledge base for long-duration missions beyond Earth orbit, enabling us to fulfill our quest for human exploration of the solar system.

Experiments flown in Space Shuttle laboratories have shown us that many biological, physical, and chemical processes are profoundly affected by gravity. Gravity drives forces that cause heavier components to settle out of mixtures, fluids to come together in solutions, and hot air to rise. Often, these forces obscure other processes at work that are of interest to researchers. In space, the confounding influence of gravity is nearly absent, allowing investigators to make breakthroughs in understanding. Space research has already resulted in processes and products to better life on Earth and in space. Access to the ISS promises to accelerate these breakthroughs, providing unprecedented space laboratory facilities, onorbit experiment time, and access to human investigators. Initially, a third of American ISS resources are set aside for commercial use. Space can and will become a new arena of commercial activity, as researchers discover new ways to improve processes and products for life on Earth and in space.

Inevitably, private interests will move to develop orbital infrastructure and resources in response to a growing demand for space research and development. The permanent expansion of private commerce into low-Earth orbit will be aided as NASA commercializes ISS support operations such as power supply and data handling. This trend is already under way with the privatization of Space Shuttle operations.

The ISS marks a new era in space. The research plans reviewed in this document are based upon our experiences to date on Skylab, the Space Shuttles, and *Mir*. New opportunities—some not even envisioned yet—will open up a new range of space activities in the academic, commercial, and Government spheres. NASA's research plans for the ISS will adjust as new opportunities come to light.

The remainder of this section (Part I) overviews NASA's current research plans for the ISS. The role of gravity in science and technology is explored, and some results to date are recounted before we review the ISS research agenda. The research is discussed in groupings according to the benefits it portends: Improving Industrial Processes, Increasing Fundamental Knowledge, Looking After Our Health, Enabling Exploration, and Researching Tomorrow's Products Today. Part II provides some specific research questions that may be answered through ISS research, while Part III, Serving Our Customers, discusses how ISS opportunities serve the research, international, commercial, and educational communities. Finally, Part IV gives a timeline for the evolution of research capability during ISS assembly, providing a visual Roadmap for Research Capability Evolution and an overview of performance factors for ISS work.

"If the Apple Did Not Fall": The Role of Gravity

Treating Gravity as a Variable

Introductory physics books invariably invoke the image of Sir Isaac Newton, sitting beneath an apple tree, being hit on the head by a falling apple. While Newton's development of gravitational theory was far more complex than this simple event would imply, our concept of a universal gravitational pull is today a standard feature of our lives. In fact, our expectation that an apple broken off from its branch will indeed fall toward the ground is the direct result of gravity's influence on our daily existence. Our experiences on Earth are continuously shaped by the normal gravitational force that acts on us and the objects around us at all times. Actually, not only do we have an expectation that the apple will fall, but we also expect the apple to fall in a certain way. On Earth, we expect it to accelerate downward at about 32.18 feet per second squared (ft/s^2) or at 1 g. Such simple acts as lifting an object, dropping an item, or spilling a liquid carry with them certain expected results. However, what would happen if the apple did not fall?

If the apple *did not fall*, we might conclude that the force of gravity was gone. However, in space we experience not the absence of gravity but the *absence of gravity's effects.* Orbiting the Earth, we are actually in free fall around the planet. Earth's gravity keeps us circling around the planet in a condition that we commonly refer to as microgravity. In a spaceship orbiting the Earth, an apple released from its branch would stay suspended in space; it would have no preferred direction of movement inside the spaceship. In this respect, the apple would not fall, and we would need to suspend all of our expectations. For early space travelers, living and working in a microgravity environment was a totally new experience. The lack of gravity's effects is perhaps the most dramatic feature of space flight and one that has caused us to change the way we look at the world and many of the phenomena that surround us.

On Earth, we are accustomed to all objects accelerating to the ground at the rate of 32.18 feet per second squared (ft/s^2). When in Earth's orbit, the gravitational pull of Earth is still there, but its effects are barely felt because an orbiting object is actually in free fall around Earth itself. Objects inside a spaceship seem to be "weightless" because they float inside the walls of the craft while they are falling with the ship around the curve of the planet.

As we have built on our earlier experiences in the space environment, we have learned two fundamental lessons:

- Microgravity is something that we can use to our advantage.
- Gravity is yet another research variable that can be studied and manipulated.

With this realization comes a release from the self-imposed limitations we have traditionally placed on our views of physical, chemical, and biological processes. We can now study and begin to understand both the impacts of gravity on such processes, as well as the true nature of such processes in the absence of gravity's effects. Microgravity can now be a tool for our use—one that will revolutionize our technology, propel us outward on missions of exploration, accelerate biomedical breakthroughs, and provide the impetus for a new generation of commercial products and services. Perhaps most importantly, we have finally recognized that the effects of gravity prevail even in the simplest processes. To truly understand our physical, chemical, and biological world, we must understand gravity's central role.

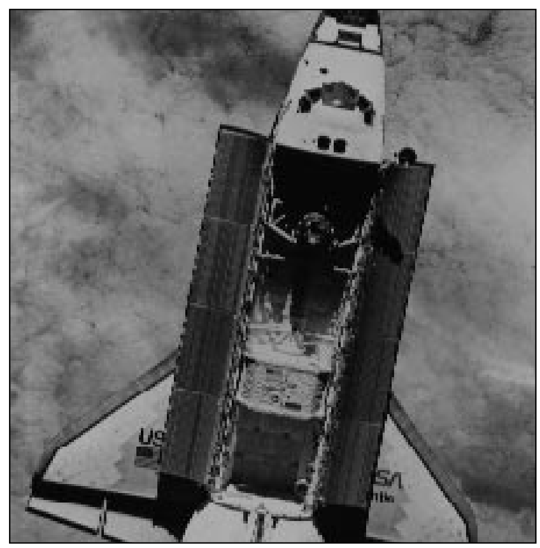
It is as if we have just realized that a world in which we thought of only in three dimensions has turned out to have four. In fact, we must now add gravity to the complex list of factors and variables as we try to comprehend the world around us. No longer can gravity be treated as "scientific overhead"—always there, unavoidable and invariable. No longer sitting on the sidelines, gravity has become an active player on the field of experimentation, as we finally understand and quantify its role in all of the physical, chemical, and biological phenomena of our lives.

Gravity Investigated

The past 40 years have borne witness to humankind's steadily increasing capability to live, work, and experiment in space. The first crewed U.S. space flights, the Mercury and Gemini programs, had as one of their goals to verify that human beings could actually survive and function in a weightless environment. Once it was determined that despite some "space sickness," astronauts could perform complex tasks in orbit, the Apollo program verified that humans could survive and readapt to Earth after periods as long as 12 days in microgravity. The experiments aboard Skylab in the 1970's lasted for up to 84 days and were the first foray by the United States into actual laboratory science in space. Space Shuttle flights since 1981 have been steadily adding to our understanding of the space environment and the influence that gravity exerts in fundamental physical, chemical, and biological processes. However, despite this regularly expanding body of knowledge, severe restrictions on the access to onorbit research time has limited the rate at which this science and its associated products have been able to advance.

While Shuttle flights have been limited to stays in space of up to 18 days, the Russian space program has had access to long-duration space flight with an operational space station for more than a decade. Indeed, flights of American astronauts and experiments on board the *Mir* station have become an important precursory step in preparing for ISS assembly and research. The Russian space program has generated considerable knowledge concerning long-duration human space flight. While *Mir*'s scientific facilities cannot be changed out mission to mission, such as those on the Space Shuttle, their accumulated "days in space" far surpass the Shuttle experience, and our nations are actively sharing the knowledge Russia's extensive space station experience has produced.

During the past 16 years of using Skylab, the Space Shuttle, *Mir,* and other space platforms, commercial, academic, and government researchers have made dramatic



Space Shuttle flights since 1981 have allowed researchers to amass a significant amount of high-quality data in microgravity. Experiments flown in Spacehab (shown inside the cargo bay here), Spacelab, and the crew cabin have addressed subjects as diverse as combustion, fluid dynamics, astronaut health, and protein crystal growth, to name just a few. While Shuttle flights are limited to less than 3-week stays in orbit, the ISS will operate continuously in space, 365 days a year, building rapidly on the knowledge that Shuttle experiments have already provided.

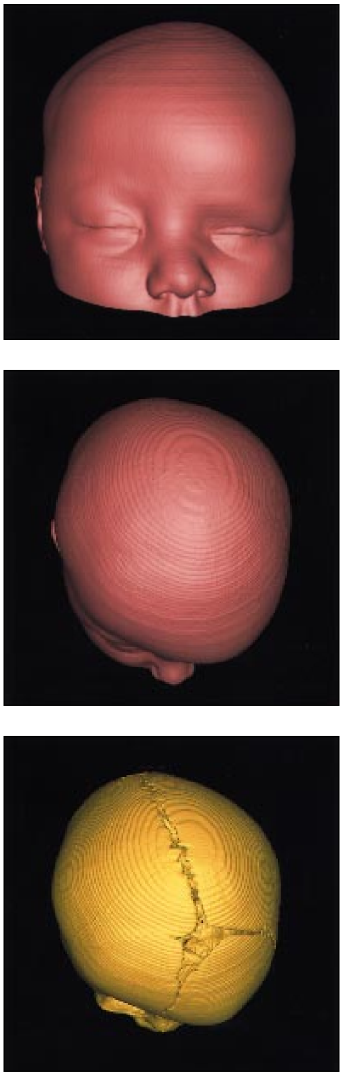
Osteoporosis is the gradual weakening of bones caused by decalcification and is often associated with aging. It affects 1 in 10 Americans, leading to 1.3 million bone fractures annually. Unless new preventative measures and treatments are found, by the year 2020 annual costs associated with the disease are expected to rise to $30–60 billion.

use of these unique facilities to challenge old theories and explore new ones. In many instances, we have been successful in applying this knowledge to ground-based processes and products. We now know that gravity has a pervasive influence at even the most microscopic structural scale. Our experiments have shown us that previously overlooked or obscured forces can play dominant roles when the masking influence of gravity is removed. This aspect of the microgravity environment enables researchers to investigate phenomena impossible to observe otherwise. Indeed, experiments in space have shown us that some phenomena we thought were well understood are actually far more complex than previously imagined.

While we now know that humans can live and work in space, we have found that the microgravity environment induces a number of changes within the human body itself. Space flight affects almost every aspect of the human body, including the heart, lungs, muscle, bones, immune system, and nerves. More specifically, astronauts experience a significant loss of both bone and muscle mass as a result of space flight. Their hand-eye coordination is also visibly affected. Simple acts, such as picking up a hairbrush or pushing a button, become complex tasks in bridging the dissociation—which occurs in the space environment—between what the eye perceives and what the hand actually does. Some immune system cells associated with fending off disease decrease in number, and other natural defenses of the body are perturbed in ways that may hamper their effectiveness. Upon return to Earth, astronauts often undergo a period of recovery, during which they regain things such as balance and coordination under the influence of gravity.

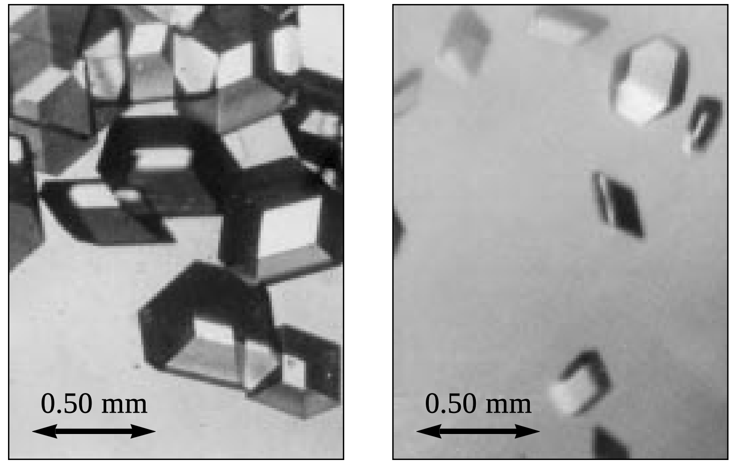
Many of the physiological changes in astronauts actually resemble changes in the human body normally associated with aging here on Earth. For instance, in addition to losing mass in the microgravity environment, bones and muscle do not appear to heal normally in space. For astronauts, time spent in microgravity seems to result in a dissociation between their physical and chronological ages. By studying the changes in astronauts' bodies, NASA might play a role in developing a model for the consequences of getting older. NASA-sponsored scientists are collaborating with the National Institutes of Health (NIH) in an effort to explore the use of space flight as a model for the process of aging.

NASA has developed a broad range of technologies in medical information systems, sensors, diagnostic techniques, decision support systems, image compression, and advanced training to support health care delivery in space. These technologies include compact, solid-state sensors that permit noninvasive monitoring of crew health and the spacecraft environment. Wherever appropriate, these products will be adapted to advance health care here on Earth. For example, NASA is using technology, originally developed for space-related scientific visualization, to simulate complex surgery. This application enables surgeons to reconstruct a patient's face and skull from computerized tomographic scans, allowing them to manipulate the bone and tissue in virtual space and consider possible surgical procedures. This technique will take its place as an important precursor to actual surgery and as a training tool for our next generation of surgeons.

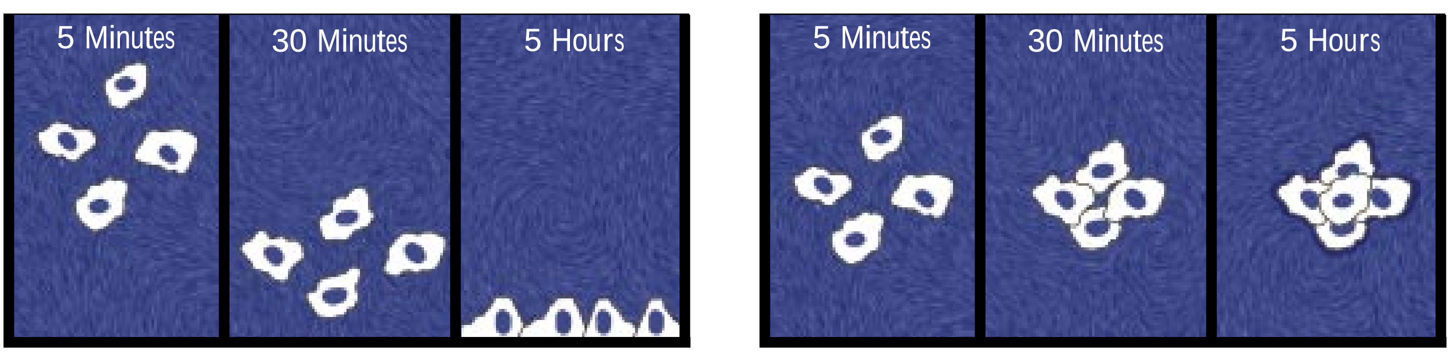


This three-dimensional reconstruction of an infant's head was made directly from computerized tomographic scans in about 20 minutes. The infant suffers from a condition where the skull fails to form properly. The reconstruction is then tilted to better illustrate the skull and facial asymmetries so that the surgeon can consider surgical options.

