RESEARCH AND SPACE MEDICINE ON THE INTERNATIONAL SPACE STATION

Introduction

The International Space Station (ISS) is a unique and unprecedented space research facility. Never before have scientists and engineers had access to such a robust, multidisciplinary, long-duration microgravity laboratory. To date, the research community has enjoyed success aboard Skylab, the Space Shuttle, and the Russian *Mir* space station. However, these platforms were and are limited in ways that the ISS is not. Encompassing a volume four times that of *Mir*, the ISS will support dedicated research facilities for at least a dozen scientific and engineering disciplines. Unlike the Space Shuttle, which must return to Earth after less than three weeks in space, the ISS will accommodate experiments that require many weeks—even months—to complete. Continual access to a microgravity laboratory will allow numerous scientific disciplines to progress at a rate far greater than that obtainable with current space vehicles.

In addition to basic scientific research, the ISS also allows us to assemble "survival skills"—a basic understanding of how to live and work in space. The human body faces multiple challenges in the space flight environment: physiological adaptations to microgravity, exposure to increased radiation, and psychosocial reactions to isolation in a confined environment. To ensure future safe, successful long-duration exploratory missions to other planets and beyond, we must learn to overcome the physiological challenges, as well as provide cutting-edge health care to space crews millions of miles from Earth.

This paper will examine the scientific research under investigation on the ISS. We will also examine the roles that specific elements of human space flight—the human factor, the system, and the environment—will play in ISS research and development.

Fundamental Research on the International Space Station

The International Space Station will serve as a unique, multidisciplinary, multinational laboratory facility that will allow sophisticated investigations to be conducted in the life and physical sciences. When completed, the ISS will include pressurized research laboratories, multi-user, discipline-specific research facilities, multidisciplinary EXPRESS racks and pallets, exposed research sites, a centrifuge, supporting equipment for power generation and operations, and at least 120 crew-hours per week for research operations.

The scientific research initiatives of the ISS have been derived in consultation with numerous scientific bodies. In addition, NASA has set aside 30% of its ISS facilities for commercial development. Research will begin with the arrival of the first crew in late 2000, even as the facility is under construction. When completed the ISS research program will address a wide range of disciplines, from fundamental knowledge into the behavior of fluids to all-encompassing views of the origin of the universe. ISS investigations will contribute applications to Earth industries—health care, fire safety, transportation, construction, and engineering, to name only a few. Table 1 presents a list of specific disciplines and research questions that investigators will explore.

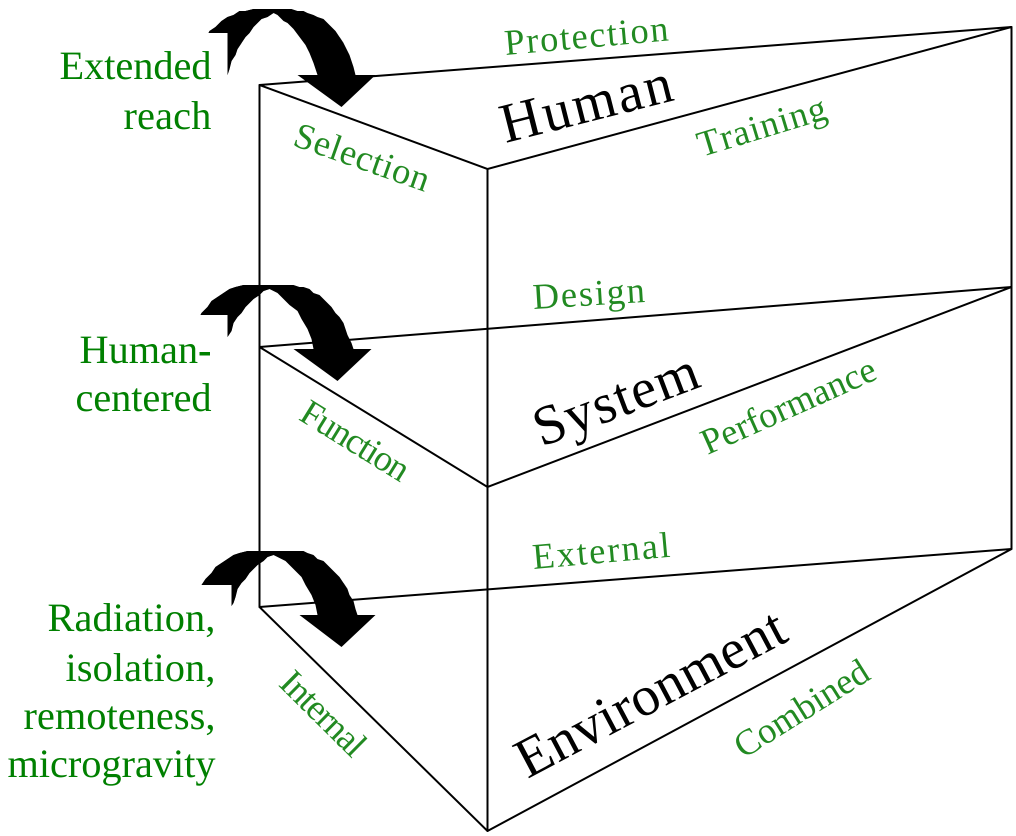
Table 1: Disciplines and Research Questions Addressed on the ISS

Discipline	Fundamental Research Questions
Advanced Human Support/ Biomedical Research & Countermeasures	What knowledge and technology are needed to allow humans to live and function productively in an environment away from the Earth's surface? How can this knowledge benefit medical care on Earth?
Biotechnology	Why do some macromolecular crystals show improved order when grown in space, and how can we utilize an understanding of the growth process to improve terrestrial efforts in structural biology? How does mechanical stress influence mammalian cell and tissue culture, and how can we apply advances in tissue culture technology to problems in biomedical research?
Combustion Science	How do the fundamental principles controlling the combustion processes vary with different fuels and in different environments? How can this understanding improve the efficiency of fuel utilization and minimize the emissions of pollutants and fire involved in these processes?
Fluid Physics	What are the fundamental physical principles controlling the behavior of fluids, and how can this understanding be applied to improve other scientific and engineering disciplines?
Fundamental Physics	Which experiments can be performed in low-Earth orbit to test the laws and theories of physics to limits that are unachievable on Earth? What resultant technologies are enabled by such experiments?
Fundamental Biology	What are the effects of altered gravity and other aspects of the space environment on the evolution, development, and function of living organisms? How do these effects impact the interaction of living organisms with their environment?
Material Science	How are the structure, properties, and processing of materials affected by gravity, and how can space-based research into materials science improve life on Earth?
Space Science	What is the origin and propagation of cosmic rays in the universe?
Engineering Research & Technology Development	What engineering advancements and new technologies will lead to enhanced capabilities on the ISS and the enablement of safe missions for humans to other solar system bodies?
Space Product Development	How can we apply the knowledge gained on the International Space Station to life on Earth?
Earth Science	How does the Earth environment change over time, and what are the causes of these changes?

ISS: Enabling Space Exploration

The ISS is not only a facility to enable research in the space environment, it is a facility where scientists and astronauts must live and work for several months at a time. To ensure the safety, productivity, and success of ISS missions, NASA health care providers and engineers have taken a three-fold approach: the monitoring of crew health, system function, and environmental parameters. Figure 1 depicts this approach and the specific factors that affect each area. The human factor—the astronauts—are carefully selected, trained, and protected so that we may safely and successfully extend our reach into the solar system. The function, design, and performance of spacecraft systems allow crews to respond to and overcome the challenges of the internal and external space flight environment. These efforts are designed to maintain a healthy and productive work environment for crews in the unique environment of space.

Figure 1: Interaction of Human, System, and Environment in Mission Planning
(From Nicogossian 1984)



The Human Element: Human Factors Research

While the duration of ISS missions brings the ability for long-term scientific research, it also introduces new questions for the astronauts and scientists who will be on orbit for longer durations. As the frequency, complexity, and duration of human journeys into space increase, human factors research and development will grow more and more important to the success of the mission. Isolation and confinement, combined with high performance demands, may adversely affect astronaut performance and, in turn, mission success. Longer duration missions will also call for greater ground support and troubleshooting assistance. Implicit in minimizing risk is that all machinery, equipment, and humans work together as safely and effectively as possible. To accomplish this, the Human Factors program within Advanced Human Support Technology (AHST) seeks knowledge of human capabilities and limitations. Through basic and applied research and technology development projects, the investigations seek to reduce human error and the resulting problems.