Researchers have found that microgravity provides them with new tools to address two fundamental aspects of biotechnology: the growth of high-quality crystals for the study of proteins, and the growth of three-dimensional tissue samples in laboratory cultures. On Earth, gravity distorts the shape of crystalline structures, while tissue cultures fail to take on their full three-dimensional structure. NASA-sponsored research is providing access to new data and techniques for the broader biotechnology community. NASA's bioreactor, developed to simulate low gravity, has proven dramatically successful as an advanced cell-culturing technology. This success has led to an extensive collaboration with NIH and numerous commercial partners. Work with bioreactors has already produced advanced cultures of lymph tissue for studying the infectivity of human immunodeficiency virus (HIV), the virus that causes AIDS. Other areas of success include cultures of cancer tumors and the growth of cartilage. Biotechnology researchers also use microgravity to produce protein crystals for drug research that are superior to crystals that



Diabetes is the third leading cause of death in the United States. The disease also causes complications such as blindness and limb amputation, for which treatment costs the Nation more than $100 billion a year. Space-grown insulin crystals (left) are much larger and more highly defined than their Earth-grown counterparts (right). In collaboration with NASA's Commercial Space Centers and Eli Lilly and Company, the Hauptman-Woodward Research Institute, Inc., of Buffalo, New York, is using data from space-grown crystals of human insulin to design a drug that will bind insulin, improving the treatment of diabetic patients.



Cell Culture on Earth

Cell Culture in Microgravity

On Earth, the attempt to culture tissue in the laboratory results in a single layer of cells (see left graphic) instead of the three-dimensional shape actually taken in the human body. In microgravity, the cells mass together into three-dimensional structures that more closely resemble the natural state of the tissue (right).

The virus that causes influenza—commonly known as the flu—is shown here superimposed with an inhibitor made possible through space research. Inhibitors block, or "inhibit," the functioning of certain enzymes in the body. The inhibitors here target the neuraminidase enzyme, which plays an essential role in the infection cycle of the flu. A new class of influenza neuraminidase inhibitors will begin clinical trials this year. The design of these inhibitors was based, in part, on the structure of influenza neuraminidase obtained by our industrial partners from crystals grown on Space Shuttle flights.

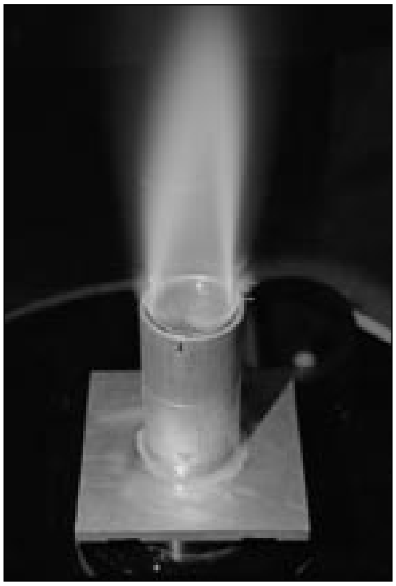
can be grown on Earth. Using high-energy x-ray beams to study high-quality crystals, scientists are better able to discern how the proteins function. Work done by researchers and pharmaceutical companies on space-grown crystals has already increased our knowledge about such diseases as AIDS, emphysema, influenza, and diabetes. New drugs are now being tested for future markets.

While we now know that complex biological systems and components are significantly affected by gravity, we have also found that even the tiniest single-celled organisms suspended in water are equipped to respond to gravity. We have used the low-gravity environment of space to investigate how cells translate physical forces, such as acceleration caused by gravity, into chemical signals that drive adaptation and response. We have begun work to explore the process by which plants respond to gravity to produce lignin, the primary component of wood. We look forward to exploring the role that gravity has played on Earth—and possibly in other places—in the genesis and evolution of life.

Commercial, academic, and government researchers have successfully used the low-gravity environment of space to understand and control gravity's influence in the production and processing of materials, including metals, semiconductors, polymers, and glasses. For example, space research has produced cadmium zinc telluride crystals that have

Aerogels, the lightest solid known, are only three times heavier than air; a block the size of a person weighs less than a pound. Despite their lack of substance, these ghost-like materials are the world's best insulators. Less than an inch thickness can shield a piece of chocolate from the heat of a blowtorch. Because of their qualities and transparent nature, aerogels are an obvious choice for superinsulating windows. Samples made on Earth contain large pores that scatter light and result in a bluish haze. Space-manufactured samples show a fourfold reduction in pore size; this results in 4,000 times less light scattering, giving enhanced clarity. According to Fortune *magazine, the global aerogel market is projected to include more than 800 potential product lines, ranging from surfboards to space satellite parts.*

A patent was awarded to researchers at the Lawrence Berkeley National Laboratory for their new method to lower pollutant emissions in natural-gas appliances, such as residential heating furnaces and hot water heaters. Off-the-shelf home heating furnaces outfitted with their "ring flame stabilizer" reduced their nitrogen oxide emissions by a factor of ten while increasing efficiency by 2 percent. Nitrogen oxides are major contributors to smog and atmospheric contamination. The title of the patent is "Apparatus and Method for Burning a Lean Pre-mixed Fuel/Air Mixture with Low NO_X Emission."



50 times lower levels of a key defect than the best commercially available crystals. These experiments ultimately help researchers improve semiconductor fabrication on Earth. There have been many theories and mathematical models developed to predict the formation and development of dendrites, the tree-like structures that are the building blocks of most metal products. On Earth, gravity's effects limit the power of experiments to validate these fundamental theories. The *Isothermal Dendritic Growth Experiment,* flown aboard the Space Shuttle in March 1994 and February 1996, has become the scientific benchmark for testing our theoretical understanding of metal formation.

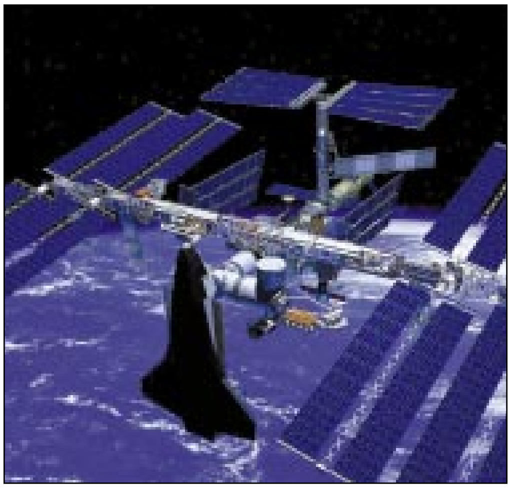
Unpredictable and often uncontrollable fires cost the United States billions of dollars each year. Often, our best defenses fail to halt devastating wild fires that destroy hundreds of acres of valuable property while endangering the local population. In many cases, combustion processes are so complex that scientists have difficulty developing accurate, complete models for them. Microgravity research has demonstrated that gravity has a profound effect on combustion phenomena; microgravity experimentation allows us to observe behaviors never before witnessed. By better understanding combustion at its most fundamental level, researchers may develop more accurate models to predict the behavior of fires, both small and large. In addition, because controlled combustion is so widely used for energy production and transportation, improvements in the commercial application of combustion stand to improve

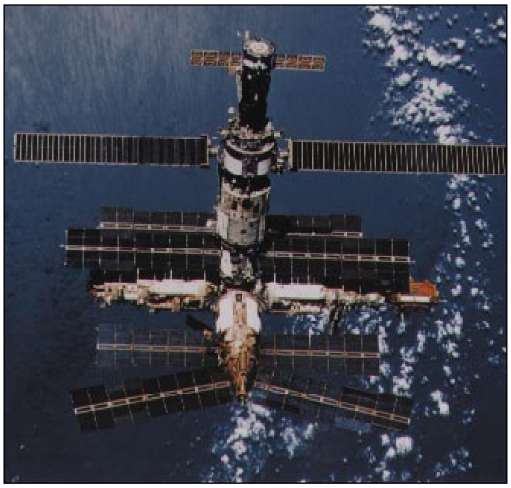
Of all the world's energy needs, 85 percent are met by combustion processes, which in turn are a major source of air pollution. Even a small efficiency increase in energy-producing combustion processes could bring about a significant decrease in world atmospheric contamination and huge savings in energy production costs.

the efficiency of a wide range of everyday technologies, generating benefits for our economy across industrial sectors while saving Americans money.

By the beginning of ISS assembly in 1998, NASA's cumulative time in space aboard the Space Shuttle will be approaching 800 days in orbit. By that same time, American astronauts will have spent more than 950 days aboard the Russian space station *Mir.* Our accomplishments to date aboard these platforms have been significant, and the experiences and lessons outlined above only briefly touch on the incredible wealth of knowledge that the Shuttle and *Mir* have helped us to acquire. However, in their own ways, both the Shuttle and *Mir* are limited in manners that the ISS is not. The Space Shuttle's maximum stay in orbit is less than 3 weeks, and much of its resources are dedicated to obtaining and returning from orbit. While *Mir* is a well-established research facility and our experiences on the Russian station have been an invaluable preparation for the ISS, it is much more limited than the ISS in size, resources, and versatility. For example, *Mir* encloses 497 cubic yards of pressurized space, while the ISS will have an internal volume of 1,716 cubic yards—nearly four times that which *Mir* contains. In addition to its six dedicated laboratory modules, the ISS will provide external truss and exposed facility sites to accommodate a broad range of attached payloads for technology, Earth science, and space science experiments. We expect at least a decade of routine research operations aboard the ISS. When this time is multiplied by the number of astronauts on board, the ISS will provide well over 25,000 "crew-days" in orbit.

This uninterrupted, long-term access to space will allow researchers to rapidly acquire the large sets of data necessary to validate new concepts and confirm previously unobserved phenomena. Investigators will be able to make multiple experiment runs in succession, obtaining statistically significant results in a matter of weeks—even days—instead of years. Whether it is improving industrial processes, increasing fundamental knowledge, looking after our health, enabling exploration, or researching tomorrow's products today, ISS research will generate tangible returns as it improves our lives on Earth and in space.





The ISS is more than just the next step beyond Mir; *it will provide almost four times the enclosed volume* Mir *does for research operations, having six outfitted laboratory modules, seven resident astronauts, and state-of-the art instrumentation for scientific, technical, and commercial investigations.*

Improving Industrial Processes

Humans have been able to make observations in the absence of gravity for less than a quarter of a century and serious laboratory experiments have been feasible in space for only about 15 years. The decade of the 1990's represents the first phase of experimentation in microgravity and the potential advent of a true laboratory science in space. Increasingly, fundamental processes that were thought to be well understood under terrestrial (1-g) conditions have, in fact, proved to behave in altered and even startlingly unfamiliar ways when observed and measured in reduced-gravity environments.

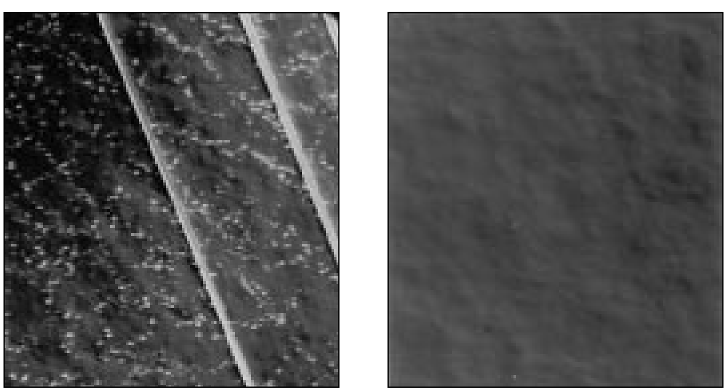
—National Research Council, *Microgravity Research Opportunities for the 1990's*, 1995

Microgravity research bears directly on many concerns of industry. Despite the relatively brief duration of onorbit research in the microgravity sciences, numerous applications have already been identified and incorporated by the private sector. These are based on both scientific findings as well as technological advances. Today, the fraction of NASA's microgravity research, conducted with financial support from other agencies and from industry, is growing. Industry is investing its resources in space aboard the Space Shuttle, and it will expand its participation in microgravity research on the ISS. Researchers will use the ISS to gain fundamental scientific knowledge through microgravity experimentation and, where feasible, apply that knowledge to commercially viable products and processes.

On Earth, gravity affects the intricate process by which atoms form crystals, often disturbing their orderly arrangement. Orbital research provides low-gravity conditions that drastically reduce the confounding effects of gravity. It allows scientists to study phenomena such as solidification, crystal growth, fluid flow, and combustion with unprecedented clarity. ISS operations will encourage and increase the involvement of American industry in space-based research and technology development. By working with our industrial partners to facilitate their access to space, we hope to foster space commerce, improve industrial processes, and keep America capable and competitive in the growing international marketplace.

The ISS offers a world-class microgravity laboratory for extensive and continuous experimentation in fields such as combustion science, fluid physics, and materials science—areas of research that are at the forefront of industrial applications. No longer will experiments in these fields need to wait months—even years—for an opportunity to fly. Neither will researchers suffer from the inability to repeat a modified experiment in a timely manner. ISS operations promise to accelerate investigations into phenomena that will improve industrial processes for Earth and in space.

Earth-grown crystals of the alloy cadmium zinc telluride (left) exhibit many more imperfections than space-grown crystals (right). By reducing the imperfections in the metal, we could improve the overall performance of devices that use the alloy, such as infrared detectors and x-ray and medical imaging instruments.



Combustion Science

Almost every chapter in the combustion textbooks will be rewritten as a result of the microgravity work.

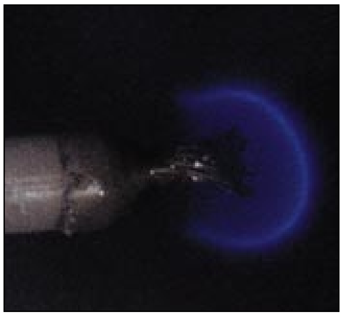
—Dr. Howard Palmer, Professor Emeritus, Penn State University, 1992

Combustion science experiments provide a better understanding of fundamental energy transformation processes, air pollution, advanced transportation designs, spacecraft and aircraft propulsion, global environmental heating, materials processing, and hazardous waste incineration. Space enables us to obtain the critical measurements needed to understand and resolve practical combustion problems. These measurements are most easily made on large, steady, slow-moving, and symmetric flames that provide good time and space resolution. Unfortunately, these simplified flames are not present on Earth because gravity causes hot flame gases to rise, leading to unsteady, fast-moving, and distorted flames typified by campfires. These difficulties disappear in the microgravity environment of space. Thus, in much the same way that observations in space avoid the disturbances of the Earth's atmosphere for astronomy, space-based experiments in combustion science avoid distortions resulting from gravity. The ISS is our best effort to date to provide a laboratory environment where combustion can be fully understood.

ISS research into combustion phenomena should produce knowledge applicable to a wide variety of goods we use here on Earth. Combustion plays a central role in heating our homes, powering our cars, and producing a broad range of synthetic materials. Improvements in controlled combustion efficiency could save the United States billions of dollars annually. In addition to generating savings, more efficient combustion processes would have the added benefit of reducing the pollutants we release daily into the atmosphere. A more complete understanding of how fires burn and grow could help us better predict and control the dangerous forest and structure fires we experience regularly.

Combustion has been a subject of vigorous scientific research for more than a century. Studies of combustion are motivated by important public health and economic problems. Combustion processes directly cost in excess of $200 billion each year in the United States. Air pollution, produced in large part by combustion-generated particulates, contributes to approximately 60,000 deaths each year in the United States. Unwanted fires cause approximately 5,000 deaths, 26,000 injuries, and $26 billion in property losses in the United States each year. By improving our understanding of the underlying processes of combustion, we stand to save billions of dollars annually.

On Earth, gravity-dependent, buoyancy-driven convection processes cause flames to take on their characteristically elongated shape (left). In space, such distortion does not occur, allowing researchers to observe aspects of combustion impossible to investigate on the ground (right).