The research areas identified within the program include perception, cognition, human physical performance, habitability, and personal, interpersonal and group dynamics.
In perception research, NASA is developing mathematical models of human perceptual systems, such as vision, pattern perception, audition, motion perception, and spatial understanding. Using these models, we can better understand the causes of such physiological alterations in space as space motion sickness (SMS). The Human Research Facility, one of the first life sciences payload racks scheduled for the ISS, will include the Eye Tracking Device. This tool will collect data on the wearer's eye and head movements to determine what types of motions tend to induce SMS. Another perception research direction is the development of haptic systems (devices allowing humans to interact with machines) in general, and in the development of computers with the sense of touch and kinesthesia in particular. These finely-tuned systems hold much potential for operations involving distances, for example medical procedures and operations.

As astronauts and cosmonauts spend greater lengths of time in space on the ISS, they will encounter psychological challenges. Cognition research investigates crewmembers' situational awareness of their mission, tasks, and normal living functions in space. This research also takes workload, sleep, and habitability of the facility into consideration. Another aspect of cognition research evaluates the usability and effectiveness of human-machine interfaces. These concerns address interfaces with robotic systems, interfaces for repair and maintenance procedures, and interfaces with a variety of automated and semiautonomous systems, such as science experiments, vehicle systems, and landing controls.

Human physical performance monitoring—data and monitoring of human strength, stamina, fatigue, and motor skills—has been ongoing since the start of the space program. Building upon data gathered from the Shuttle/*Mir* program, the ISS will provide an even longer duration over which to observe how the human body responds to the reduced-microgravity environment of space. These data help in the development of effective countermeasures and in the understanding of how specific physiological/biochemical systems operate in space as opposed to on Earth.

The interaction of the crewmembers is critical to mission success. As the ISS will allow for longer durations in space and involve scheduled crewmember switches, reserachers are investigating personal, interpersonal, and group dynamics. Personality measures, performance monitors, effects of various command structures, team decision making and cooperation strategies, cultural diversity issues, and evaluation metrics are specific areas of current research.

Fundamental habitability issues are also under investigation. The overriding concern in this area is the maximization of physical and psychological health of the crew, taking specific factors as food, environment, clothing, noise levels, privacy, recreation, and hygiene into account. Although we have been working to fully address these issues since the first orbital flights, we require additional improvements to minimize the stresses that can affect mission success.

In concert with current research into human factors, researchers are working to develop technologies that ensure optimal conditions and usage in flight. This research takes place in the areas of advanced displays and controls development, human-machine function allocation, human interaction (with other humans and with intelligent machines, intravehicular and extravehicular activity), and analogue studies in training facilities and high-fidelity mock-ups. The capabilities derived from these areas will provide long-duration space crews with equipment to carry out their missions efficiently and effectively.

Environmental Systems

The microgravity, radiation, vacuum, and isolation of the space environment present special challenges to mission planners. The remote and closed environment of spacecraft puts special emphasis on systems that sustain a habitable environment with a minimum of outside support. Consumables such as air, food, and water must be regenerated or resupplied. The spacecraft environment must be kept clean from waste and contaminants, and must perform effectively while minimizing volume, mass, power, thermal controls, and crew time requirements. The Advanced Life Support (ALS) program within AHST develops regenerative life support systems that provide the basic functions that sustain life and are directed at long-duration missions. These systems combine physical, chemical, and biological components to provide for a safe, reliable, and habitable environment.

With its current design, the International Space Station will be a nearly closed-loop life support system, where supplies and environmental components (air, water) are resupplied as needed. Current technology is capable of recovering water from humidity condensate, hygiene water, and crew urine at 80-90% efficiency. However, researchers are still developing systems to regenerate food and air from waste. As research progresses and effective technologies develop, the Station will be upgraded to become a more self-sufficient, completely closed-loop environment.