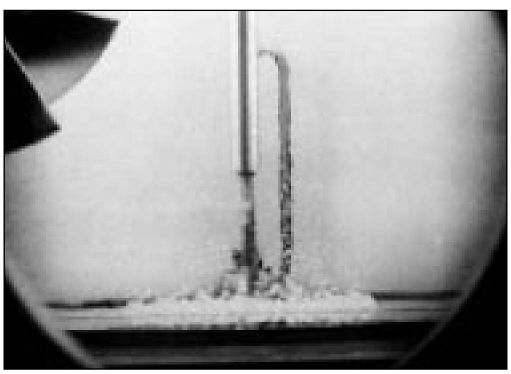


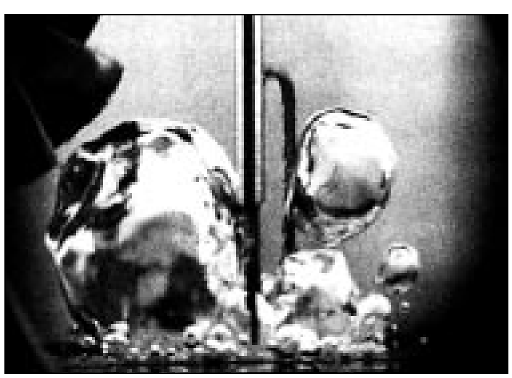
Fluid Physics

Everyone has practical experience with fluids (liquids and gases), and we know how a fluid will behave under many "normal" circumstances. Steam rises from the surface of a hot spring or a boiling pot, and water spilled on a tabletop runs over, then off, the surface. Gravity drives much of the fluid behavior to which we are accustomed on Earth. In space, however, fluids behave very differently.

Forces normally masked by gravity here on Earth, such as surface tension, control fluid behavior in microgravity; as a result, many of our intuitive expectations about fluids do not hold up in orbit. For instance, surface tension causes drops of any liquid to form almost-perfect spheres when the influence of gravity is absent. While differences in fluid behavior often present spacecraft designers and astronauts with practical problems, they also offer scientists and commercial researchers unique opportunities to explore different aspects of the physics of fluids.

Research conducted in microgravity is increasing our understanding of fluid physics to provide a foundation for predicting, controlling, and improving a vast range of technological processes. The behavior of fluids is at the heart of many phenomena in materials science, biotechnology, and combustion science. The performance of a power plant depends on the flow characteristics of vapor-liquid mixtures. Oil recovery from partially depleted reservoirs depends on how liquids flow through porous rocks. The safe engineering of buildings in earthquake-prone areas requires an understanding of fluid-like behaviors of soils under stress. Advances in materials engineering require a better grasp of how fluid behavior determines the structure of solid materials during solidification.

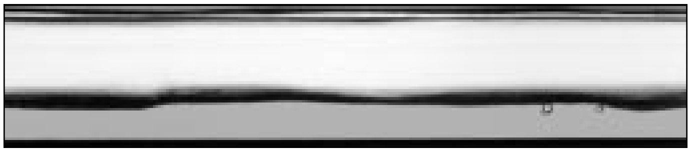


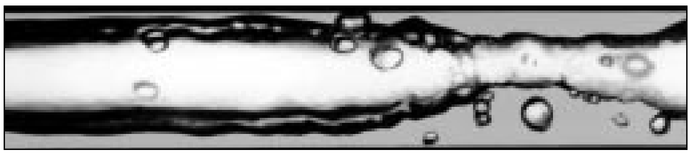


These images show boiling liquid in the 1-g environment of Earth (top) and in microgravity (below). The question of how liquids boil in the reduced-gravity environment of space has puzzled scientists for decades. To the surprise of many investigators, Space Shuttle experiments have found that steady boiling is not only feasible in microgravity but can result in enhanced heat transfer, compared to normal gravity under certain conditions. If steady microgravity boiling can be attained on a predictable basis, it has the potential to generate major breakthroughs in heat transfer equipment for space. This research is also providing greater fundamental understanding of boiling itself and may result in more efficient designs of steam generators, which are used to produce most of the world's electric power.

Many products that require high-precision manufacturing processes could directly benefit from greater control over fluid flow. Surface-tension-driven flows, for example, affect some techniques of semiconductor crystal growth, welding, and the spread of flames on liquids. The behavior of liquid drops is an important aspect of chemical process technologies and meteorology.

ISS research will provide fluid physics researchers unprecedented opportunities to investigate and understand the underlying physics behind these important phenomena. By improving our understanding of the behavior of fluids through ISS research, U.S. industry can generate direct benefits for the American people in Earth-based applications.





These pictures depict how fluids flow differently in microgravity. On Earth, the fluid flows through the bottom of the pipe while the air remains trapped in the top half of the pipe (above). In space, however, the fluid flows more symmetrically, clinging to the sides of the pipe all along its length. A column of air is left down the center of the pipe (below).

MATERIALS SCIENCE

Materials science investigates the relationships among the structure, properties, and processing of materials. Structure is the arrangement of the atoms in the material; properties include physical, chemical, electronic, thermal, and magnetic characteristics; and processing is the method by which materials are formed. Materials can be solidified, evaporated and condensed, or dissolved and then separated from a solution. The unique characteristics of the microgravity space environment can be used to study fundamental issues in materials solidification, crystal growth, and microstructure development, to name only a few.

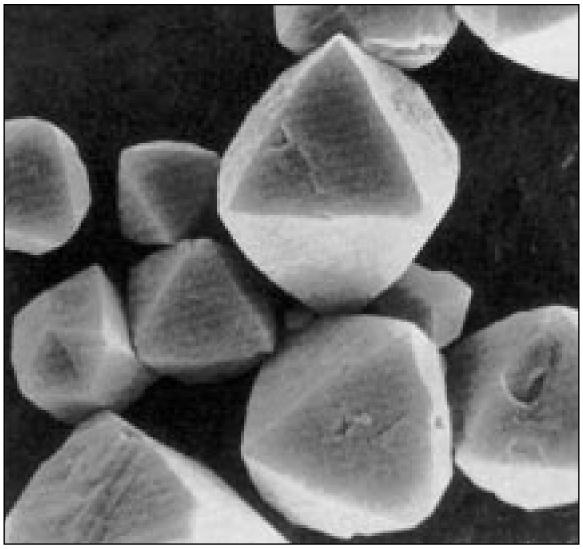
The production processes for most materials include steps that are very heavily influenced by the force of gravity. The chance to implement and observe these processes in microgravity promises to increase our fundamental understanding of them and of the materials they produce. By carefully studying and controlling the processes by which materials are formed, commercial researchers can design new alloys, ceramics, glasses, polymers, and semiconductors to improve the performance of products ranging from contact lenses to car engines and medical instruments.

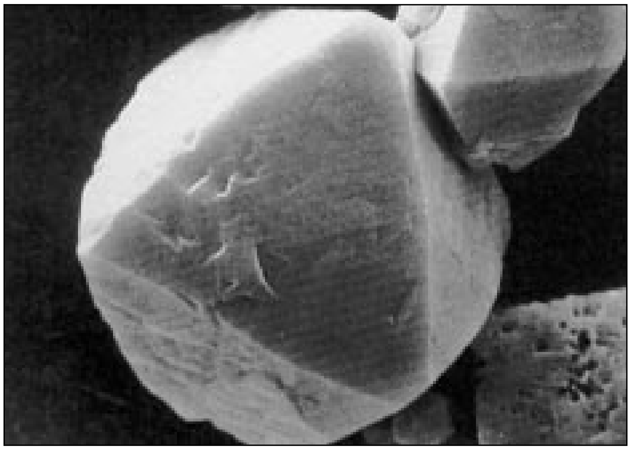
Rather than being limited to a week or two aboard the Space Shuttle, ISS microgravity experiments will stretch over periods comparable to experiments on Earth, greatly increasing the number and types of materials and processes that can be studied. This will be a distinct advantage in areas such as solution and vapor crystal growth, which require 15 to 30 days of continuous growth to produce crystals with the desired characteristics.

The productivity of laboratory research is directly tied to a researcher's ability to respond to the unexpected. Consequently, it is imperative that crew observation, interaction, and control be established to realize the full potential of a low-gravity

> Cutting tool tips often break because of weak spots or defects in the materials used to make them. Based on a new concept called "defect trapping," space offers a novel environment to study defect formation in molten metal materials as they solidify. The Consortium for Materials Development in Space at the University of Alabama at Huntsville, along with Teledyne Advanced Materials, McDonnell Douglas, and Wyle Laboratories, is studying metals sintered in space so that the U.S. tool industry can enhance the quality of its products, making America more capable and competitive on the world market.

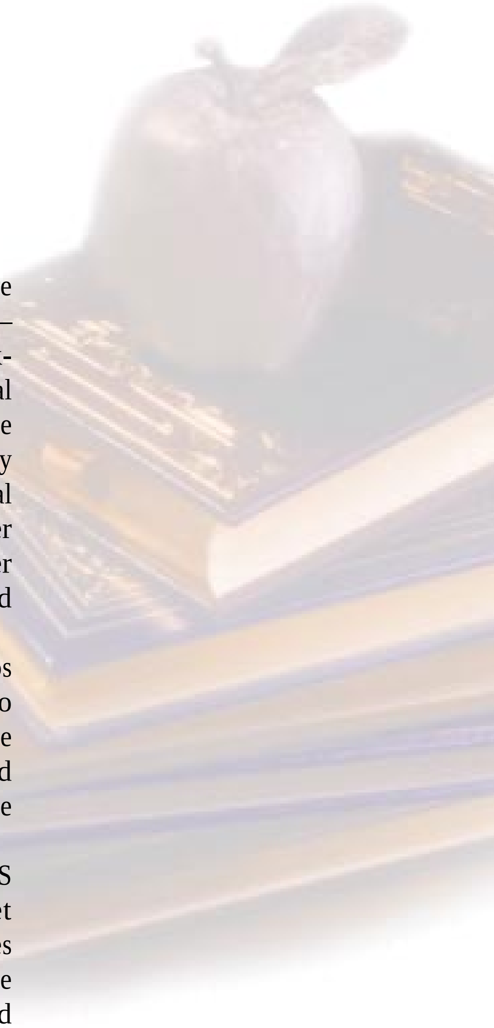
Zeolites are a class of crystalline materials that are typically used in petroleum refinement as adsorbents and catalysts. Their use makes possible $90 billion in annual exports by the United States. Improvements in composition and size of the zeolites vastly enhance their performance. According to the National Research Council, a 1-percent increase in gas yield per barrel of oil equals a $400-million savings to U.S. industry. Space-grown zeolite crystals (bottom) are by far the largest and highest quality crystals ever produced to date, much larger than their Earth-grown counterparts (right). Improved control over zeolite structure and composition makes space processing a powerful tool to increase petroleum yield.





NASA and its partners have identified vacuum as a major attribute of space. By using a special device known as the Wake Shield Facility, researchers have produced a vacuum in space greater than anything achieved on Earth. Researchers have already grown record-quality semiconductor thin films with the device. The Wake Shield Facility was released by the Shuttle's robotic arm to fly free and away from contaminants that might inhibit the vacuum, such as gas released from the Shuttle itself. The vacuum-produced semiconductor films are expected to significantly increase the quality and capacity of mobile communications equipment.

environment. The benefits that accrue from being able to conduct a sequence of experiments, in which results from one investigation can be used to refine a subsequent approach, are enormous. On the ISS, with crew members to observe experiments and with equipment for analyzing samples in orbit, it will not be necessary to return all specimens to Earth for analysis before running the next experiment in space. This will allow researchers to conduct experiments in a series, each experiment building on the results of those before, without having to wait for another launch opportunity. The ISS represents our best effort to design an environment in which human involvement in the control and sequencing of experiments may speed the maturation of this still-young field of inquiry.



Increasing Fundamental Knowledge

The quest for knowledge and an enhanced understanding of the world in which we live serve a number of essential roles. While the quest for knowledge is often inspirational—and serves as the underpinning of our desire to explore—the fundamental scientific breakthroughs of today provide the foundation for tomorrow's technology. Technological advances in turn lead to enhanced living standards for our society. Perhaps the most visible example of this pattern is the breakthrough in semiconductor physics that ultimately enabled the communications revolution and today's information society. The National Aeronautics and Space Act of 1958 tasked NASA with helping us move toward a greater understanding of the world around us. Researchers on board the ISS will seek to answer exciting fundamental questions as NASA capitalizes on the Station's unique capabilities and vantage point to advance fundamental fields of inquiry.

Instead of a fragile and transient thing, life is now recognized as a robust, perhaps inevitable, consequence given just a few general conditions. As our Nation makes plans to look for life in the far reaches of the solar system, scientists are seeking to understand the role that gravity has played in the origin and evolution of living systems, both plant and animal. The ISS will provide a one-of-a-kind, robust laboratory for investigations into the origin, evolution, and destiny of life in the solar system.

Reflecting NASA's desire to make the most efficient use of resources possible, the ISS will also serve as a convenient platform for observatories that look down at our planet and out toward the stars. An observing window in the U.S. Laboratory and external sites on the Station will accommodate systems for looking at the Earth and the cosmos. The ISS will take advantage of its unique human-tended capabilities to run an adaptable and unique series of observations that further our understanding of our home and its extended neighborhood, the universe.

All of the research outlined in this overview will increase fundamental knowledge. However, foremost among our Nation's efforts to advance basic science via space-based experiments and viewing are our plans for fundamental physics, gravitational biology and ecology, Earth system science, and space science.

Fundamental Physics

To test in the greatest detail some of the fundamental laws that govern our physical world, it is often necessary to go beyond the surface of the Earth. This is so when extremely uniform samples—free from compression due to their own weight—are required, when objects must be freely suspended in space, or when the mechanical disturbances present in Earth-bound laboratories must be eliminated. Thus, NASA and its academic, industrial, and international partners will use the microgravity environment of the ISS to conduct fundamental scientific studies that have as their goal to contribute to the world's supply of knowledge, which will one day enable the technology of future generations.

Fundamental science on the ISS will support many different areas of study, including low-temperature and condensed matter physics, gravitational and relativistic physics, and laser cooling and atomic physics. One type of study will involve the collection of atoms cooled to extremely low temperatures by slowing down their motion with laser beams (the rate of motion of an atom is directly tied to its temperature). On Earth, these ultracooled samples would be disturbed by contact with the walls of the holding chamber—contact that will not occur in the microgravity environment of space. In turn, these samples can be used to measure time by observing the light emitted from the atoms (resulting from electronic transitions within the atoms themselves). These clocks will be much more accurate than those operating on Earth, and they will permit new experiments to test Einstein's theory of relativity with far greater accuracy than in the past. They also serve the practical and immediate application of a highly accurate clock for corrections to such time-dependent systems as the Global Positioning System. The navigation system is even now being incorporated into airplanes, naval vessels, and personal automobiles.

Fundamental physics investigations on the ISS will also support a number of concurrent technology development efforts. Examples of such efforts include the development of superconducting magnetometers for more efficient resource mining and noninvasive medical diagnostics, the management of extremely low-temperature fluids for life support systems and manufacturing use, and the design of highly accurate, industrial-grade clocks to support day-to-day navigation needs and communications applications.

Gravitational Biology and Ecology

Biology is not just science of what we are and how we came to be—it is also the science of what we can become.

—Steve Olson, National Research Council, *Shaping the Future, Biology and Human Values*, 1989

The dawning of the space age brings an incredible opportunity to understand how the force of gravity has shaped the evolution of all forms of life. Scientists will use the space-based laboratories of the ISS to learn how plants and animals that evolved under terrestrial gravity respond to space. In doing so, we further our understanding of the role that gravity plays in life on Earth. We know that life has evolved with the capability to sense and react to gravity, yet we can only begin to understand the full complement of mechanisms through which organisms interpret, respond to, and rely on gravity. If we were limited to Earth, then, we would perhaps never fully understand gravity's role in the origin and evolution of life. Fortunately, the space age has expanded our horizons, and the ISS will play a critical role as the only place where microgravity and partial gravity can be used as experimental variables in a competent laboratory setting.

Using a wide variety of cells and tissues from plants and animals, researchers have shown that terrestrial life can survive in the virtual absence of gravity for lengthy periods. Despite this, exposure to microgravity is known to weaken the muscles and bones in rodents, monkeys, and humans; however, even after weeks or months in a weightless environment, many physiological changes reverse within days of returning to Earth. *But what would happen after many generations in a weightless environment? Will muscle and bone cells lose the ability to respond to gravitational loads?* The ISS will provide a unique platform for multigenerational studies in the microgravity conditions of space flight. Specimens will include a wide variety of organisms, ranging from single-cell bacteria to complex plants and animals. We will finally be able to observe life over its full cycle, from germination to its next cycle of reproduction.

In order to accomplish this exciting research, the ISS will use a variety of experimental tools to conduct basic and applied research in cell and molecular biology, developmental biology, plant biology, and systems and comparative biology. One of the Station's most powerful tools will be its centrifuge; with the centrifuge, the ISS will have the unique capability to expose specimens to gravitational fields from the normal microgravity level on board, up to twice the gravitational pull of Earth.

Wheat plants completed almost an entire life cycle on board Mir. *While some of the plants seemed a bit disoriented in the microgravity environment, they grew well and even produced heads (which normally carry the seeds). Another plant,* brassica rapa*—a member of the mustard family—moved through several generations on* Mir, *successfully reproducing a number of times. These experiments are promising for plans to use plants to produce food and oxygen on long-duration space flights.*

ISS research will be fundamentally important for Earth-based applications and the future human exploration and development of space. Evolutionary biology investigations on board the ISS will help us characterize the role of gravity in the evolution of closed ecosystems (of which Earth is a very large example), contributing to our understanding of our planet. This same knowledge may be applied to the successful design of a closed-loop life support system. On its most basic level, the knowledge of plant biology supports the use of plants for ecological purposes, such as air quality management or food—uses vital for environmental engineering and food production efforts both on Earth and in space.

On board the ISS, many biological processes, such as organism development and multigenerational cycles, will be able to take place over extended periods with onorbit observation. Technically advanced facilities and onorbit analysis will, for the first time, allow for the immediate analysis of structures, products, and phenomena that are modified during space flight. Advanced sample preparation and preservation technology will greatly enhance the science return from onorbit experiments by increasing the preservation options and the variety of samples available for more sophisticated analyses back on Earth.

The ability to apply the results of past U.S. and international flight experiments often has been limited because experiments are rarely replicated. The combination of state-of-the-art hardware and ISS capabilities promises to provide the required time and statistically valid number of samples required for a clear interpretation of results. Moreover, a continuously operating laboratory in space will allow experiments to be replicated much more quickly than the current 2+ years required to manifest followup experiments and take advantage of exciting discoveries.

Earth System Science and Space Science

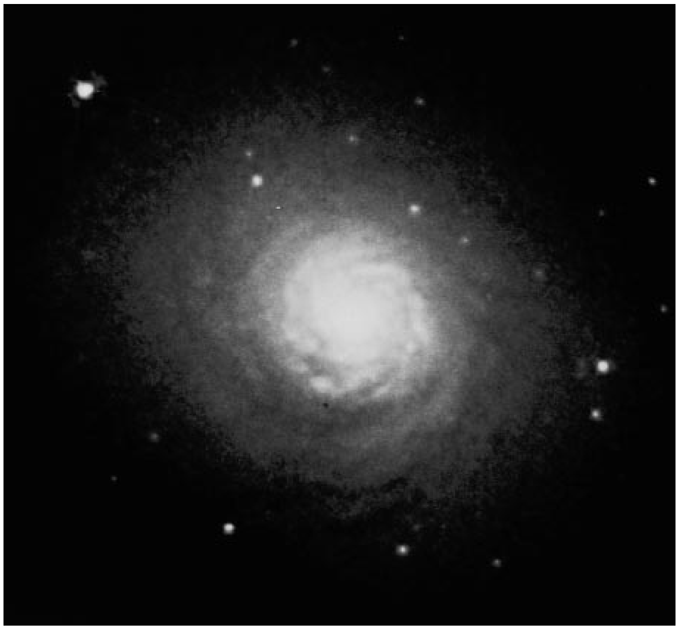
As the Apollo astronauts journeyed toward the Moon three decades ago, they looked back at our home planet and saw Earth as a shimmering, blue orb floating against the vast recesses of space. That vision led the coinage of the now familiar phrase, “Spaceship Earth.” In the intervening years since the Apollo astronauts set foot on the Moon, our relationship to the planet we inhabit and its surrounding universe has changed dramatically. The ISS will serve as a resource for the Earth and space science communities to explore that relationship in more detail.

Various combinations of research accommodations, from externally attached exposed sites to a laboratory research window, will allow us to view space in virtually all directions. The ISS will serve as a convenient platform on which we can deploy a variety of sensors to further our understanding in Earth and space science. By maximizing the ISS as a resource in this manner, we can complement ongoing efforts in Earth and space science by making the most efficient use of the platforms available to us.

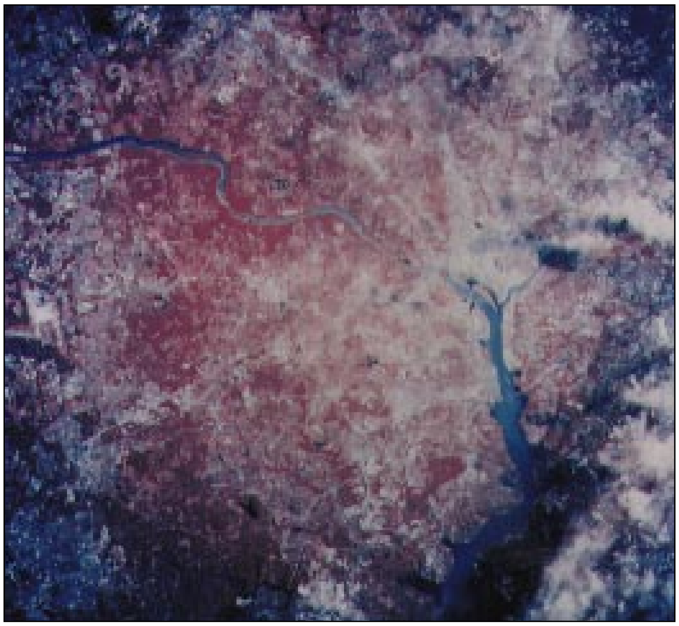
One unique aspect of the ISS for Earth and space science investigations is the ability to include human intervention in the operations loop. We have seen the advantages such intervention can bring in the ongoing operations of the Hubble Space Telescope. Space Shuttle servicing missions have now twice upgraded Hubble’s science equipment, and future Shuttle rendezvous missions with the telescope are planned. The dynamic nature of our planet and the Sun means that the capacity for operations run and managed by humans on a day-to-day basis will be a valuable resource. The astronauts will be able to take full advantage of human adaptability to observe trends, respond to the unexpected, and alter the research approach when necessary. They will respond quickly to observe, record, characterize, and assess the impact of natural events when they occur, furthering our understanding of our planet as a system.

Space science research may use the ISS as a platform for making space-based observations of the galaxy, for sampling the space environment for subatomic particles, cosmic rays, and interstellar and interplanetary materials, and for performing experiments that test the physical and chemical interactions that occur in space. The ISS will be a quick-response, adaptive platform to observe events that are believed to have an impact on Earth’s climate, such as solar flares and coronal mass ejections (the emission of highly charged plasma particles from the Sun’s surface).

A primary Earth science payload already identified for the ISS is the Stratospheric Aerosol and Gas Experiment (SAGE). SAGE is the third instrument of its kind to sample Earth’s atmosphere using the Sun as an energy source. SAGE III will take global profiles of atmospheric aerosols, targeted molecular constituents, temperature, and pressure while assessing the spatial and temporal variability of these measures. This will help us better understand the role of certain compounds in climatic processes, biogeochemical cycles, and atmospheric chemistry. SAGE III will fly on the ISS as an attached payload for a minimum period of 5 years, overlapped in part by a higher altitude and inclination flight of an identical instrument aboard a Russian spacecraft.



The Hubble Space Telescope took this image of a distant galaxy, NGC-7252, showing a "minispiral" disk of gas and stars. The clusters of stars in this galaxy are 50–500 million years old and were probably born following the collision of two disk-shaped galaxies about a billion years ago. Instruments on the ISS such as the Alpha Magnetic Spectrometer (see box below) will search for evidence that some distant galaxies may be made of antimatter. The spectrometer will also search for indirect evidence of dark matter around the Milky Way galaxy, among others.



This infrared image of the greater metropolitan Washington, DC, area was taken from the Space Shuttle in 1996. Use of the Window Observational Research Facility will enable astronauts on the ISS to take selected images of Earth's oceans, land masses, and atmosphere.

Earth science research will use the ISS as a platform for conducting ongoing projects such as the study of the daily buildup of cloud cover or the response of vegetation suffering from drought. The moderately inclined orbit of 51.6 degrees that the ISS will occupy permits frequent revisits to selected sites at midlatitudes. Test sites can be studied throughout the day-night cycle, allowing us to observe the same phenomena in a variety of wavelengths (for example, visible, infrared, or ultraviolet). In addition, observations of the Earth when the Sun or Moon is behind the planet will enable us to measure key aspects of our atmosphere.

The Alpha Magnetic Spectrometer is a premier state-of-the-art particle detector containing a large permanent magnet. The science objective of the spectrometer is to search for cosmic sources of antimatter and dark matter. The instrument is being funded and built by an international team led by the U.S. Department of Energy, and it will be the first large magnet ever placed in Earth orbit. Current plans call for operating the spectrometer on board the ISS as an attached payload for a 3-year period. As an attached payload, the spectrometer will benefit from ISS power and communications resources, enabling it to operate for a much longer period than otherwise possible.

Looking After Our Health

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

—Dr. Michael DeBakey, Chancellor Emeritus, Baylor College of Medicine,
U.S. House of Representatives, June 22, 1993

Gravity plays a central role in the development and function of the human body. On the ISS, we will begin indepth examinations of the fundamental effects of microgravity on human health during long-duration space flights. Not only will we be able to better predict and address the effects of microgravity on space travelers, but we will better understand the human body at its most basic level, using that knowledge to further research here on Earth. Understanding the effects of gravity on the human body is a fundamental question of substantial scientific value in our quest to understand life. At the same time, a greater understanding of gravity's effects has the potential to bring about a boom in commercial medical products here on Earth. Access to the research facilities of the ISS will enable researchers to study the functions of biological systems in the absence of gravity in a continually operated and more capable laboratory setting.

The ISS will serve as a testbed for new remote medical and life-support technologies that will enable NASA to provide high-quality health care and environmental conditions to our next generation of space travelers. Some of these technologies have already found applications on Earth. NASA-developed telemedicine systems have been used to provide high-quality medical advice, instruction, and education to parts of our Nation and the world where advanced medical care is not always available. Remote medical capability and advanced support technologies will be an important part of keeping our astronauts safe when the Nation sends a human mission to Mars and perhaps beyond. Only a permanently crewed space station with substantial laboratory capabilities will allow research in these directions to proceed productively.

ISS research will address women's health concerns. Microgravity allows us to produce high-quality tissue cultures, such as breast and ovarian cancer, on which scientists can test promising treatments without risking side effects to a patient. Astronauts experience a number of symptoms and conditions that are somewhat similar to those seen in the elderly here on Earth. The ability to use space flight as a model for aging could be especially relevant to women, because they are five times more likely than men to suffer from osteoporosis, the medical term applied to the elderly's weakening bones. In addition to addressing osteoporosis, space flight provides insight into anemia, the loss of muscle mass, and balance disorders. Because women are so much more likely than men to have osteoporosis, falls caused by balance disorders pose a greater threat of broken bones.

BIOTECHNOLOGY

I view the Space Shuttle program as a stepping stone to the ultimate program that will guarantee prolonged efforts in microgravity. . . . Ultimately our hope is to be able to crystallize proteins in microgravity, conduct all x-ray data collection experiments in space and transmit the data to Earth for processing. This can only be done in a Space Station.

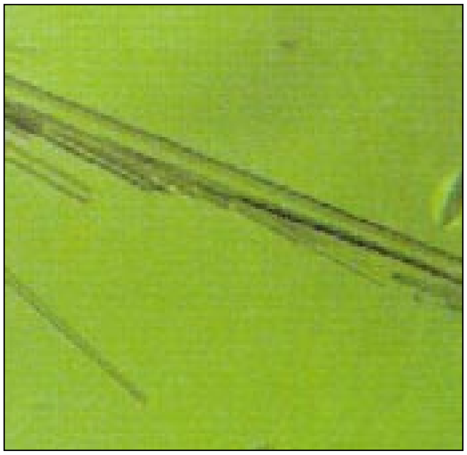
—Dr. T.L. Nagabhushan, Vice President of Biotechnology Development, Schering-Plough Research Institute, letter to Daniel Goldin, July 6, 1994

Biotechnology is a multidisciplinary effort that is projected to dominate the economy in the 21st century. Broadly defined, biotechnology is a set of techniques for rearranging and manufacturing biological molecules, tissues, and living organisms. This field is one of the most dynamic segments of our "high-tech" economy. On board the ISS, NASA will continue its dynamic research in protein crystal growth (growing crystals from organic molecules with thousands of atoms) and cell/tissue culturing (the study of how cells interact in a low-gravity environment). In addition, new opportunities—some just now being explored—will open up in biotechnology on the ISS. Investigators will look into the use of biologically inspired materials and the role that gravity plays in genetic expression.

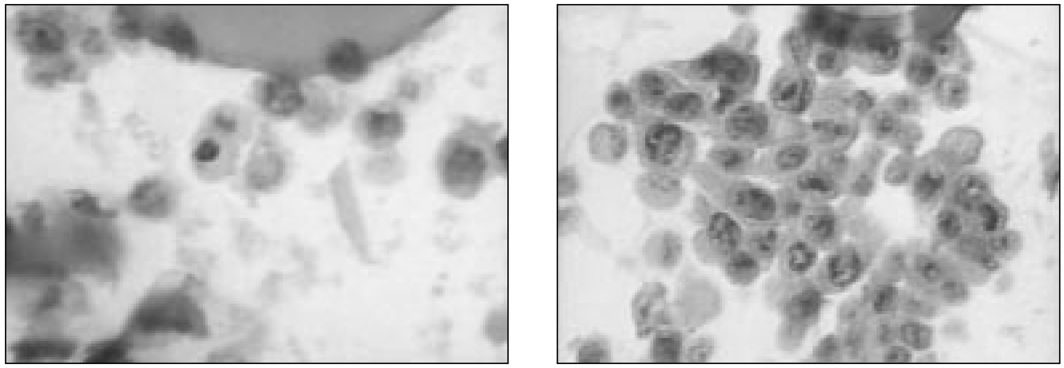
On the ground, gravity interferes with the growth of protein crystals, preventing the type of precise measurements necessary to define the fine structure of these molecules. Researchers use data on the structure of proteins to design drugs to treat diseases. Armed with new space-based information on the structure of key proteins, researchers are already creating a new generation of drugs. This approach promises to help produce superior drugs for a wide range of conditions.