NASA currently directs research in waste water treatment, contaminant removal and neutralization, oxygen regeneration, food production, and solid waste management. Researchers are also developing sensor technologies to monitor the spacecraft environment, and to measure and identify a range of contaminants. Research also examines how to minimize the production of wastes and chemical and biological contaminants. Using closed environments as ground-based analogues to space, NASA will continue to develop the technologies to fulfil these functions.

Space Medicine: Systems to Help the Human Survive the Environment

The International Space Station will enable longer stays in space, as well as longer periods over which studies can be conducted. Accordingly, this presents challenges to a crew on board the ISS who will need a highly reliable and efficient way to ensure its health. The ISS will be an active testbed for advanced technologies and improvements to current medical capabilities, serving as a springboard to enable future long-duration missions into deeper space.

Possibilities do exist that ISS crew will encounter medical situations that exceed the capabilities on board the facility. Should the patient be put in a potentially life-threatening position, the problem exceed the crew medical officer's capability, or the illness be exacerbated by a lack of on-board equipment or supplies, then a focused decision should be made about how to proceed. Real-time decision making will involve the mission commander, the crew surgeon, the flight director, and the mission management team. If evacuation is necessary, then the crew will be able to employ escape vehicles to return safely to Earth. The Russian Soyuz capsules are planned to be utilized for this purpose, as well as Space Shuttle if immediately available or the Crew Return Vehicle (CRV) currently under development.

Space medical systems are evolving from mechanical and human-dependent machines into semiautonomous and adaptive systems. With the goal of long-duration space exploration, however, another phase of evolution must occur. Capitalizing on innovations in this field, space medicine investigators are examining methods to effectively address medical care challenges as well as the logistical constraints of time and distance, thereby ensuring the health of the crew and mission success. Medical care for long-duration mission crew members require minimally invasive approaches, smart systems and intuitive interfaces, miniaturized systems with low power requirements, and reliable, maintainable tools than can be used in all pressurized vehicles.

To meet these requirements for use and test on the International Space Station, rapid progress is being seen in portability and miniaturization, nanotechnology, virtual reality, biologically-inspired technology, and haptic "smart" systems. Miniaturization and portability of instruments allow medical diagnosis and treatment when the patient is far from the physician. This will indeed be the case for those aboard the ISS. The NASA "smart suit," for instance, also known as the "range-of-motion" suit or the anthropometric measurement suit, senses the position of the wearer's limbs and movements. Data is fed into a computerized database and the wearer's movements can be modeled and analyzed in real time. In addition, a miniaturized blood pressure monitor has been developed to monitor astronaut blood pressure semi-automatically. It permits highly accurate blood pressure measurement, even by untrained personnel. And importantly, at a weight of only six pounds, it can be carried anywhere.

Both medical informatics and telemedicine have been used since the first days of the space program. Medical informatics is the technology that allows for the synergy of operational strategies, policies, and procedures and electronic data capture, sharing, transmission, and retrieval. Combined with telemedicine—the real-time transfer of medical information, data, and expertise over a distance—astronauts are able to receive comprehensive medical support from the ground crew and flight surgeons. The Telemedicine Instrumentation Spacepack (TIP), for instance, provides a suitcase-sized comprehensive suite of medical diagnostic equipment to survey the health of the astronaut and communicate that data back to physicians on Earth. The ISS will be equipped with the Crew Health Care System (CHeCS) to provide the ISS crew with routine health care, advanced life support, and partial countermeasures to the physiological effects of microgravity. In addition to basic medications and intravenous delivery tools, the CHeCS system will also include a heart monitor, defibrillator, respiratory support pack, blood pressure monitor, and medical equipment computer to collect and download data to flight surgeons. However, constraints of bandwidth and signal delay still exist, especially beyond low-Earth orbit, so crewmembers must be medically trained to respond to any situation, normal or emergency. Astronauts on the ISS will have undergone extensive training to effectively use the medical technology available to them, and they will undergo periodic retraining while on orbit to refresh their memory and skills.