Even if we could fly six Space Shuttle flights per year, each successfully producing crystals to reveal the structure of 1,000 different proteins per flight, it would still take 35 years to learn the structure of all human proteins. Based on *Mir* experience, access to the ISS promises to increase the rate of advancement in this field by a factor of ten. Station facilities will enable investigators to analyze crystals onorbit, decreasing the cost and increasing the quality of research. The ISS could become one of the world's premier sources for critical data on the protein structures needed for this new method of drug development. In addition, the Station will be used to study and understand the physics involved in protein crystal growth, helping overcome the difficulties that currently limit much of this research on Earth.

In the past, gravity-induced sedimentation in cellular cultures made it virtually impossible for researchers to grow representative tissue samples outside of the human body. Often, the result was more two-dimensional than three-dimensional, limiting the sample's usefulness as a research tool. After experimenting in microgravity, scientists have found that a low-gravity environment allows cells to cluster together in three dimensions, often closely resembling the shape such tissue takes in the human body. By using space-based experiments as a model, researchers have developed a "bioreactor" for terrestrial applications that uses



This is a time-exposed image of HIV protease crystals combined with an inhibitor, grown on the United States Microgravity Laboratory-2 Space Shuttle mission. Microgravity research is producing high-quality crystals of proteins that HIV needs to reproduce. Using these crystals, researchers can better define the enzyme's structure so that effective pharmaceuticals can be developed to treat the deadly disease.



A stationary cell culture of colon cancer on Earth (left) fails to take on the three-dimensional structure that tissue takes in the body itself. In microgravity (right), a three-dimensional structure is realized, making the sample much more useful as a research tool. Scientists are looking at ways to improve the bioreactor to more closely imitate the space environment. Three-dimensional cellular culturing technology offers the prospect of engineering tissues for research, transplantation, and the production of pharmaceutical agents.

horizontal rotation to mimic the microgravity environment. Today, researchers are using the bioreactor to successfully culture tissue samples as diverse as liver, muscle, cartilage, and bone. Perhaps most significantly, the bioreactory has grown tumors from just a few cancer cells; these tumors can be used to test and study treatments, such as chemotherapy, without risking harmful side effects to a patient. Researchers can also use the bioreactor to study how cells actually form the tumors themselves. Because space research sheds light on the fundamental effects of gravity on tissue formation and development, continued cell culture research on board the ISS will allow scientists to refine Earth-based biomedical techniques. Ultimately, tissues cultured outside the body may be used to replace damaged tissues, treat diseases, or eventually replace entire organs.

New fields in biotechnology are opening up as we make our research plans for the ISS. Scientists are now looking at biological systems as models for new materials. ISS research may explore the application of such biologically inspired materials for use in new radiation and thermal protection coatings. We are just beginning to understand the role that gravity plays in gene expression (the particular traits that an organism shows, such as brown versus blue eyes). As we develop this field, investigators may use organisms bioengineered in space to control aspects of the spacecraft environment, such as air quality and humidity.

In addition to its role as a basic research laboratory in biotechnology, the ISS will be available to commercial interests as a platform to test and verify space-based biotechnology products and services. In this manner, NASA and its partners will help the United States move forward into the 21st century as a leader in the globally competitive field of biotechnology.

Biomedical Research in Space

One thing that has happened as we look into the life- and bio-sciences in the NASA program has been that we find some notable parallels between what happens to astronauts in space and what happens to the elderly right here on Earth. And if we can find what triggers some of these similarities, perhaps we will have a whole new handle on approaching difficulties that people have right here on Earth.

—Senator John Glenn, *Congressional Record*, U.S. Senate, September 3, 1996

Biomedical research has the explicit and unique dual responsibility among the space sciences of pursuing both basic and applied research. Basic research answers questions of intrinsic value by using the weightless environment of space as a tool to learn about fundamental physiological processes in humans, as well as the implications of space flight for human health. Applied research develops procedures and countermeasures that prevent or mitigate the undesirable effects of space flight on humans. The overriding goal of these activities is to enable human exploration and development of space by minimizing risks and optimizing crew safety, well-being, and performance. In so doing, it also expands our knowledge base of human physiology, resulting in new medical products and services that benefit life on Earth and in space.

NASA has worked cooperatively with industry to develop a Sensing and Force-Reflection Exoskeleton that senses hand and finger motion as human operator input and provides force-reflective feedback to the operator for both telerobotic and virtual environment applications. The project's technology base could be used to develop a biomechanically sound resistance exercise system that is adaptable for use by both astronauts and the terrestrial population.

Certain physiological changes that occur in space also occur with aging. For instance, cardiovascular deconditioning, balance disorders, weakening bones and muscles, disturbed sleep patterns, and depressed immune responses are common to astronauts and the elderly alike. When in space, an astronaut's muscles and bones do not have to continually support the body against the pull of gravity. In some ways, this may mimic the results of a sedentary lifestyle, often caused by aging, paralysis, weakness, injury, or prolonged bed rest on Earth. This can cause a downward spiral in an individual's health over time, increasing susceptibility to bone fractures and slowing any recovery from injuries and other ailments. Gerontologists, life scientists, and commercial researchers are collaborating to determine how our bodies' adaptation in space can be used to study the aging process here on Earth.

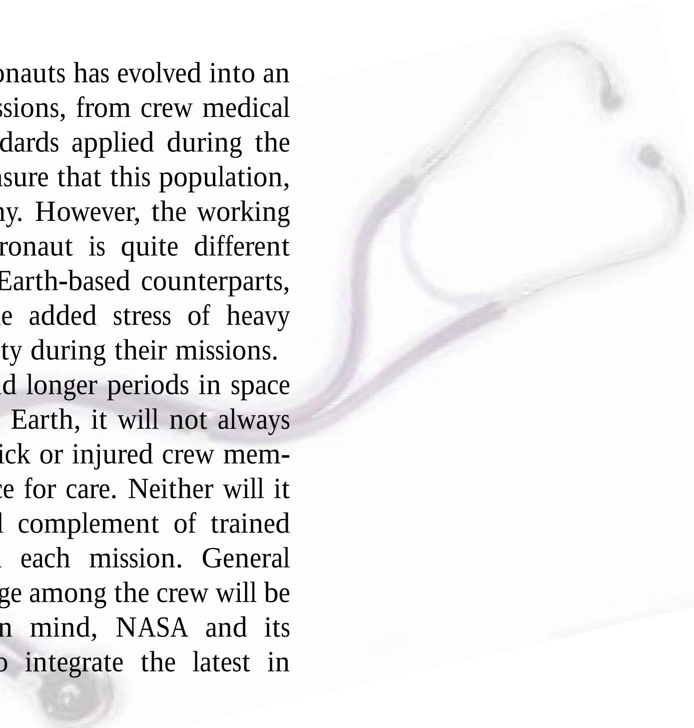
The ISS will provide a microgravity laboratory that is unmatched for the continual study of the human body in space. Within the first 5 years of full operations, we expect to match the combined experimental yield from the previous four decades of space flight.

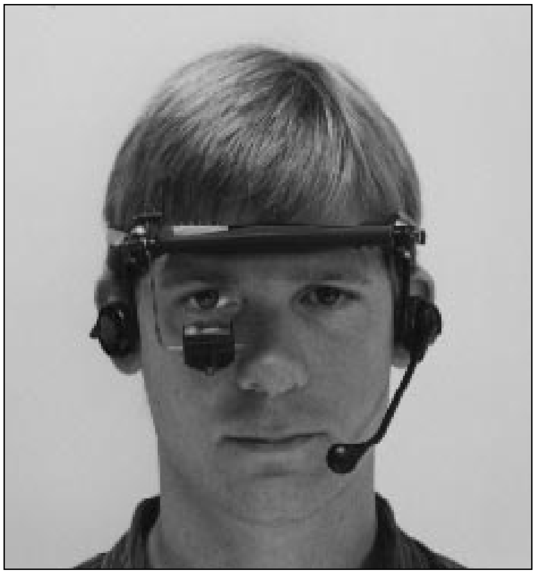
Medical Care in Space

The ongoing effort to provide health care for sick or injured astronauts has evolved into an integrated system that encompasses all phases of human space missions, from crew medical selection through long-term health followup. Strict medical standards applied during the selection of astronauts ensure that this population, at least initially, is healthy. However, the working environment for an astronaut is quite different from that of his or her Earth-based counterparts, and the crews carry the added stress of heavy responsibility and visibility during their missions.

The highly successfully Spacebridge to Russia program—a joint effort between NASA and the Russian Space Agency—is an Internet-based telemedicine testbed that links academic and clinical sites in the United States and Russia for clinical consultations and medical education. A predecessor project—Spacebridge to Armenia—was used to provide medical consultation services during the recovery from the Armenian earthquake in 1988.

As our astronauts spend longer periods in space at greater distances from Earth, it will not always be practical to return a sick or injured crew member to our planet's surface for care. Neither will it be possible to fly a full complement of trained medical personnel with each mission. General paramedic-level knowledge among the crew will be the norm. With this in mind, NASA and its partners are working to integrate the latest in



NASA has developed technology that will allow ISS astronauts to receive up-to-date visual and audio data anywhere on the Station without the encumbrance of wires or other bulky equipment. Astronauts will wear a small headset, such as the prototype pictured above, to communicate visual and audio information through a two-way wireless link to the ISS communications infrastructure. The astronauts may also wear a suite of miniature, lightweight, and wireless biosensors that will monitor an astronaut's physiological characteristics, such as heart rate and blood pressure, and feed that information back to the astronaut through the headset's audio and visual links. In addition to biofeedback, the head-mounted display can transmit information about the medical state of other astronauts, imagery (such as wiring diagrams), or text (such as task lists or step-by step experiment instructions) sent from within the ISS or from Mission Control on Earth. The easy portability and wear of the heads-up display system will allow its widespread use to benefit health, safety, and productivity on Earth and in space.

A Telemedicine Instrument Pack has been designed to collect medical audio, video, and data from patients in space. The support components, including the embedded computer, flat panel liquid crystal display, remote video camera, light source, and power supply, provide a basic infrastructure for the medical instrumentation. Data capabilities include electrocardiogram, heart rate, blood pressure, and blood oxygen saturation measurements. The pack has been evaluated via several telecommunications links and has proven to be reliable and efficient. Terrestrial applications include rural telemedicine systems and disaster-response consulting stations.

telecommunications, computers, and medical technologies in health care to provide our astronauts the best medical care possible.

Emerging technologies, such as virtual reality and wireless medical monitoring, are being incorporated into advanced remote health care systems. Telemedicine—the practice of medicine from a distance through the use of advanced information and communications systems—will ensure that our crews receive the best medical care we can deliver. NASA is currently conducting ground research on an automated portable intensive care unit. Work in cybersurgery—surgery using digital models and virtual reality—is also ongoing. As our knowledge in these areas matures, we will incorporate these technologies into the ISS medical support systems. New technologies, coupled with better clinical practices tailored to the space environment, will bring about the evolution of a robust system of medical care for our astronauts as they expand the frontiers of human space exploration. At the same time, we can use these technologies to better our system of health care delivery on Earth. Many of the more remote parts of our world have little or no access to health care. Even in the United States, many rural areas lack the kind of specialty expertise that can often mean the difference between life and death in acute medical cases. Advanced technologies such as telemedicine will enable specialized medical knowledge to serve more people than ever before.

As we work to advance the state of medical care technology, space clinical practices will incorporate the knowledge gained from ISS research on the effects of microgravity on the human body. The classical medical triad of *prevention, diagnosis,* and *treatment* will be refined to reflect the effects of space travel. Therefore, facilities for basic biomedical research will be used in conjunction with the ISS crew health care system to advance our state of knowledge and care for our astronauts.

ISS research into the effects of microgravity on the growth cycles of plants and animals will help designers devise a comprehensive life-support system for space travelers. During interplanetary transit, day-to-day foodstuffs may have to be grown on board the transport in order to maximize resource efficiency and overall spacecraft mass.

Advanced Human Support

Living and working in space is neither easy, inexpensive, nor completely free of risks. Since its formation in 1958, NASA has worked continuously to decrease both the risk and cost of space activity. With the advent of continuous operations aboard the ISS, we are now more concerned than ever that our astronauts operate in a safe, comfortable, and productive environment. This is why the Station will serve as a testbed for systems and hardware arising out of advanced human support research.

Such research operates in cooperation with NASA's basic research efforts, taking the knowledge gained from basic science and translating it into technologies that will make space travel safer, less costly, and more productive. Advanced human support activities concentrate on closed-loop life-support systems, advanced environmental monitoring and control, and a field called human factors engineering, which aims to maximize the efficiency and comfort of our astronauts living and working in space.

As human missions to other parts of the solar system become a reality, demands on a mission's crew and life-support system will grow in proportion to the length of time spent in space. The farther our astronauts travel, the more costly it becomes to carry expendables that are used once and simply thrown away. It will become increasingly important that advanced life-support systems recycle virtually all components of onboard consumables. For example, in 1997 NASA successfully demonstrated a total water purification system using biologically active filters. With such a system, it becomes vital that the astronaut's environment be continually monitored for any signs of harmful substances. Decreasing the size, power requirements, and commensurate costs of these systems will be a primary focus of advanced human-support research on the ISS.

As research on the ISS brings down the costs and risks of space flight, the knowledge gained from such work can readily be used for Earth-based applications. For example, advanced recycling technologies are increasingly important in our environmentally conscious society, while human factors research into worker comfort and productivity may be applied to make American industry more competitive.

Enabling Exploration

The space frontier beckons to us with the promise of new and exciting discoveries. Humans will be an integral component of a comprehensive and vigorous program of solar system exploration. A person's adaptability, resourcefulness, and autonomy are irreplaceable for tasks such as the construction of a robust lunar outpost and advanced geologic field work on Mars. Many challenges remain before living and working in space can become a natural extension of our lives here on Earth.

The ISS is the next logical step in our quest to prepare humans to explore and develop the solar system. The Station will be *a technological testbed, a microgravity laboratory, and a model for international cooperation;* on it, we will strive to understand the adjustments that need to be made to our Earth-based methods before we send astronauts to Mars and beyond. ISS work that will enable exploration can be broken down into two primary categories: *engineering* research into the technology, system architecture, and operational standards that will be necessary to live and work far from Earth, and the *science* that will serve as the bedrock for our understanding of how to utilize this new environment.

Engineering Development

Reducing the costs and improving the performance of future government and commercial activities in space will require continual engineering research and technology development . . . the International Space Station will be a valuable location. . . .

—National Research Council, *Engineering Research and Technology Development on the Space Station,* 1996

As a technological testbed, the ISS will enable us to validate the engineering systems necessary to facilitate long-term, human exploration beyond low-Earth orbit. Much remains to be known about living and working in space, including the choice of radiation and debris-resistant space construction materials, power generation and storage in space, the use of advanced robotics and remote technologies for space operations, the design of rugged life-support systems, and the provision of adequate medical care far from Earth. It is the goal of ISS research not only to protect our next generation of space pioneers, explorers, and developers, but to learn how to best utilize space to benefit humankind while maximizing space traveler comfort, productivity, and state of mind.

The space environment poses challenges for humans and their technology beyond the mere absence of gravity. Outer space is characterized by an extreme vacuum, solar and cosmic radiation, extreme cold, and the presence of space debris. These characteristics indicate that certain materials and protective measures must be used to guard astronauts and their hardware over long periods in space. Special research facilities will track the effect of radiation on a variety of materials that we expect to use in the future. Certain protective coatings, including special variations of paint, will be tested to assess their effectiveness. We will use this knowledge to design hardware that is capable of

(Left) In the future, the Station may be used to test and validate entire systems intended for human exploration missions, such as the Mars habitat testbed depicted above. Work performed on board the ISS will contribute to the technologies required to support humans in distant and inhospitable environments as we explore our solar system.

(Right) Human exploration of the solar system will require long periods of space travel far from home. Space vehicles will need to sustain the astronauts for months, even years, without resupply from Earth. ISS research into advanced recycling and environmental monitoring technologies will make it possible for spacecraft designers to develop advanced life-support systems for vehicles such as the conceptualized interplanetary transport pictured above.

withstanding the harsh environment of space with little to no maintenance and the highest degree of reliability.

The ISS will be used to test and validate a number of advanced, lightweight power creation and storage systems. Utilizing new, highly efficient generations of solar power cells, the Station will test alternative schemes for storing the energy such solar arrays produce. One such concept involves the use of a fly-wheel based system, in which the rotation acts both as an energy storage technique and as an auxiliary system to control spacecraft orientation. Other concepts include using the Sun's heat to generate power and developing advanced batteries as a traditional means of energy storage in space.

The ISS will use an externally mounted robotic arm to manipulate experiments mounted on the outside of the Station. Engineers will use this arm to test advanced robotic control techniques for use in and around the next generation of space stations, space transports, and lunar and Martian outposts.

In the coming decades, the ISS will help us develop and test engineering systems that will permit future space explorers to become less reliant on Earth infrastructure. Station research will validate

Research in our city in space will seek ways to create a comfortable and productive working environment. The psychological and social stresses incumbent on crews of space stations and interplanetary transports are known to have critical impacts on mission success and astronauts' health. ISS work will seek to better understand how to alleviate the stress of working in such a limited environment. Observation of crew interaction with the ISS habitat will be used to design more Earth-like surroundings for space travelers as we look to make space flight a natural extension of our lives.

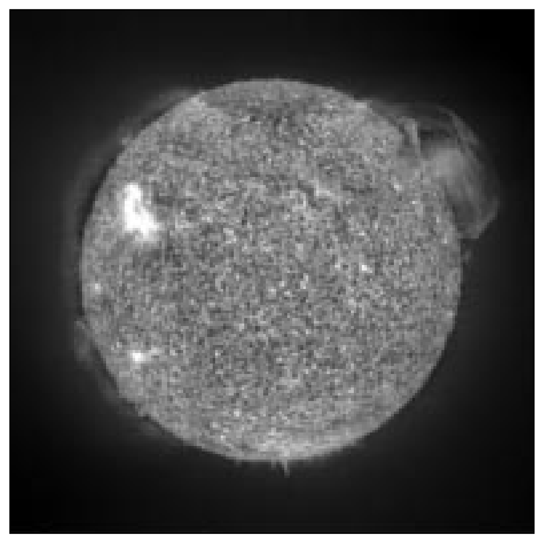
technologies that will automatically perform routine maintenance, repair, and even new construction on orbiting platforms. Our goal is to devise systems that will free people on board from the routine aspects of space flight, allowing them to dedicate their time to more productive pursuits.

Foundations in Science

The development of engineering technologies inherently depends on fundamental scientific principles. ISS investigations in basic fields of inquiry such as fluid and fundamental physics, combustion and materials science, and gravitational biology and ecology will underpin tomorrow's technology for the exploration and development of space.

Critical choices and technologies for space exploration depend on advances in fundamental scientific understanding. For example, a more thorough understanding of combustion in microgravity will enable us to choose the best fire-resistant and breathable atmosphere for future spacecraft. Advances in fluid physics will help us comprehend complex weather patterns on planetary surfaces such as Mars, leading to better operational parameters and choice of base sites. Progress in combustion science and fluid physics will also enable us to develop cost-effective methods for manufacturing spacecraft and generator fuel from resources found onsite in places such as the Moon and Mars. Advances in gravitational biology and ecology will allow us to design extraterrestrial habitats that require no resupply from Earth. These are just a few examples of the ways that progress in fundamental fields of inquiry plays a critical enabling role in the exploration and development of space.

Much remains to be done before we can send astronauts to Mars and beyond. We must understand and counterbalance the reaction of the human body to the microgravity environment; we must develop the requisite protective and supportive technologies required for advanced human habitats in space; and we must comprehend the fundamental processes that ultimately enable our ability to make use of available resources in space and "live off the land," no matter where that land may be. The ISS is the next logical step in the human exploration and development of space.



The Sun presents a major radiation hazard for astronauts traveling outside of Earth's protective magnetosphere. Periodic events such as solar flares and coronal mass ejections (as seen here), where large amounts of energetic particles are ejected from the Sun, could prove deadly if proper protective measures are not taken. Researchers will use the ISS to monitor the Sun's activity while testing materials that might help shield space travelers from dangerous radiation events.

Researching Tomorrow's Products Today

In the 20th century, space exploration has had a profound impact on the way we view ourselves and the world in which we live. Viewing our planet from space for the first time gave us a unique perspective of Earth as a single, integrated whole. Observations of the Earth's atmosphere, land, and oceans have allowed us to understand our planet better as a system and, in doing so, our role in that integrated whole. Many aspects of our lives we now take for granted were enabled, at least in part, by NASA's investment in space. Whether we are making a transpacific telephone call, designing with a computer-aided design tool, using our mobile phone, wearing a pacemaker, or going for an MRI, we are using technology that space exploration either developed or improved. Today, commercial interests bring a myriad of products and services to our lives that either use the environment of space or the results of research performed in microgravity. Just a few examples include:

The investment by NASA and its industrial partners in visualization and telescience technologies has led to the development of a variety of virtual reality applications. Today, virtual reality simulations are used in applications that vary from workplace design to medical training, as medical students practice on "virtual patients." Current plans call for the technology's use to train future ISS astronauts in a virtual Station environment.

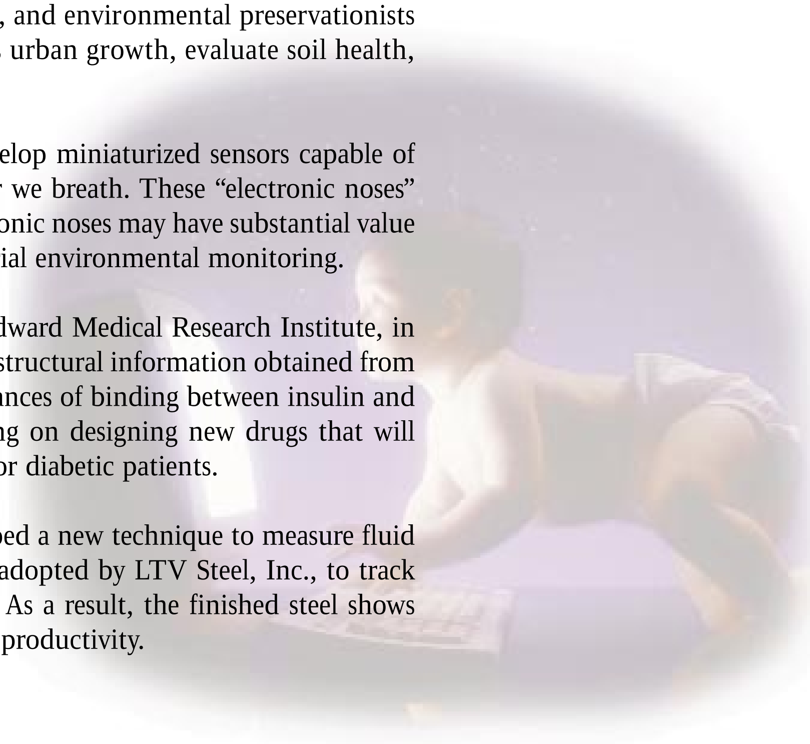
- *Satellite Communications:* Private companies have operated communications satellites for decades. Today, private interests build, launch, and operate a rapidly expanding telecommunications infrastructure in space. Our Nation's initial investment in space helped fuel the information revolution that spurs much of our economy today.

- *Earth Observation/Remote Sensing:* A growing market for Earth imagery is opening up new commercial opportunities in space. Private interests now sell and buy pictures taken from Earth orbit. Land-use planners, farmers, and environmental preservationists can use the commercially offered imagery to assess urban growth, evaluate soil health, and track deforestation.

- *Electronic Noses:* NASA is currently working to develop miniaturized sensors capable of detecting small amounts of contaminants in the air we breath. These "electronic noses" will be used to monitor air quality on the ISS. Electronic noses may have substantial value for use in fields such as food processing and industrial environmental monitoring.

- *Recombinant Human Insulin:* The Hauptman-Woodward Medical Research Institute, in collaboration with Eli Lilly and Company, has used structural information obtained from crystals grown in space to better understand the nuances of binding between insulin and various drugs. The researchers are currently working on designing new drugs that will bind to insulin, improving their use as treatments for diabetic patients.

- *Improvements in Steel Production:* NASA has developed a new technique to measure fluid flows in space experiments. This method has been adopted by LTV Steel, Inc., to track fluid flows in ground-based steel-casting processes. As a result, the finished steel shows fewer defects, cutting back on waste and increasing productivity.

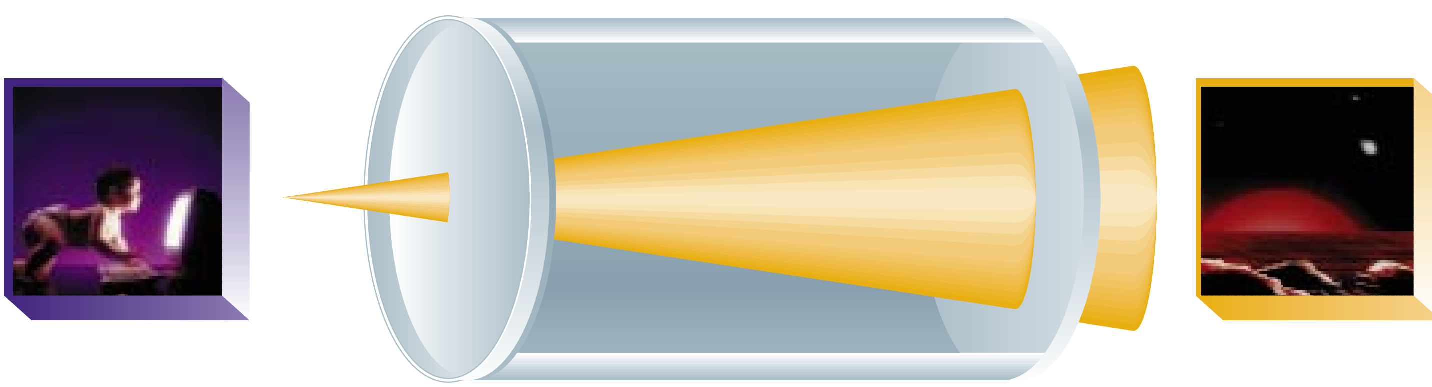


Of the 50 million contact lens wearers in the United States, 12 million must wear semirigid contact lenses. While soft lenses are better known for their comfort, they lack durability. Unfortunately, semirigid lenses with the comfort and breathability of soft lenses do not exist—yet. Paragon Vision Sciences is cooperating with NASA in space polymer research that may improve semirigid contact lenses. Samples prepared in space are more uniform and porous, allowing more oxygen to pass through to the eye. The results from space research may be used to develop a new breed of contact lenses.

To date, commercial involvement in microgravity research has been limited by scarce flight opportunities and only sporadic access to orbit. Access to the permanent ISS will significantly expand the envelope of opportunity for space-based entrepreneurship. With a continually operated and accessible ISS, commercial interests can now begin planning how to best use the environment of space to their advantage, bringing about the next boom in space development.

Research on board the ISS may lead to a new generation of space products, processes, and services. Space research holds the key to a plethora of benefits that span industrial sectors. Further research into the physiology of plants might lead to a new category of plant-based pharmaceuticals. Work in gravitational biology and ecology could show us ways to design hardier, disease- and drought-resistant crops. Crystals grown in space may improve catalysts used to extract oil, enhancing the yield of American petroleum. The use of microgravity and vacuum-production techniques in space could be responsible for a new generation of highly pure and accurate semiconductors for use in our electronics. Protein crystals grown in space already serve as models for highly targeted pharmaceuticals for the world's deadliest diseases. Demand for resources such as power and data handling may spur new space services such as commercial space power companies. Knowledge from Shuttle and ISS research will

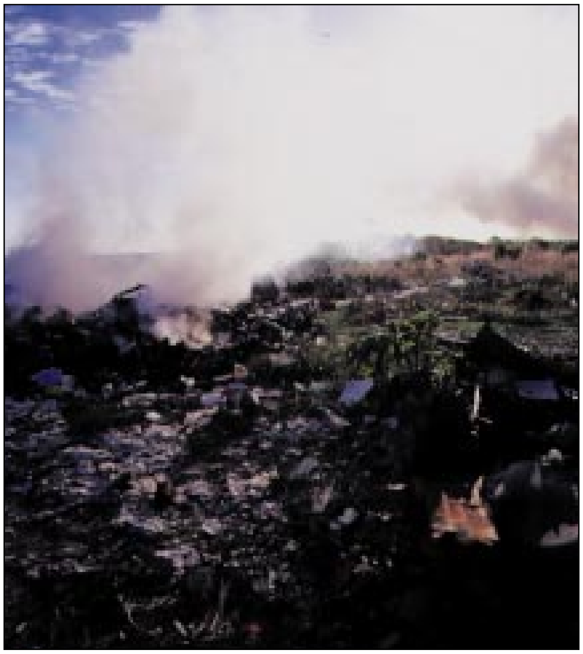
ISS Research



NASA and its industrial partners will research tomorrow's products today on board the ISS; a bull market for space in the early 21st century could fuel the next great step in space exploration and development.

blossom next century into the development of space infrastructure. For all these reasons and more, the ISS will serve as a laboratory and testbed for the development of new processes, products, and services to benefit life on Earth and in space.

NASA is vigorously preparing for the approaching day when the ISS "opens for business." Unprecedented in-house research is under way, in cooperation with the financial investment community and consumer product companies, to determine the most effective means of bringing the rigor of the private capital markets to bear on identifying and underwriting the most promising new business propositions. It is NASA's objective to deliver the much-needed laboratories and testbeds, initially assign at least a third of the U.S. share of ISS accommodations to the U.S. private sector, and then get off the critical path to product commercialization.



NASA research on solid waste processing for human life-support systems in space has led to a highly effective method for toxic waste removal. This technology, called supercritical wet oxidation, is now commercially available from MODAR Corporation. It is currently being used by the U.S. Department of Defense in a pilot study on toxic waste cleanups associated with chemical weapons.