Nanotechnology is a specialized form of miniaturization. While traditional miniaturization makes existing technology smaller, nanotechnology is building small technology from the level atom and up. This capability has particular application in space medicine for life support – it can create highly sensitive sensors and effectors. In addition, medical care applications of diagnostic probes, treatment and delivery, and tissue replacement will improve. Another avenue for this technology, not necessarily related to space medicine, is autonomous exploration. This idea involves use of a robotic probe, or "human on a chip," with the programmed capability of human observation. This capability would allow for human exploration of environments in which a human could not survive.

Next-generation virtual reality (VR) simulators are rapidly expanding capabilities for pre-flight and in-flight training. These VR simulators allow interaction in an environment on the other side of the planet, the other side of the solar system, or in a completely computer-generated "virtual" environment. This capability can be extremely helpful for mission preparatory training, planning for future needs and potential situations, and testing system and operating procedures before and during a mission. The area of immersive robotic surgery allows a surgeon to be inside a virtual environment. Wearing a VR headset, the surgeon "sees" the patient in front of him and uses robotic haptic tools to perform the surgery. This technology will be particularly useful in emergency scenarios for the ISS, in cases where the crew on board are not medically trained to perform an operation or procedure.

Haptic systems create a virtual environment that provides the user with feedback input from a remote location. This capability will allow a smart interface that will nullify distance as an inhibiting factor. For example, cybersurgery would allow the surgeon to "feel" in the virtual environment what the robotic probe in the actual environment is encountering.

Biologically-inspired technology takes design principles from living systems and translates them into adaptive, anticipatory, collaborative, self-modeling, and self-repairing systems. These characteristics aid in the creation of human-centered systems, robotic systems, and smart materials and structures – all of which will contribute to the space medicine systems of future exploration. Such applications include systems to maintain spacecraft operator alertness; cognitive prostheses; artificial hair cells and sensors; motor proteins as molecular cargo; artificial neural devices; and artificial trunks, tentacles, worms, snakes, and whiskers.

These technologies are currently under development. In the isolated and extreme environment of space, these technologies will help ensure the safety and health of crewmembers on the ISS and in future missions that take crews far beyond low Earth orbit.

Concluding Remarks

As the International Space Station enters the assembly phase, we are clearly on the verge of a new era in scientific research. In some instances, experimentation on the ISS will better allow us to seek solutions to overarching questions that have puzzled scientists for centuries. As we seek out these answers to important questions in science and technology, we will undoubtedly uncover new and exciting branches of research that may cause us to refine—perhaps even alter—our questions and their priority. In addition, the knowledge and capabilities we discover as we strive to ensure crew health and safety will translate into new medical technologies to improve health care on Earth.

We do believe that the questions with which we begin today have set us upon the correct path. The peer-review process will continue to guide us in the selection of the most scientifically sound hypotheses to be tested on the ISS. The scientific and technological communities will continue to send their best and brightest to this research platform; they will be armed with innovative approaches that maximize the value of the ISS and its potential for discovery. As we embark upon our journey of discovery in this new era, we will confirm our current knowledge of our world and universe and continue asking ourselves questions about what lies beyond our immediate home on Earth. We will also continue to disseminate the results and benefits of space research. This approach to the utilization of space as a scientific and outreach resource will lead to the evolution of tomorrow's advanced technologies, the development of new and exciting industries on Earth, and an improved quality of life for each of us.

References

Space Studies Board, National Research Council, 2000. *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies*. National Academy Press, Washington, DC.

Space Studies Board, National Research Council. 1998. *Report of the Workshop on Biologically-Based Technology to Enhance Human Well-Being and Function in Extended Space Exploration.* National Academy Press, Washington, DC

National Aeronautics and Space Administration. 1998. *The International Space Station, Improving Life on Earth and in Space: The NASA Research Plan, an Overview*.

National Aeronautics and Space Administration. 1998. *The Phase I Program: Preparing for the International Space Station.*

Committee on Use of the International Space Station for Engineering Research and Technology Development, Aeronautics and Space Engineering Board, National Research Council. 1996. *Engineering Research and Technology Development on the Space Station*. National Academy Press, Washington DC

Committee on Advanced Technology for Human Support in Space, Space Studies Board, National Research Council. 1997. *Advanced Technology for Human Support in Space*. National Academy Press, Washington DC

Nicogossian AE. *Space Physiology and Medicine NASA SP-477*. Government Printing Office: Washington DC, October 1984.