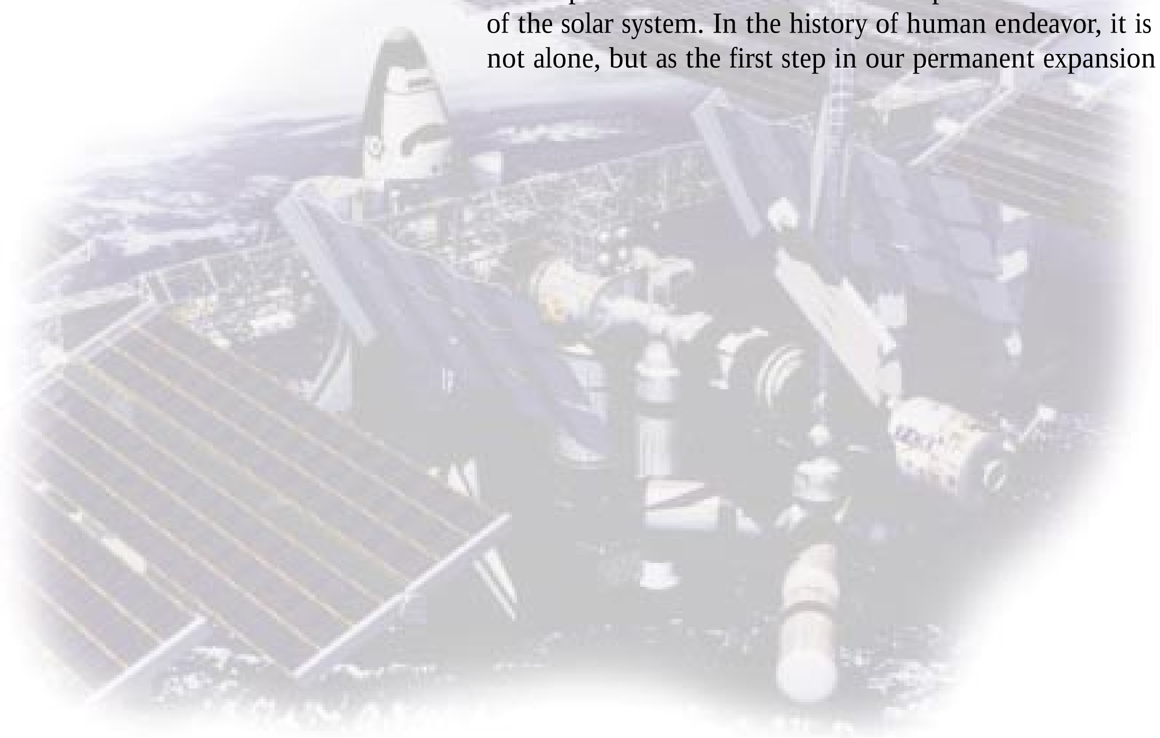
Many commercial payloads will fit into specialized experiment racks designed to service a number of diverse, moderate-sized payloads. These racks are named EXPRESS, for EXpedite the PRocessing of Experiments to Space Station. The idea is to provide multiple users with a simple, standard interface to plug into ISS research capabilities, such as power and data handling. The ISS will support four EXPRESS racks during its period of assembly in support of early research capability. In addition, during this time two EXPRESS pallets will be attached to the outside of the station to support exposed payloads; one of the EXPRESS pallets is already known as the Technology Experiment Facility.

Putting Space to Work for Us

The ISS is an unmatched multinational endeavor in science, technology, and industrial cooperation. Governments, corporations, and academic institutions around the world are collaborating on a project of a magnitude and breadth never before attempted on an international scale. What we once took for granted we now know to be an important and manageable variable in scientific and technological inquiry. Gravity influences almost every physical, chemical, and biological process that surrounds us. The ISS represents a unique opportunity to delve into the unknown intricacies of gravity's effect on our world. As astronauts and cosmonauts live and work above our planet, Earth-bound citizens will use the tools of telecommunications and information technology to enjoy a virtual presence on board the ISS, conducting ISS research without leaving the convenience of their classroom, boardroom, or laboratory.

As the Station progresses through assembly into full research operations, we should begin to see the very tangible benefits the work performed on the ISS will bring to our lives. As the Station fulfills its roles as an advanced testbed for technology and human exploration, a world-class research facility, and a commercial platform for space development, results from its research will be applied on Earth for everything from new pharmaceuticals to improved cutting tools for our Nation's industries. Whether through improving industrial processes, advancing the state of scientific knowledge, looking after our health, enabling a vigorous program of space exploration, or researching tomorrow's products today, work performed on board the ISS will benefit the citizens of the United States and our global partners by taking full advantage of the unique environment of space.

Ultimately, our experiences, research results, and technology validation efforts on the ISS will be put to use as our Nation and its partners take the next steps in the human exploration of the solar system. In the history of human endeavor, it is our intention that the ISS stands not alone, but as the first step in our permanent expansion beyond Earth orbit.



Part II

Excerpts From the Research Agenda for the International Space Station

COMBUSTION

- How can we reduce the pollution generated by the burning of various fuels?
- How can we improve the efficiencies of combustion processes?
- How can we prevent unwanted fires and explosions?
- How can we use combustion processes to produce new high-value products?
- How can we use combustion processes to destroy hazardous wastes in a safe, nonpolluting fashion?

FLUIDS

- What role do fluid mechanics play in biological processes such as protein crystal growth and fluid flows in the human body, and how does variable gravity affect the transport of fluids?
- How do solid-like to fluid-like transition behaviors in granular materials affect geomechanics applications (such as earthquakes and "quick" soil conditions)?
- How do magnetic and electric forces affect fluid transport in variable gravity environments?
- How can the application of these forces affect the properties of fluids for the development of new terrestrial and space-based technologies?

MATERIALS

- How does a solid first form from a liquid or vapor, and how is that formation influenced by impurities, free liquid surfaces, and containers?
- How can microgravity and vacuum experimentation help us to develop mathematical models that are sufficiently realistic to advance our understanding of the processing of materials?
- What are the values of the thermophysical properties of materials (such as thermal conductivity, surface tension, and viscosity) that control the relevant processes, especially in liquids?
- Heat and mass (atoms) can move in response to various types of stimuli (such as temperature differences, and concentration differences). How can these various transport phenomena that are important in materials processing be distinguished and understood?

- What is the role of these various transport phenomena in the generation of defects (flaws in a material ranging in size from microscopic to visible to the naked eye) as a material forms?

Gravitational Biology and Ecology

- How do living things sense and respond to gravity at the molecular, genetic, and cellular levels?

- What role does gravity play in the development of plants and animals?

- What are the long-term (multigenerational) consequences of exposure to low gravity?

Earth System Science

- What are the nature and extent of land-cover and land-use changes and the consequences for sustained productivity?

- How can we enable regionally useful forecasts of precipitation and temperature on seasonal to interannual timeframes?

- Can we learn to predict natural hazards and mitigate natural disasters?

- What are the causes and impacts of long-term climate variability, and can we distinguish natural from human-induced drivers of climate change?

- How and why are concentrations and distributions of atmospheric ozone changing?

Space Science

- What physical processes take place in extreme environments such as black holes?

- How did the universe begin, and what is its ultimate fate?

- How and why does the Sun vary, and how do the Earth and other planets respond?

- How is the evolution of life linked to planetary evolution and to cosmic phenomena?

- How do galaxies, stars, and planetary systems form and evolve?

Protein Crystal Growth

- What are the fundamental factors influencing protein crystal formation and growth, and which of these factors are responsible for increasing the quality of protein crystals grown in microgravity?

- How can the work done on protein crystal formation and growth in microgravity be extended to protein work on Earth?

- How can we extend our work on protein crystals in microgravity to more complex systems, such as glycoproteins, lipoproteins, and integral membrane proteins?

Cell Culture

- How can cell and tissue culturing be improved in microgravity, and how can we extend that to work here on Earth?

- What are the limits of cell culturing in ground-based bioreactors, and are these limits exceeded in the microgravity environment?

- Is the bioreactor useful for investigating environmental health issues that arise in space?

- Can we grow tissues in the bioreactor to support human viability on interplanetary missions; how do we apply that knowledge to Earth?

Biomedical Research

- How does the space environment affect human physiology, and what additional health risks will occur with space flight?

- What are the long-term consequences of exposure to space radiation for humans?

- How does microgravity and the space environment affect human behavior and performance?

- Is space flight a reversible model of the effects of aging on Earth?

Medical Care in Space

- What are the effects of the microgravity environment on utilization, route of administration, metabolism, elimination, and efficacy of medications?

- How do bone, muscle, and connective tissues react to stress and injury in the microgravity environment; what countermeasures can prevent such injury; and how can we best heal and rehabilitate these tissues after stress and injury in space?

- Can successful cardiopulmonary resuscitation and other methods of advanced cardiac life-support be done in flight?

- What best procedures should be implemented to preserve blood and blood substitutes, and how should blood losses be treated, in light of “space anemia”?

- What are the appropriate astronaut selection criteria to ensure crew compatibility on long-duration missions, including those with international and multicultural crews?

Advanced Human Support

- How do life-support technology components interact with each other and with the crew over the long term in a closed microgravity environment?

- How can missions take advantage of recent revolutionary advances in microelectronics and biological/chemical sensing technologies to unobtrusively maintain a safe crew environment?

- What tools and techniques are best suited for humans to use in microgravity during long-term space flight?

- How can we enhance human performance in space flight?

- How can we reduce the cost of maintaining humans in space?

Commercial Product Development

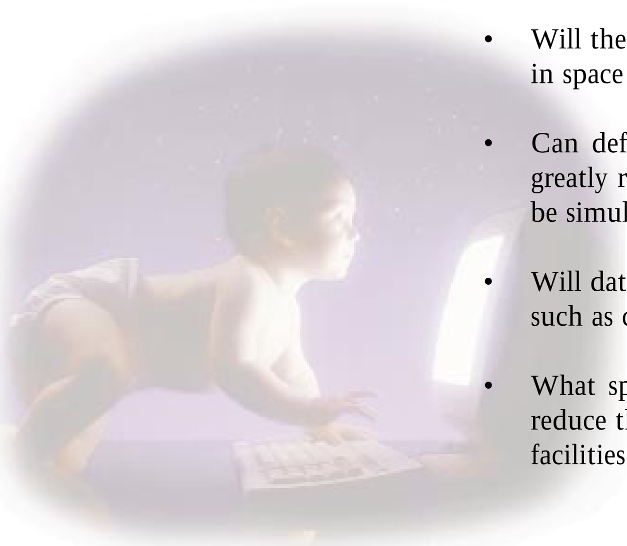
- How can we best apply the answers to the above research questions to develop more competitive products, create jobs, and improve our quality of life here on Earth?

- Will the growth of protein crystals, cell cultures, plants, and other biological materials in space lead to better commercial products that can be produced on Earth?

- Can defects in polymer materials—ranging from optic fibers to contact lenses—be greatly reduced or eliminated in space-produced materials, and if so, can this process be simulated in ground laboratories and manufacturing facilities?

- Will data from materials research in space lead to the development of better products, such as cutting tools, catalysts for the chemical industry, and fiber optics?

- What space manufacturing activities can be conducted profitably, and how can we reduce the costs of accessing and operating in space so that more space manufacturing facilities can operate profitably?



Part III

Serving Our Customers

ALLOCATING PRECIOUS RESOURCES

Access to experiment resources on the ISS will be a precious commodity. Work performed on the ISS will be a mix of scientific, technological, and applications-oriented research; a balance is sought among fundamental science, technology development, commercial investigations, and even educational uses. NASA intends to manage the allocation of Station resources with a variety of protocols that will adapt as Station operations mature and as we reassess our research priorities.

Scientific investigations for the ISS are already being solicited through annual NASA Research Announcements. Experiments chosen for flight must be thoroughly ground-tested and reviewed for scientific soundness, feasibility, and readiness for flight; this is done via a peer-reviewed system of selection. The principal elements considered in the evaluation of proposals solicited by a NASA Research Announcement are intrinsic merit, relevance to NASA's objectives, and cost.

NASA will use a variety of methods to select commercial projects for flight on board the ISS. One of the more established means is through NASA's designated Commercial Space Centers (CSC). When an industrial interest becomes convinced that a space research activity is of potential economic benefit, it can approach a CSC with a proposal.[2] This partnership generally begins with "expert-to-expert" discussions and progresses to an industrial commitment, the development of a research plan, and the identification, modification, or development of research hardware. Selection for flight is based on the relative contribution of the industrial partner and its plans for applying and marketing the knowledge gained from flight experimentation.

IN THE SPIRIT OF COOPERATION

Each cooperating government partner (the United States, Russia, the European Space Agency, Japan, and Canada) is allocated a share of Station resources in accordance with its contribution to the program. The partners then use internal mechanisms to parcel out space and research capability to their scientific, technological, and commercial interests. In addition to the majority of the attached payload sites, the United States will have the use of the U.S. Laboratory module and 46.7 percent of the European and Japanese pressurized laboratory space. To coordinate their research objectives, the partners have established bilateral and multilateral working groups. These working groups are investigating the advantages of equipment sharing, the pooling of resources, and the standardization of procedures. In an effort to ensure compatibility of research hardware and scientific equipment, all partners will use "International Standard Payload Racks," into which the majority of scientific facilities and hardware will fit. As experimental fields progress, ISS research equipment will be exchanged to meet the changing needs of the scientific, technical, and commercial communities.

Protocols, procedures, and hardware will be modified over time to meet evolving research needs. Toward this end, the research program is closely coordinated and integrated with the international partners, allowing them full access through the NASA Research Announcement

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[2] See *http://www.hq.nasa.gov/office/olmsa/spd/index.htm* for a complete and current listing of the Commercial Space Centers and their descriptions.

process to compete for the use of NASA ISS facilities. Through this process, we also ensure that their capabilities are factored into our plans to avoid duplication of hardware and maximize Station-wide research capability.

LOOKING FOR BUSINESS

NASA's investment in the ISS is creating opportunities for commercial interests to benefit and profit from space. Much as the railroad forged the way West earlier in U.S. history, the ISS infrastructure is opening the space frontier. Commercial interests are already active on the space frontier, as ISS experiments are even now being developed cooperatively between NASA and industry. As the value of space products is realized in areas such as materials processing, drug design, and space services, companies will provide their own proprietary hardware and pay their share of launch costs. Certain companies may form consortia to invest in unique, onorbit facilities that can be leased to other users.

As traffic increases on the highway to space, industry will invest in orbital infrastructure, perhaps beginning with an ISS-serviced, free-flying platform dedicated to commercial research and space product manufacturing. Next, commercial interests will add space operations to their portfolios. The government-developed ISS infrastructure is already being privatized so that industry can run the operations and provide mission services *for profit.* Demands for private research in space will require more resources on orbit, such as electrical power, crew time, and experiment space. Here, industry will recognize additional opportunities and respond with commercial endeavors with titles such as *Space Power, Inc.* In some cases, industry will invest in space infrastructure products—such as self-inflating, ready-to-use modules—where profits are realized not through their space-based sales, but through the sales of Earth-based versions for camping, exploring (on Earth), and disaster relief.

Beyond their role in businesses, private individuals will participate in the ISS via virtual reality, using virtual work stations to feel as though they are actually on board the ISS. Hopefully one day, popular interest and entrepreneurship will open the space frontier to tourism. Meanwhile, NASA will build on the Shuttle and ISS experience as the Nation expands the space frontier beyond low-Earth orbit. Industry will be ready with commercial products to feed, house, and even entertain space travelers. Only when commercial entities predominate in low-Earth orbit will we be able to truly say that the space frontier is *open for business.*

Educational outreach is an important component of NASA's mission. Some experiments on board the ISS will be taken at the request of our schools. This image of the Israeli coast was taken from the Space Shuttle at the request of Burst Academy School in Charleston, South Carolina.

EDUCATING FOR THE FUTURE

The ISS will provide a "window of opportunity" for assisting educators in promoting academic scholarship and in achieving systemic reform in science classrooms. Educators will utilize the ISS as a relevant, real-time learning tool that demonstrates the essential role of science in daily life. Through the use of telescience capabilities, the ISS promises to be the ultimate field trip, experiential lab tour, and research demonstration of scientific processes and concepts. Investigations performed aboard the ISS in the microgravity environment of space will enable educators to engage students in a fresh approach to discovering science facts, becoming acquainted with what scientists and engineers do, and experiencing the interdependency of science and technology necessary for communicating potential solutions to complex problems. The ISS will exemplify science as collaborative research efforts dedicated to examining current issues and problems familiar to many students.

Part IV

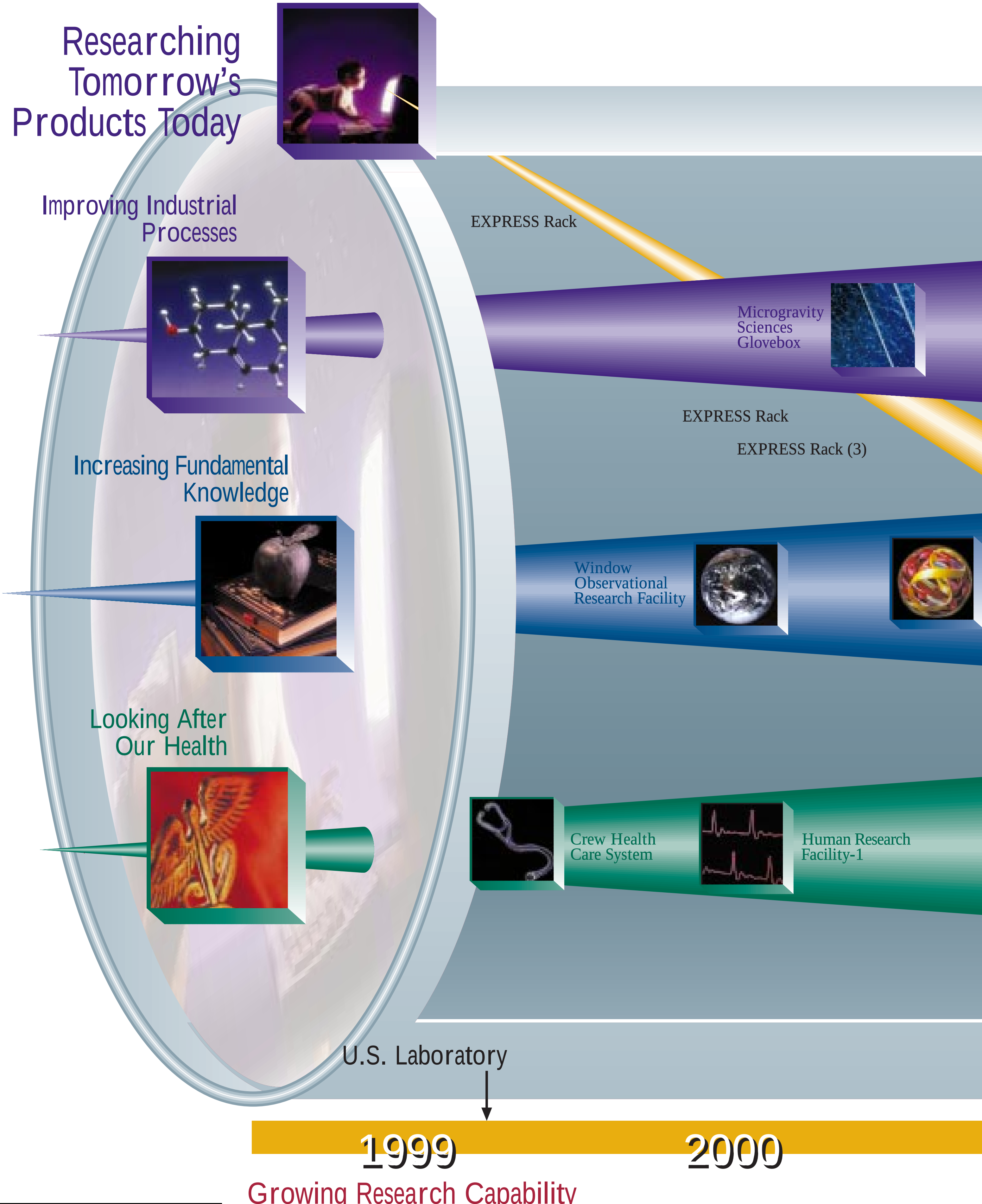
Research Capability Evolution

Outfitting the ISS for research operations will take place over a number of years. The U.S. Laboratory itself will be placed onorbit in 1999. Experimental facilities that fit inside the U.S. Laboratory and on attached sites will follow in subsequent years. As ISS assembly proceeds, NASA's onorbit research capability will grow commensurate with the deployment of additional experimental facilities. To plan and manage the growing research capabilities of the Station, NASA and the ISS partners maintain an evolving facility deployment and assembly schedule. This sequence may change as the ISS program and Station payload plans mature. Plans as of January 1998 call for the following annual growth in ISS research capabilities.

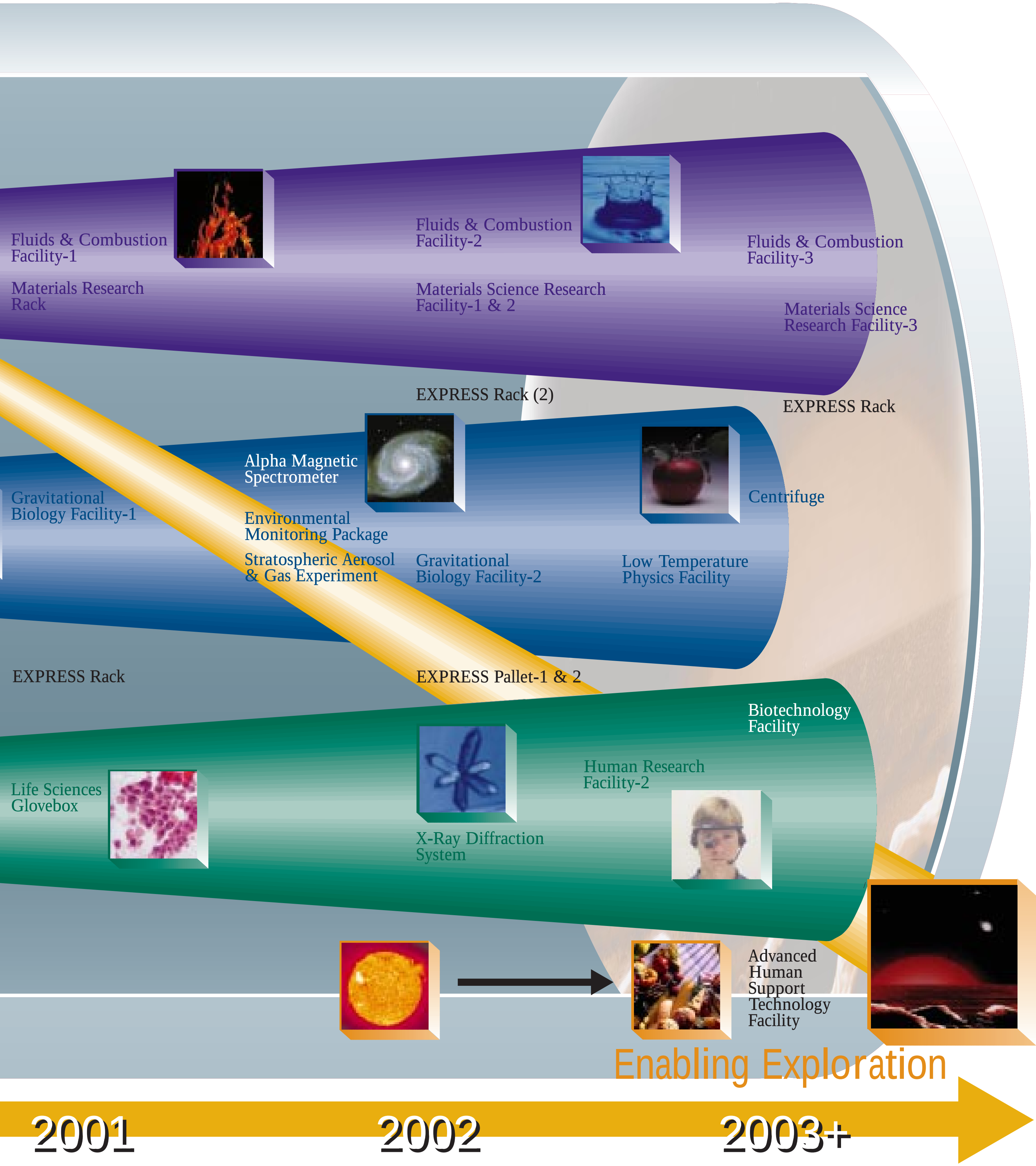
SCHEDULE FOR RESEARCH CAPABILITY BUILD-UP

FLIGHT	EQUIPMENT DEPLOYED	RESEARCH AREA
1999	EXPRESS Rack	Multidisciplinary*
2000	Human Research Facility-1	Biomedical Research
	Window Observational Research Facility	Earth Observations
	Microgravity Sciences Glovebox	Biotechnology, Combustion, Fluid, and Materials Science*
	EXPRESS Rack (3)	Multidisciplinary*
2001	Gravitational Biology Facility-1	Gravitational Biology & Ecology
	Materials Research Rack	Materials Science & Physics
	Fluids and Combustion Facility-1	Combustion Science
	Life Sciences Glovebox	Biomedical Research, Biotechnology, and Gravitational Biology & Ecology
	EXPRESS Rack	Multidisciplinary*
2002	Alpha Magnetic Spectrometer	Space Science/Space Physics
	Stratospheric Aerosol & Gas Experiment	Earth Science
	Environmental Monitoring Package	Space Science/Space Plasma Physics
	Gravitational Biology Facility-2	Gravitational Biology & Ecology
	Fluids and Combustion Facility-2	Fluid Physics
	Materials Science Research Facility-1 & 2	Materials Science
	X-Ray Diffraction System	Biotechnology/Gravitational Biology*
	Human Research Facility-2	Biomedical Research
	EXPRESS Pallet-1 & 2	Engineering Research*
	EXPRESS Rack (2)	Multidisciplinary*
2003	Low Temperature Physics Facility	Fundamental Physics
	Centrifuge	Gravitational Biology & Ecology
	Biotechnology Facility	Biotechnology/Gravitational Biology*
	Fluids and Combustion Facility-3	Fluids & Combustion Science
	Advanced Human Support Technology Facility	Life Support/Environmental Monitoring
	Materials Science Research Facility-3	Materials Science
	EXPRESS Rack	Multidisciplinary*

* Denotes commercial participation as of December 1997.
The Crew Health Care System will be deployed in 1999 on assembly flights; while contributing to biomedical research, the system's primary purpose will be to serve the operational health needs of the astronauts.


Researching Tomorrow's Products Today
Improving Industrial Processes
Increasing Fundamental Knowledge
Looking After Our Health
EXPRESS Rack
Microgravity Sciences Glovebox
EXPRESS Rack
EXPRESS Rack (3)
Window Observational Research Facility
Crew Health Care System
Human Research Facility-1
U.S. Laboratory
1999
2000
Growing Research Capability

Roadmap for Research Capability Evolution



Measuring Performance

The ISS is an investment in our Nation's future. Success in this endeavor must be measured in terms of the return on our investment. The *inputs* necessary to generate this return are the ISS research instruments (facilities), ISS resources (power, data-handling, communications, crew time), and access to space. As shown on the Roadmap for Research Capability Evolution, as ISS assembly proceeds, the research input to the Station will grow as additional experimental facilities are launched and more crew time and station resources are freed from immediate assembly needs.

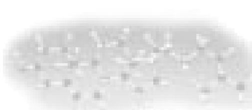
In the *near term,* metrics designed to measure Station research capabilities and outputs will be used to assess the productivity of ISS research and to determine whether the Station is providing us the best possible return on our investment. Measurable *output* indicators include actual commercial product opportunities, scientific publications, and new educational materials, textbooks, and programs.

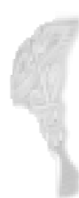
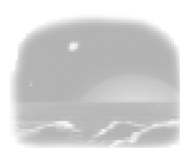
As our research output grows, so will the implications of ISS research for our society. *Intermediate-term outcomes* are represented on the Roadmap by the three research benefit areas: improved industrial processes, better understanding of the world around us, and improvements in looking after our health.

Ultimately, we will measure the Station's performance in terms of its *long-term impacts* on our society: the development of commercial products to better life on Earth and the attainment of fundamental, operational, and technical advances that will enable human exploration. These impact areas are represented on the Roadmap as the bounding sides of the cylinder that "contains" our growing research capabilities.

The following chart summarizes the ISS performance factors:

today	Inputs	• ISS research instruments (facilities) • ISS resources (power, data-handling, communications, crew time) • Access to space
	Outputs	• Commercial product opportunities • Scientific publications • Educational materials and programs
	Outcomes	• Improved industrial processes • Increased fundamental knowledge • Better health measures
tomorrow	Impacts	• Human exploration of the solar system • Building tomorrow with commercial products




Appendix:

Additional Reading

The following independently produced reports offer additional information on the topics discussed in this document:

Aeronautics and Space Engineering Board, National Research Council, *Advanced Technology for Human Support in Space* (Washington, DC: National Academy Press, 1997).

Aeronautics and Space Engineering Board, National Research Council, *The Capabilities of Space Stations* (Washington, DC: National Academy Press, 1995).

Aeronautics and Space Engineering Board, National Research Council, *Engineering Research and Technology on the Space Station* (Washington, DC: National Academy Press, 1996).

National Committee on Space, *Space for America: Meeting Needs in the 21st Century* (San Diego, CA: American Astronautical Society, December 13, 1995).

Space Studies Board, National Research Council, *Earth Observations From Space: History, Promise, and Reality* (Washington, DC: National Academy Press, 1995).

Space Studies Board, National Research Council, *Microgravity Research Opportunities for the 1990s* (Washington, DC: National Academy Press, 1995).

Space Studies Board, National Research Council, *Radiation Hazard to Crews of Interplanetary Missions: Biological Issues and Research Strategies* (Washington, DC: National Academy Press, 1996).

Space Studies Board, National Research Council, *A New Science Strategy for Space Astronomy and Astrophysics* (Washington, DC: National Academy Press, 1997).

Space Studies Board, National Research Council, *A Science Strategy for Space Physics* (Washington, DC: National Academy Press, 1995).

Space Studies Board, National Research Council, *Scientific Opportunities in the Human Exploration of Space* (Washington, DC: National Academy Press, 1994).

Space Studies Board, National Research Council, *Space Science for the Twenty-First Century: Imperatives for the Decades 1995 to 2015* (Washington, DC: National Academy Press, 1988).

Space Studies Board, National Research Council, *A Strategy for Space Biology and Medical Science for the 1980s and 1990s* (Washington, DC: National Academy Press, 1987).

Space Studies Board, National Research Council, *Toward a Microgravity Research Strategy* (Washington, DC: National Academy Press, 1992).

This document was developed by the NASA Enterprise for the Human Exploration and Development of Space (HEDS) through the Office of Life and Microgravity Sciences and Applications (OLMSA) with the assistance of the Johnson Space Center's Space and Life Sciences Directorate.

For more information on ISS Research, please visit the OLMSA web site at *http://www.hq.nasa.gov/office/olmsa.* Also visit the Station web site at *http://station.nasa.gov.*

A technical ISS Research Plan, with detailed flight-by-flight research capability buildup information, will be made available later in 1998.